CORNEAL GROWTH IN THE NORMAL AND APHAKIC CHILD

A thesis

submitted by

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To my parents

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ABSTRACT

Previous studies relating to total astigmatism in the young were collected and reviewed. Information on the source(s) of this astigmatism was found to be scarce in infants and children. It was proposed to study the corneal astigmatism in subjects under 5 years of age which would involve making measurements of their corneal radii in the principal meridia.

Methods of measuring corneal radii were considered with particular emphasis placed on those suitable in young subjects. It was decided that photokeratoscopy would be the most practical method to be adopted for this study. A portable photokeratoscope was calibrated for use and its accuracy and reliability assessed. Strong linear relationships were found between the corneal radii and corneal astigmatism measurements obtained using the photokeratoscope and a conventional keratometer on 10 adult eyes.

The photokeratoscope was used to record the HVID, flattest and steepest corneal radii and corneal astigmatism from 1 eye each of 152 normal subjects aged 1 month to 5 years and from 1 eye each of 35 aphakic binocular congenital cataract subjects aged 1 month to 15 years.

In the normal eyes, the HVID was found to increase sharply up to 6 months of age after which there appeared to be little change. This increase with age was statistically significant. The HVID values recorded in males were also significantly higher than those recorded in females. The mean values of the flattest and steepest corneal radii were seen to increase up to 6 months of age but these increases were not statistically significant. No significant differences were also present between the sexes. The incidence of corneal astigmatism $\geqslant$1D was observed to decrease significantly with age. A reduction in the mean values of corneal astigmatism was also seen as age increased.

In the binocular congenital cataract eyes, the HVID values tended to be smaller than those observed in normal eyes up to the age of 5 years. The corneal radii values mainly fell in the range found in normal eyes. The majority of the corneal astigmatism measured in the aphakic eyes was between 1 to 3 D.

The results on normal eyes supported the view that a major cause of total astigmatism in subjects under the age of 3 years is corneal in origin.

SYMBOLS AND ABBREVIATIONS

°	Degrees
%	Percent
>	More than
<	Less than
al	Along
ATR	Against-the-rule astigmatism
cm	Centimetre
D	Dioptre
f	Female subject
FLOM	Fenestrated lens for optic measurement
HVID	Horizontal visible iris diameter
m	Male subject
max	Maximum
min	Minimum
mm	Millimetre
mo	Month
NI	Not indicated
nm	nanometre
N.P.L.	National Physical Laboratory
PMMA	Polymethylmethacrylate
s.d.	Standard deviation
W	watts
wk	Week
WTR	With-the-rule astigmatism
yr	Year

CHAPTER 1

INTRODUCTION

Total refractive astigmatism in the young has attracted much attention since Mohindra et al. (1978) and Howland et al. (1978) reported high incidences of total astigmatism $\geqslant$1D in children under the age of 2 years. As a consequence, this aspect of refractive error is now fairly well-documented in infants and children up to the age of 5 years. Whilst the cornea is established to be the main source of total astigmatism in adults (Duke-Elder and Abrams, 1970:274), a review of the literature showed that scarce information is available on corneal astigmatism in children under 5 years of age. The very few investigations relating to this aspect of the cornea were carried out by Blomdahl (1979) on newborn infants, York and Mandell (1969), Howland (1982a, b), Howland and Sayles (1985) on subjects aged from 0 to 6 years, and Woodruff (1969, 1971) on subjects aged from 2 to 6 years. The data of York and Mandell (1969) (who was not primarily interested in investigating corneal astigmatism in young corneas) was on a very small sample of subjects and thus was not conclusive. Woodruff (1969, 1971) reported an increase in the incidence of corneal astigmatism from 2 to 6 years of age whereas Howland and Sayles (1985) showed the opposite occurring from 0 to 5 years of age. These factors aroused the present author's interest to investigate corneal astigmatism in pre-school aged children. (In fact, at the start of the present study the data of Howland and Sayles, 1985 had not been reported yet, giving even less information available at the time.) In order to study the corneal astigmatism in young subjects, their corneal radii in the principal meridians would have to be measured first. Thus, it was hoped to be able to build a cross-sectional study on the variation of corneal radii and corneal astigmatism with age.

A critical period in which the eye is susceptible to visual deprivation has been shown in animal studies (Wiesel and Hubel, 1963a, b; Hubel and Wiesel, 1970; Dews and Wiesel, 1970; von Noorden and Crawford, 1979). This critical period has also been demonstrated in human studies by Taylor et al. (1979) and Vaegan and Taylor (1979). Knowledge of the critical period in humans is particularly relevant to the treatment of infants with congenital cataracts. Congenital cataracts are the most common cause of preventable blindness in infancy (Taylor and Migdal, 1982). Clinical experience on congenital cataract subjects indicate the need for early removal of congenital cataracts followed by prompt optical correction to reduce the effects of stimulus deprivation (Taylor et al., 1979; Vaegan and Taylor, 1979; Beller et al., 1981; Jacobson et al., 1981; Parks, 1982; Gelbart et al., 1982; Robb et al., 1987). Contact lenses of various types have been used and still remain the main method of optical correction in congenital cataract cases (Sato and Saito, 1959; Morris et al., 1979; Halberg, 1983; Matsumoto and Murphree, 1986; Pe'er et al., 1987; Pollard, 1987). Obviously, data on corneal dimensions is relevant in the design of contact lenses for these subjects but an examination of the literature showed that only 2 studies have been carried out in any detail on corneal radii and diameters in subjects with congenital cataracts (Enoch, 1972; Moore, 1987). (At the start of this study, only the data reported by Enoch had been available.) An attempt to collect corneal information from congenital cataract subjects was then started by the present author in order to supply more data on these subjects. It was hoped that the results from the congenital cataract cases would allow comparisons to be made with those cases with normal eyes who would also be examined in this study.

CHAPTER 2

TOTAL ASTIGMATISM IN INFANTS AND CHILDREN

2.1 Introduction

Astigmatism is defined as a refractive anomaly in which "no point focus is found owing to the unequal refraction of the incident light by the dioptric system of the eye in different meridians "(Duke-Elder and Abrams, 1970 : 274). The resultant sum of the astigmatism of all the components of the ocular refractive system or its total astigmatism is made up of curvature astigmatism of the anterior and posterior surfaces of the cornea, the crystalline lens, decentration of the optical system of the eye or variations in the refractive index of the crystalline lens (Borish, 1970 : 123-141; Duke-Elder and Abrams, 1970 : 274-292).

In the past, the majority of studies on refraction in infants have been concentrated on their spherical refractive errors. However, publications by Mohindra et al. (1978) and Howland et al. (1978) reporting high incidences of astigmatism amongst infants have created an upsurge of interest in this neglected field. As a result, there now exists considerable literature on the total astigmatism in the very young. These investigations have been collected together and are summarized in Table 2.1 . The term "astigmatism" used in this study will be used to denote the total astigmatism of the eye unless indicated otherwise.

Full-term healthy infants were involved in all the studies listed in Table 2. 1 except for those of Fletcher and Brandon (1955), Graham and Gray (1963), Hosaka (1963), Shapiro et al. (1980) and Dobson et al. (1981) who observed babies born prematurely. Mathew and Sawney (1970) observed both full-term and premature infants. Also included in the Table is a study by Rutstein et al. (1986) on the refractive astigmatism in a group of 18 normal birth weight infants and a group of 20 intrauterine growth retardation (IUGR) infants. IUGR is an intrauterine condition in which the full-term newborn infants is significantly retarded in weight at the time of birth. The major reasons for the weight retardation may be unknown in some cases but for others may included chromosomal disorders, intrauterine infections, maternal disease, and placental insufficiencies. The methods of determining the amount of total astigmatism for each study has been indicated and also whether cycloplegics had been used. Most of the earlier studies did not report the axes of the astigmatism detected but after 1980, an interest in this aspect of infant astigmatism was expressed by the researchers in this field.

Attention has to be drawn to 2 studies (Fulton et al. 1980; Dobson et al. 1981) included in Table 2.1 because of apparent discrepancies in their reported data.

The figures given for the number of infants and children investigated by Fulton et al. (1980) in the same report do not appear to tally with each other. Results shown on a Table at the end of their report indicate that the total number of infants aged between 0 to 60 weeks who were refracted was 75. However, earlier in the text (pp.24) these authors stated that "the number of normal youngsters with astigmatism in the first year was 71 (19.9 percent)." Furthermore, in the following paragraph on the same page, it is also stated that "when the data was combined over the first three years, 63 (16.8 percent) normal children.... were astigmatic." In Table 2.1 , the figures indicated for 0 to 60 weeks age group is copied from the Table given by Fulton et al. (1980) and those for the 60 to 109.9 weeks and 110 to 159.9 weeks age groups are taken from Figure 3 of their publication.

Dobson et al. (1981) also investigated the incidence of total astigmatism ($\geqslant$ 1D) in premature infants. Their results were summarized in Figure 3 of their report which suggested that 71 percent of the left eyes and approximately 66 percent of the right eyes investigated had astigmatism $\geqslant$1D. This contradicts the text where Dobson et al. report that 71.3 percent of the right eyes and 65.8 percent of the left eyes examined in the study showed at least 1D of astigmatism. The figures given in Table 2.1 are taken from the text of Dobson et al. and not from Figure 3 of their report.

Table 2.1 Investigation of total astigmatism in infants and children: Literature survey.

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D	>2D	Axis WTR ATR Oblique
Santonastaso (1930) as cited by Banks (1980)	0-1wk.	15	Retinoscopy, cycloplegia (Atropine 1%)	47	0	NI
	1-4wk.	14		79	0	
	1-2mo.	18		50	19	
	2-4mo.	16		75	17	
	4-6mo.	11		55	0	
	6-9mo.	24		33	17	
	9-12mo.	10		30	18	
	0-1wk.	15	Retinoscopy, no cycloplegia	60	28	NI
	1-4wk.	11		82	32	
	1-2mo.	16		56	21	
	2-4mo.	15		50	6	
	4-6mo.	10		45	14	
	6-9mo.	24		33	12	
	9-12mo.	9		27	0	
Cook and Glasscock (1951)	Newborn	1000 eyes	Retinoscopy, cycloplegia (Atropine 1%)	38 (Amounts of astigmatism detected NI)		NI
Fletcher and Brandon (1955)	Premature	NI	Retinoscopy, NI	"On retinoscopy it was found that these infants have a rather high cylinder (two to five diopters) which changes in degree as well as in axis from day to day."		
Meyeke et al. (1962) as cited by Mathew and Sawney (1970)	Newborn	250	NI	30.4 (Amounts of astigmatism detected NI)		NI
Graham and Gray (1963)	Premature	150	Retinoscopy, cycloplegia (Hyoscine 1%)	3	4	Not clear

Cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D	>2D	Axis WTR	ATR	Oblique
Hosaka (1963)	Premature	60	Retinoscopy, cycloplegia (Atropine 1%)	17	14	100	0	0
Mehra et al. (1965)	Newborn	100	Retinoscopy, cycloplegia (Atropine 1%)	NI	12		NI	
Gonzalez (1965)	Newborn	296	Retinoscopy, no cycloplegia	63 astigmatic) Amount of) astigmatism 74 astigmatic) detected NI			NI	
Woodruff (1969, 1971)		See Table 2.5						
Patel et al. (1970)	0 - 1 day	250	Retinoscopy, cycloplegia (Atropine 1%)	20 astigmatic (Amounts of astigmatism detected NI)			NI	
Mathew and Sawney (1970)	Premature Newborn	100 200	Retinoscopy, cycloplegia (Atropine 1%)	20 30		"Excepting 10 eyes all had hyper- metropic astig- matism with axis around 180^{o}"		
Zonis and Miller (1974)	2 - 3 days	300	Retinoscopy, cycloplegia (ethyl- picolyl-amid)	15 astigmatic (Amounts of astigmatism detected NI)			NI	

cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D	>2D	Axis WTR	ATR	Oblique
Mohindra et al. (1978)	0 - 1 wk	17	Near retinoscopy, no cyclo- plegia.	0	15		NI	
	1 - 10 wks	86		13	29		NI	
	11 - 20 wks	113		23	30	40	40	20
	21 - 30 wks	29		14	20		NI	
	31 - 40 wks	17		29	15		NI	
	41 - 50 wks	14		37	13		NI	
Howland et al. (1978)	1 - 9 days	15	Photo- refraction, no cyclo- plegia	26	0	For astigmatism of 0.75D, 77 out of 110 eyes, the axes were hori- zontal and vertical. Ten showed oblique astigmatism and in 23 the axes were between the hori- zontal vertical and oblique orientat- ions.		
	1 mo.	16		45	18			
	2 - 3 mo	36		40	17			
	6 - 8 mo.	14		50	0			
	9 - 12 mo.	12		16	17			
	Adults	26		0.75D ⩽ 8 ⩽ 1 D				
Ingram et al. (1979)	1 yr	148	Retinoscopy, cycloplegia (Cyclopento- late 1%)	15.5 ⩾ 1.5D		Not clear but stated "that the axis of the astig- matism when recorded as + cylinders was in the (nearly) horizontal axis as often as it was in the nearly vertical axis."		

cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D	>2D	WTR	Axis ATR	Oblique
Ingram and Barr (1979b)	$3\frac{1}{2}$ yrs. same children as for Ingram et al. (1979)	148	Retinoscopy, cycloplegia (Cyclopentolate 1%)	6.7 ⩾ 1.5D			NI	
Ingram (1979)	1 yr.	1648	Retinoscopy, cycloplegia, (Atropine 1%)	13.2 ⩾ 1.5D			NI	
Ingram and Barr (1979a, b)	1 yr.	614	Retinoscopy, cycloplegia, (Cyclopentolate 1%)	17.4 ⩾ 1.5D			NI	
Blomdahl (1979)	Newborn	28	Retinoscopy, cycloplegia, (Cyclopentolate 1%)	43 (Amount of astigmatism detected not indicated)		75	0	25
Atkinson et al. (1980)	17 - 20 mo.	22	Photo-refraction, no cycloplegia	4.5		50	0	50
	2 yrs 9 mo. - 3 yrs.3 mo.	20	Photo-refraction, no cycloplegia	0		0	0	100

cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D	>2D	Axis WTR	ATR	Oblique
Fulton et al. (1980) (see text)	0 - 60 wks	75	Retinoscopy, cycloplegia, (Cyclopento-late 1%)	19		18	82	0 "When data combined over first 3 years, 71% had ATR astig., 21% WTR & 8% oblique."
	60 - 109.9 wks	NI		8	6		NI	
	110 - 159.9 wks	NI		7	8			
Shapiro et al. (1980)	6 mos. - 1 yr.	11	Retinoscopy, cycloplegia (Cyclopento-late 0.5%, 1%)	46 ≥1.25D			NI	
	1 - $1\frac{1}{2}$ yrs.	24		42				
	$1\frac{1}{2}$ - 2 yrs.	29		31				
	2 - $2\frac{1}{2}$ yrs.	27		48				
	$2\frac{1}{2}$ - 3 yrs.	39		56				
	3 - $3\frac{1}{2}$ yrs.	78		45				
Dobson et al. (1981) (see text)	Premature infants	146	Retinoscopy, cycloplegia (Cyclopento-late 1%)	RE 23	48	10	83	7
				LE 28	37		NI	
Howland (1982a)	1 - 3 mo.	35	Photo-refraction, no cyclo-plegia	48	20	"Most of the astig-matism is against-the-rule."		
	3 - 6 mo.	30		40	12			
	6 - 9 mo.	33		32	24			
	9 - 13 mo.	18		38	16			
	13 - 26 mo.	26		26	11			

cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D		>2D	Axis WTR	ATR	Oblique
Atkinson and Braddick (1983)									
Kettering	6 mo.	804 eyes	Retinoscopy,	39		15	74	11	15
Cambridge	6 mo.	184 eyes	cycloplegia,	37		16	33	48	19
			and photo-						
			refraction,						
			no cyclo-						
			plegia						
Howland and Sayles (1984)	0 - 1 yr	117		42		20	4	54	42
	1 - 2 yr.	61		35		6	4	72	24
Tompkins Country Area	2 - 3 yr.	29	Photo-	4		10	0	50	50
	3 - 4 yr.	60	refraction,	11		0	0	76	24
	4 - 5 yr.	70	no cyclo-	12		0	10	80	10
	5 - 6 yr.	7		1		0		NI	
	0.5 yr.	26			59		4	48	48
Seattle Area	1.0 yr.	21	Photo-		46		0	54	46
	1.5 yr.	60	refraction		44 $\geqslant$ 1D		0	74	26
	2.0 yr	3	no cyclo-		98		0	32	68
	2.5 yr.	19	plegia		30		0	32	68
	3.0 yr.	30			28		0	0	100
Dobson et al. (1984)	0 - 0.5 yr.	46			17		0	100	0
	0.5 - 1.5 yr.	187	Retinoscopy,		19		22	76	2
	1.5 - 2.5 yr.	98	cycloplegia,		11		28	36	36
	2.5 - 3.5 yr.	97	(Cyclopento-		32 $\geqslant$ 1D		30	56	14
	3.5 - 4.5 yr.	105	late 1%)		37		46	28	26
	4.5 - 5.5 yr.	108			50		36	30	34
	5.5 - 6.5 yr.	87			41		64	19	17

cont. Table 2.1

Investigator	Age	Number of infants/ children	Technique	Percentage of subjects with astigmatism 1-2D		>2D	WTR	Axis ATR	Oblique
	6.5 - 7.5 yr.	93			45		60	24	16
	7.5 - 8.5 yr.	90			18		68	12	20
	8.5 - 9.5 yr.	68			13		42	34	24
Gwiazda et al. (1984b)	0 - 5 mo.	440		23		32	38	46	16
	6 - 11 mo.	81		24		18	38	44	18
	12 - 17 mo.	29		28		13	15	58	17
	18 - 23 mo.	34	Near	38		9	20	54	26
	24 - 29 mo.	34	retinoscopy,	21		8	40	60	0
	30 - 35 mo.	52	no cyclo-	26		6	31	63	6
	36 - 41 mo.	68	plegia	21		3	31	63	6
	42 - 47 mo.	69		19		1	36	64	0
	48 - 53 mo.	80		12		5	8	70	22
	54 - 59 mo.	60		15		5	9	43	48
	60 - 65 mo.	37		18		6	56	44	0
	66 - 71 mo.	16		19		6	74	26	0
Rutstein et al. (1986)	7 mo. (IUGR)	20	Retinoscopy,		41			NI	
	7 mo.	18	cycloplegia	27		0		NI	
			(Cyclopento-						
			late 0.5%						
			and Pheny-						
			lephrine						
			2.5%)						

2.2 Incidence of astigmatism

The trend which emerges from these investigations is the presence of a high incidence of clinically significant astigmatism ($\geqslant$1D) amongst infants in their first 2 years of life. The estimates vary from 13 percent of a sample of 1,648 one-year-old infants ($\geqslant$1.5D astigmatism) as found by Ingram et al. (1979) to 60 percent of a sample of 93 infants aged from birth to one year ($\geqslant$0.75D astigmatism) as found by Howland et al. (1978). These figures can be compared with the 10 percent incidence of $\geqslant$1.0D astigmatism found in young adult males by Sorsby et al. (1960). The non-clinically selected sample of 1,033 subjects ranging in age between 17 and 27 years were examined under cycloplegia by static retinoscopy and the results checked subjectively. In close agreement with the results of Sorsby and his co-workers, a recent survey by Parssinen (1987) on a Finnish population of 208 26-year-old and 255 46-year-old male and female subjects showed a 10.5 percent incidence of astigmatism of $\geqslant$1.0D. The sample was refracted subjectively under cycloplegia and an analysis was made of the data for the right eye only.

Astigmatism is clinically detectable in 95 percent of eyes. However, estimates of the frequency of "significant astigmatism" differ amongst different researchers, varying with the degree of astigmatism taken as the starting point (Duke-Elder and Abrams 1970 : 280). The term "significant astigmatism"is commonly taken by investigators listed in this chapter to mean magnitudes of 1D or more. This lower limit of 1D of astigmatism is based on older studies which have indicated that in the majority of cases, the amount of astigmatism detected is less than 1D (Duke-Elder and Abrams 1970 : 280). Kronfeld and Devney (1930) have shown that the distribution of astigmatic errors of 1.0D and less is markedly different to that of higher astigmatic errors. Whilst the former was found to occur most frequently in the region of spherical emmetropia, the latter was most commonly associated with higher spherical errors. This difference in distribution points to a difference between the lower (physiological) degrees of astigmatism and the higher (aphysiological) amounts.

Various methods were used by the investigators to ascertain the amount of astigmatism present in their young subjects.

Santonastaso (1930), Cook and Glasscock (1951), Graham and Gray (1963), Hosaka (1963), Mehra et al. (1965), Gonzalez (1965), Patel et al. (1970), Zonis and Miller (1974), Ingram (1979), Ingram and Barr (1979a, b), Ingram et al. (1979), Blomdahl (1979), Fulton et al. (1980), Shapiro et al. (1980), Dobson et al. (1981, 1984) and Rutstein et al. (1986) employed conventional retinoscopy with or without the use of cycloplegia or both.

Mohindra et al. (1978) and Gwiazda et al. (1984b) used a technique called near retinsocopy. In this method, the infant is held on the parent's lap in a completely darkened room. Retinoscopy is performed at a working distance of 50 cm with the infant gazing at the light from the retinoscope. The eye which is not being refracted is occluded during the procedure (Mohindra 1975, 1977a, b). Repeated refractive measurements taken on 13 infants on the same day rarely deviated by more than $\pm$ 0.5D. The number of persons performing the measurements were not given (Mohindra et al. 1978). As no cycloplegics are used in this technique, accommodation would presumably be free to vary. However near retinoscopic refraction of infants by two investigators appeared to be highly correlated with their cycloplegic refractions both as the spherical (correlation coefficient $r = 0.88$) and cylindrical ($r = 0.85$) components. The P values were not given. The axes of the cylinders found by near retinoscopy did not differ significantly from those found by conventional retinoscopy (Mohindra, 1977a). Another study on 31 school children aged 5-7 years showed a high correlation between the spherical components of near retinoscopy and cycloplegic retinoscopy but a low correlation between the cylindrical components. The measurements were performed by 2 retinoscopists. The low correlation of the amounts of cylinder found was blamed on the low magnitude of the astigmatism present. (Mohindra and Molinari, 1979). Kohl et al. (1987) assessed the reliability of the near retinoscopy technique by using 5 trained clinicians to test 14 infants aged 0 - 2 years. Large variations found in the mean and ranges of refractive errors recorded both within and between the clinicians led Kohl and his co-workers to question the usefulness of this technique on young subjects. These results point to the need for more studies to be initiated into the validity of near retinoscopy.

Howland et al. (1978), Atkinson et al. (1980), Howland (1982a), Atkinson and Braddick (1983), and Howland and Sayles (1984, 1985, 1987) employed photorefractive techniques to measure the astigmatism of their young subjects. The basic principle in photorefractive techniques is that light from a small flash source situated some distance away from the subject's eyes (eg. 75 cm), enters the subject's eyes and is reflected from their fundii. The pattern of light recorded by a camera close to the flash source gives information about the refractive state of the eyes. Two photorefractive methods have been used by the above researchers, namely, orthogonal photorefraction (Howland and Howland, 1974) and isotropic photorefraction (Howland et al. 1979, 1983). The magnitude of the astigmatism but not the sign can be determined from orthogonal photorefraction whereas the sign and axis of astigmatism are more easily determined from isotropic photorefraction (Braddick and Atkinson,1984). Both methods can be calibrated by calculating the size of the image recorded on the film by computer ray tracing methods (Howland et al., 1983). However in practice it is preferred to photograph eyes of known refractions through a series of trial lenses. Measurements based on this latter calibration technique used when screening large groups of 6 to 9-month-old infants showed good agreement with retinoscopic refractions of the same infants. Both the photorefractions and retinoscopy in this study were done under cycloplegia. A group of 69 infants were also photorefracted twice with a brief interval in between, and the photographs were independently measured by different individuals. Differences over 0.5D in readings were rare

(Atkinson et al. 1984). Howland (1982a) performed conventional noncycloplegic retinoscopy on 50 eyes (25 infants) and compared the cylinders measured by retinoscopy with those measured by photorefraction. The relationship he obtained between them was:

$$RA = 0.78\ PA + 0.26$$

where RA is the retinoscopic astigmatism, and PA is the photorefractive astigmatism. The correlation coefficient regression was 0.82, $P<0.001$. The agreement between the axis of the retinoscopic and photorefractive findings was said to be always within 22.5 degrees in this group as stated in a later report by Howland and Sayles (1984). The repeatability of their photorefractive technique was evaluated by Howland and Sayles (1987) by photographing a group of infants twice. Good correlations were found between the first and second measurements of the cylinder magnitude (correlation coefficient $r = 0.997$ for 13 eyes with astigmatism >0.5D).

It is of interest to note a publication by Molteno et al. (1983) who described another photographic technique which is capable of detecting refractive astigmatism. Although the purpose of their study was not to detect the incidence of refractive errors in young children, the results on 161 patients aged between 6 months to 10 years showed a promising new development which may play an important role in recording the refractive status of infants and young children.

The incidence of clinically significant astigmatism ($\geqslant$ 1D) found in infants one-year-old and younger are similar even though different techniques of non-cycloplegic refraction were used. The results are presented in Table 2.2.

Table 2.2 Incidence of astigmatism ($\geq$1D) in infants aged one-year-old and younger using non-cycloplegic techniques.

Technique	Investigator	No. of infants	Incidence of $\geq$1D astigmatism (%)
Conventional retinoscopy	Santonastaso (1930)	100	60
	Rutstein et al. (1986)	18	27
Near retinoscopy	Mohindra et al. (1978)	276	45
	Gwiazda et al. (1984b)	521	52
Photorefraction	Howland et al. (1978)	93	49
	Howland (1982a)	116	61
	Howland and Sayles (1984)	117	62
	" " " "	47	59

Fulton et al. (1980) suggested that there may be a difference in the incidence of astigmatism amongst infants depending on whether the refractions had been done under cycloplegia or not. This suggestion was based on their measurements of astigmatism by conventional cycloplegic retinoscopy which showed that the incidence of infant astigmatism ($\geqslant$1D) in their study was 2 to 3 times lower than the non-cycloplegic studies by other researchers. The results of Ingram et al. (1979), Ingram and Barr (1979a, b), Ingram (1979), Dobson et al. (1984), all using conventional cycloplegic retinoscopy supported the view of Fulton and her co-workers.

However, the older studies of Santonastaso (1930) and Gonzalez (1965) indicated that both cycloplegic and non-cycloplegic retinoscopy yielded very similar results. Blomdahl (1979) reported a 43% incidence of astigmatism (amounts of astigmatism were not given) in a group of 28 newborn infants using conventional cycloplegic retinoscopy. The results of Atkinson and Braddick (1983) on 2 groups of 6-month-old infants using conventional cycloplegic retinoscopy showed an incidence of about 50 percent with $\geqslant$ 1D astigmatism. Photorefraction of these same infants also done under cycloplegia gave similar results to those using retinsocopy.

One cannot dismiss the possibility that there may be some differences if the infant's accommodation is suspended pharmacologically or not, as Ingram and Barr (1979a) found that the use of cyclopentolate as a cycloplegic yielded a higher incidence of astigmatism of $\geqslant$1.5D than the use of atropine in their infant studies. Santonastaso (1930) cited by Fulton et al. (1980) found a 50% incidence of astigmatism using cycloplegic retinoscopy but had noted that cycloplegia was incomplete in many of the babies refracted 24 hours after the instillation of 1 drop of 1% atropine. Goldschmidt (1969) maintained that the drug used to obtain cycloplegia in infants was an important factor in obtaining reliable refractions in his own study on spherical refractive errors. Howland and Sayles (1984) postulated that the difference between results using cycloplegic retinoscopy and non-cycloplegic techniques like near retinoscopy and photorefraction, could be due to whether or not the infant was fixating. In the latter two techniques, the infant fixates a visual target, whereas in cycloplegic retinoscopy, this is not always clear. It is suggested that the act of fixation may increase the tonus of the horizontal recti muscles, which in turn increases the corneal component of the infant's against-the-rule astigmatism.

2.3 The axis of astigmatism

The researchers in this field have attempted to determine if there is a prevalence in the direction of the axis of infantile astigmatism. Generally, the astigmatism has been classified as with- or against- the-rule depending upon whether or not the negative cylinder axis lay within ± 15 degrees of the horizontal or vertical respectively. The majority of studies indicate that most of the axes in infantile astigmatism tend to be located along the horizontal or vertical although Howland and Sayles (1984) claimed that a higher incidence of oblique astigmatism could possibly be found if a more accurate method of evaluating the angles of the axes of astigmatism was used.

Fulton et al. (1980), Howland (1982a), Dobson et al. (1984), and Howland and Sayles (1984) reported finding a prevalence of against-the-rule astigmatism amongst their infants of age 2 years and under. Equal incidences of with-the-rule and against-the-rule astigmatism were found by Mohindra et al. (1978), Ingram et al. (1979), Gwiazda et al. (1984b).

Atkinson and Braddick (1983) investigated the axes of astigmatism in 2 separate groups of infants and came up with different results. The infants who were screened in the Kettering area showed predominantly with-the-rule astigmatism whilst those from the Cambridge area showed similar occurrences of with-the-rule and against-the-rule astigmatism. These results led Atkinson and Braddick to suggest that even though the incidence of infantile astigmatism appeared to be high in general, there may be population differences with regard to the axis of astigmatism.

2.4 Duration of infantile astigmatism

At present, it is still unclear how long the astigmatism when present in an infant lasts. Several longitudinal studies have been carried out in an attempt to find the answer.

Mohindra et al. (1978) tracked the refractions of the right eyes of 28 infants who had 2 to 3 D of astigmatism between the age of 3 and 6 months. Using near retinoscopy, these infants were refracted for 5 or more times during their first year of life. The results showed that by the age of 50 weeks, half of the group showed no astigmatism, a quarter showed a reduction of 1 or 2 dioptres, and another quarter maintained the amount which was present initially.

Atkinson et al. (1980) followed up a group of 20 infants who had been observed to have had ≥0.75 D astigmatism at either 1, 3 or 6 months of age. These infants were photo-refracted a second and sometimes a third time between 9 and 24 months of age. It was then discovered that the amounts of astigmatism had reduced in all but one infant. The exceptional case showed an increase in the magnitude of astigmatism when measured at 16 months of age, but when re-measured at 22 months of age, the astigmatism had dropped to below 0.75 D. The actual changes observed on the 20 infants were given in the paper.

Ingram et al. (1979), Ingram and Barr (1979b) published a longitudinal study of 148 infants examined initially when they were a year old. These same infants were re-examined at 3½ years of age. The incidence of astigmatism ≥1.5 D at 1 year old was 15.5% and this had dropped to 6.7% when they were aged 3½ years.

Dobson et al. (1984) studied a group of 11 children who had exhibited ≥1D of astigmatism at less than 18 months of age. These same children were subsequently refracted between 5 to 11 years after the initial examination. Most of the children showed decreased astigmatism at the second refraction. Only 6 of the 22 eyes in the study showed more than 1D of astigmatism at the follow-up examination. The axes of astigmatism of these 6 eyes were identical to the axes found in the child's first examination. The plots of the change in astigmatism for the 11 children were published also.

Gwiazda et al. (1984b) periodically refracted a group of 29 infants who were found to have ⩾1D of astigmatism at 6 months of age. Their results indicated that the amounts of astigmatism had been greatly reduced or eliminated by the time the children were aged 4 to 6 years. Out of the 16 of the infants who had against-the-rule astigmatism at the age of 6 months, a third had smaller amounts of against-the-rule astigmatism, a third had shifted axis to small amounts of with-the-rule astigmatism, and the remaining one third had no astigmatism. 8 of the infants who had with-the-rule astigmatism at 6 months showed a change to smaller amounts of with-the-rule astigmatism or to no astigmatism at all with increasing age. The 5 infants who had oblique astigmatism at 6 months were found to have small amounts of with-the-rule astigmatism at 5 years of age. Parallel to this study, 19 children who had < 1D of astigmatism in the first year of life, were refracted periodically until they were at least 4 years of age. Only 1 child developed a significant amount of astigmatism in that period. 1.5D of astigmatism was found in one eye at the age of 2 years and that amount was retained until the age of 6 years.

Howland and Sayles (1984) plotted the magnitude of astigmatism of the right eyes of 26 infants whose mean age at the initial examination was 6 months. Their mean age at the final examination was 1.9 years. An overall reduction with time in the frequency and amounts of astigmatism was seen in the group. However, in a few cases the amount of astigmatism present actually increased with time.

In a later study, Howland and Sayles (1987) recorded the amount of astigmatism in the more astigmatic eye of 360 children aged from 2 months to 5 years. The study was mainly a cross-sectional one and the results indicated that the amount of astigmatism decreased over the first 5 years of life.

The rate with which infantile astigmatism changes with age may be related to the axis of astigmatism as Atkinson et al. (1987) reported that infants whose horizontal axis showed the greater hyperopia showed a faster rate of reduction in the amount of astigmatism.

Another question which remains to be answered is "When does the high levels of incidence of astigmatism in infancy decrease to adult levels of 10 percent?"

The researchers who have investigated the incidence of astigmatism amongst school children present a relatively similar picture in that the incidence of astigmatism found amongst older children is much lower than that found in infants and young children.

Hirsch (1963) published the results of a longitudinal study on the astigmatism of 167 school children who had an average age of 6½ years at the first examination. They were refracted by conventional non-cycloplegic retinoscopy twice yearly for eight years. Their average age at the final examination was 12½ years. At all the ages between 6½ and 12½ years, 4 to 6 percent of the children were found to have astigmatism in excess of 0.75D as shown in Table 2.3. The astigmatism was almost exclusively with-the-rule. This proportion did not appear to decrease with age, and if it did change at all, it seemed to increase. Against-the-rule astigmatism in excess of 1.25D was not present in any of the children.

Table 2.3 Astigmatism of 167 children (333 eyes) at different ages. (After Hirsch, 1963)

	Percentage			
Ages (years)	$6\frac{1}{2}$	$8\frac{1}{2}$	$10\frac{1}{2}$	$12\frac{1}{2}$
With-the-rule astigmatism $\geqslant$0.75D	4.2 (14)*	5.4 (18)	5.1 (17)	6.0 (20)
Against-the-rule astigmatism $\geqslant$0.75D	0 (0)	0.6 (2)	0.6 (2)	0.3 (1)

* Numbers in brackets indicate the number of eyes.

The total number of eyes examined in each age group was 333.

The rate of change for each of these age groups was found to be minimal, only 35 percent of the eyes were found to change at a rate of between 0.03D to 0.07D per year. Thus, Hirsch concluded that the amounts of astigmatism present during the school years did not alter significantly.

Johnstone and McLaren (1963) examined 1,817 Tanganyikan school children aged 8 to 14 years from 6 different areas. Retinoscopic findings were recorded under cycloplegia on children from 4 of the areas, and whithout cycloplegia in the remaining 2 areas (Singida I and Singida II). The incidence of astigmatism greater than 1D was recorded for the different areas. The results are summarized in Table 2.4. Of the total 3,590 eyes refracted, only 184 (5 percent) had cylindrical errors greater than 1D.

Coleman (1970) published the results of visual screening of 3,623 school children from kindergarten to grade 6 in one American school. 6 optometrists were involved in the study which included refraction by retinoscopy (whether cycloplegia was used was not specified). Out of the total number of children, 2 percent were found to have refractive astigmatism $\geqslant$1D. The incidence recorded may be low due to the categorization of the refractive error found into its major component only, that is, hyperopia, myopia or astigmatism.

Prakash et al. (1971) investigated the refractive errors in an Indian population of children aged from birth to 15 years, with the majority of the children aged between 10 to 15 years. A very low incidence of astigmatism (1.6 percent) was recorded using cycloplegic retinoscopy.

Wong (1976) screened 633 youths held in a detention centre ranging in age from 7 to 18 years, the majority being between 12 and 17 years. 4.3 percent of the group were found to have refractive astigmatism in excess of 1D and no astigmatism over 3D was found.

Table 2.4 Cylindrical errors in Tanganyikan children. (After Johnstone and McLaren, 1963.)

	Areas investigated						Total
	Mwanza	Bukoba	Shinyanga	Singida I*	Singida II*	Mvumi	
Percentage of eyes >1.0D astigmatism.	1.0	0.9	1.9	2.9	11.0	10.3	5.1
No. of eyes >1.0D astigmatism.	10	5	2	13	50	104	184
Total no. of eyes examined.	1,011	559	105	444	456	1,015	3,590

* No cycloplegia used.

Woodruff (1986) recorded the results of visual screening on 8,085 six-year-old school children, which included their astigmatism measured by conventional non-cycloplegic retinoscopy. 15.9 percent of the population had astigmatism $\geqslant$ 0.5D, and 7.2 percent had astigmatism $\geqslant$1.0D. 12.8 percent of the children with astigmatism $\geqslant$0.5D exhibited against-the-rule or oblique astigmatism.

Nathan et al. (1986) measured the astigmatism in a group of 79 normal school boys aged between 13 and 16 years. Conventional retinoscopy without cycloplegia was used to estimate the amounts of astigmatism present. 6 percent of this particular sample were observed to possess astigmatism $\geqslant$1.00D.

Thus the refraction data from school-aged children show a much lower incidence of astigmatism than that found in infants. This implies that much of the astigmatism must be eliminated or reduced between 1 and 6 years of age. The majority of longitudinal studies mentioned earlier already show that this does happen.

Cross-sectional studies present some differences in opinion as to when the adult level incidence of significant astigmatism is reached. Atkinson et al. (1980) estimated that adult levels of incidence are reached by the time the infants are 18 months of age. This conclusion is disputed by Howland and Sayles (1984) who claim that this is not achieved until the infants are aged between 3 to 5 years of age.

Amigo (1973) conducted a study to design a series of tests suitable for examining the visual performance of pre-school children. 2 groups of children aged $3\frac{1}{2}$ to $5\frac{1}{2}$ years were assessed using static retinoscopy (whether cycloplegia was used was not specified) and keratometry. In the first group of 105 subjects, 11 percent were found to have astigmatism of $\geqslant$1D, whilst in the second group of 100subjects, 4 percent were found to have astigmatism of $\geqslant$1D. It is not clear whether the figures given by Amigo related to refractive or corneal astigmatism or both.

A cross-sectional study by Woodruff (1969, 1971) adds further to this confusion. He investigated the incidence of astigmatism in 395 children from the age of 1 to 6 years by using conventional non-cycloplegic retinoscopy. No cycloplegia was said to be used unless fixation of the child was unstable. No differentiation was made by Woodruff to indicate which of the results were obtained under cycloplegia. In fact, when a comparison was made between the spherical errors found using both cycloplegic and non-cycloplegic retinoscopy on the same day on his subjects, no significant difference was found. His results showed an incidence of 4 percent in 1-year-old children who showed $\geqslant$0.75D astigmatism. This figure rose to 10 percent in the group of 6-year-old children. Most of the astigmatism from the age of 2 years onwards was with-the-rule. His results are presented in Table 2.5. Woodruff's data contradict those of the other researchers in this field who reported high incidences of astigmatism in the 1 and 2-year-olds and a decrease in the frequency of astigmatism with age.

In general, it can be deduced from the studies mentioned with the exception of the study by Woodruff (1969, 1971) that the incidence of astigmatism decreases over the first five years of life.

Table 2.5 Number and percent of eyes with astigmatism determined by retinoscopy in 395 children. (After Woodruff, 1969 and 1971).

	Astigmatism		Age (Years)	1	2	3	4	5	6	Total
WTR	2.25 and up	Percent				0.60	1.12	1.40	3.33	0.88
		Number				(1)	(2)	(2)	(2)	(7)
	1.25 to 2.24	Percent			3.20	1.80	1.12	0.72	1.66	1.51
		Number			(5)	(3)	(2)	(1)	(1)	(12)
	0.75 to 1.25	Percent				1.20	1.68	3.57	5.00	1.64
		Number				(2)	(3)	(5)	(3)	(13)
	0 to 0.74	Percent		96.18	94.82	97.92	86.05	89.98	89.99	93.15
		Number		(87)	(148)	(163)	(158)	(126)	(54)	(736)
ATR	0.75 to 1.24	Percent		4.44		1.20	2.24	2.14		1.64
		Number		(4)		(2)	(4)	(3)		(13)
	1.25 to 2.24	Percent					1.12	0.72		
		Number					(2)	(1)		
	Oblique	Percent			1.92		0.56	1.40		
		Number			(3)		(1)	(2)		
	Total % (Eyes)			100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Total No. (Eyes)		as given by Woodruff	(90)*	(156)	(166)*	(178)*	(140)	(60)	(790)
	Total No. Children			45	78	83	89	70	30	395

*The present author's own addition of the total no. of eyes given by Woodruff for each of the age gaps 1, 3 and 4 years are 91, 171 and 172 respectively and not the numbers as stated by Woodruff.
NOTE: Columns do not total 100 percent exactly due to rounding errors. The term "oblique" was not defined by Woodruff.

2.5 Discussion on the methods of refraction

The practical problems of measuring refractive errors in the young are considerable.

Firstly, control of the visual fixation in infants is obviously difficult especially if they are non-cooperative. In spite of this, most of the investigators using conventional retinoscopy listed on Table 2.1 failed to discuss how an axial refraction was obtained. An important potential problem in assessing the astigmatism in infants is that off-axis retinoscopy may create an apparent astigmatism of a considerable degree (Bennett and Rabbetts 1984: 302, 303, 368). In view of this it is essential to control the fixation of subjects while performing refractions. Nonetheless, only a small incidence of astigmatism detected along oblique meridians has been noted by several investigators (Table 2.1). Howland and Sayles (1984) pointed out that the seemingly small incidence of astigmatism along oblique meridians may be due to the fact that more accurate methods of axis assessment were not used. Mohindra et al. (1978) said that the examiner performing near-retinoscopy made vocal sounds to maintain the stable fixation of their young subjects. Howland et al. (1978) also used sounds from the photographer to attract the infant's attention and photographs were only taken when the infant was judged to be fixating the operator's face close to the camera. It was claimed that in this way the camera was always within 5 degrees of the optical axis of the eye at the moment of exposure. It is unclear how the photographs which fulfilled this requirement could be checked, but a recent study by Howland and Sayles (1987) investigated the accuracy of their method in refracting close to the visual axes in 16 children. The results showed that the average deviation of the photorefracted axis was 3.6 degrees from the visual axis of the subject. Howland and Sayles (1987) claimed that their photorefractive results were representative of the refractive status of their subjects as it had been shown by Ferree and Rand (1942) that measurements of up to 5 degrees off the visual axis in adults do not differ significantly from measurements taken on the axis.

A number of investigators listed in Table 2.1 did not perform cycloplegic refractions. Thus, the accommodation of their infants was not controlled. The variation in the accommodative state of the eye may lead to swings in the refractive state of the eye with time as had been observed by Fletcher and Brandon (1955) and this may consequently cause changes in the refraction between the different meridians. Therefore, an eye may be recorded to possess an astigmatic error even if it has not. However, in spite of this, high incidences of astigmatic errors have been detected using cycloplegia (Santonastaso, 1930 ; Blomdahl, 1979; Atkinson and Braddick, 1983). This has been discussed in fuller detail in section 2.2 of this chapter. Also, Howland et al. (1978) using photorefractive techniques examined 2 orthogonal meridians of the eye simultaneously and still observed a high incidence of astigmatism.

Very few of the researchers mentioned if the lids of their subjects were retracted during the measurements and if so, by what means. This is another important consideration as slight pressure on the globe can distort retinoscopy findings (Graham and Gray, 1963). Wilson et al. (1982) have shown that lid retraction using a lid speculum or even with gentle finger pressure affects the magnitude of corneal astigmatism measured which would in turn affect the total astigmatism measured by refraction.

Finally, the reliability of the methods used in these infantile astigmatism studies were not indicated except those involving near retinoscopy and photorefraction. These 2 methods of refraction have already been discussed in section 2.2 of this chapter.

This criticism of the techniques used in the infant studies must not detract from the fact that the phenomenon of a high incidence of infantile astigmatism has been recorded by a large number of independent researchers using different techniques of refraction and as yet there is no firm evidence refuting the findings of these investigators. So in deference to the professional standing of the workers involved in this field and recognising the roles of the referees of their published papers, it is reasonable to accept that a high prevalence of astigmatism is present in the infant population.

2.6 Implications of infantile astigmatism

Given than a high percentage of infants are astigmatic, the question arises as to whether their vision is affected. It is possible that the astigmatism has little effect on the vision of young infants due to their poor visual acuity as shown by behavioural and electrophysiological data (Dobson and Teller, 1978; Dobson, 1980) and their large depth of focus (Green et al., 1980; Powers and Dobson, 1982). This idea is supported by the research of Dobson et al. (1983) and Howland et al. (1987) which demonstrated using photorefraction that astigmatic 2- to 10-month-old infants did not accommodate differentially to vertical and horizontal gratings. A possible explanation for this was that the defocus produced by the astigmatism to the changes in the orientation of the grating stimuli was less than the infants' large depth of focus, thus making it unnecessary for them to accommodate.

Teller et al. (1978) measured the acuity of an astigmatic infant who had 2.5D astigmatism using a forced preferential looking technique. The infant was tested at 4, 5 and 6 months of age. When the infant was tested at 4 and 5 months without correcting her astigmatism, a difference in the acuity was found between the horizontal and vertical gratings. However, this difference was eliminated when she was tested with her astigmatism corrected with spectacles at the age of 6 months. The optical correction was worn during the testing period only.

Gwiazda et al. (1976), Held et al. (1977), and Held (1978) reported the results of acuity testing on both non-astigmatic and astigmatic ($\geqslant$ 1D WTR or ATR) infants by forced preferential looking techniques. The non-astigmatic infants (23-50 weeks old) were found to prefer horizontal or vertical gratings over oblique gratings at one spatial frequency (at acuity threshold), whilst astigmatic infants (of comparable ages) typically preferred the horizontal and vertical gratings over the oblique ones at most or all of the spatial frequencies tested. These results could be explained by the fact that selective accommodation sharpens either the horizontal or vertical edges but not the oblique edges. The effect seen in the astigmatic infant could be reproduced in non-astigmatic infants by placing a cylindrical lens in front of their eyes. In agreement with the results of Teller et al. (1978), this group of researchers found that the performance of astigmatic infants when optically corrected did not differ significantly from non-astigmatic infants.

Studies of early astigmatism are important as adult astigmats have been demonstrated to have reduced acuity in the meridians which correspond closely to their axes of astigmatism (Mitchell et al.,1973; Mitchell and Wilkinson 1974; Cobb and MacDonald,1978). This condition which cannot be improved optically has been termed "meridonial amblyopia."

Mitchell et al. (1973) investigated 38 adult astigmatic subjects to assess their ability to resolve gratings placed at different orientations after full optical correction of their refractive errors. Their acuity was found to be substantially reduced for the orientation which was habitually defocused by the ocular astigmatism. The degree of meridonial amblyopia was found to be related to the amount of astigmatism present, and this depressed acuity was though to be permanent in that the reduced acuity was present even in subjects who had worn their full optical corrections for many years. However, it was noted that the subjects with meridonial amblyopia did not wear their optical correction until after the age of 6 years. Also the fact that one astigmat who was corrected optically at the age of 3 years displayed normal acuity in all meridians is worth noting. Furthermore, this meridonial variation in acuity was still detected when measurements were made with interference fringes formed directly on the retina, thereby bypassing the optics of the eye. This led Mitchell and his co-workers to deduce that meridonial amblyopia was of neural origin.

Similarly, Mitchell and Wilkinson (1974) demonstrated reduced meridonial acuity in 2 adult subjects with high astigmatism who had not been optically corrected until the age of 10 years. Their findings went in agreement with those of Mitchell et al. (1973) as the reduced acuity again corresponded to the meridian which was most defocused before optical correction and the differences in orientational resolution persisted even when interference fringes were formed directly on the retina.

Cobb and MacDonald (1978) also measured the grating acuity along various meridians in 12 astigmatic subjects aged 20 to 47 years in an attempt to determine the critical period during which the human visual system responsible for detecting contours could be influenced by its visual environment. Their results showed that those astigmatic subjects optically corrected below the age of 7 years showed significantly smaller meridional amblyopia than those corrected later than that age. This led Cobb and MacDonald to suggest that the age of 7 could mark the end of a 'plastic' period after which the visual system for contour processing ceases to be influenced by visual input.

The results of Teller et al. (1978), Held et al. (1977) and Held (1978) seem to indicate that the meridonial amblyopia found in adults is not present in astigmats in early infancy. Held et al. (1977) and Held (1978) did not detect meridonial amblyopia present in their sample of infants before one year of age. Mohindra et al. (1978) report that the earliest instance that their group had detected meridonial amblyopia was just prior to the end of the third year of life.

Gwiazda et al. (1984a) investigated the acuity of 6 children who had been found to have large amounts of myopic astigmatism at 6 months of age and in whom later the amount of astigmatism had been eliminated or reduced to <1D. When these children were tested at the age of 6 months and 1 year, wearing optical corrections, no meridonial amblyopia was detected. However, when they were re-tested at the age of 6 years, reductions in acuity were found for the orientations along the formerly myopic focus.

The data of Teller et al. (1978), Held et al. (1977), Mohindra et al. (1978) and Gwiazda et al. (1984a), suggest that meridonial amblyopia occurs some time after the first year of life. Norcia et al. (1986) is of the opinion that a possible reason why Gwiazda et al. did not detect the meridonial amblyopia at the age of 6 months was that the pattern deprivation was occurring above the behavioural thresholds at which the study was done, at sufficient levels to result in the amblyopia which was detected later in childhood. This proposal was based on a study of the contrast sensitivity functions in a group of 4 to 6-month-old infants using the visual evoked potential.

In addition to the risk of meridonial amblyopia developing in uncorrected young astigmats, there is a possibility that astigmatism in infants may influence the development of myopia in the immature visual system. This suggestion was put forward by Fulton et al. (1982) who analysed the relationship between myopia and astigmatism in 298 myopic children aged from birth to 10 years. The group as a whole showed no significant increase in the degree of myopia with age. However, the eyes with $\geqslant$1D astigmatism were found to be associated with higher degrees of myopia than the non-astigmatic eyes. Also, children aged 3 years and under with $\geqslant$1D astigmatism tended to show a progression in their myopia whilst the same was not found in non-astigmats of the same age. The idea of astigmatism encouraging the development of myopia is plausible as the data of Kronfeld and Devney (1930) and Parssinen (1987) demonstrates that the more the eye deviates from spherical emmetropia, the more likely the occurrence of an astigmatic error. However, the suggestion that the presence of astigmatism causes myopia does not explain why both Kronfeld and Devney (1930) and Parssinen (1987) showed an increase in the amounts of astigmatism detected with an increase in both myopic and hyperopic spherical errors. Based on these observations, it may be more reasonable to suggest that astigmatism is more likely a consequence of a spherical refractive error rather than a cause of one.

These observations of meridonial amblyopia and the possible linkage of infantile astigmatism with spherical refractive errors emphasizes the importance of early detection of refractive errors in the very young. More research is needed into the age at which infantile astigmatism can affect the visual development of the young eye.

2.7 Source(s) of infantile astigmatism

A review of the literature into the research carried out to determine the source or sources of infantile astigmatism shows a scarcity of information in this area. The few studies which have investigated this aspect of the astigmatism of infancy do point to the astigmatism being predominantly corneal in origin (Blomdahl, 1979; Howland, 1982a, b; Howland and Sayles, 1985).

Blomdahl (1979) investigated the corneal curvature of 28 fullterm newborn babies. Keratometric readings were obtained on 15 of these and the amounts of corneal astigmatism computed. Five of the babies were found to have no corneal astigmatism, and five had astigmatism with-the-rule ranging from 1 - 4D. The remaining five showed an oblique astigmatism ranging from 1 - 2D. Blomdahl had also performed retinoscopy on these infants under cycloplegia. The retinoscopy and keratometric results were presented of one eye of each the 15 infants and these are summarized in Table 2.6. The results of Blomdahl indicate a high corneal involvement in the refractive astigmatism of these infants. Out of the 15 infants, 66 percent were found to have corneal astigmatism $\geq$1.0D.

Table 2.6 The retinoscopic and corneal astigmatism findings on 15 newborn infants. (After Blomdahl, 1979.)

Infant no.	Retinoscopic cylinder (D)	Corneal astigmatism (D)
1	0	0
2	4.0 WTR	4.0 WTR
3	0	0
4	0	0
5	0	0
6	1.0 oblique	1.5 oblique
7	2.0 WTR	2.0 WTR
8	0	0
9	2.5 oblique	2.0 oblique
10	0	1.0 oblique
11	1.0 WTR	0
12	1.0 oblique	1.0 oblique
13	0	1.5 oblique
14	1.0 WTR	2.0 WTR
15	1.0 WTR	1.0 WTR

Howland (1982a, b) reported using photokeratometry in conjunction with photorefraction on infants mainly in their first postnatal year to determine whether the nature of infantile astigmatism was corneal in nature. A good correlation ($r = 0.75$, $P < 0.01$) was found between the total astigmatism measured by photorefraction and the corneal astigmatism measured by photokeratometry for 53 eyes of infants with a mean age 3.5 months. The relationship obtained between the total and corneal astigmatism was:

$$PA = 0.66\ CA + 0.16$$

where PA = total astigmatism measured by photorefraction

and CA = corneal astigmatism measured by photokeratometry

Using the same methods as Howland (1982a, b), Howland and Sayles (1985) also investigated the relationship between corneal and total astigmatism. This later study encompassed data from 148 eyes of 103 infants aged from 2 months to 5 years of age. The results showed that the amounts of corneal and total astigmatism were approximately of equal magnitudes and were positively correlated with each other up to 3 years of age. Also both the mean values of photo-refractive (total) and corneal astigmatism decreased with age over the first 5 years of life.

Mohindra et al. (1978) mentioned in their study that kerato-scopic measurements were carried out to determine the source of cylinder power in their astigmatic infants. However, no report of their findings dealing with this aspect has been discovered by the author.

York and Mandell (1969) measured the difference in radii between the 2 principal meridians of the cornea in 35 infants and young children aged between 7 days to 6 years of age. Their results are reproduced in Table 2.7.

Table 2.7 Variation of central corneal toricity with age. (After York and Mandell, 1969)

Age of subjects (years)	No. of eyes	No. of eye $\geqslant$ 1D corneal astigmatism	Percentage of eyes $\geqslant$ 1D corneal astigmatism
Under 1	13	4	30
1 - 2	4	0	0
2 - 3	4	1	25
3 - 4	5	0	0
4 - 6	9	3	33

As can be seen from Table 2.7 , no real conclusions can be drawn from these results due to the very small number of subjects investigated.

In contrast to the minimal information available on the source(s) of infantile astigmatism, it is well established that the curvature astigmatism of the anterior surface of the cornea is responsible for the majority of cases of total astigmatism in adults. The average refractive power difference between the two principal corneal meridians is between 0.5 to 0. 75D (Helmholtz 1864; Duke-Elder and Abrams 1974: 274). Based on this knowledge of mature eyes, it is not unreasonable to predict that a major portion of the infantile astigmatism is corneal in origin. The idea of infantile astigmatism being corneal in nature has already been shown to have support from the small number of investigations described earlier (Blomdahl 1979; Howland 1982a,b; Howland and Sayles,1985). In addition to this, Tait (1966) proposed that lenticular astigmatism was hardly of any importance in the total astigmatism present in children. Tait's study involved a sample of 485 children aged between 4 to 14 years, with 90 percent of the children being under 10 years of age. An analysis of the differences between the keratometric cylinder and cycloplegic retinoscopy cylinder values showed that 90 percent of the keratometer readings lay within 0.50D of the objective refraction cylinder. Although, it may be argued that Tait's study was on older children, there is no reason to expect the minor role played by the crystalline lens in the total astigmatism of the eye to be different in infants or younger children. Fledelius (1976) claimed that his experience based on examining a large sample of 10-year-old children was in keeping with that of Tait's (1966).

Animal studies also lend support to the theory that the major component of infantile astigmatism is corneal. Anterior corneal curvature measurements in kitten and adult cats using photokeratoscopy and keratometry show that young kittens appear to have more corneal astigmatism than adult cats (Freeman et al., 1978; Freeman, 1980). Their results are seen in Table 2.8 .

Table 2.8 Incidence of corneal astigmatism in kittens and cats. (After Freeman, 1980)

Age	No. of eyes investigated	Percentage with $\geqslant$ 1.0D of corneal astigmatism
Kittens	68	60
Adult cats	26	4

Apart from Blomdahl (1979), Howland (1982a,b), and Howland and Sayles (1985), only 1 other investigation (Woodruff 1969, 1971) appears to have dealt with the measurement of corneal astigmatism in the very young human eye.

Woodruff (1969, 1971) reported an increase in the frequency of corneal astigmatism with age based on keratometry findings on a total of 540 eyes in subjects aged from 2 to 6 years. His results are presented in Table 2.9 .

Table 2.9 Incidence of corneal astigmatism in children aged 2 to 6 years. A cross-sectional study by keratometry. (After Woodruff, 1969, 1971)

Age of subjects (years)	No. of eyes	Incidence of corneal astigmatism (%)	
		$\geq$ 0.87D	$\geq$1.25D
2	84	13.9	1.0
3	140	15.8	2.9
4	148	15.1	4.4
5	108	20.7	7.6
6	60	21.6	16.5

The increase of corneal astigmatism with age supported Woodruff's findings of an increase in the incidence of total astigmatism determined for 1 to 6 year-olds. As has been discussed earlier, the increase found in the incidence of total astigmatism was incongruous with the majority of the reports by other investigators who suggested that the opposite was taking place. Similarly, Woodruff's results on corneal astigmatism are in dispute with those of Howland and Sayles (1985) who found a decrease in the frequency of corneal astigmatism $\geq$1D with age. The results of Howland and Sayles are produced here in Table 2.10 for comparison with Woodruff's data.

Table 2.10 Incidence of corneal astigmatism in infants and children up to 5 years of age. (After Howland and Sayles, 1985)

Age of subjects (years)	No. of subjects	No. of eyes	Incidence of corneal astigmatism $\geqslant$1D (%)
0 - 1	28	44	47.7
1 - 2	40	73	15.1
2 - 3	13	26	38.5
3 - 5	9	18	0.0

Slightly more data is available on corneal astigmatism in school-aged children and it is relevant to compare these with the findings on infants and younger children as Hirsch's (1963) study showed that there is very little change in the total astigmatism in children aged between $6\frac{1}{2}$ to $12\frac{1}{2}$ years. In support of Hirsch, Elliott (1971) also found no appreciable change occurring in the amount of total astigmatism during school age years.

Castrén (1955) investigated the corneal astigmatism in 480 children (average age 9.2 years) who had been born prematurely and in 270 children (average age 9.0 years) who were full-term at birth. An incidence of $\geqslant$0.50D corneal astigmatism was found in 5.8 percent of the premature group and in 4.6 percent of the full-term group. The difference in incidence between the 2 groups was not significant.

Lyle (1965) conducted a cross-sectional study on a total of 1,208 eyes in subjects ranging in age from under 10 years to over 60 years. The sample was a selected one as the records were obtained from optometry clinics. In the total of 104 eyes in the under 10-year-old age group, keratometry revealed an incidence of corneal astigmatism of 53 percent with $\geqslant$0.87D, and 23 percent with $\geqslant$1.25D. Most of the corneal astigmatism was with-the-rule. Unfortunately, Lyle did not give the ages encompassed in the under 10 year-old age group.

Anstice (1971) investigated the total subjective astigmatism, corneal astigmatism and residual astigmatism in 621 subjects also taken from optometric clinics. The subjects ranged in age from 5 to over 75 years. Of the 15 subjects aged 5 to 9 years, 80 percent were found to have $\geqslant$0.50D corneal astigmatism. Of the 43 subjects aged 10 to 14 years, 65 percent were found to have $\geqslant$0.50D corneal astigmatism. Woodruff (1969, 1971) found an incidence of 52 percent in the 5 and 6 year-old groups with $\geqslant$0.50D corneal astigmatism.

Lyle et al. (1972) reported the distribution of corneal astigmatism on a non-clinically selected sample of 323 Caucasian children aged from 7 to 14 years. Keratometry was performed by one person using the same instrument throughout the study. Measurements taken from the right eye of each subject were considered for statistical analysis. Of the total sample 13 percent were found to have corneal astigmatism in excess of 1D.

Fledelius (1976) published the results of corneal astigmatism found in a group of 237 10-year-old school-children. 12.6 percent of the group had corneal astigmatism of 1.25 - 2.5D and 1.9 percent had corneal astigmatism of > 2.5D. On comparing these figures with those found in a group of 269 similar aged children but who had been born prematurely, Fledelius found no significant difference between the 2 groups concluding that prematurity did not prove to exert any obvious influence upon the degree of corneal astigmatism. 18.0 percent of the premature group had corneal astigmatism of 1.25 - 2.5D and 1.7 percent had corneal astigmatism of >2.5D. In both groups, more than 86 percent of the children had with-the-rule corneal astigmatism.

As can be seen from comparing these studies on school-children, a large variation is seen although figures of the frequency of corneal astigmatism ≥1.25D appear to in fairly good agreement between those of Lyle (1972) and Fledelius (1976).

CHAPTER 3

METHODS OF CORNEAL MEASUREMENT

3.1 Possible Methods

The first attempt at quantitative investigation of corneal curvature has been attributed to C. Scheiner in 1619 (cited by Levene, 1965). He seated the subject opposite a window whence the image of the cross-bars could be observed reflected in the cornea. Using marbles of various diameters (about 10 to 20 mm in diameter) held near the cornea and comparing the size of the corneal reflex, a value of the corneal radius was obtained. Petit (1723 - 1730) was also said to have attempted the measurement of corneal curvature by using segments of different radii cut from sheets of thin copper plate and matching them to the curve of the cornea (cited by Reading, 1973).

Various methods have since been developed for the measurement of corneal curvature. These methods may be listed as follows:-

(i) Stereophotogrammetry,
(ii) Profile methods ,
 (a) Direct profile photography
 (b) Slit lamp section photography
 (c) Casts
 (d) Ultrasound
(iii) Moiré fringe techniques,
(iv) Interferometry,
(v) Autocollimation,
(vi) Retinoscopy method,
(vii) Contact lens and fluorescein methods,
(viii) Keratometry and peripheral keratometry and
(ix) Keratoscopy and photokerascopy.

A review of these methods is necessary to determine the most practical method for use on infants and young children in the present investigation. The first part of this chapter deals with all the possible means of recording corneal curvature and section 11 deals with those methods which have actually been used to obtain measurements on young subjects. Mathematical terms relating to corneal topography found in this chapter are dealt with more fully in Appendix A.

3.2 Stereophotogrammetry

In this method, topography of the cornea is mapped from stereoscopic photographs of the cornea. As the cornea is transparent, it is necessary to sprinkle it with a substance to render it opaque.

Erggelet (1922) has been cited by Bonnet and Cochet (1962) as having been the first to apply this technique for assessing ocular contours. Bertotto (1948) studied the topography of the conjunctiva and cornea by first administering akinesia and local anaesthesia, then sprinkling the eye with lamp black and finally photographing it with a Zeiss stereoscopic camera. Reconstruction of the anterior surface of the eye were then made from the stereoscopic pair of photographs using a stereophotogrammetric instrument. An accuracy of 0.017 mm was claimed as the accuracy of reconstruction of the corneal points but no details were given as to how this figure was deduced.

Rzymkowsky (1954) used stereophotogrammetry to study the scleral contour in the 1940s.

Bonnet in 1959 (cited by Le Grand, 1961) studied the cornea by dusting it with talcum powder after local anaesthesia. Bonnet reported an average error in corneal height found from this method as 0.03 mm which if expressed in terms of radius of curvature is an error of 0.03 mm for an average corneal radius of 8 mm. Ludlam and Wittenberg (1966) questioned this claimed accuracy of radius in view of the stated variability in corneal height. Le Grand (1961) used Bonnet's method to study the corneal contour in the aphakic eye.

El Hage (1971, 1972c) also proposed projecting a convergent pencil of ultraviolet radiation through a plate containing many fine holes onto a tear layer containing fluorescein. The resultant fluorescent spots are photographed by a camera with a telecentric stop. As can been seen from the Figure 3.1 , y can be measured from the photograph and the value x can be determined from:-

$$\tan \alpha = \frac{b - y}{-a + x}$$

$$\text{so that } x = \frac{b - y}{\tan \alpha} + a$$

As the values a, b and α are known from the construction of the plate, the two coordinates x and y can be determined for any point on the cornea. On tests carried out on model corneas, the best precision for determining the coordinates was 0.05 mm.

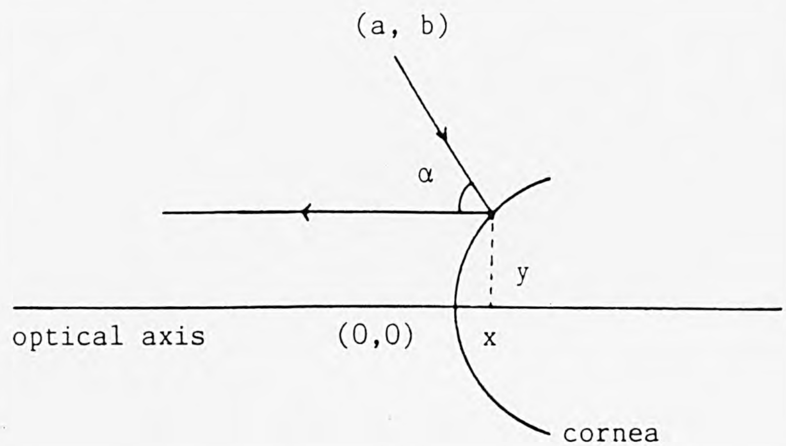


Figure 3.1. After El Hage (1971). The coordinates of the exciting source of u.v. radiation are (a,b) and those of the point of incidence (x,y). After exciting the fluorescein, the emitted light passes into an observation system with a telecentric stop so that only light parallel with the axis is admitted.

Grimm and Rehm (1983) proposed a method of projecting a lattice structure on to a cornea which has fluorescein in the tear film and stereographic pictures are taken and mathematically evaluated to provide information about the corneal topography (cited by Kemmetmüller, 1984 ,   1986).

3.3 Profile Methods

This method enables the corneal surface to be assessed by examining its profile from the side.

Profile information of the cornea can be obtained by several methods. These include: (a) direct profile photography, (b) slit lamp section photography, (c) casts and (d) ultrasound.

3.3.1 Direct Profile Photography

Evershed-Martin (1959), Mandell (1961a), May (1963) and Taylor (1963) are several researchers who have attempted to use profile photography to determine corneal topography. The profile photographs are enlarged and then analysed by matching them with templates. As the corneal surface is aspherical, it is necessary to match templates to several small arcs of the corneal contour in order to get an accurate picture of the topography of the cornea. Mandell (1961a) reported an accuracy of only about 4.00 dioptres when matching the corneal curvature over a 1 mm arc with templates that is, a cornea of cental radius 7.5 mm appeared to match any of a series of template curves from radii 7.1 mm to 7.9 mm. This low accuracy is due to the difficulty of matching small arcs of a circle with templates.

Mandell (1961a) also measured the sagitta of the cornea from profile photographs using a measuring microscope. The corneal radius could then be computed from the sagitta of the cornea. However, only a slight improvement over the template matching technique was found, the accuracy of the method being limited by the blurred border of the anterior corneal profile in the photographs.

McMonnies (1971) recorded the measurements in the central region of 8 human corneas by recording their profile images on very fine photographic plates. His data showed that the curvature of the central cornea which included the keratometer reflection areas was spherical in the sense that its curvature was found to vary over an amount less than 0.05 mm of radius.

Carney and Clark (1972) took vertical profile polaroid photographs of 2 subjects (before and after applanation of their corneas) in order to get coverage of the corneal region right up to the limbus. These photographs were examined with profiles of known surfaces. The authors claimed that this method was capable of detecting deformations greater than 0.1 mm.

Chandler et al. (1979) and Knoll (1986) reported using horizontal profile photographs taken of 438 corneas to measure semi-chordal diameters and sagittal heights of the corneas. These values were combined with central corneal radii readings using keratometry to evaluate "shape factor" values for each cornea assuming that a cross-sectional cornea profile could be represented by the following quadratic equation:

$$x^2 - 2Ry + ky^2 = 0,$$

where R = apical radius of the cornea

K = corneal shape factor = $1 - e^2$

e = eccentricity value

x = semi-chordal corneal diameter

y = sagittal corneal height

Wechsler and Miller (1981) photographed corneal profiles of the vertical meridian of right eyes of 4 subjects, and matched the contours with computer-drawn curves of a circle, an ellipse, a parabola and a catenary. Their results indicated that the corneal profiles resembled a parabola or a catenary rather than a circle or an ellipse.

3.3.2 Slit-lamp section photography

A meridonial section of the cornea can be obtained by taking a slit-lamp section through the cornea. This section can then be enlarged and analysed.

Bitonte and Bitonte (1967) described a photographic slit-lamp apparatus called the Corneoptor - Corneagraph. Polaroid corneal section photographs taken with this equipment at twice the actual corneal size were then analysed by matching them with a series of templates with radii from 5.54 to 9.04 mm. No figures were given as to the accuracy of using this method of measurement. Bitonte et al. (1968) and Bitonte and Bitonte (1970) discussed various cases of contact lens fitting with the aid of the Corneopter. Rowsey et al. (1981) reported using this instrument on a population of normal eyes.

Niesel (1966) and Cocks (1968) also described instruments which were very similar to the Corneoptor - Corneagraph. Cocks stated that "no reports have been found which describe the use of slit-lamp microscopy for measuring quantitatively the contour, thickness or nature of the cornea". In fact von Bahr (1956) and Donaldson (1966) had both used slit-lamp techniques to measure corneal thickness and both authors actually gave a review of previous work of other researchers who had also used the slit-lamp microscope for corneal thickness measurements.

Like Mandell (1961a), Stone (1962) also evaluated the accuracy of matching the corneal profile with templates. She found that in order to determine the corneal radius to an accuracy of $\pm$ 0.1 mm for an average corneal radius of 8.0 mm, an arc of contact of 8.05 mm was necessary. As this was larger than the central corneal zone, this method was not satisfactory for determining its contour accurately. Attempts to measure the apparent sag of the cornea using a measuring microscope and computing the corneal radius from it were also made. Difficulty was experienced in judging the position of the anterior corneal surface due to the grain of the film so that the accuracy of judging the apparent sags and chord lengths was less than 0.01 mm. As an increase in the apparent sag of 0.01 mm corresponded to a decrease in radius of about 1.4 mm (for a radius of 8 mm and a chord length of 2 mm), Stone felt that this method of measuring the film was also inaccurate.

Smith (1977) photographed profiles of spherical steel balls and attempted to measure their curvature from these using various techniques. Using a projection technique, the profile image was focused on a wall 20 feet away. Graph paper was put on the wall and points were marked along the paper. It was unclear as to how the curvature of the steel balls was calculated from this, but he estimated an accuracy of 5-6 dioptres and 2 dioptres in the centre and periphery of the curve respectively. The poor accuracy obtained was attributed to the relatively blurred projected margin of the profile. He also attempted measurements of the profiles with a Toolmaker's microscope which gave an accuracy of 2 dioptres. The same degree of accuracy was obtained when measurements were attempted with a microdensitometer.

Buschner et al.(1982) described how an image of the anterior segment of the eye could be obtained on a digital picture system by illuminating the anterior segment with a conventional slit lamp and taking an optical section of the eye using a television camera mounted at 40^{o} to the optical axis of the slit lamp. The television signal was read into the digital picture system and the anterior segment of the eye would then be displayed. The anterior surface of the cornea could be seen clearly and the researchers used a least squares method of fitting a circle to the corneal curvature. For a cornea of radius 7.8 mm measured on a conventional instrument (the instrument was not specified), its computed radius using the least squares fitting method was 8.4 mm. Buschner et al. claimed that the error of determining the central corneal radius could be reduced by using a digital system with a higher resolution.

Fonda et al.(1982) also reported a similar procedure using a television mounted on a slit-lamp. 6 images of the anterior segment were acquired at equal spaced angles during rotation of the slit-light axis. The television signal was fed into a computer system for acquisition and image processing and the anterior corneal profile could then be fitted by a circle equation using chi-squared criteria. It was found that normal adult corneas gave sufficiently good results but keratoconic corneas could not be fitted by a spherical surface. No actual figures as to the actual accuracy of the method were given and also the extent of the central cornea covered in their measurements was not indicated.

3.3.3. Casts

In this technique, a cast or mould is taken of the eye and a positive cast is then made from the impression taken of the eye. The positive cast is then matched with templates or the cast is photographed and the resulting picture is compared to templates.

Elliott (1956) proposed a method of projecting positive casts of eye moulds on to a screen at a magnification of 10 times. From this, a tracing or photograph could be made from the projection. He then suggested the base curve of a suitable corneal lens could be selected by drawing the curve which would clear the apex of the tracing by 1.2 mm to 1.5 mm across the meridian of least curvature.

Mandell (1961a) photographed profiles of casts and found no improvement in accuracy compared with the direct profile photography method.

Stone (1962) stated her reasons why the cast method would not measure the contour of the cornea properly. They were:-

(a) a certain amount of deformation of the cornea takes place due to the presence of the impression material and the shell,
(b) some aqueous humour may be expressed from the globe during the procedure,
(c) the corneal epithelium is usually damaged slightly in the process, leading to corneal oedema,
(d) shrinkage of the impression material and also the positive cast material as they set, and
(e) the inaccuracy of matching the profile of a cast with a matching template.

Marriott (1966) photographed profiles of positive casts of the eye. The photographs were then projected on to a sheet of drawing paper and a tracing of the magnified image (about 13 to 14 times) was made. He was interested in the scleral contours rather than corneal contours in this study and no accuracy of the method was discussed.

Miller et al. (1967) compared the keratometer readings of 13 eyes before ocular impressions were made with the corneal curvature obtained by projecting cast profiles after the impressions. The projected profiles were matched with semi-circles ranging in radii from 4 to 11 mm and drawn in 0.1 mm steps. This method was checked with spherical steel balls and claimed to be "reliable with 0.03" (presumably mm). Based on their findings, the authors deduced that ocular impressions did not cause a significant change in corneal curvature.

Clark (1968) reported that in 1966, he observed human corneas (magnified 100 x) and matched them with circular templates. Like Mandell (1961a) and Stone (1962), he found the inaccuracy of the method lay in having to match short arcs of curvature with templates. He estimated errors in radius measurement of $\pm$ 10 percent.

Storey and Vale (1970) reported the use of a "poly-sulphide rubber compound" to make ocular casts. Its manufacturers had claimed that this materials produced dental casts with greater accuracy than other available materials. Work was carried out with this material on rabbit corneas and two human volunteers but no accuracy of the ocular casts produced were given.

3.3.4 Ultrasound

Giglio and Ludlam (1966) used the B-scan technique to delineate the cornea and other ocular structures. However, their accuracy was only ± 0.2 mm in sagitta.

Coleman (1969) demonstrated how a photographic negative of a B-mode ultrasonogram of the eye could be used to measure corneal and lens curvatures. It was claimed that the curves could be easily approximated by using projection techniques and known overlays. Computation of the appropriate curvature values could then be made using a time reference. No indication as to the accuracy of the method was given but one would expect the same errors as Mandell (1961a) and Stone (1962) had found when trying to match corneal profile with templates.

3.4 Moiré fringe techniques

Moiré patterns are produced when two periodic structures eg. two Ronchi rulings or two diffraction patterns are made to overlap. When two gratings overlap to form moiré fringes, the orientation and spacing of the fringes are a function of the width and spacing of the grating bars and of the angle formed between the bars of each grating. If the characteristics of the gratings are known, the moiré fringes are predictable and can be used as a measuring system (Mandell, 1966).

Ludlam and Kaye (1966) described an instrument utilizing this principle called the Toposcope. The toposcope consists of a microscope with a variable magnification of 4 to 20 times. It is used for observation of the virtual image of the target grating formed by the convex surface (cornea or contact lens) to be measured. In the eyepiece of the microscope is a second similar grating. When the target is observed reflected from a spherical test surface, and the microscope lens system is adjusted to the magnification appropriate for that particular radius of curvature, then straight-line parallel moiré fringes are seen. If the surface is not spherical, the fringes will appear curved. The magnification is monitored by a dial attached to a counter which reads the radius directly correct to 0.01 mm. Blackstone (1966) stated that the range of radius of curvature measurable on the Toposcope was from 6.0 to 15.0 mm.

Poster et al.(1968-1969) modified a Toposcope for the study of the cone in keratoconus by adding a camera and fixation target. The modified Toposcope was described as having a 'sensitivity' of 0.05 mm in radius of curvature after tests carried out on spherical steel balls. Arner (1967) implied that an unmodified Toposcope could be used to detect changes of 0.02 mm in the radius of curvature of corneal lenses. He was interested in investigating the stability of the "base " curves of corneal lenses which were manufactured using slightly different techniques.

Mandell (1966) described a moiré-fringe keratometer which consisted of a microscope with a target grating. The target acted as the mires of a keratometer, with the image size varying with the corneal radius. The image of the target formed by the cornea and the objective of the microscope was focused at the focal plane of the eyepiece, where another grating was located. Thus the target image and grating at the eyepiece were seen as if they were superimposed through the eyepiece. A "zoom" lens was used to match the spacing of the target image with that of the second grating. The 'zoom' lens was calibrated in terms of the radius of curvature of the cornea. Mandell found that the standard deviation of 10 repeated measurements on the corneas of each of 8 different subjects was 0.009 mm. Mandell and Polse (1969) used this instrument on keratoconic corneas. In spite of its high accuracy in measurement, it was found to be ineffective for early diagnosis of early keratoconus as the moiré fringes in these cases were of the same appearance as those of normal corneas.

Cochet and Amiard (1969) proposed taking a photograph of the reflection of a grating from a cornea and then superimposing this on a photograph of the grating reflected from a sphere of known radii. The resultant moiré pattern could then be examined and corneal radii deduced.

Garner (1970) studied corneal topography by projecting a grid on to a cast of an eye impression by using a collimated beam. The projection of the grid on to the cast produced a distorted pattern on the surface of the cast which was analysed by superimposing the original grid. The resulting moiré pattern produced was photographed.

Meadows et al. (1970) and Takasaki (1970, 1973) proposed a method of producing moiré fringes by positioning a grid close to an object, and observing the shadow cast on the object by the grid through the grid. This method will only generate moiré fringes on diffuse and opaque surfaces so the cornea would have to be made into a diffuse surface for it to work. Takasaki actually produced moiré fringes on living human bodies but both authors did not attempt to produce any fringes on the cornea.

In another method used by Idesawa et al. (1977) called projection-type moiré topography, a grating shadow produced by projecting a grating on the object surface is observed through another grating. This method eliminates the necessity of applying the grating close to the cornea which is necessary for the method proposed by Meadows et al.(1970) and Takasaki (1970, 1973).

Chander et al. (1976) attempted to obtain corneal contours by projecting a grating on to the cornea and photographing the reflected image from another angle. To produce moiré fringes, this same photograph was then re-exposed to the reflection of the grating from a plane glass plate which was placed in the position where the cornea originally was. The two images then produced a moiré pattern, and contour map of the corneal surface. The authors stressed that the fringe contrasts had to be improved before this method could be used accurately.

Kawara (1979) generated moiré fringes directly on the human corneal surface. Fluorescein was instilled on to the subject's cornea and a grating pattern was projected on the corneal surface by blue light for excitation. The image from the cornea was then imaged on another reference grating, producing moiré fringes. Kawara claimed an accuracy in radius measurement of about 0.005 mm.

3.5 Interferometry

Interference fringes of constant thickness can be used to test the shape of the corneal surface. One of the main requisites for interferometry is that the tested surface and the measuring wavefront should be stationary relative to each other.

Uhlig (1967) presented two proposals for the construction of a corneal interferometer. He did not attempt interferometric observation of living human corneas but gave an example of photographs taken on the eye of an insect with a Michelson micro-interferometer.

Wray (1970) proposed interferometric holography to determine the topography of the cornea. As far as could be seen from his report he did not carry out any experiments to see if this technique would be feasible on the human cornea.

Clark (1973g) claimed that he managed to obtain interference patterns on in vivo human corneas. A problem encountered during the procedures was the difficulty in maintaining a steady position of the cornea. Clark also found that the use of high speed photographic film or an image intensifier were needed to record the images. In addition to this, the observed fringes were seldom still enough to allow successful single exposures so motion picture recording was suggested.

Smith (1977) attempted holographic interferometry on the corneas of rabbits but was not successful.

3.6 Autocollimation

This method is based on the Drysdale's principle which states that for a convex spherical reflecting surface, the two positions for which a convergent beam of light is returned along its original path is (a) when the light is focused on the surface and (b) when it is focused towards the centre of curvature of the reflecting surface. These are the two positions of autocollimation. The distance between the two positions is the radius of curvature of surface. This principle is illustrated in Figure 3.2.

In 1925, Fincham proposed a method for corneal radius measurement based on Drysdale's method (Le Grand, 1961; Bennett 1964).

Bennett (1964) described an instrument based on this principle in which he devised an optical system allowing simultaneous observation and focusing of the two autocollimation positions. This removed errors which would arise due to the movement of the cornea between one focus setting and the other. The surface image is produced and viewed by an annuluar optical system arranged outside an axial optical system used to produce and view the image formed at the centre of curvature of the surface. Independent adjustment of the two systems permits simultaneous focusing of the two images, and the radius of curvature is thus obtained. The observed area of the corneal surface was stated to be about 1 mm in diameter.

Douthwaite (1987b) also described a keratometer which utilizes Drysdale's principle. This prototype instrument also allows simultaneous observation and focusing of the two autocollimation positions. The device was evaluated and compared with the Zeiss keratometer.

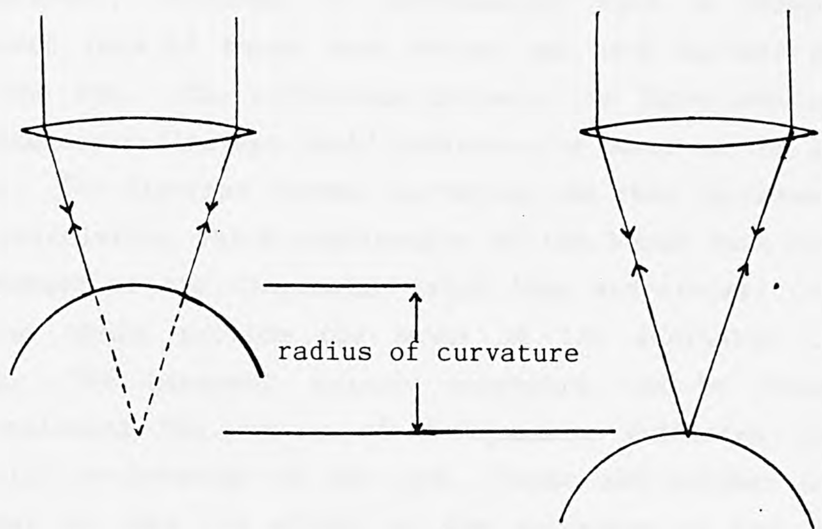


Figure 3.2. Radius of curvature measurement based on Drysdale's principle.

3.7 Retinoscopy method

When a rigid contact lens is placed on the eye a fluid meniscus (liquid lens) is formed between the lens and the cornea. In order to correct the refractive powerof the eye, the back vertex power of this contact lens - liquid lens system must equal the refractive power of the eye (Bennett, 1985).

This concept has been used by Ridley (1948) and Soper and Goffman (1976) to determine corneal curvature. In this method, a standard retinoscopic refraction of the eye is undertaken, followed by retinoscopy with a diagnostic contact lens (of known back vertex and back surface powers) in the eye. The difference between the first and second retinoscopic findings would indicate the power of the liquid lens. The flattest corneal curvature can then be determined by calculating which combination of the known back central curvature of the diagnostic trial lens and central corneal radius would provide the power of the indicated liquid lens. The steepest apical curvature can be estimated by relating the amount of astigmatism indicated in the initial retinoscopy of the eye. Soper and Goffman do not appear to take the effect of the thickness of the liquid lens in their calculations but Bennett (1985) shows that for average contact lens curvatures and powers, each 0.1 mm of fluid thickness adds approximately 0.12 dioptre to the effective power of the liquid lens.

3.8 Contact lens and flourescein methods

The instillation of fluorescein in the conjunctival sac which is then viewed under suitable blue-violet radiation allows the tear fluid in the eye to fluoresce. The fluorescent pattern present if a contact lens is placed on the eye gives a quantitative indication to the contact lens practitioner of where the lens touches the cornea and where it stands off. If the back surface shape of the contact lens is known, then the clearance indicates the departure of the cornea from the known curve. Stone (1962) pointed out that the lens must be kept stationary on the eye for the measurement to be valid.

Bier (1956) used this method to deduce the presence of a "negative" zone on the cornea from an analysis of about 300 cases. Moss (1959) by clinical observations with fluorescein claimed that the "negative" zone was real. However, his study was only based on 10 cases.

Forknall (1959, 1961) claimed that he was able to measure corneal clearances of a haptic lens by means of a slit lamp to within an accuracy of 1 to 2/100th of a mm.

Marriott and Woodward (1964) incorporated a doubling device onto a slit lamp to also measure the corneal clearance of a haptic lens. By measuring the corneal clearance at various points of the contact lens, it was then possible to calculate the corneal curve from the measured clearances, provided the lens was properly centred. Corneal radii measurements were attempted using a F.L.O.M. lens. Each depth measurement was considered accurate to 0.005 mm but no claims as to the accuracy of the corneal radii measurements were made.

Brungardt (1965) used this method with a series of diagnostic monocurve trial lenses with optic zones of 11.8 mm and of which the vaults had been measured. In his study, 42 right eyes were selected by photographing the eyes and choosing only those for which the visible iris diameters were 11.8 ± 0.1 mm. The diagnostic lenses were placed on the eye, and the curvature of the lenses were decreased until a point was reached when apical touch occurred. Thus, when the lens touched the apex of the cornea, the vault of the contact lens is equal to the sagitta of the cornea. Using the central corneal radius from keratometer readings on each eye, the sagittal difference was found at the lens boundary. This difference gave a measure of the average corneal asphericity.

Brungardt (1984) in a later study used trial lenses with optic zones of 10.8 mm to calculate the eccentricity values of one eye on each of 84 subjects. The mean eccentricity value has found to be 0.48 $\pm$ 0.11 mm (s.d.), with a range from 0.15 to 0.70 mm. The eccentricity values were found to have no correlation with the corneal curvatures measured by keratometry or with their refractive errors.

Cooke and Young (1986) described the use of a computer to simulate rigid contact lens fluorescein patterns while the contact lens is on the eye. It makes an assumption of an ellipsoidel corneal model and also that the cornea is symmetrical about its major meridians. This method has the potential to allow contact lens designers to easily see the effects of varying various parameters of a contact lens design (eg. back central optic radius and peripheral radii) and also to test a given lens design on a range of corneal topographies (eg. corneas with the same central curvature but varying degrees of peripheral flattening).

3.9 Keratometry and peripheral keratometry

3.9.1 Keratometry and its principles

Light rays that enter the eye are refracted at the two surfaces of the cornea and the two surfaces of the crystalline lens. As these surfaces are curved, the light rays are also reflected at these interfaces. These images of reflection called catoptric images were first described by Johannes Purkinje in 1823 and were first used by Louis Joseph Sanson in 1838 for diagnostic purposes. Hence they are commonly called Purkinje-Sanson images (Duke-Elder and Abrams, 1970 : 96).

In keratometry, the reflected image formed by the anterior surface of the cornea is used to determine the front radius of curvature of the cornea. Small targets called 'mires' representing the ends of an object are reflected by the convex surface of the cornea and are imaged as a diminished virtual image about 4 mm behind the corneal surface (Borish 1970:621). By measuring the size of the reflected image of an object of known size and position, the radius of curvature of the cornea can be determined.

The theory of keratometry is illustrated in Figure 3.3.

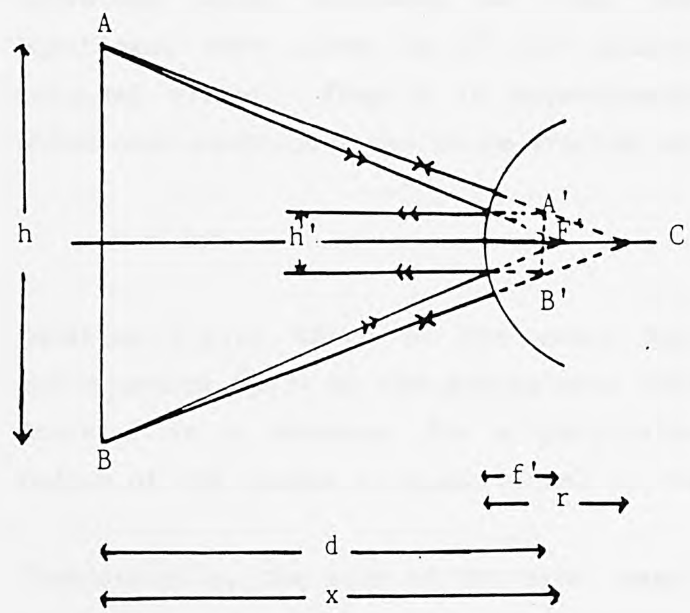


Figure 3.3. Principle of keratometry.

AB is an object of height h. A'B' is the image of AB formed by reflection at the corneal surface and is of height h'. It lies just short of the principal focus F' of the cornea.

By similar triangles

$$\frac{h'}{h} = \frac{f'}{x} = \frac{-r}{2x} \qquad \text{(Equation 3.1)}$$

where x = distance between object AB and principal focus F'
f' = distance between the vertex of the cornea to F'
r = radius of curvature of the cornea

$$\text{Thus, } r = 2mx \qquad \text{(Equation 3.2)}$$

where m = the magnification of the reflected image = $\frac{h'}{h}$

In practice, AB represents the separation of the mires on a keratometer. m is of the order of 0.03 for keratometer mires positioned approximately 15 cm from the eye. As the mire image is so small, a long focus microscope (or short focus telescope) is used to measure its size. In keratometry, the distance d between the mire image and the target image is large compared with the radius of curvature being measured so that the mire image is positioned very close to F' the principal focus of the corneal mirror. Thus d is approximately equal to x in which case equation 2 can be re-written as:-

$$r = 2md \qquad \text{(Equation 3.3)}$$

Equation (3.2) known as the exact keratometer equation and equation (3.3) as the approximate keratometer equation. Since d is a constant for a particular instrument, the radius of the cornea is proportional to the magnification m.

Theoretically, the size of the mire image could be measured simply by placing a measuring graticule within the microscope. However, due to the continual movement of the subject's eye, this measurement would prove difficult. This problem is overcome by incorporating the doubling principle into the keratometer (Borish 1970:622).

As well as giving the cornea's anterior radius of curvature, the keratometer can also given an estimate of total corneal power - that is, the combined power of the anterior and posterior surfaces. The true refractive index of the cornea is 1.376 (Cotlier, 1975). In order to calculate the total corneal power, a knowledge of its posterior radius of curvature and thickness is needed. However, Listing and Helmholtz considered that the total corneal power could be represented by a single curved surface of refractive index 1.3375. Gullstrand considered a refractive index of $^4/3$ to be a more accurate estimate (Emsley 1976:313). Olsen (1986) suggested that a refractive index of 1.3315 would provide more accurate corneal power calculations. The calibration index used by current keratometer manufacturers range from 1.332 (Zeiss) to 1.3375 (Haag-Streit and Bausch and Lomb). Although these will give rise to different values of the total corneal power they do not result in any significant difference in the calculated amounts of corneal astigmatism (Stone and Francis, 1980). For this reason, comparison between different keratometric expressed experiments is best expressed in terms of millimetres of radius rather than dioptres.

The principles of keratometry were described using the exact keratometer equation (3.2) and the approximate keratometer equation (3.3). These were derived from paraxial theory. Bennett (1966) has shown by ray-tracing techniques how the use of paraxial theory in the design of the keratometer would result in errors of about 4 to 5 percent in corneal radii measurements. Keratometers are usually calibrated by exact ray tracing techniques and with steel balls of known radii.

Keratometers used in the conventional way are centred about the point where the visual axis of the subject intersects the corneal surface. However, as the mires are reflected from two small areas on each side of this point the radius recorded by the instrument is not actually that of the corneal position to which it is directed. The separation of these two areas on the cornea depends on the corneal curvature and the instrument used. Thus, two different keratometers may not give the same measurement of radius for the same cornea. Mandell (1964) and Lehmann (1967) have calculated the separation of these areas in different keratometers for different radii of curvature. See Figure 3.4.

Error in the use of the keratometer can be introduced by incorrect focusing of its eyepiece as this affects the working distance of the instrument to the cornea. Rabbetts (1977) has studied the degree of error in radius measurement caused by this factor on various keratometers. Some instruments have a device built in to the design of the instrument to overcome this problem.

Charman (1972) studied the limits of diffraction on the accuracy of keratometers. For typical keratometers, the lower limit of reproducibility has set to about 0.2 dioptres which represents a spread of about $\pm$ 0.04 mm on average radius.

Clark (1973b) produced a review of the accuracy of keratometry as investigated by various researchers. He concluded that on living human corneas, an estimate of the standard deviation for radius of curvature was 0.015 mm.

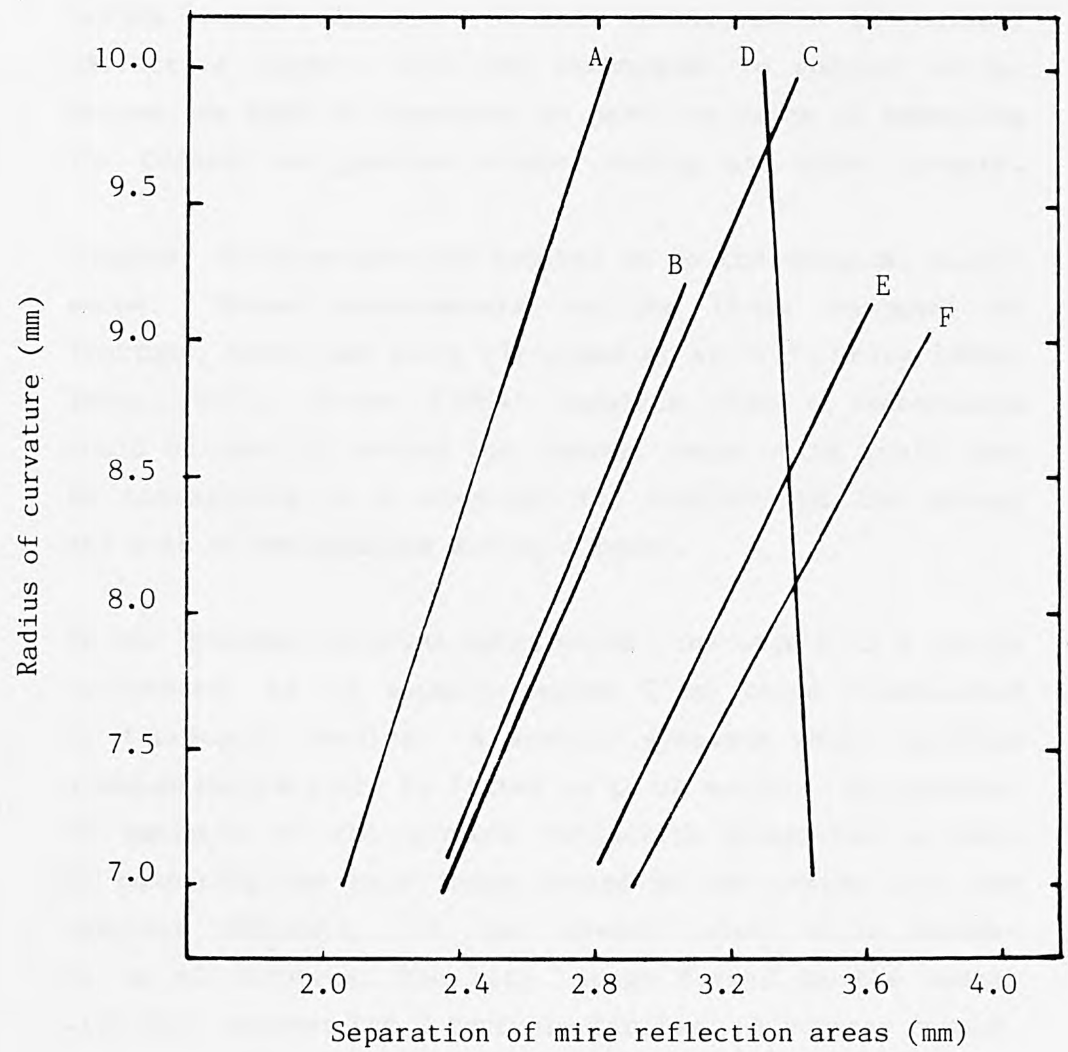


Figure 3.4. Separation of mire reflection areas for various keratometers. (After Mandell, 1964 and Lehmann, 1967.) Symbols: A Gambs, B American Optical Company, C Zeiss, D Haag-Streit, F Bausch and Lomb.

3.9.2 <u>Surgical keratometers</u>

Postoperative astigmatism results primarily from deformation of the cornea by surgery. This astigmatism must be minimized if soft contact lenses and intraocular lenses are to be fully utilized to provide comfortable clear visual results without the need of a spectacle overcorrection for aphakic patients. Surgical keratometers were developed to minimize unwanted postoperative astigmatic errors by enabling the surgeon to assess and modify corneal curvature during would closure. Recent developments in corneal refractive surgery with new techniques to correct astigmatism has made it important to have the means of measuring the corneal astigmatism before, during and after surgery.

Surgical keratometers are mounted on to the surgical microscope. These keratometers include those designed by Troutman, Cravy and Terry (Troutman et al,1977 ; Cravy,1980a; Terry, 1980). Drews (1984) suggests that a videocamera could be used to record the corneal image which could then be transmitted to a computer for analysis of the amount and axis of astigmatism during surgery.

In the Troutman surgical keratometer, the object is a circle perforated by 12 equally spaced 2 mm rings illuminated by fibreoptic bundles. A special eyepiece which includes a measuring reticule is fitted on to the surgical microscope. An estimate of the corneal refractive power can be made by comparing the mire image formed by the cornea with the eyepiece reticule. If the corneal power falls between 42 to 45 dioptres, the ring image formed by the cornea will fall between the 2 reticule circles. A steeper cornea, that is > 45 dioptres will image the ring within the inner reticule ring. If corneal astigmatism is present, the light ring will be distorted to an oval shape. One crosshair of the reticule is placed on the longer axis of the oval image which corresponds to the flatter meridian of the cornea. The amount of astigmatism as well as its axis could then be approximated by its relationship to the reticule circles (Figure 3.5). The accuracy of this instrument if used by an untrained observer was claimed

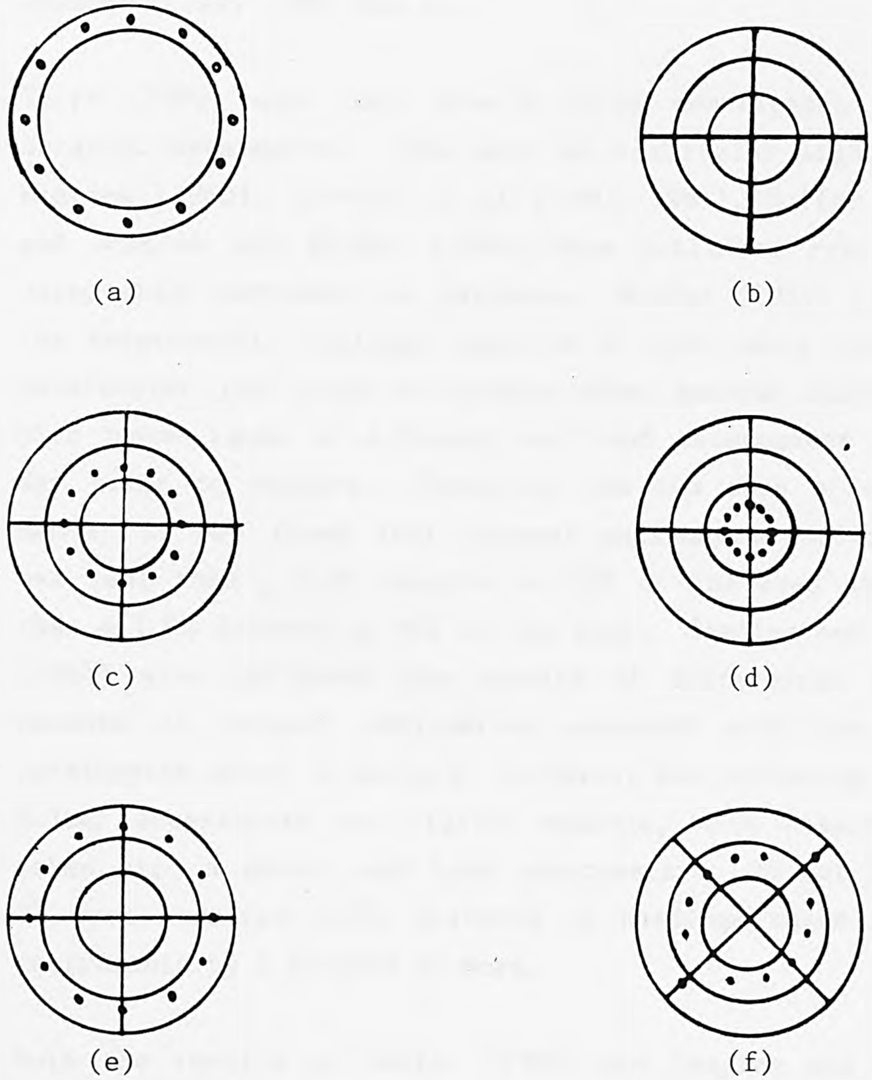


Figure 3.5. Troutman's keratometer. (After Troutman et al., 1977.) (a) Target, (b) Measuring reticule in eyepiece, (c-f) Light ring imaged by cornea as viewed through Troutman keratometer when the corneal curvature is : (c) between 42 to 45D, (d) steeper than 45D, (e) flatter than 42D, (f) astigmatic.

to be about 2 dioptres (Troutman et al. 1977; Troutman, 1980).

Only a very brief description of the Cravy surgical keratometer is available. In this instrument, a single light ring acts as a target. This target can also be mounted on to a 35 mm camera enabling photokeratographs to be taken pre-and post-operation. This very simple device is only meant for qualitative assessment of the corneal contour (Cravy 1980a and b).

Terry (1980) also only gave a brief description of his surgical keratometer. The mire is a circular light ring. Blaydes (1980), Colvard et al. (1980, 1981), Hoffer (1984) and Samples and Binder (1984) have published results of using this instrument on patients. Hoffer (1984) compared the keratometric readings taken on 87 eyes using the Terry keratometer just prior to surgery under general anaesthesia with those taken on a Bausch and Lomb keratometer on the day prior to surgery. Comparing the two sets of measurements, it was found that corneal astigmatism differences was less than ± 0.50 dioptre in 53% of the eyes and less than ± 1.00 dioptre in 80% of the eyes. Samples and Binder (1984) also published the results of differences in the amounts of corneal astigmatism measured with the Terry keratometer prior to surgical incision, but following retrobulber anaesthesia and digital massage, with measurements taken with a Bausch and Lomb keratometer. 10 out of the 27 eyes measured (37%) differed in readings taken on the instruments by 1 dioptre or more.

Both the results of Hoffer (1984) and Samples and Binder (1984) indicate that keratometric readings taken in an operation setting either before or after surgery may not necessary reflect the status of the cornea seen pre- or post-operatively in a clinical setting. So although theoretically the surgical keratometer should provide the same measurements on the cornea of a supine patient as when they are obtained in a clinic situation, other variables may lead to a difference in measurements. These variables as pointed out by Hoffer and Samples and Binder include:

position of the eye in the orbit, weight and position of the lid speculum, local or general anaesthesia, reconstitution of the anterior chamber, microscope magnification during readings, integrity of the corneal epithelium and intraocular pressure.

3.9.3 Auto-keratometers

These automated instruments of new and sophisticated design give more information about the corneal contours than the usual keratometers and, this information is provided almost instantly. Four such instruments available commercially are the Humphrey, Canon, Topcon and Nidek Auto-Keratometers.

The Humphrey Auto-Keratometer projects three beams of near infrared light on to the cornea in a triangular pattern within an area of about 3 mm in diameter. This diameter varies with the corneal curvature being measured. For a corneal radius of 7.03 mm, the diameter of the zone measured is about 2.60 mm, whereas for a radius of 8.76 mm, the diameter is increased to 3.24 mm. After reflection, the beams are received by photodetectors which isolate the rays making a predetermined angle with the keratometers optical axis. From this information, the principal radii and meridians of the measured cornea on the visual axis are calculated by an internal computer. Measurements of the cornea can also be made peripherally as in addition to a central fixation light, two further fixation lights are provided allowing ocular rotation to 13.5° on each side of the central fixation. This additional information enables the position of the corneal apex, the true apical radii and the value e^2 (where e = eccentricity) of the ellipse which best fits the data, to be estimated (Bennett and Rabbetts, 1984 : 421-422; Rabbetts, 1985).

Elstrom (1981) gave a very brief description of this instrument.

Comparisons between the Humphrey Auto-Keratometer and manual keratometers on the accuracy and reproducibility of corneal readings have been made by Halberg et al. (1982), Tate et al. (1987) and Lusby et al.(1987).

Loran et al. (1983) have used this instrument to compare the peripheral corneal flattening between Caucasian and Oriental Corneas. The results indicated an e^2 value of 0.20 ± 0.04 (where e = eccentricity) for

Caucasians, and an e^2 value of 0.12 ± 0.08 for Orientals.

Henslee and Rowsey (1983) used the Humphrey Auto-Keratometer and a Reynold's Corneascope to measure the corneal shape change after radial keratotomy in 50 subjects.

Similarly, Starr (1987) recorded the change in corneal contour following radial keratotomy in 16 eyes.

The accuracy and measurement reliability of the Canon Auto-Keratometer K1 have been reviewed by Nakada et al. (1984), Port (1985), Tate et al. (1987) and Jarvis et al. (1987). The eye being measured is imaged by a videocamera on to a television screen. The reflected image of the single collimated round mire is then focused by using a joy-stick control. When the mire image has been properly centred and focused by the operator, a measurement button is then pressed. This triggers off a flash tube behind the mire producing enough reflected light for image processing to take place. A few seconds after measurement, the processed data is displayed at the bottom of the screen and a print-out facility is available. It supplies the following data: the flattest and steepest radii of the cornea, their corresponding powers and meridians, and the amount of corneal astigmatism. Measurements on the peripheral cornea can be made by using fixation positions 10 degrees from the primary position. Unlike the Humphrey instrument, it does not provide an indication of the peripheral corneal shape or the corneal apex position.

Nakada et al. (1984) compared the corneal radius values obtained with the Canon automated keratometer with those obtained with a conventional Bausch and Lomb keratometer on 275 eyes. The subjects ranged in age from 3 to 72 years. There was a good correspondence between the two readings. The difference between the two radius measurements were $\leq \pm$ 0.05 mm in 65 to 68 percent of the eyes measured.

Port (1985) found a range of 0.03 mm between the maximum and minimum values in the central corneal radii measurements and a range of 0.04 mm for peripheral corneal measurements.

The main source of error which Port noted in using the instrument was the degree of blur on either side of the correctly focused position which would give an 'acceptable' signal. This depth of focus could produce a radius range of 0.07 mm.

Tate et al. (1987) compared the accuracy and reproducibility of keratometric readings between the Canon, Humphrey and a manual Haag Streit keratometer. On average, all 3 instruments showed a good correlation (correlation coefficient r = 0.88) in corneal power readings with each other.

Jarvis et al. (1987) evaluated and compared the performance of the Canon Auto-Keratometer with the Bausch and Lomb manual keratometer on 207 eyes. No significant difference in accuracy and reliability was detected between the 2 devices.

Inagaki et al. (1985) re-arranged the Canon instrument to allow corneal measurements to be made on supine babies.

Port (1988) recently provided details of the Nidek KM-800 and Topcon CK-10000 instruments.

3.9.4 Peripheral keratometry

Peripheral keratometry was developed in order to provide more information about the shape of the cornea by obtaining keratometric readings at various fixed points along a particular meridian.

Bonnet and Cochet (1962) and Borish (1970:649-655) indicated the main difficulties of using this method. They are:

(i) Definition of the exact area being measured on the cornea is difficult as either the eye or the instrument has to be moved to obtain peripheral keratometric readings,

(ii) The assumption of a surface of constant radius of curvature between the two reflection points in central keratometry presents a greater error in peripheral keratometry due to the rapid flattening of the peripheral cornea, and

(iii) The method is very laborious and time-consuming as many settings have to be made to plot a complete meridian on the cornea. Bonnet and Cochet (1962) said that topographical keratometry was "totally impossible for very young subjects." The youngest subject they managed to obtain measurements from was a 6½ year old child.

Borish (1970:649-655), Stone (1975), Sheridan (1971, 1980) and Mandell (1981) have produced general reviews of this method.

3.10 Keratoscopy and photokeratoscopy

3.10.1 Introduction

Keratoscopy is a qualitative or quantitative method of assessing the anterior corneal contour by observing reflections from its surface. The advantage of the keratoscope is that its target may be composed of many parts which act as separate objects whose images may be used to obtain curvature values for a relatively large area of the cornea. The simplest keratoscopes are those which utilize concentric black and white circles like the Placido disc and the hand keratoscope. Photographic recording of the image formed by reflection of the target at the anterior corneal surface is called photokeratoscopy. The extent of separation of the corneal reflection images on the photograph is a function of the corneal curvature.

The invention of the keratoscope has been attributed by Levene(1965) to Henry Goode (1847). He devised this instrument during an endeavour to determine whether the cause of ocular astigmatism in a subject was corneal. Goode described the use of his instrument as follows:

> "In order to ascertain if it were possible to detect any error of curvature on the surface of the cornea, I observed the appearance of a small luminous square held a few inches from the eye; but in the central part of this structure the reflected image was perfectly square, while the distortions produced at the circumference were equally produced in the sound eye; and there was no reason to conclude that the defect of vision arises from any defect in the cornea."

Antonio Placido in 1880, the Portuguese ophthalmologist appears to have invented the hand keratoscope independently (cited by Levene, 1965). His description of the instrument in a letter published in 1881 was of a thin, light flat disc of uniform thickness. On one side of the disc, alternate white and black bands were drawn. In the centre of the disc was a circular aperture. A central tube was also present on the disc to achieve alignment and to enable viewing. Correspondence published in April 1881 and May 1882 attributed the incorporation of photography into keratoscopy to Placido (cited by Levene,1965).

Louis Emile Javal in 1881 also invented the photokeratoscope independently (cited by Levene, 1965). He is also credited with the first description of the application of photokeratoscopy in a keratoconus case. Javal was originally a mining engineer and later qualified as a medical doctor.

3.10.2 Flat target keratoscopes

Gullstrand (1896) was the first to use photokeratoscopy to analyse corneal curvature quantitatively from the separations of the reflected images in the cornea. The target of Gullstrand's instrument as shown in Figure 3.6 was a flat one consisting of four white rings which were concentric with the objective of the camera. A fine dark line was drawn in the middle of each white ring. In the negative, the white rings appeared black and the dark line transparent making it easier for the cross-hair of the measuring microscope used to be aligned with it. The angle formed by normal to the cornea at the reflecting point with the optical axis of the instrument for the outermost ring was $17^{\circ}\ 6'\ 30''$ which corresponds to a chord length of 2.3 mm from the camera axis for a 7.8 mm radius cornea. In order to increase the area of the cornea covered, Gullstrand took 6 exposures of each eye, 2 at central fixation, and 1 each for fixation superiorly, inferiorly, left and right. Using this technique, the areas covered in the four quadrants were:

Nasally up to 5.851 mm from the camera axis,
Temporally up to 5.385 mm from the camera axis,
Superiorly up to 4.948 mm from the camera axis, and
Inferiorly up to 5.587 mm from the camera axis.

Hartinger (1930) described a clinical model of Gullstrand's design, a photograph of which appears in Figure 3.7.

Amsler (1930) also used a target similar to Gullstrand's. The lines on the target appeared to be of equal width and spacing so that in the image reflected from a spherical surface, they were not uniform but were narrower towards the periphery.

Von der Heydt (1931) gave a brief description of a Placido-like disc apparatus with a camera which was manufactured commercially by Carl Zeiss.

Howard (1936) described a flat Placido-like disc supported on a hollow rubber handle which enclosed two electric leads

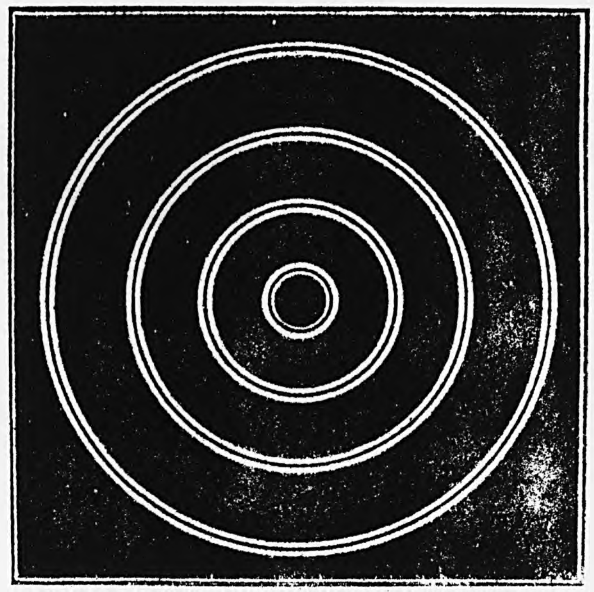


Figure 3.6. Gullstrand's target. (Reproduced from Gullstrand, 1896.)

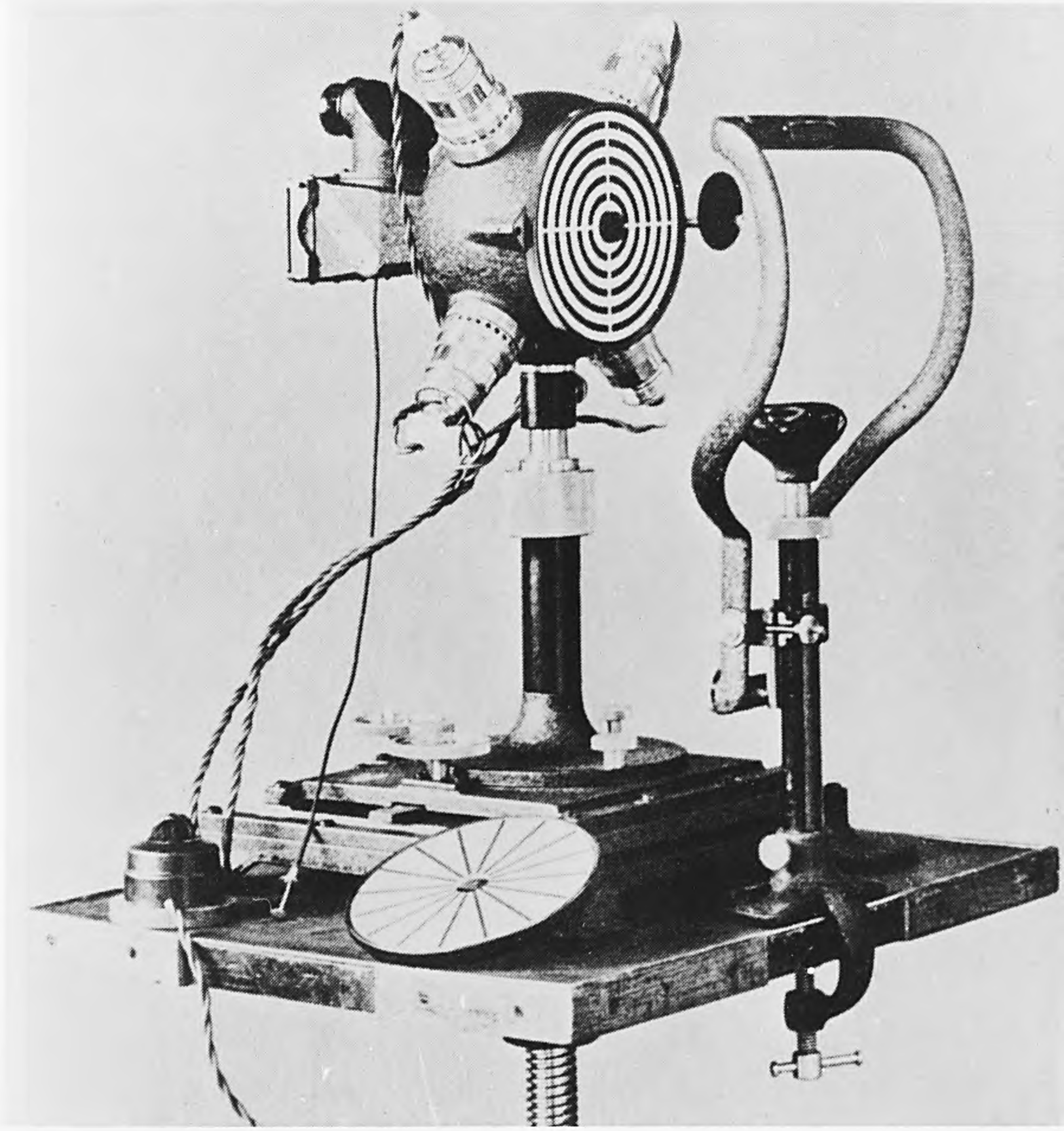


Figure 3.7. Clinical model of Gullstrand's photokeratoscope. (Reproduced from Hartinger, 1930.)

leading to a small transformer and operated on an alternating current. This apparatus seemed to be intended for qualitative analysis only.

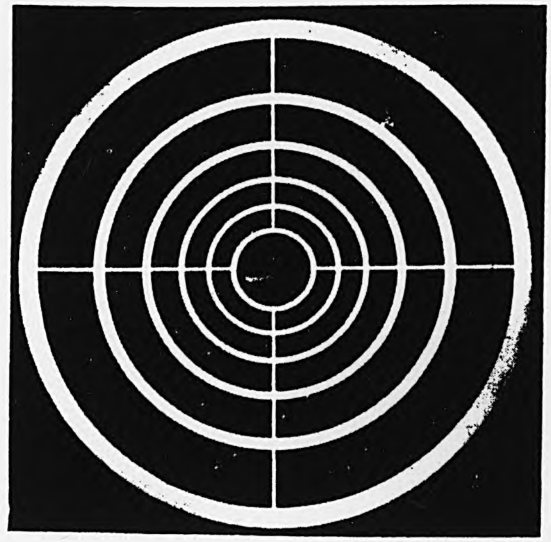
Kokott (1938) used a flat target and photographed the reflections with a stereoscopic camera to enable the corneal contour to be viewed in 3-dimension.

Fincham (1953) designed a flat target consisting of 6 concentric rings designed such that when reflected from a spherical surface, the lines in the reflected image would appear to be equal in width and equally spaced. The diameter of the target was 20 cm and was designed to be used at a distance of 6 cm from the eye. Fincham claimed that a corneal diameter of 7 mm was covered if the radius was 8 mm. (See Figure 3.8.)

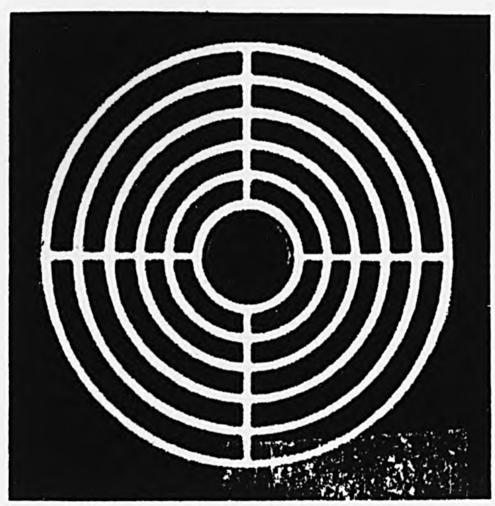
Philps and Hansell (1954) described the A.I.M. photokeratoscope based on Fincham's design. The ring diameter on a keratograph could be related to its corresponding corneal curvature by referring to a calibration graph. Alternatively, a range of keratographs cut in half of different known radii of curvature was also present at the edge of the calibration chart, allowing the rings from the measured cornea to be matched to the keratographs of known curvature.

Morris (1956) described the A.I.M. keratograph as "a simplified and clinical version of Fincham's photokeratoscope." The target which consisted of a series of concentric black and white rings was printed on a sheet of opal perspex. The width of the rings were designed such that when they were reflected by a spherical surface, the rings appeared equally thick and had equal separations.

Gasson and Stone (1977) modified the A.I.M. photokeratoscope by incorporating a polaroid camera. Their aim was to evaluate the usefulness of the instrument in soft lens



(a)



(b)

Figure 3.8. Fincham's target. (Reproduced from Fincham, 1953.) The target (a) is designed such that when reflected from a spherical surface, the lines will be equal in width and equally spaced as seen in (b).

fitting. They concluded that definite distortion of the photokeratoscopic image was obtained only if the lenses were markedly steep of flat fitting.

Klein (1958) reported that the rings of a Placido disc device could be self-illuminating if mounted on to an ophthalmoscope hurdle.

Levene (1962) used the instrument described by Klein to assess its reliability in detecting corneal astigmatism. He concluded that the minimum amount of corneal astigmatism which could be reliably detected by this method was in the order of 2.50 dioptres.

Sivak (1977) described how he constructed a photokeratoscope by attaching the Placido disc device of Klein's to the lens of a single-lens reflex camera. He claimed that the corneal radii measured with this instrument were within $\pm$ 1.00D of central keratometric readings. This instrument has been used to estimate corneal curvature in birds (Sivak et al., 1985).

Stein (1958) constructed a target consisting of 3 concentrically arranged circline fluorescent tubes for qualitative corneal analysis.

Hoftsetter (1959) conducted a survey on 13,395 eyes using a flat target consisting of 5 concentric black rings. The aim was to classify the pattern seen as spherical, irregular or keratoconic.

Plummer and Lamb (1961) described how a target based on Fincham's design could be produced cheaply by making a stencil and painting it on to a circular piece of opal perspex. The instrument was calibrated with 3 ball bearings of known radii.

Brown (1969) reported on a target also based on Fincham's design which was mounted on a camera and attached to a slit-lamp which provided the necessary movements for centring and focusing the target. The target was painted on a metal plate 8.6 cm in diameter. This instrument appeared to be only for qualitative analysis of the cornea.

Nakajima (1971) demonstrated how Placido disc images of the cornea could be used to derive its asphericity coefficient. The photokeratoscope used had a flat target consisting of 5 rings.

Hirano et al. (1977) claimed that stereoscopic observations of Placido disc images on soft contact lenses aided in detecting very small irregularities on their surfaces.

Cotrain and Miller (1987) described a Placido disc device consisting of 6 clear concentric rings on an opaque black background as an attachment to a photo slit lamp. The diameters of the rings were calculated such that when reflected from corneas of "normal" curvature, virtual images of concentric and equally spaced circles were formed. This device appeared to be only for qualitative analysis of the cornea.

Reynolds and Kratt (1959) designed the "Photo Electronic Keratoscope" (P.E.K.). In this method, a polaroid camera was used to obtain rapid photokeratoscopic records and these were scanned by an electronic device to establish the variation in radius over the corneal area up to 8.50 mm in diameter (Reynolds, 1959). The target was a flat one as seen from a photograph in a report by Martin (1967). Norton and Sullivan (1962) also published a photograph of the P.E.K. but made no reference to Reynolds and Kratt. Cummings (1967) and Ziff (1967) published reports of using the P.E.K. method as an aid to the fitting of contact lenses.

The accuracy of the P.E.K. was assessed by photographing artificial corneas and spherical steel balls of known curvature and the film were measured by a computer (Reynolds, 1959). The average error found was 0.03 mm in the radius measurement. The corneal topography of 1,000 normal corneas and the effect of diurnal variation, temperature variations, ovulation and menstruation on some subjects were also studied by Reynolds.

Blair (1960) evaluated the P.E.K. by taking a series of 3 photographs from a steel ball of 5.94 mm radius. 60 readings taken on the first keratograph gave an average radius of 5.94 mm, the range in values ranged from 6.06 mm to 5.84 mm. On the second keratograph, the measuremens ranged from 6.12 mm to 5.88 mm. The extreme values recorded on the third keratograph were 5.87 mm and 6.10 mm. Of the total of 180 readings taken on the steel ball of 5.84 mm radius, 64 percent were within 0.04 mm of the correct value making 36 percent of the measurements in error by 0.04 mm or greater. Measurements of a series of 3 photokeratographs of a steel ball of radius 7.47 mm showed that out of a total of 90 readings, 55 percent were within 0.04 mm of the correct value. Mandell (1961b) pointed out that the average value for the readings with the P.E.K. were not as important as the spread of the readings obtained as in normal use of the instrument, only one, or, at most, a few readings would betaken for each cornea. Also these tests were done on steel balls so the precision on human corneas would be exptected to be less.

The above researchers all used flat object targets. The main difficulty presented by a flat target is that its virtual image formed behind the cornea is curved. As the photographic plane also lies on a flat plane, this results in blurred peripheral photographic images. Gullstrand (1896) overcame this problem by using a small target covering a small corneal area and varying the fixation of the subject. Another solution to obtain clear peripheral photographic images is to reduce the aperture size of the camera. However, that also increases the camera's depth of focus which will permit a greater variation in working distance. More importantly maximum aperture photography allows an assessment of the accuracy of this working distance from the clarity of the photographic images. As the accuracy with which a photokeratoscope can be used to determine the radius of a surface is dependent on a known working distance, more errors would be caused by using a small aperture. Another disadvantage of a flat object surface is that it would need to be very large in order to cover a large area of the corneal surface. In order to overcome these difficulties object targets of different shapes were designed.

3.10.3 Curved target keratoscopes

Berg (1929) used miral objects painted on a pair of mutually perpendicular arcs. The eye to be measured was placed at the common centres of the two arcs and the reflected image photographed. These arcs were painted black and marked at regular intervals with white paint. The camera was focused using a wide aperture but was stopped down when the photograph was taken to decrease the blurring effect of the curvature of field on the keratograph.

Dekking (1930) found that rings of constant size with their centres on the optic axis of the camera and located at various distances from the cornea produced least curvature of field of the image. Dekking did not attempt any mathematical analysis of corneal curvature from his keratographs as he was interested primarily in the detection of pathology.

Knoll et al.(1957) designed a target made of a hemisphere of opal glass with transilluminated rings serving as multiple objects. Black concentric rings 5 mm in width and spaced 5 mm apart were painted on its inner surface.

The photographs were taken at an aperture of F11 which enabled a sharp image of the rings reflected from a wide extent of the cornea. However, this aperture size would have made the depth of focus of the camera quite large making it difficult to check if the correct working distance had been maintained. The authors claimed that the area covered by this instrument subtended 90 degrees at the centre of curvature of the cornea.

Knoll (1961) described a cylindrical object surface with a light intensity flash tube. The target consisted of 11 aluminum rings of varying width and spacing with 10 of the rings lying on the surface of a cylinder having an inside diameter of 5 inches. The eleventh ring lay at the base of the cylinder. 4 wedge-shaped strips were attached to the inner surface of the rings for easy location of the meridians. Photographs were taken at unit magnification with an effective stop of F16. The instrument was calibrated with steel balls. Photographs were taken of 67 eyes from subjects aged between 22 to 62 years and the corneal curvature was analysed in the horizontal meridian only. Knoll claimed an accuracy of ± 0.20 mm in radius determination with this instrument. Ritz (1963) published the same photographs of Knoll's photokeratoscope and photokeratograms as were in Knoll's 1961 paper, but made no reference to Knoll.

Stone (1962) constructed a hemispherical object surface using point sources of light instead of rings as sources for reflection. These were placed along meridians of 45^{o} apart. A measuring microscope having 0.01 mm graduations were used to measure the distances between the image spots on the films. Repetition of measurements gave a variation as much as 0.11 mm with an average discrepancy of 0.08 mm. Measurements carried out on photographs of steel balls led Stone to conclude that the radii of the steel balls could be measured to an accuracy of ± 0.25 mm peripherally and ± 0.06 mm centrally. Measurements of the steel ball photographs were repeated using a microdensitometer but calculations showed no improvement in the accuracy of measurement.

Westheimer (1965) described a new technique of photo-electronic keratoscopy which made use of an incident beam which swept across the cornea by a rotating lucite cube. The direction of the reflected beam was detected by an array of photocells.

Ludlam and Wittenberg (1966a) derived that the optimum object locus required to produced a flat reflected image from a spherical surface was an elliptical target. However, as the cornea is aspheric, they concluded that a solution for exact planatism was impossible but "the cylindrical focus afforded a functional compromise."

Ludlam et al. (1967) used a modfied Knoll photokeratoscope on steel balls and a human cornea. Attempts to measure the photographs with a powerful microscope were abandoned as it proved to be quickly fatiguing. Instead, the negative was mounted between glass slides and clamped to the stage of a micrometer measuring stage and projected at a magnification of 20 times on to a screen. The readings could be interpolated to the nearest 0.001 mm. One of the methods used to assess the reliability of the photokeratoscope was to make measurements of the sixth ring of 5 keratographs each of a steel ball and a human cornea. The sixth ring was located approximately 3.5 mm from the instrument axis. The results indicated that the radius of the steel ball and the cornea lay within a range in variability of ± 0.036 mm and ± 0.061 mm respectively at the 95 percent level of confidence.

Mandell (1967) described a portable photokeratoscope for use on infants. Details of the instrument are given later in section 11.4 of this chapter.

Mandell and St. Helen (1968) constructed a photokeratoscope with an ellipsoidal type target to investigate the stability of the corneal topography in adult corneas. The target consisted of a series of aluminium rings which had V-groves cut in their inner surfaces. The grooves were filled with black paint. The reflected image was photographed using a fixed focus camera and the films measured with a measuring microscope. The reliability of the method was assessed by measuring 5 photographs of the cornea twice in 1 semi-meridian. On the basis of these measurements, an estimate was made that a corneal radius change of 0.08 mm would have to occur before it could be detectable by this method. The corneal area covered from a single photograph was said to be limited only when the target ring images formed by the cornea were blocked by the nose, lids, and or brows of the subject. Measurements extending to the limbus were often possible in the horizontal meridian.

Mandell and St. Helen (1971) used the same instrument in an attempt to find a mathematical curve to approximate the central cornea. Measurements were made on the right eyes of 8 adult males and an elliptical model was selected as being adequate to resemble the central cornea. The range in eccentricity values was from 0.20 to 0.85, the mean value being 0.48.

Townsley (1967) modified the original flat target of the P.E.K. so that the rings now lay on an ellipsoidal surface. The shape chosen was based on the work of Ludlam and Wittenberg (1966a) mentioned earlier. Townsley's method of analysing the photokeratographs was criticised by Clark (1973a) which evoked a rejoinder (Townsley and Clark, 1974).

Bibby (1976a, b) gave further details of the revised P.E.K. target design (Wesley-Jessen System 2000 Photokeratoscope) as being made up of 7 concentric rings lying on an ellipsoidal surface so that when reflected in a 44.00 dioptre cornea, the virtual image formed behind the cornea would lie in a flat plane.

The relevant measurements of the reflected rings on polaroid photograph are processed by the P.E.K. computer to locate the flattest corneal meridian and the meridian 90 degrees to it, the central radii of curvature for these two meridians, and the "shape factor" for the two meridians. The term "shape factor" for this instrument is defined as the square of the "eccentricity" of the cornea. Each instrument is claimed to have been tested to measure the radii of 3 accurately known spheres within 0.015 mm of their true value. Also a maximum standard deviation of $^{1}/16$th dioptre in the curvature of a steel ball was obtained from reproducibility studies (Bibby 1976a).

The P.E.K. has been used in several studies on corneal topography. Wesley (1969) used a least squares method of fitting curves to P.E.K. data. He found that an ellipse of eccentricity between 0.3 and 0.6 and whose vertex was generally displaced slightly from the optical axis of the instrument, fitted the data points of most normal corneas.

Townsley (1970) assessed the corneal topography of 350 contact lens patients using the P.E.K. 259 of the patients were largely referrals and special cases and the remaining 91 were more 'normal' cases. Results of the eccentricity of the cornea were given for both groups in the horizontal and vertical meridians. It was found that in normal eyes an ellipse could be fitted to any corneal meridian and that the range of eccentricity values were in the range of 0.4 to 0.9 with the frequency distribution curve centred around an eccentricity value of 0.55.

Bibby and Gellman (1976) calculated a mean "shape factor" of 0.21 from the horizontal meridian of 32,000 subjects.

Bibby (1979) reported on the sagittal depth of the cornea at 12 mm diameter which was calculated from P.E.K. measurements of the flat meridian of 18,387 eyes.

Tomlinson and Schwartz (1979) determined the position of the corneal apex for 100 normal eyes (50 right and 50 left) from P.E.K. data analysis.

Edmund and Sjøntoft (1985) used a least squares method of analysing the P.E.K. data in the horizontal andvertical meridian from both eyes of 40 normal subjects. They stated that the characteristics of the corneal profile in any meridian could be better specified by 2 values that is K (the curvature of the cornea at its apex) and RV (where RV = 15 x $\frac{\text{eccentricity}^2}{K^2}$). A mean value of K was found to be 7.86 mm in the horizontal meridian and 7.65 mm in the vertical meridian. The RV value was found to be approximately 0.70 x 10^{-2} mm^{-2} in the 2 meridians which implies a change in radius 1 mm and 5 mm from the corneal apex by 0.7 % and 17.7 % respectively.

Guillon et al. (1986) investigated both normal eyes of 110 subjects who ranged in age between 17 to 60 years with an aim to establish a corneal model for the normal population. The instruments used were a Bausch and Lomb keratometer and the Wessley Jessen P.E.K. From the results an ellipsoidal corneal model was proposed. The radius of curvature in the flattest meridian had a mean value of 7.85 $\pm$ 0.25 mm (s.d.), and the steepest meridian 7.70 $\pm$ 0.15 mm (s.d.). The mean p-value (as defined by Bennett, 1968 - 1969) was found to be 0.85 $\pm$ 0.15 (s.d.). The majority of the corneas flattened towards the periphery but in a significant number of cases, the cornea did not flatten towards the periphery but remained unchanged. In some cases the cornea steepened in the periphery.

The P.E.K. has also been used in corneal topography studies involving individuals with congenital mystagmus (Dickinson and Abadi, 1984), orthokeratology (Lim, 1980), contact lens subjects (Douthwaite and Atkinson, 1985) keratoplasty subjects (Ruben and Colebrook, 1979) and radial keratotomy subjects (Astin, 1986; Starr, 1987). Carrington and Woodward (1984) have used the same instrument to measure the corneal topography in domestic cats. El-Nashar (1983) and El-Nashar and Larke (1986) performed P.E.K. photokeratoscopy over hydrogel lenses in situ to study wave front aberration.

Cochet (1968) described a photokeratoscope with luminous filaments (a later model used light conductors) as target objects. The lamp filaments were arranged on 2 perpendicular cardioid shaped arms at 5 degree intervals from 10 degrees to 40 degrees where they were illuminated by a circular flash tube surrounding a camera lens. The photographs were measured by 2 methods:

(i) by projection on to a graduated screen in a long room where a magnification of 100 times was achieved, and

(ii) by stereo-microscopy with readings correct to 0.001 mm.

Cochet and Amiard (1969) also described an automatic system for measurement of the photographs. The error in radius determination was said to be 0.01 mm (s.d.) which was inconsistent with the statement in the same report by Cochet and Amiard (1969) which said "This possible distortion is in fact of little consequence if the film is properly processed, and does not affect precision more than 1 percent." 1 percent of a 7 mm radius cornea is 0.07 mm not 0.01 mm.

Lim (1980) reported using the above instrument and the Wessley-Jessen P.E.K. to monitor the cornea in an orthokeratology study.

Holden (1970) constructed an ellipsoidal target locus photokeratoscope with a series of light sources mounted on adjustable metal rods acting as targets. A light was used to mark the position of the optical axis of the camera permanently on the film. The photokeratographs were measured by projecting them at a magnification of 100 times on to a graduated screen enabling measurements to be made correct to 0.0025 mm. The use of microdensitometry to measure the photographs was attempted but difficulty was found in aligning the film images with the direction of travel of the microdensitometer stage and also in judgment of the centre of each image. These difficulties with the microdensitometer were also pointed out by Stone (1962). Measurement using a measuring microscope was found to be a very tedious process. Measurements of images of 3 steel balls recorded on several films were made using the projection methods. The average standard deviation on image heights obtained was 0.022 mm in radius, the range of standard deviations in radius being from $\pm$ 0.011 to 0.074 mm. The accuracy of corneal radii measurements was found by using data from 7 photokeratographs of 1 eye. The average standard deviation found in radius was 0.023 mm.

El Hage (1972a,b) described a cylindrical target photokeratoscope made up of 10 plastic rings with an electronic ring flash placed between the camera and the first ring. A telecentric stop was placed at the back focal plane of the camera objective lens. In order to ensure correct positioning of the cornea, two mires were projected on to the cornea and coincidence of the mires was obtained if the corneal position was within $\pm$ 0.2 mm of the correct camera to cornea distance. From tests conducted on metal spheres and aspheric surfaces, the sagittal depth at the corneal periphery was considered to be measured to an accuracy better than 0.02 mm.

El Hage and Baker (1986) used the above instrument to record the corneal topography in 8 post-operative radial keratotomy subjects before fitting them with rigid gas-permeable contact lenses for controlled keratoformation.

Donaldson (1972) designed an instrument with a hemispherical target comprising of 12 circular translucent rings separated by black opaque surfaces. A stereo-camera was used to photograph the reflected images but its use was stated not to be necessary and only increased the definition of the photographs. Calibration was carried out by using steel balls. No details of how the films were measured were provided except that they were measured under magnification. No estimate was also given for the accuracy of the method.

Clark (1972) described an autocollimating photokeratoscope made up of a set of 12 concentric rings. Light from the rings was directed on to the corneal surface at near-normal incidence. The unit consisted of 2 optical systems, enabling an image of the reflected rings to be photographed simultaneously with a profile of the cornea. The corneal profile was used to give an approximate value of the corneal radius. The size and position of the image of each ring was analysed to obtain the corneal shape, the aim being to describe corneal topography in terms of the departure from the sphere which most closely fitted the central region of the cornea. Clark (1973a) argued that this asphericity value of the corneal surface allowed precise comparison in inter- and intra-subject topographical studies. Clark (1972) claimed that a corneal diameter of about 10mm was covered by this instrument. Calibration of the instrument was carried out with a precision glass sphere. Target ring positions were measured with a travelling microscope to the nearest 0.01 mm. Tests carried out by Clark (1972, 1974a) on spheres of known radii and an aspheric surface revealed that the s.d. of calculated asphericity at the edge of a 9 mm diameter zone was 0.004 mm. Kiely et al. (1982b) also investigated the accuracy of this method by analysing 9 photographs of a glass calibration sphere. The radius was determined to be 7.22 $\pm$ 0.02 mm (s.d.) and its asphericity to be - 0.01 $\pm$ 0.01 mm (s.d.). 6 photokeratographs of a single cornea were also measured and its radius and asphericity were found to be 7.35 $\pm$ 0.02 mm (s.d.) and - 0.30 $\pm$ 0.04 mm (s.d.).

A fairly extensive series of corneal topography studies have been conducted with this instrument. These are now listed below.

Carney and Clark (1972) investigated the recovery of the corneal surface from deformation after applanation. 99 percent of the central corneal displacement was found to have recovered within 8 seconds after retraction of a tonometer probe.

Clark (1973e) studied the effects of accommodative effort and of turning the eye in a horizontal temporal direction. No measured corneal changes were found in the right eye of the 3 subjects involved in the study.

Clark (1973f) also observed the diurnal variations in corneal topography of 4 eyes (3 subjects) over a period up to 14 months. The variations found were comparable with errors of the measurement system.

Clark (1974b, c) found considerable differences in corneal topography both within and between individuals in different semi-meridians. Both eyes of 41 male and 41 female subjects were measured in the study. Asymmetry of asphericities about the ophthalmometric axis between different semi-meridians were usually found in individual corneas and also in the pooled results. The mean optic-cap radius was 7.759 $\pm$ 0.260 mm (s.d.).

Carney (1975a) conducted trials on 6 subjects wearing PMMA contact lenses whilst their corneas were exposed to gases of varying oxygen contents. Measurements of central and peripheral corneal thickness and corneal topography showed that corneal topography changes after hard contact lens wear may be due to an unevenly distributed corneal thickness change and, or a mechanical moulding of the cornea.

Carney (1975b) also performed similar trials with hydrophilic lenses and concluded that wear of hydrophilic lenses has little effect on corneal topography as unlike PMMA lenses they cause an almost evenly distributed central and peripheral change in corneal thickness.

Kiely and Carney (1978a) investigated the effects of instilling various ophthalmic solutions (topical anaesthetic, mydriatic and a contact lens solution) on 1 eye of each of 3 subjects. Only 1 of the above solutions was applied on any 1 day. Photokeratographs were taken before and immediately after instillation of the solution, and at 5 and 20 minutes after. In almost all instances, no significant alteration of corneal topography was detected.

The effects of lid pressure on the corneal surface was studied in 8 subjects by Kiely and Carney (1978b). No significant topographical changes were detected on normal blinking, lid retraction and hard forced blinking except in 1 isolated instance.

Bowman and Carney (1978) measured the effects of non-contact tonometry on the corneal topography of 6 subjects. 5 tonometry measurements were performed consecutively on 1 eye of each subject. Corneal photokeratographs were taken about 20 seconds after the final tonometer reading. No significant difference was found in the asphericity values before and after the tonometry indicating that there was no significant change in the corneal topography.

Corneal shapes of 176 normal eyes belonging to 49 males and 39 female subjects aged between 16 to 80 years were investigated by Kiely et al. (1982b). Using a least squares method of fitting the photokeratoscopic data from the 176 corneas and assuming a rotational symmetrical form, an ellipsoid was found to be the best fitting conic for corneal shape. The mean value of the central corneal radius was found to be 7.72 ± 0.27 mm (s.d.), the range of values being from 7.06 to 8.64 mm. The mean value of the corneal asphericity was recorded as - 0.26 ± 0.18 (s.d.). (This asphericity value is related to the eccentricity e by : Asphericity = $-e^2$). This gives an equivalent p-value (as defined by Baker, 1943 and Bennett, 1968 - 1969) of 0.74, which corresponds well with other studies conducted by Townsley (1970), and Guillon et al. (1986) who found mean p-values of 0.70 and 0.85 respectively. Kiely et al. (1982 b) also derived a more complex non-rotational conicoid corneal model and found that their results indicated that the cornea is significantly asymmetric in both radii of curvature and asphericity along 2 meridians which are perpendicular to each other.

Kiely et al. (1982 a) also conducted another study on one eye of 21 normal subjects to investigate the diurnal stability of the central corneal radius of curvature and overall corneal topography. Measurements were carried out with a Bausch and Lomb keratometer and Clarke's photokeratoscope. The accuracy of each measurement method used was assessed and the results are reproduced below:

Method of measurement	Std. error of the mean	No. of measurements
Keratometry (horizontal)	0.004 mm	6
Keratometry (vertical)	0.007 mm	6
Radius (R) from photokeratoscopy	0.009 mm	5
Asphericity (Q) from photokeratoscopy	0.017 mm	5

Measurements made hourly for 12 hours within 10 minutes of lid opening, showed that the cornea was flattest on awakening and steepened as the day progressed. The asphericity value of the cornea fluctuated throughout the day but no clear trend was detected. A relationship was indicated between central corneal thickness (measured by pachometry) and horizontal corneal curvature.

The change in central corneal curvature and corneal topography over 1 complete menstrual cycle was assessed in 6 women all aged 19 years (Kiely et al.,1983). Again the Bausch and Lomb keratometer and Clark's photokeratoscope were used for the measurements. Steepening of the horizontal and vertical curvatures were found at the beginning of menstruation and flattening occurred after ovulation.

Kiely et al. (1984) measured the corneal topography of both eyes in 98 subjects (54 males and 44 females) along 4 meridians. The central corneal radius was found to vary between different meridians but little difference was found between the asphericity values. Ellipsoids were determined to be the best fitting conicoids for 99.7 percent of all the corneal meridians.

Maruyama and Fujii (1971) and Fujii et al. (1972) developed a telecentric instrument with multiple collimated beams of light arranged semi-circularly to act as targets. An area of the cornea of about 10 to 11 mm in diameter was claimed to be covered by this design. Fujii et al. (1972) derived an equation to describe corneal configuration after making corneal measurements on 30 normal subjects. The mean central radius of curvature determined in this group was 7.84 ± 0.23 mm (s.d.).

Pulvermacher and Rott (1972) described how the use of a fine cross reflected in the central cornea could be used for adjusting the cornea to the correct position for their photokeratoscope. An accuracy of $\pm$ 0.015 mm in reproducing the corneal contour was claimed.

Aan de Kerk et al. (1973) constructed a portable photokeratoscope with a cylindrical target based on Dekking's (1930) design. The instrument was claimed to give complete corneal coverage. No mention was made of the accuracy of the method.

Charman and Tucker (1973) reported the use of a microscopic adaptation of the "conventional photokeratoscope" to study the anterior corneal surface of the goldfish. No details were given of the instrument except that the target consisted of concentric black and white annuli.

Fry (1975a) described the incorporation of an auxiliary lens into the optical system of a photokeratoscope to make the system telecentric. He claimed that he first introduced the idea in the 1950's. The auxiliary lens was placed such that its principal focus lay at the centre of the camera objective lens. Fry claimed that this would simplify the analysis of the photokeratoscopic data. Fry (1975b) showed how the raw data using the telecentric photokeratoscope could be used to supply information about the corneal configuration. Various complex equations were derived to define corneal shapes.

Adati et al. (1979) and Kato et al. (1980) proposed a simple technique for photokeratoscopy in infants. This is described in section 11.4 of this chapter.

Kuyama et al. (1979), Itoi (1979) and Maruyama (1981) described a photokeratoscope (Sun PKS - 1000) with a hemispherical shaped target consisting of 11 circular rings made of optical fibres which were illuminated by 5 xenon flashes. The instrument was calibrated with steel balls. Measurements of the reflected images were made along 4 meridians: vertical, horizontal and two oblique ones. The data was fed into a computer which calculated the corneal shape and presented the results as a graphic display showing an isometric map of the cornea. Photographs of the graphical display of a cornea could then be scanned by an automatic photoreader which input the data to another computer which calculated the dimensions of a contact lens suitable for that particular cornea. No actual figures were given by these authors as to the extent of the cornea covered by this instrument but from a graph of their results a diameter of about 10 mm on the cornea appeared to be involved in their measurements. Klyce (1984) claimed that this instrument gave more corneal coverage than Reynold's Corneascope (described later).

Several researchers have published reports of the use of this photokeratoscope and their work is briefly noted here.

Nakayama et al. (1979) reported using this instrument as an aid to fitting contact lenses to Japanese keratoconus patients.

Hasegawa et al. (1981) investigated the corneal topography in a group of myopic, hyperopic and emmetropic eyes. Comparative studies of the central and peripheral region of the cornea were also made.

Yamamoto et al. (1981b) studied 14 cases of abnormal corneal curvature (over 8.20 mm and under 7.00 mm). He found that for the patients in general, the long diameter of the inner second ring in the photokeratograph indicated the base curve of the contact lens needed for any particular case.

Klyce (1984) photographed corneas of emmetropic, keratoconic and severely astigmatic eyes with this photokeratoscope. Calibration of the instrument was carried out with 6 lucite hemispheres over a radius range of 6.9 to 8.4 mm. The original polaroid photographs were enlarged 5 times and the data from the photograph was encoded using a graphics digitizing tablet. A computer programme was then used to analyse the data, which presented the corneal shape as well as its departure from a sphere graphically. The system was claimed to have an overall error of less than 0.10 mm in the measurement of radius of curvature based on measurements on test spheres. A comparison between this instrument and Reynold's Corneascope was also made.

The computer analysis system described by Klyce (1984) was further elaborated to produce figures representing gradations of corneal surface power in monochrome or colour. These contour maps of the cornea were claimed to enhance the interpretation of keratoscope photographs and especially in corneal refractive surgery (Maguire et al., 1986, 1987a). This colour-coded system of topography analysis was used by Maguire et al. (1987b, c) to examine the corneal power distribution in 7 myopic patients who had undergone epikeratophakia and in 2 patients with pelluid marginal degeneration (an uncommon, non-ulcerative, thinning disorder of the inferior peripheral cornea).

Manabe et al. (1986) monitored the corneal shapes in 40 patients following unilateral corneal transplants. The photokeratoscopy findings showed that the corneal topography was quite flat and irregular during the early period following penetrating keratoplasty, becoming steeper and more regular with time. After suture removal, the central cornea became more spherical but a considerable amount of toricity remained near the host-graft junction. One month after suture removal, 30 of the patients were fitted with contact lenses based on their photokeratoscopic data and refractions.

Murakami et al. (1981) described a method of photokeratoscopy whereby the reflected image of a target consisting of Placido rings was recorded by a videocamera. The curvature of the corneal surface was claimed to be measured by this system to an accuracy of 0.02 mm.

Drews (1980) briefly mentioned a small cylindrical keratoscope designed by Van Loehnan, a corneal surgeon based in Rotterdam who died in 1976. The instrument was hand-held about 1 cm above the eye during surgery to aid in monitoring the amount of corneal astigmatism during surgery.

Vijfvinkel and Van Loenen Martinet (1982) described an instrument very similar in appearance to that given by Drews (1980). This hand-held keratoscope was made of an inner cylinder of clear perspex and a white teflon outer cylinder. The inner side of the outer cylinder was engraved with 8 black lines which when projected on to a steel ball of radius 7.5 mm, would reflect lines of equal thickness and separation. In the operating theatre, the device could be placed on the globe and illuminated by the light of the operating microscope from the side. It was also designed to be used at the slit-lamp by holding the cylinder very close to the patient's eye.

Rowsey et al. (1981) reported the use of a commercially available instrument originally developed by A. E. Reynolds in 1974 called the "Corneascope." The target is hemispherical and consists of 9 concentric rings. The reflected image is recorded on a polaroid photograph, which is magnified 4.1 to 6.3 times to match the reflected rings to a standard set of rings on a 'comparator' screen. It is not clear as to how the actual measurement is carried out as it was only reported that "the amount of magnification required to match photographed rings to the corresponding standard comparator rings determines the radius of curvature of the cornea at that point." No indication as to the accuracy of this method of photokeratoscopy was given. A corneal area of diameter 8.3 mm is claimed to be covered for a radius of 8.40 mm radius and similarly a diameter of 6.7 mm for a corneal radius of 6.70 mm. The instrument was used to study a population of normal eyes and it's aid in diagnosing keratoconus from other corneal conditions which also produce irregular astigmatism was discussed.

Various researchers have published work on corneal topography using the Corneascope and brief details of their studies now follow.

Iwasaki et al. (1980) and Iwasaki (1981) described how the rings reflected from the corneal surface using the corneascope need not be photographed. They proposed a method by which the reflected rings were recorded by a photodiode array which in turn triggered off a signal to a computer which then calculated the corneal dimensions almost instantaneously.

Doss et al. (1981) also described how the Corneascope data could be processed by a computer and used to calculate the corneal profile and its surface powers along any particular meridian. In order to assess the accuracy of this method, the ring radii of a Corneascope photograph of a 9.52 mm radius sphere were measured with a micrometer and the readings entered into the computer programme. The calculated mean radius of curvature of the mire rings was 9.663 mm with a standard deviation of 0.2385 mm. The authors claimed that a higher degree of accuracy could be achieved if the Corneascope photograph were to be magnified further by projection to improve the accuracy of measurement of the ring radii and to incorporate the use of a digitizer for the measurement and direct input of the ring radii into the computer.

Cohen et al. (1984) obtained keratographs for regular, astigmatic and keratoconic subjects using the Reynold's Corneascope. The patterns of the outer 8 rings were manually traced from a projection of the photograph. The Photogrammetric Index Method (PIM) was described in which the traces are digitized and analysed by a computer programme to give information that can be used to quantify the magnitude and nature of corneal distortion. The PIM method was used to design keratorefractive surgery to reduce corneal astigmatism in a cornea which had suffered a penetrating injury (Cohen and Tripoli, 1987).

The Corneascope has also been used in corneal topography studies after keratorefractive surgery. Henslee and Rowsey (1983) recorded the corneal shapes in 50 subjects who had undergone radial keratotomy at various times up to 3 years post-operatively. Waring et al. (1983) proposed that photokeratoscopy using the Corneascope was to be part of the regular procedures involved in a 5-year follow-up study of the safety and efficacy of radial keratomy for myopics in about 500 patients. Rowsey (1983) observed the topographic changes following surgical or traumatic incisions using Corneascope photography. Rowsey et al. (1986) reported that Corneascope photographs were taken pre- and post-radial keratotomy surgery. Terry and Rowsey (1986) used the Corneascope to evaluated the change in corneal topography following a method of astigmatism surgery on 10 human cadaver eyes.

Arciniegas and Amaya (1984) used the Corneascope to monitor corneal astigmatism changes in scleral surgical procedures to induce corneal curvature changes in rabbits' eyes.

Freedman (1978) proposed a method of contact lens design by superimposing contour maps of contact lenses with different base curves on to photokeratographs taken with the Corneascope or P.E.K. of the cornea to be fitted.

Rowsey et al. (1981) also claimed to have a new design of a modified flat Placido disc to be used as a hand-held instrument.

Howland (1982a, b) and Howland and Sayles (1985) reported the use of photokeratometry on infants and young children. Further description of the apparatus is given in section 11.2 of this chapter.

Sergienko (1983) proposed that gratings consisting of black and white squares be used instead of the usual series of rings in photokeratoscopy, in the belief that they would provide more detail.

Kemmetmüller (1984, 1986) described a photokeratoscope with Placido-disc rings claimed to be based on work carried out at the Charite-Eye Hospital in Berlin and with a Japanese company called Graphics. The photographs were recorded on polaroid film and the corneal radii were then calculated by the computer. A graphic surface description of the cornea was also produced. Full coverage of the cornea was claimed but no figures on the accuracy of the instrument were given. This instrument has been used to monitor corneal curvature in contact lens wear (Kemmetmüller, 1987).

Kivayev et al. (1985) described a photokeratoscope consisting of 15 concentric rings situated on the inside of a spherical surface. An aperture was present in the focal plane of the camera objective lens making the system telecentric. An accuracy in radius determination of $\pm$ 0.02 mm was claimed. The corneal topography of 992 patients were examined including myopes, aphakics, hyperopics and keratoconus cases. A control group with healthy corneas were also examined. These authors described the corneal shapes with 3 values, asphericity, toricity and asymmetry. A comparison of these values were made between the groups studied.

Amoils (1986) described the use of a device called an "Astigmometer" to aid in precise suturing during ocular surgery and reduce the amount of post-operative corneal astigmatism. The instrument consisted of a circular arrangement of high intensity light-emitting diodes which was attached to the body of the operating microscope. The reflected light ring produced by the anterior corneal surface was then matched with a self-illuminating ring in the focal plane of 1 eyepiece. The self-illuminating ring would be rotated about its axis by means of a dial. The amount of rotation needed to superimpose the reflected image of the cornea gave an indication of the amount of astigmatism present.

3.11 Methods of measurement used on infants and young children

3.11.1 Introduction

The measurement of corneal curvature in infants and young children is difficult due to the virtual impossibility of holding the fixation of the subject for more than a few seconds unless the measurement is performed under general anaesthesia. In spite of this, reports of corneal curvature in young subjects have been made by several researchers and a summary of their methods of measurement and the difficulties they encountered are now presented.

3.11.2 Keratometry

Keratometry appears to be the most widely employed method for the measurement of corneal radii in adults as well as in the young.

Recording of the corneal radii using keratometry has been carried out as part of biometric and developmental studies in infants (Forsius et al.,1964; Rivara and Gemme, 1965; Grignolo and Rivara, 1968a, b; Woodruff, 1969, 1971; Molnār, 1970; Ehlers et al., 1976; Blomdahl, 1979; Hoffer, 1980; Yamamoto et al., 1981a; Inagaki et al., 1985; Donzis et al., 1985; Gordon and Donzis, 1985; Inagaki, 1986; Insler et al., 1987). These measurements did not appear to be made under general anaesthesia with the exception of Gordon and Donzis (1985) who examined some cases under general anaesthesia. Blomdahl (1979) and Insler et al. (1987) reported that local anaesthetic was administered into the conjunctival sacs of the newborn infants before measurements were undertaken. Hoyt et al. (1981) measured the corneal curvatures of 8 infants with unilateral axial myopia under general anaesthesia.

Reports of keratometry as part of the procedure being carried out prior to the fitting of contact lenses to infants and young children not placed under general anaesthesia have been published by Enoch (1972), Levinson and Ticho (1972), Rogers (1980), and Cutler et al. (1985). Those who performed keratometry for the same purposes but with their subjects under general anaesthesia include Cassady (1963), Gould (1969), Shapiro (1970), Enoch (1972, 1979a), Friendly and Oldt (1977), Ellis (1977), Massin and Vincent-Aubry (1980), Jacobson et al. (1981), Pollard (1982, 1987), Brent (1983), Pratt-Johnson and Tillson (1985), Matsumoto and Murphree (1986), and Moore (1987).

More recently, keratometry has been used to monitor central curvature changes following corneal refractive surgery in infants and young children (Arffa et al., 1985, 1986; Kelley et al., 1986; Morgan et al., 1986, 1987).

Surgical keratometers have been used for corneal measurements on young subjects under general anaesthesia (Weissman, 1983; Arffa et al.,1985, 1986). Others used conventional keratometers which were modified for use in the operating theatre on supine children (Shapiro, 1970; Friendly and Oldt, 1977; Ellis,1977; Brent, 1983 ; Inagaki et al., 1985 ; Inagaki, 1986 ; Matsumoto and Murphree,1986).

Shapiro (1970) and Friendly and Oldt (1977) described how a Bausch and Lomb keratometer was placed on an instrument stand with the chin-rest of the keratometer rotated 90 degrees away from the operating table. The head of the supine child was then turned to face the keratometer. Insler et al. (1987) reported using the same procedure with an American Optical keratometer.

Ellis (1977) was able to instal a Javal-Schiotz (Haag-Streit) keratometer on to an operating microscope stand.

Similarly, Brent (1983) mounted a Bausch and Lomb keratometer (with its forehead rest and chin rest removed) vertically on to an operating microscope stand.

Matsumoto and Murphree (1986) modified a Bausch and Lomb keratometer by the use of an attachment which allowed the use of the keratometer on a supine child. The description of the modification was published in a later paper by Szirth et al. (1987).

Inagaki et al. (1985) , Inagaki (1986) re-arranged the original Canon Auto-Keratometer system in order to measure the corneal radii in supine infants.

Cassady (1963), Ehlers et al. (1976), Blomdahl (1979), Pollard (1982) and Pratt-Johnson and Tiller (1985) reported that corneal readings were taken with the babies held upright in front of the keratometer.

Blomdahl (1979) described that after the eyes of his newborn subjects were anaesthetized, a speculum was inserted to keep the lids apart. Then with the infants held in an upright position, their heads were put on the chin and forehead rest of the keratometer. Measurements were attempted on 28 infants but successful measurements were only achieved on 15. Blomdahl found it impossible to centralize the reflexes on the cornea in the 13 remaining babies .

Pollard (1982) gave a more detailed account than the majority of the other researchers on how she actually got her young subjects into position for measurements. The infants under general anaesthesia (intubated for safe control of the airway) was strapped in an infant seat by a wrap round the chest and abdomen. The forehead rest was removed from the keratometer and a nurse held the seat containing the infant in front of the keratometer. A small infant speculum was used to hold the eyelids open. This whole procedure was estimated to take about 10 minutes!

Surprisingly, very few of these authors described the difficulties which they encountered whilst carrying out their measurements. The exceptions were Cassady (1963), Friendly and Oldt (1977) and Brent (1983) who gave an account of the set-backs they experienced when conducting keratometry on subjects under general anesthesia. Likewise Forsius et al.(1964), Woodruff (1969, 1971) and Howland and Sayles (1985) discussed how hard it was to obtain keratometry readings from unanaesthetized infants and young children.

Cassady (1963) who carried out corneal measurements on a 14-month-old infant following cataract surgery and still under general anaesthesia noted that he experienced difficulty in holding the patient securely in front of the keratometer and also a tendency for the corneal surface to dry.

Friendly and Oldt (1977) and Brent (1983) also noted having to moisten the cornea with saline in order to overcome the drying of its surface when the patient was under general anaesthesia.

Friendly and Oldt (1977) cautioned that the assistance and permission of the anaesthetist had to be obtained before turning the patient's head and body to face the keratometer (if it was not vertically mounted) as it was easy for the endotracheal tube to be moved easily during head and body rotation. Brent (1983) also stressed the importance of letting the anaesthetist know in advance that the eyes of the infant had to be maintained in a straight-ahead position as centring the eyes using forceps could possibly distort the cornea, and result in misleading keratometer readings.

Forsius et al. (1964) who conducted a study on corneal refraction in the vertical and horizontal meridians on a population aged from birth to over 70 years remarked that "Since some of the children in the series were very young, which made measurement difficult, the results for the group under 10 years of age must be viewed with caution." Deviations of as much as 1D were observed during keratometry measurements on children in this age group whereas in adults, a deviation exceeding 0.25D was seldom seen.

Woodruff (1969, 1971) investigated the refraction in normal subjects aged 1 month to 6 years. Part of the study involved recording corneal power readings using a Bausch and Lomb keratometer. It was reported that the use of an assistant and a squeaking noisemaker were of help in obtaining these measurements, especially on the one and two-year-old child. Woodruff claimed that keratometry was successfully performed on 80 percent of the group of 2-year-old children with the majority of the failures aged under $2\frac{1}{2}$ years. Keratometric results were only presented for subjects aged 2 years and upwards and although no reason was given for the absence of results under the age of 2 years, one may reasonably assume that the measurements obtained for that group were not reliable.

Howland and Sayles (1985) reported that they were unable to obtain reliable measurements using conventional keratometers on infants due to their restless nature.

Of all the studies mentioned in this section only Forsius et al (1964) and Woodruff (1969, 1971) gave an estimate of the accuracy of their keratometric findings. The low reliability of keratometry in children under 10 years of age as found by Forsius et al. has already been noted earlier. Woodruff (1969, 1971) claimed that his corneal power readings were correct to within $\pm$ 0.25D.

So far, all the workers mentioned in this section have used conventional or surgical keratometers for their measurements. An instrument which was specifically designed for use on infants was that described by Howland (1982 a, b) and Howland and Sayles (1985). These authors did not mention that the target of this photokeratometer was very similar to that on the Troutman surgical keratometer (Troutman et al.,1977) as in both instruments the target consisted of fibre-optic light guides arranged in a circle. In the instrument used by Howland (1982a, b) and Howland and Sayles (1985), the 8 light guides were arranged around the optic axis of a 35 mm camera and their tips illuminated by light conducted from an ordinary flash gun. The combination of the camera working distance of the camera, the light ring diameter and corneal curvature resulted in an average diameter of reflected lights at the cornea of 2.9 mm (see Figure 3. 9). The radii of corneal curvature were computed after measuring the distance between opposite corneal reflections to the nearest 0.001 mm using a measuring microscope. Each measurement was repeated 3 times and the average value was used to calculate the corneal radius. The mathematical basis for the computation of corneal radius was detailed in the paper by Howland and Sayles (1985). The accuracy of the instrument was assessed by photographing 2 steel balls and 13 measurements of orthogonal meridia were made. From these measurements, the mean cylinder value (which should have been 0) was determined for the 0 and 90 degree meridian and the 45 and 135 degree meridian. The cylinder found for the 0/90 degree meridian was not significantly different from 0

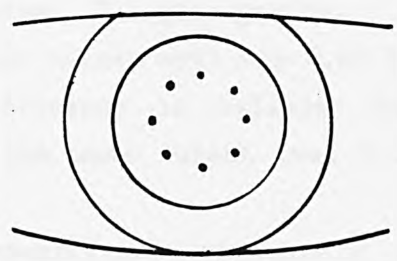


Figure 3.9. Photokeratometer target as imaged by cornea. (After Howland and Sayles, 1985).

whilst the value for the 45/135 meridian had a value of slightly less than 1/10th of a dioptre. In addition to this, corneal cylinder values measured on 19 adult subjects (38 eyes) using the photokeratometer were compared with those using a conventional keratometer. Although the photokeratometric cylinder values showed slightly more with-the-rule astigmatism than these keratometric values, a high correlation was found between the photokeratometric and keratometric cylinders (correlation coefficient r = 0.82, 95 percent limits). The repeatability of measurements of corneal astigmatism (?) was evaluated by measuring 2 separate photographs of 9 adult subjects (18 eyes) and 19 infants (38 eyes). For the adult eyes, a correlation coefficient r = 0.89 (95 percent limits) was found for measurements from 2 photographs. The corresponding coefficient r for infant eyes was 0.87 (95 percent limits). The average difference in cylinder found between any 2 photographs of the same infant was 0.24D $\pm$ 0.18D (s.d.).

Even though conventional keratometry appears to be the most popular method of measurement employed by workers who have measured corneal radii in the very young, it was decided that its use would not be suitable in this study for the following reason. Attempts by the author to make corneal radii measurements using a conventional keratometer on subjects under the age of 2 years were not successful as their attention and fixation could not be kept long enough for reliable measurements to be taken. This problem could be overcome if these young cases could be examined under general anaesthesia although this had its share of difficulties as shown earlier. However, as a large proportion of the subjects involved in this study would be seen in ordinary clinic conditions, it rules out the use of conventional keratometry for this particular study. The photographic method devised by Howland (1982a, b) and Howland and Sayles (1985) holds promise as it appears to have been used successfully on a large number of infants. The only criticism is that because the target consisted of a ring of dots, any irregularity present in the corneal surface would not be detected easily. This aspect is important as a group of congenital cataract cases would be included in this study and it would be of interest to note if their corneal surfaces were regular following cataract surgery.

3.11.3 Contact lens and fluorescein methods

The use of contact lenses with known back surface curvatures and fluorescein to determine central corneal curvature in infants have been reported by various workers. The measurements are usually carried out on subjects in the operating theatre with diagnostic trial lenses (Enoch,1972, 1979a; Levinson and Ticho,1972; Belkin et al.,1973; Enoch and Rabinowicz,1976; Belkin and Levinson,1977; Bier, 1979; Ronen et al.,1979; Levinson, 1980; Yamamoto et al., 1981a; Yankov, 1982: Weissman, 1983; Rose et al., 1985; Pe'er et al., 1987). Levinson and Ticho (1972), Belkin et al. (1973), Belkin and Levinson (1977) and Levinson (1980) claimed that central corneal curvature in infants under general anaesthesia could be measured to a 0.05 mm accuracy using this method. Belkin et al. (1973) reported that trial lenses with a back optic diameter of 8 mm were used for their measurements.

Yankov (1982) measured the corneal radii in 100 full-term babies during the first 5 days following birth, and claimed an accuracy of ± 0.10 mm.

Cassady (1963) noted the difficulty of verifying his keratometric readings of a 14-month-old infant with trial lenses and fluorescein due to the lack of normal tearing when under general anaesthesia. It is surprising that the other authors have not mentioned this difficulty as in the author's experience, this tends to happen and the eye has to be kept irrigated with saline.

The use of trial hard contact lenses and fluorescein for corneal radii measurements on unanaesthetized infants would be impossible. As was mentioned earlier, the majority of subjects invluded in this study would not be seen under such conditions and thus this method of determining corneal curvature is not feasible for this investigation.

3.11.4 Photokeratoscopy

Mandell (1967), Adati et al.(1979) and Kato et al.(1980), have reported the use of photokeratoscopy on infants.

Mandell (1967) designed a portable instrument for use on infants. The target consisted of a plastic cylindrical shell, 44 mm in diameter and 85 mm in length, painted in black and then lathed on its inside surface to make a series of 10 clear rings. The cylindrical shell was attached to the lens housing of a 35 mm single-reflex camera. A circular fluorescent lamp surrounded the lens housing enabling light to be transmitted through the cylinder by internal reflection and transillumination of the rings. A pistol grip was used enabling the user to support and trigger the apparatus with one hand. The photokeratoscope was aligned by viewing through the camera and varying its position until the corneal image of the target rings was centred with respect to the subject's pupil. The subject was not restrained in any way and triggering was delayed until there was no eye movement or lid closure. 10 to 20 photographs were made of each subject in order to obtain 3 which were perfectly focused and aligned. The area of the cornea measured by this method was not given but from graphs of the results, a total corneal diameter of about 8 mm appeared to be involved.

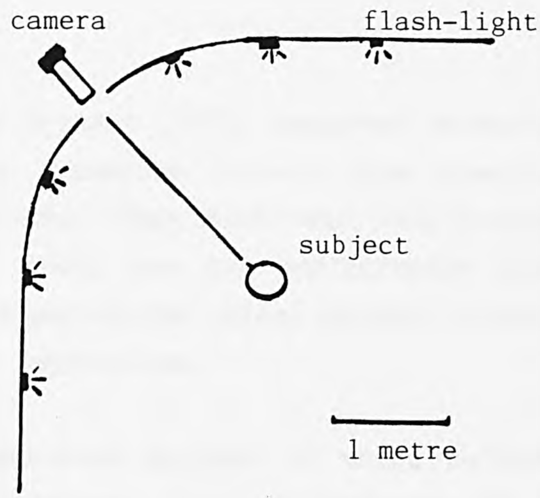
Mandell and York (1969) described how the above photokeratoscope was calibrated with steel balls based on an elliptical corneal model of eccentricity 0.48. This model was chosen based on results from a study on corneal contours of 8 adult subjects by Mandell and St. Helen (1971).

York and Mandell (1969) gave details of the accuracy of using this photokeratoscope. The reliability of using a semi-automated measuring microscope for measuring the photograph was tested by measuring a single photokeratograph of a steel ball 10 times and the standard deviation of the ring separation measurement was calculated. The range was from 0.0032 to 0.0071 mm. Similarly, the same method was used on a single photograph of a cornea. The standard deviations obtained ranged from 0 to 0.015 mm. These measurements were not related to the error in radius determination by the authors.

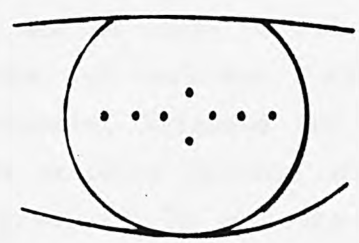
Freeman et al. (1978) used the portable photokeratoscope designed by Mandell (1967) to investigate the corneal curvature in 4 kittens and 2 adult cats.

Adati et al.(1979) described a technique of photokeratoscopy used in infants in which the distance between the target and the subjects is considerably more than in conventional photokeratoscopy. The baby is seated on the mother's lap facing the target plane. The distance between the chair and the target plane is 2 metres. 3 electronic flash lights are mounted on the target plane. Standard lenses with known surface curvature are placed near the baby's eyeball. The reflex images on the cornea as well as the standards are recorded on film through a telephoto lens. The error of calculated curvature of the cornea was claimed to be less than 2 percent.

Kato et al.(1980) described a similar technique in which the camera is also placed at a distance of 2 metres from the cornea. It records the reflex of xenon flash lights which are located at angles of 22, 46 and 71.5 degrees with respect to the cornea-camera line. (See Figure 3.10.)



(a)



(b)

Figure 3.10. A photokeratoscopy system for infants. (After Kato et al., 1980.) : (a) Arrangement of flash-lights at angles of 22, 46 and 71.5 degrees to cornea-camera line, (b) Flash lights imaged by cornea.

3.11.5 Other methods

Enoch (1979 b) designed a pair of calipers for use on infants to measure the corneal sagitta. The corneal radius could then be computed from the sagitta and diameter of the cornea.

Fletcher and Brandon (1955) reported measuring the corneal curvature of premature infants from plastic mould casts of their corneas. They noted that this method of obtaining the corneal radii was not sufficiently accurate. Ruben (1969) also examined the apical corneal curvature of infants using ocular impressions.

The above-mentioned methods of using calipers and ocular impressions require local anaesthesia of the subject's cornea and therefore would not be suitable on subjects seen in this study.

Rivara and Gemme (1965), Grignolo and Rivara (1968 a, b) mainly measured the central corneal curvature in their studies on infants and young children by keratometry but when this was not possible, measurements were obtained by juxtaposition of concave stencils representing arcs of circles along the corneal meridians. These stencils were of known radii and in steps of 0.5 mm. Measurements were repeated 3 times for each eye. Although the latter method appears inaccurate, Grignolo and Rivara (1968 b), reported testing the validity of this method by comparing measurements on a group of 20 patients using both keratometry and by juxtaposition of stencils. It was claimed that an analysis of the variations obtained were within acceptable limits although no details of this were given in their report.

3.11.6 Choice of method for this investigation

After reviewing all the possible methods of corneal radii measurement, and paying particular attention to those which had been used in infants, it was decided that a combination of photokeratoscopy and photokeratometry would be the most practical choice for this study based on the following reasons:-

(i) The most important deciding factor was the very short span of attention and fixation required in order to obtain measurements using these photographic methods.

(ii) Secondly, the subjects would not need to be put under general or topical anaesthesia for the measurements. As already indicated earlier, it was envisaged that most of the subjects would be seen under ordinary clinic situations and so the need for general or topical anaesthesia would be undesirable.

(iii) These photographic techniques would not be unpleasant for the subjects except for bright flashes of light. Most infants and children are familiar with having their photographs taken and so this method should not frighten them.

(iv) The instrument used for recording these measurements could be portable enabling it to be transported easily from 1 clinic to another. This was another considerat-ion as the subjects would most probably be seen in various locations.

(v) Finally, the use of photographic methods provided a means of recording the corneal findings permanently.

CHAPTER 4

THE PHOTOKERATOSCOPE USED IN PRESENT STUDY

4.1 Description of apparatus

After reviewing all the possible methods of corneal radii measurement, it was decided that photokeratoscopy/photokeratometry would be the most practical method of obtaining this information from very young subjects.

A portable photokeratoscope designed by Mr. David Taylor F.R.C.S., was made available to the author for the purpose of this study. This instrument is illustrated in Figures 4.1 and 4.2. The main features of the device consisted of a 35 mm Nikon camera with a 55 mm micro Nikkor lens. A metal ring mounted on the camera supported 4 electronic flash guns. A perspex hemispherical shell attached to the front of the micro Nikkor lens housing, acted as the target. The surface of the shell was painted a matt white. 3 concentric rings were lathed on its inner surface and these were painted matt black (Figure 4.3). In order to maintain more stability when taking photographs, the author added a pistol grip holder. The film used was Kodak panchromatic Tri-X A.S.A. rating 400.

Figure 4.1. Photokeratoscope used in present study.

Figure 4.2. Photokeratoscope used in present study.

Figure 4.3. Target of photokeratoscope.

4.2 Camera magnification

The magnification of the camera was assessed by photographing a 20 mm scale (with 0.1 mm divisions) twice on 2 films (Figure 4.4). The scale negatives were then measured with a measuring microscope correct to 0.01 mm. Each negative was measured twice and the camera magnification was calculated to be 0.5 (Appendix B).

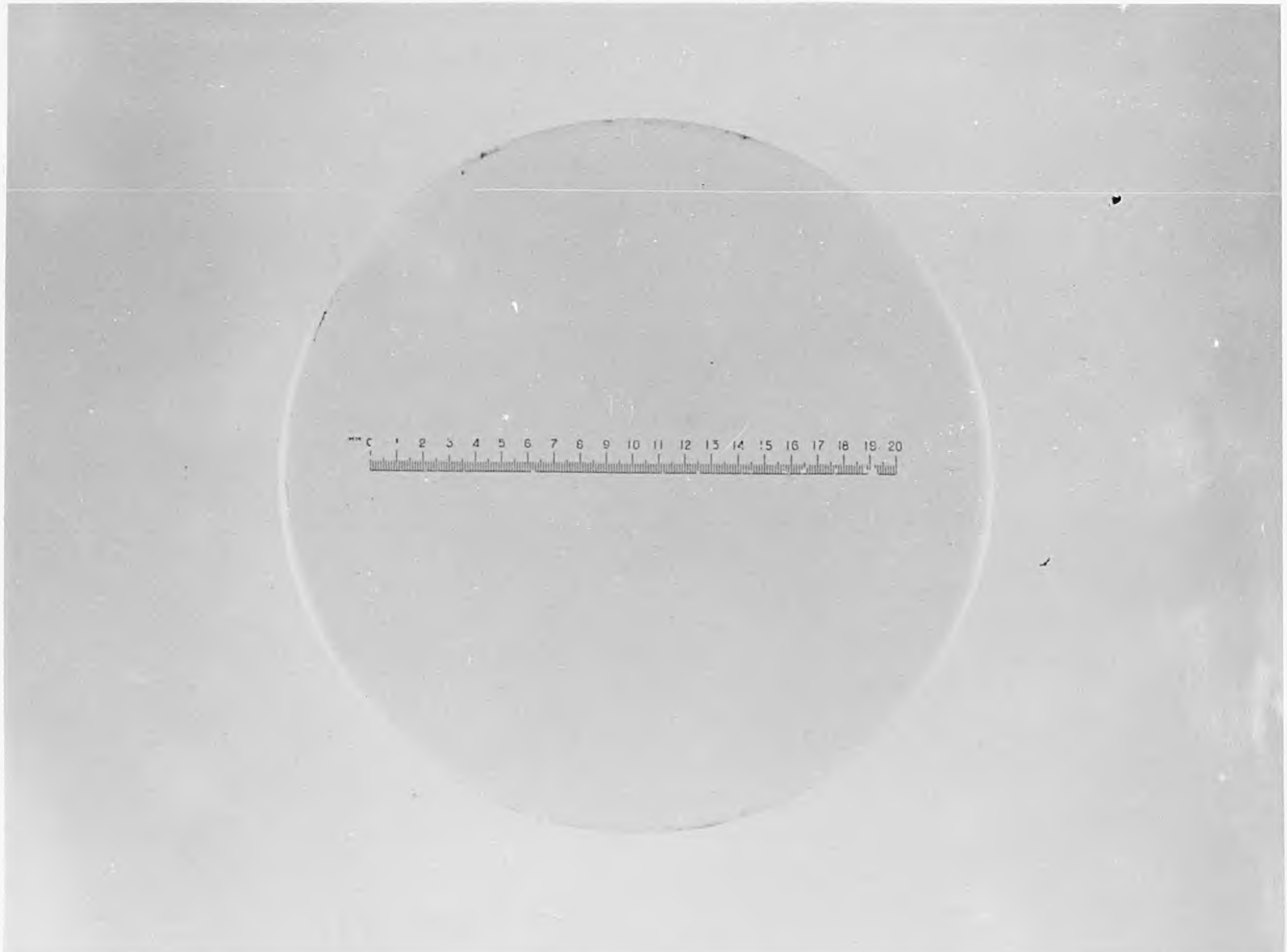


Figure 4.4. Scale used to determine camera magnification.

4.3 Camera aperture

The maximum aperture of F 3.5 was used for all the photographs. This resulted in a small depth of focus which enabled accurate focusing just before the photographs were taken. More importantly, it was used as a means to check from the clarity of the photographed rings on the negative whether the working distance from the instrument to the surface to be measured was correct. A blurred image of the rings would result if the working distance was incorrect.

In order to determine the effects of incorrect working distances on the diameters of the photographed rings, a series of photographs were taken on a steel ball (7.50 mm nominal radius) at various working distances. The photokeratoscope and steel ball were mounted on to an optical bench. The position of the steel ball was monitored by a vernier gauge which could be read to 0.1 mm accuracy. The photokeratoscope was placed at distances shorter and longer than the correct working distance from the steel ball. 2 photographs were taken at 1.0 mm intervals away from the correct position of the photokeratoscope. The ring diameters on each negative were each measured 3 times with a measuring microscope correct to 0.01 mm. The results of the incorrect working distance on the diameter of the photographed rings are given in Table 4.1 . A visual inaspection of the negatives under a measuring microscope indicated that an error of >1.0 mm from the correct distance between the photokeratoscope and the steel ball resulted in a detectable blur in the photographed ring images.

Table 4.1 Relationship between distance of photokeratoscope from steel ball and diameters of ring images.

Error in working distance (mm)	Photokeratoscope too close to steel ball 3.0	2.0	1.0	Correct position 0.0	Photokeratoscope too far from steel ball 1.0	2.0	3.0
Diameter of rings on negative ±s.d. (mm)							
1st ring	0.925 ±0.008	0.906 ±0.005	0.895 ±0.008	0.871 ±0.005	0.853 ±0.008	0.825 ±0.006	0.782 ±0.008
2nd ring	1.838 ±0.008	1.794 ±0.008	1.775 ±0.006	1.743 ±0.007	1.708 ±0.008	1.688 ±0.008	1.630 ±0.006
3rd ring	2.715 ±0.056	2.680 ±0.006	2.638 ±0.004	2.613 ±0.005	2.560 ±0.006	2.522 ±0.008	2.4683 ±0.008

4.4 Radiation from apparatus

The use of four electronic flash guns in the instrument made it necessary to consider the possibility of any radiation hazards. The potential hazards arising from radiant energy are outlined in Appendix C.

The total radiant exposure at the corneal plane was determined when the photokeratoscope was in use. A fast response photodetector was used for this measurement and the total flux emitted was sampled and stored in a digital storage oscilloscope. The total radiant energy incident at the corneal plant was measured to be 0.06012 mJ/cm^2.

Following consultation with Professor John Marshall at the Institute of Ophthalmology, London, a yellow filter was incorporated in all the electronic flashes to prevent any risk from the blue light component of the source. The yellow filter selected was Kodak Wratten filter number 12 which cut off all radiation at wavelengths of 500 nm and below. This particular filter was chosen as the most suitable after assessing its transmittance with several other possibilities using a recording spectrophotometer (Appendix C).

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4.5 Calibration of apparatus

The instrument was calibrated by using 8 steel balls with nominal diameters of 10.00 to 17.00 mm in 1.00 mm steps. 2 photokeratographs of each steel ball were taken on the same film. The diameter of the 3 rings on each negative was measured 3 times with a measuring microscope correct to 0.01 mm (Figure 4.5). The mean of the readings from the 2 negatives (that is, a total of 6 readings for each ring) was recorded. The results are shown in Table 4.2.

The diameters of the 8 steel balls used in the calibration of the photokeratoscope were measured with a bench micrometer to an accuracy of 0.01 mm. The micrometer had been calibrated with precision slip gauges correct to 0.01 mm. Each steel ball diameter was measured 10 times. Their mean measured diameters are shown in Table 4.3.

As can be seen from Table 4.2, steel balls of different radii produce varying ring image diameters. Thus, any ring diameter measured on the negative could be assigned a particular "radius" value.

The data in Table 4.2 indicate that as the radii of the steel balls increase, an increase also occurs in the diameter of the photographed rings. The simplest relationships that could hold between these 2 values would be that of a straight line. In order to test the validity of such a relationship in this case, the method of least squares was used.

The general equation for any straight line is of the form:

$$y = a + bx$$

where in this case

- x = measured photographed ring diameter
- y = radius of the steel ball
- a = intercept on the y-axis
- b = the shape of the line

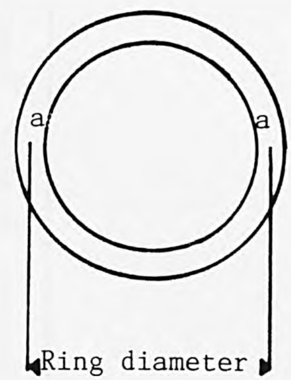


Figure 4.5. Illustration to show measured diameter of photographed ring. (a) is the mid-point of ring width.

Table 4.2 Ring diameters for different steel ball radii.

Nominal steel ball radius (mm)	5.00	5.50	6.00	6.50	7.00	7.50	8.00	8.50
Diameter of 1st ring ± s.d. (mm)	0.5567 ±0.0052	0.6333 ±0.0052	0.6983 ±0.0041	0.7517 ±0.0026	0.8133 ±0.0052	0.8708 ±0.0049	0.9383 ±0.0075	1.0000 +0.0063
Diameter of 2nd ring ± s.d. (mm)	1.1383 ±0.0041	1.2758 ±0.0049	1.3983 ±0.0052	1.5050 ±0.0055	1.6108 ±0.0049	1.7425 ±0.0042	1.8600 ±0.0063	1.9783 ±0.0075
Diameter of 3rd ring ± s.d. (mm)	1.7417 ±0.0075	1.9067 ±0.0075	2.0808 ±0.0020	2.2633 ±0.0052	2.4158 ±0.0066	2.6133 ±0.0052	2.8017 ±0.0075	3.0000 ±0.0063

Table 4.3 Diameters of steel balls used in calibration.

Nominal diameter of steel ball (mm)	Mean diameter of steel ball using micrometer (mm)	Standard deviation of diameter (mm)
10.00	10.003	0.007
11.00	11.000	0.007
12.00	11.998	0.009
13.00	13.003	0.008
14.00	14.002	0.009
15.00	14.997	0.007
16.00	15.995	0.010
17.00	16.999	0.007

The data from Table 4.2 was fed into a computer programme (Appendix B) which calculated the coefficients a, b and the coefficient of determination r^2. The value r^2 gave an indication of the quality of fit achieved by the regression line. Values of r^2 close to 1.00 indicate a better fit than values close to zero. The results are presented in Table 4.4 for each ring.

Table 4.4 Regression lines between ring diameters and steel ball radii.

Ring No.	Regression Line	Coefficient of determination r^2
1	$y = 0.444 + 8.055x$	0.999
2	$y = 0.148 + 4.222x$	0.999
3	$y = 0.183 + 2.791x$	0.999

4.6 Film processing

The films (35 mm panchromatic Tri-X) were developed using Kodak Microdol - X developer. The manufacturer's recommendations regarding developer temperature, agitation intervals and development time were followed.

4.7 Subject sample

A total number of 288 Caucasian subjects with normal eyes were photographed. They ranged in age from 1 month to 5 years. All the subjects had normal ocular and general health and were fullterm at birth. Usable data was obtained from 152 (80 male and 72 female) of these subjects. Data from one eye of each subject was included in this study.

A total number of 85 bilateral congenital cataract subjects were photographed. The subjects ranged in age from 1 month up to 15 years. Usable data was obtained from 35 (19 male and 16 female) of these subjects. As for the sample with normal eyes, one eye of each subject was included in this study. All 35 subjects were aphakic at the time of photography and were otherwise healthy with the exception of 8 subjects who had the following conditions:-

Congenital rubella syndrome	-	3 cases
Cof's syndrome	-	1 case
Lowe's syndrome	-	1 case
Cerebral palsy	-	1 case
Polysyndactyly	-	1 case
Galactosaemia	-	1 case

All the 35 cases were Caucasian in racial origin except for 6 cases who were of the following races:-

Middle-Eastern	-	1 case
Asian	-	3 cases
West-Indian	-	1 case
Negro	-	1 case

4.8 Procedures for taking corneal photographs

Verbal consent was obtained from the parents or guardians of all the subjects before any photographs were taken. The camera was aligned on the subject's pupillary axis by viewing through the instrument and adjusting its position until the corneal image of the target rings was centred with respect to the subject's pupil. The subject's eye was taken in the normal "open eye" state without retracting the lids by any means. 2 to 3 photographs were taken of each eye depending on how restless the subject was. The majority of the subjects with normal eyes were seen in post-natal clinics before they were examined by a medical doctor. Others with normal eyes were photographed at an optometry practice. The aphakic subjects were seen at the contact lens department at Moorfields Eye Hospital. They were usually photographed prior to being examined by an ophthalmologist or prior to contact lenses being inserted.

For babies aged 6 months or less, the photographs were usually taken with the infants lying on their front or back on a bed. Occasionally, some were taken with the infant held by the parent acrossthe lap or across their shoulder. Older subjects usually stood or sat facing the author.

Like York and Mandell (1969), it was found that subjects younger than 6 months and those older than 4 years were easiest to photograph. The subjects in between these two age groups tended to be more restless and also many of the subjects aged between 2 to 4 years tended to be very shy. The aphakic subjects were difficult to photograph as many possessed poor fixation. Examples of photographs taken on normal and aphakic subjects are seen in Figures 4.6, 4.7 and 4.8.

Photography was attempted on infants with congenital cataracts in the operating theatre under general anaesthesia. One of the difficulties encountered was getting to the right height and position above the operating table without falling on to the subject. The photographs were usually taken just prior to surgery on the eye and thus had to be undertaken rapidly so that the operation could be carried out as soon as possible. The corneal surface also had a tendency to dry very quickly even though it was irrigated with saline (Figures 4.9 and 4.10). Some photography was attempted just following surgery to remove the congenital cataracts but this was even more difficult due to the anterior chamber usually still being flat as seen in Figure 4.11. All in all, the photographs taken in the operating theatre were not successful and were not used for measurements.

Figure 4.6. Photograph of 16-month-old infant.

Figure 4.7. Infant reaching out for target.

Figure 4.8. Photograph of 2-year-old aphakic (congenital cataract). Only case seen with irregular images.

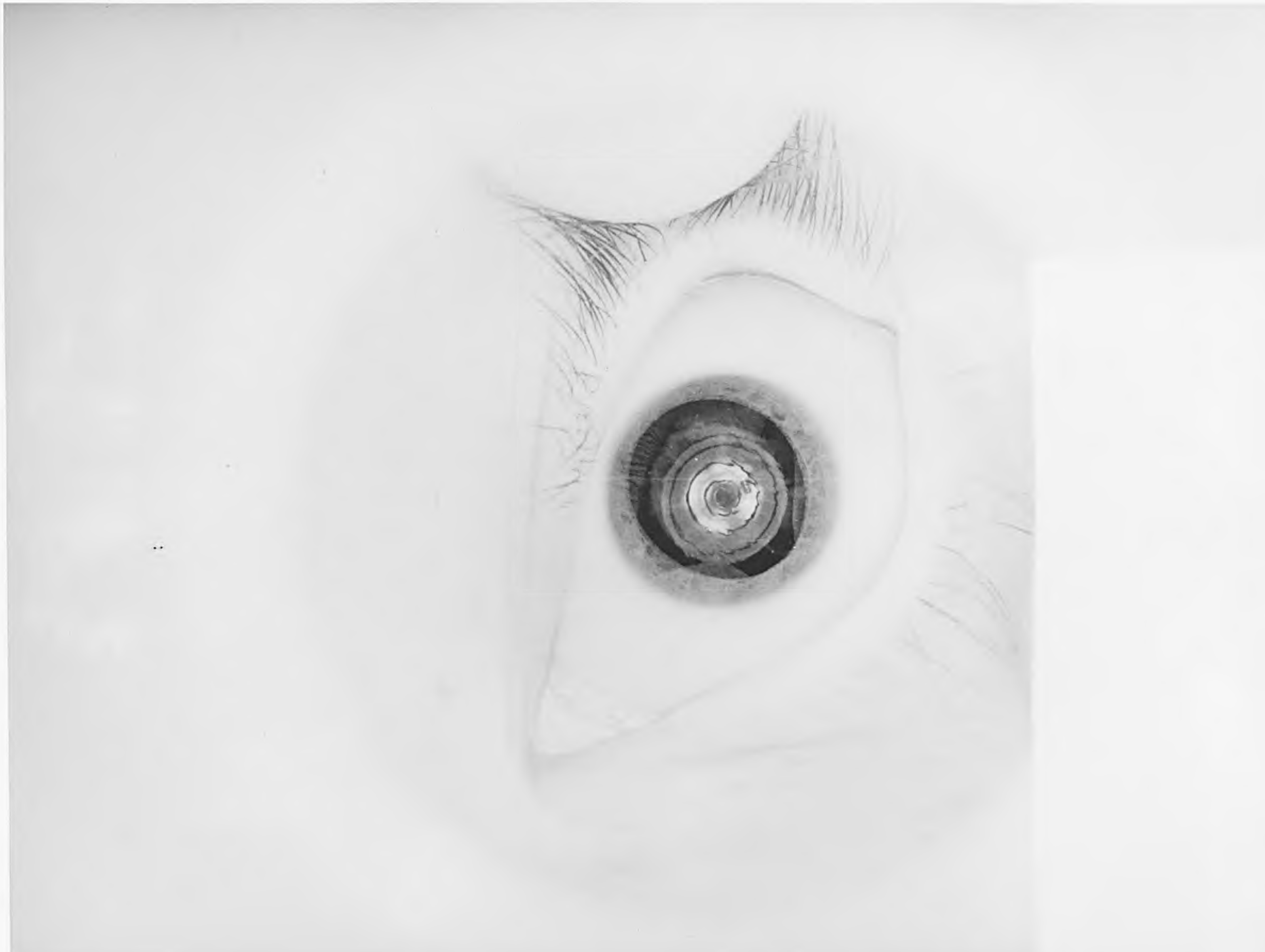


Figure 4.9. Drying of corneal surface in operating theatre.

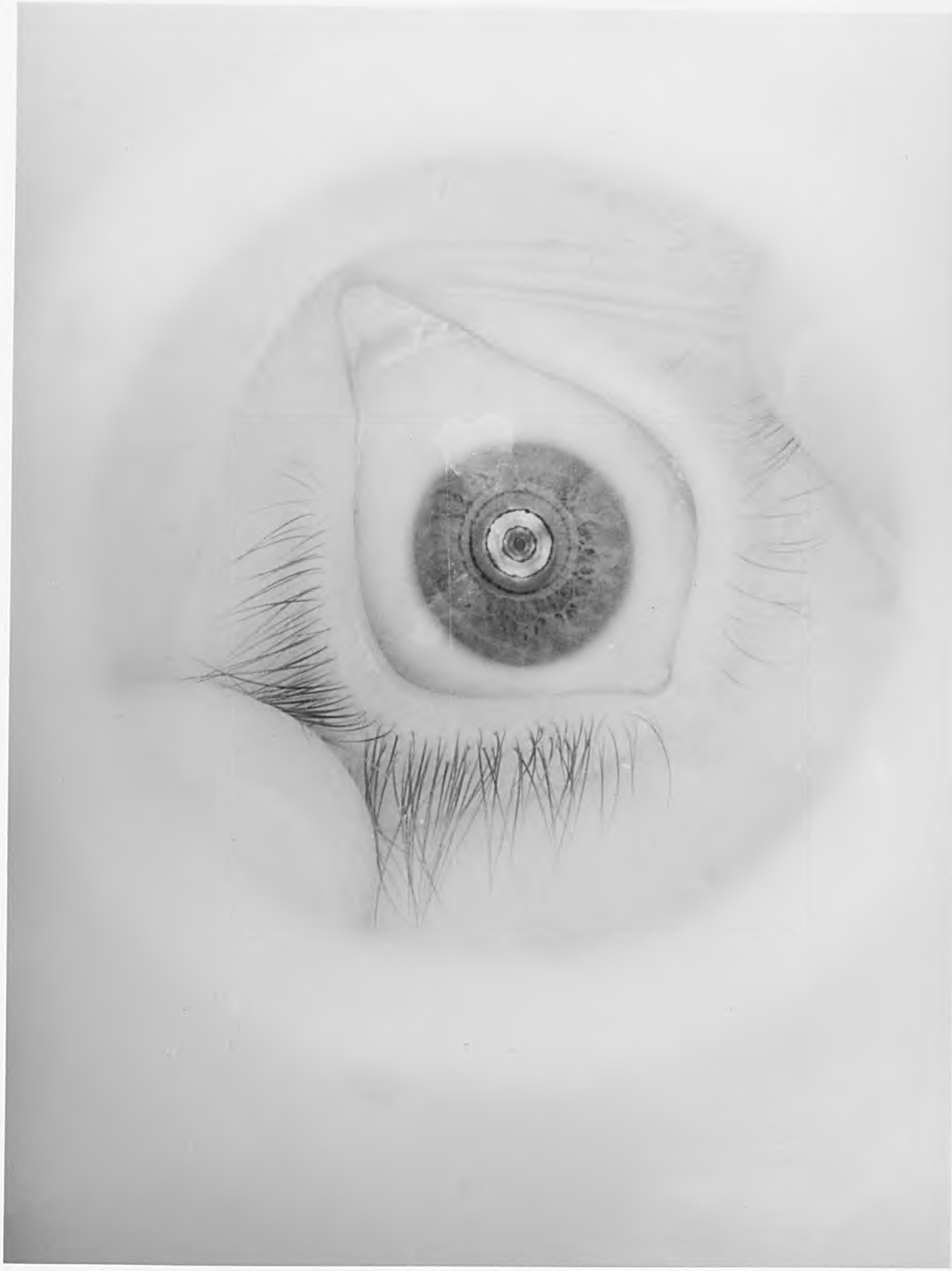


Figure 4.10. Drying of corneal surface in operating theatre.

Figure 4.11. Flat anterior chamber following surgery.

4.9 Location of principal corneal meridians

A problem which had to be solved before undertaking measurements of the corneal photographs was how to locate the principal meridians of the cornea. These could easily be obtained in adults by using keratometry and then measuring along the corresponding meridian in the photokeratographs. However this would not be possible with the young subjects involved in the present study.

Howland and Sayles (1985) overcame this difficulty by determining the major axes of astigmatism from photorefractive pictures of the infants. The corneal cylinder was then obtained by measuring the photokeratometric pictures in the corresponding meridian.

Mandell and York (1969) located the principal meridians by using a method which required measurements along 3 meridians of known angular separations on the corneal photographs. A similar method was devised by A.G. Bennett (1983) for this study (Appendix B). This also involved measurements of 3 meridians on the corneal photographs, the chosen 3 meridians being the horizontal, vertical and 45^{o} for convenience. The calculations which yielded the flattest and steepest corneal radii, the magnitude of corneal astigmatism and the direction of the flattest corneal meridian were programmed for use in a computer (Appendix B).

4.10 Measurement of negatives

In order to derive the corneal information from the photokeratographs, the photographed ring diameters had to be measured as accurately as possible. This is the most tedious part of photokeratoscopy as it involves measurements of a large number of photographs. Various methods of measuring the photographs were considered including microdensitometry, projection of the image on to a graduated screen and measuring microscopy.

Stone (1962) and Holden (1970) attempted microdensitometry for measurement of their photographs but both expressed difficulties in placing the films in the microdensitometer so that it could track accurately across the various meridians. As the present study would involve making measurements along 3 meridians, this method would not be suitable.

Cochet (1968) and Holden (1970) both used the projection method but this entailed the use of a long room to attain readings correct to 0.01 mm on the film. As the use of such a room was not readily available, this method of measurement had to be discounted.

Stone (1962), Ludlam et al. (1967), York and Mandell (1969), Holden (1970) and Howland and Sayles (1985) have all used measuring microscopy as a method of measurement. Stone (1962) found that this method gave the same degree of accuracy of measurement as using microdensitometry. Holden (1970) remarked that using the measuring microscope was a very laborious method and preferred to adopt the projection method instead. Ludlam et al. (1967) and York and Mandell (1969) modified the measuring microscopes they used to make the task less fatiguing.

A measuring microscope was used for the measurement of all negatives in this study. It allowed measurements correct to 0.01 mm in the horizontal and vertical without having to rotate the negative. A thin piece of film with a thin black line drawn on it was placed in the plane of the eyepiece of the microscope to locate the 45 degree meridian (Figure 4.12).

As it was difficult to centre and focus the target on the young subjects' eyes, not all the photokeratographs were of the same quality. Only those which showed a good focus with good centration of the rings (within 0.20 mm of pupil centre or centre of HVID if pupil margin was not distinct) were used for measurement. The negative selected for measurement was placed on a glass slide. Another glass slide with a very thin line scratched on it was placed on top of the negative (with the line facing the negative) so that it connected the canthi of the eye. This line was taken to be horizontal meridian of the eye. The negative was then placed on the stage of the microscope such that its horizontal meridian lay parallel to the horizontal axis of microscope. Measurements of the ring diameters were made along the horizontal, vertical and 45 degree meridians for the 2nd ring but only in the horizontal for the remaining rings. Each measurement was repeated three times and their average value was used in the computation of the corneal radii.

The dimensions of the 2nd ring image was chosen to represent the principal curvatures and astigmatism of the cornea for the following reason. The mean diameters of the rings measured from a photograph taken with a steel ball of 7.50 mm nominal radius were 0.87 mm, 1.74 mm and 2.61 mm respectively (Table 4.2). As the magnification of the photokeratoscope system had been calculated to be 0.5 (see section 4.2), this meant that the actual separation of the areas on the steel ball covered by the 3 rings were 1.74 mm, 3.48 mm and 5.22 mm. As the separation of the areas covered by the 2nd ring of 3.48 mm was closest to those measured using conventional keratometry (Mandell, 1964; Lehmann, 1967), the dimensions of the photographed 2nd ring were chosen to compute the principal corneal radii and corneal astigmatism. This would enable comparisons to be made with other studies which mainly used keratometry as a method of measurement for corneal radii.

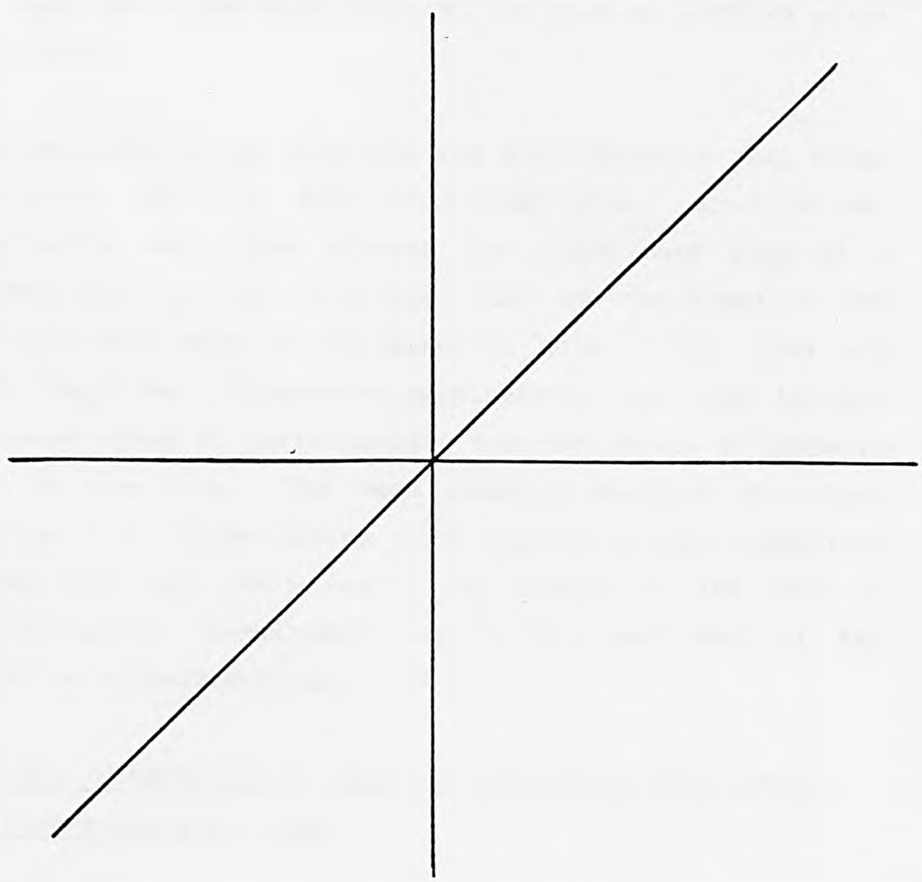


Figure 4.12. View through measuring microscope system.

The horizontal visible iris diameter (HVID) was also measured on the negatives using a measuring magnifier (Figure 4.13). The measuring device gave 7 times magnification and readings were possible to the nearest 0.1 mm (Figure 4.14). Measurements were taken parallel to the line joining the nasal and lateral canthi of each eye. Two readings were taken from each negative and the average value was used to calculate the HVID.

In order to minimize the possibility of film size altering with age, the films were measured as soon as possible after development.

The dimensions of one negative was also measured just after development and one year following this. Longitudinal measurements were made between the right hand edge of a sprocket hole at the left hand side of the negative and the right hand edge of the sprocket hole at the other end of the negative. Transverse measurements were made between the inside edges of corresponding sprocket holes on opposite sides of the film. The mean results obtained are shown in Table 4.5. These showed that changes in the dimensions of the film were very small, the change in the mean of the longitudinal measurement was 0.007% and that of the transverse measurement was 0.05%

Table 4.5 Dimensions of negative just after development and after a one year span.

	Dimension of negative (mm)			
	Longitudinal		Transverse	
	Mean	s.d.	Mean	s.d.
Just after development	136.06	0.006	25.31	0.013
1 year after development	136.05	0.006	25.30	0.005

Figure 4.13. Measuring magnifier used for HVID measurements on negatives.

Figure 4.14. Scale of measuring magnifier.

4.11 Accuracy and reliability of method

The accuracy of measurement of the images on the negatives and the reliability of the method was estimated by examining the reproducibility of the results on a steel ball and a cornea.

The variability in repeated measurements from 1 photograph was estimated by recording each ring diameter 10 times from a single negative of a steel ball. The same procedure was repeated with a single photokeratograph of an adult cornea. The results are presented in Tables 4.6 and 4.7.

Table 4.6 Variation in ring diameters from a single photokeratograph of a steel ball.

Ring No.	Mean diameter (mm)	Standard deviation (σn-1) Diameter (mm)	Radius (mm)
1	0.8710	0.0057	0.0459
2	1.7430	0.0067	0.0283
3	2.6160	0.0084	0.0234

Table 4.7 Variation in ring diameters from a single photokeratograph of an adult cornea.

Ring No.	Mean diameter (mm)	Standard deviation (σn-1) Diameter (mm)	Radius (mm)
1	0.9280	0.0063	0.0058
2	1.8625	0.0043	0.0182
3	2.8460	0.0084	0.0234

It is interesting to compare the above results with those obtained by other researchers.

Stone (1962) carried out measurements between adjacent image spots on her film negatives and found that "repetition of measurements gave a variation of as much as 0.11 mm with an average discrepancy of 0.08 mm." It is not clear whether these measurements were made on a single negative or several ones. In the present study, the maximum variation between the maximum and minimum values in the measured ring diameters for all the 3 rings was 0.02 mm. This finding was based on measuring single photokeratographs of a steel ball and a cornea 10 times.

York and Mandell (1969) who used a photokeratoscope designed for infants measured the variation in the separation of the rings 10 times from single photokeratographs of a steel ball and a cornea. The standard deviations of ring separations recorded on the steel ball photograph ranged from 0.0000 to 0.0071 mm whilst those recorded on the corneal photograph ranged from 0.0000 to 0.015 mm.

Holden (1970) reported that standard deviations in image heights ranging from 0.002 to 0.004 mm were recorded from 20 readings on 1 photokeratograph. He did not specify if the photokeratograph was that of a steel ball or of an eye.

To test interphotograph variability, 10 photographs each of a steel ball and an eye were each measured twice. The results are seen in Tables 4.8 and 4.9.

Table 4.8. Variation in ring diameters from 10 photokeratographs of a steel ball.

Ring No.	Mean diameter (mm)	Standard deviation (σ_{n-1}) Diameter (mm)	Radius (mm)
1	0.8665	0.0056	0.0451
2	1.7408	0.0061	0.0259
3	2.6153	0.0068	0.0190

Table 4.9. Variation in ring diameters from 10 photokeratographs of a cornea.

Ring No.	Mean diameter (mm)	Standard deviation (σ_{n-1}) Diameter (mm)	Radius (mm)
1	0.9303	0.0057	0.0462
2	1.8593	0.0061	0.0259
3	2.8410	0.0066	0.0185

York and Mandell (1969) reported an estimate of the reliability of the photokeratoscopy system they developed. The standard error of the means of 10 photokeratographs of a steel ball (each measured 10 times) ranged from 0.0014 to 0.0032 mm. The corresponding values obtained in this study for the 1st, 2nd and 3rd rings from 10 photokeratographs (each measured twice) were 0.0013, 0.0014 and 0.0015 mm respectively. York and Mandell (1969) also calculated the standard error of the means for 10 photokeratographs of a single cornea (each measured 10 times). These values ranged from 0.0031 to 0.011. The corresponding values recorded in this study for the 1st, 2nd and 3rd rings were 0.0013, 0.0014 and 0.0015 mm respectively.

The results of Ludlam et al. (1967) and Holden (1970) are reported and compared with the appropriate results from this study in Tables 4.10 and 4.11. Ludlam et al. (1967) recorded the measurements made by 3 observers from 10 photographs of an 5/8th inch and 9/16th inch diameter steel ball. Each photograph was measured twice by each of 3 observers. The results obtained on the photographs of the 5/8th inch steel ball by 1 of the observers is included in Table 4.10. In order to evaluate the variability in measurement of photographs of the human cornea, each of 2 observers measured the ring diameters twice on each of 7 photographs of 1 cornea. The results from 1 of the observers is seen in Table 4.11 (Ludlam et al., 1967). Holden (1970) assessed the consistency of his photo-keratoscopy method by assessing 9 films of a 7.00 mm radius steel ball, 27 films of an 8.00 mm radius steel ball and 13 films of an 8.50 mm radius steel ball. Each film had 3 photographs of the steel ball. The results for the 7.00 mm radius steel ball is included in Table 4.10. Holden (1970) also recorded data from 7 photokeratographs of 1 eye. His findings are shown in Table 4.11.

Other researchers have also given estimates of the accuracy they achieved with the photokeratoscopes they used. These are now listed.

Knoll (1961) estimated that he could measure corneal radii to an accuracy of ± 0.2 mm using a photokeratoscope with a cylindrical shaped target.

Stone (1962) using a hemispherical target claimed that steel ball radii could only be measured to an accuracy of ± 0.06 mm centrally and ± 0.025 mm peripherally.

Ludlam et al. (1967) stated that using measurements from 5 photographs each of a steel ball and a cornea, the radius of the steel ball and the cornea lay within a range in variability of ± 0.036 mm and ± 0.061 mm respectively at the 95 percent level of confidence.

Mandell and St. Helen (1968) after measuring 5 photographs of a cornea twice in 1 semi-meridian claimed that a corneal radius change of 0.08 mm would have to occur before it could be detectable by their system.

Table 4.10 Comparison of reliability of other photokeratoscopes with the photokeratoscope used in present study on steel balls.

Ludlam et al. (1967)		Holden (1970)			Present study		
Mean ring diameter (mm)	s.d. ring diameter (mm)	Image sep. (mm)	s.d. image sep. (mm)	s.d. radius (mm)	Mean ring diameter (mm)	s.d. diameter (mm)	s.d. radius (mm)
		0.7869	0.0013	0.011	0.8665	0.0056	0.0451
		1.6803	0.0031	0.013	1.7408	0.0061	0.0259
2.5608	0.0054	2.3589	0.0054	0.016	2.6153	0.0068	0.0189

Table 4.11 Comparison of reliability of other photokeratoscopes with the photokeratoscope used in present study on corneas.

Ludlam et al. (1967)		Holden (1970)			Present study		
Mean ring diameter (mm)	s.d. ring diameter (mm)	Image sep. (mm)	s.d. image sep. (mm)	s.d. radius (mm)	Mean ring diameter (mm)	s.d. ring diameter (mm)	s.d. radius (mm)
		0.9140	0.0041	0.037	0.9303	0.0057	0.0462
		1.9729	0.0027	0.011	1.8593	0.0061	0.0259
2.4404	0.0059	2.7957	0.0061	0.018	2.8410	0.0066	0.0185

Cochet and Amiard (1969) reported an error in radius measurement of 0.01 mm (s.d.) which contradicted another statement in the same paper which estimated the error to be 1 percent which is a 0.07 mm error for a 7.0 mm corneal radius.

El Hage (1972a, b) derived that using his system, the sagittal depth at the corneal periphery could be measured more accurately than 0.02 mm.

Pulvermacher and Rott (1972) claimed an error of $\pm$ 0.015 mm in measuring sagittal differences in the corneal periphery.

Bibby (1976a) said that reproducibility studies using the Wesley Jessen System 2000 photokeratoscope on a steel ball produced a maximum standard deviation of 1/16th dioptre in the curvature of a steel ball. This is equivalent to a radius error of 0.0054 mm.

Adati et al. (1979) using their photokeratoscopy system on infants stated that the error in radius determination was estimated to be less than 2 percent. This would be equivalent to an error 0.15 mm in radius measurement for a 7.50 mm corneal radius.

Murakami et al. (1981) estimated that the curvature ofthe cornea could be measured to an accuracy of 0.02 mm in radius using their method of photokeratoscopy.

Doss et al. (1981) processed the data from a Corneascope photograph of a sphere of known radius with a computer and a standard deviation in radius of 0.2385 mm was obtained.

Kiely et al. (1982) using Clark's (1972) autocollimating photokeratoscope reported a similar error in radius measurements for a glass sphere and a cornea. The standard deviation recorded in both cases was 0.02 mm in radius based on measurements of 9 photographs of a glass sphere and 6 photographs of a cornea.

Klyce (1984) estimated an overall error of less than 0.10 mm in the measurement of radius of curvature using the photokeratoscope PKS-1000 produced by the Sun Contact Lens Co. based on tests carried out on reference spheres.

Kivayev et al. (1985) evaluated that their photokeratoscopy system could determine corneal radii to an accuracy of ± 0.02 mm.

The accuracy in mm of radius obtained on a single cornea with the photokeratoscope in the present study was 0.046 mm for the first ring, 0.026 mm for the second ring and 0.019 mm for the third ring. This was based on measurements made from 10 photokeratographs of a single cornea.

In order to evaluate the accuracy of determining the amount of corneal astigmatism, 2 separate photographs of an adult eye were each measured 3 times. The average values were then used to calculate the difference in corneal astigmatism found between the two photographs. A difference of 0.29D in the astigmatism was found (Appendix B). Howland and Sayles (1985) estimated an average difference between any two photographs of the same infant to be 0.24D.

Measurements from ring 2 of the photokeratographs were chosen to represent the central curvature measurements as the extent of the cornea covered by this ring was close to that covered by conventional keratometers (see Section 4.10). It was therefore of interest to compare corneal values obtained using the 2 instruments on the same subjects. Measurements were made of the flattest and steepest corneal radii and the corneal astigmatism using the photokeratoscope and a Topcon keratometer on 10 adult eyes (10 subjects). The keratometer had been calibrated before its use by using a steel ball with a nominal radius of 7.50 mm. A sum of 3 readings were made on the keratometer for the principal meridians of each eye and the corneal astigmatism was calculated using a refractive index of 1.3375. The radii of curvature and corneal astigmatism obtained by keratometry were compared with those obtained by photokeratoscopy (Appendix B).

Regression analysis showed that strong linear relationships existed between the values obtained on the 2 instruments (Appendix B). These relationships are shown in Table 4.12. The correlation coefficient values (r = 0.99 for both the flattest and steepest radii, r= 0.95 for the corneal astigmatism) indicate a very high correlation between the photokeratoscopic and keratometric values. Guillon et al. (1986) also found that central corneal measurements using the PEK and a conventional Bausch and Lomb keratometer were highly correlated.

Table 4.12 <u>Regression lines between photokeratoscopic (P) and keratometric (K) measurements.</u>

Corneal value	Regression line	Correlation coefficient r	Coefficient of determination r^2
Flattest corneal radii (mm)	P=1.055K-0.423	0.99	0.98
Steepest corneal radii (mm)	P=1.081K-0.603	0.99	0.98
Astigmatism (D)	P=1.094K-0.118	0.95	0.90

In order to assess the accuracy of measuring the horizontal visible iris diameter (HVID), 1 photograph of an adult cornea was measured 10 times over a 2-week period. A standard deviation of 0.07mm was obtained.

Also this photographic method of obtaining the HVID was compared with the more usual clinical method of using a millimetre rule (1mm divisions). The results using both methods on 10 adult eyes are shown in Appendix B.

There appeared to be good agreement between the 2 methods. The largest difference found between HVID values for the 10 eyes was 0.20mm using the 2 methods. No particular trend was detected as to whether the photographic method tended to give the larger or lesser values compared with the ruler method.

CHAPTER 5

RESULTS

5.1 Introduction

The following corneal information was collected from the useable photographs:-

(i) Horizontal visible iris diameter (HVID),

(ii) Corneal radii, and

(iii) Amount of corneal astigmatism and its orientation.

Data was included from only 1 eye of each subject in this study. Usable photographs were obtained from 152 normal eyes but the number of eyes analysed for the above 3 quantities varied due to the conditions present at the point of photography. For instance, in some photographs the limbal margins were not distinct enough to facilitate reliable measurements of the HVID. As the lids were not retracted by any artificial means when the photographs were taken, the top lid blocked the corneal reflection of the 2nd ring along the vertical and 45° meridia in a proportion of cases thus preventing calculations of the principal corneal radii and the resulting corneal astigmatism.

The detailed results for all the subjects included in this study are in Appendix D and E. Details of statistical analyses of the results are in Appendix F.

5.2 Horizontal visible iris diameter (HVID)

Data from a total number of 146 normal eyes and 30 aphakic eyes were analysed.

5.2.1 Normal eyes

Table 5.1 indicates the mean HVID measurements for males, females and both sexes for each age group. Included are the maximum and minimum observed values and the number of eyes investigated in each age group.

Figure 5.1 illustrates the variation of mean HVID with age. A large increase in HVID was seen up to the age of 6 months after which there appeared to be little increase. Also in each age group the mean value for the male cornea was consistently higher than the corresponding value in the female. The only exception was seen at the 3 to 6 month age group when both values were equal. Taking the results over all the age groups, the mean values recorded for 74 males and 72 females were 11.80 ± 0.43mm (s.d.) and 11.62 ± 0.42mm (s.d.), respectively. Combining both sexes, the mean HVID recorded from 146 eyes was 11.71 ± 0.35mm (s.d.).

Statistical analysis was carried out using a two-way analysis of variance. Significant differences at the 5 percent level were found in the mean corneal diameters between the age groups and between the sexes.

5.2.2 Congenital cataract eyes

The individual values for the HVID recorded from 30 binocular congenital cataract cases are recorded on Figure 5.2. Included in the Figure are the maximum and minimum values recorded on normal eyes in this study. For the age groups older than 5 years, the maximum and minimum values shown are those recorded in Hyme's (1929) study on HVID in males and females.

Over all the age groups, the minimum HVID value observed in this study was 9.40 mm and the maximum value was 12.30 mm. Figure 5.2 shows that up to the age of 5 years, a large proportion (10 out of 19 eyes) of the aphakics possessed corneal diameters which fell below the minimum values observed in normal eyes.

Table 5 .1 Mean values of horizontal visible iris diameters (HVID).

Age	Sex	No. of eyes	HVID (mm)			
			mean	s.d.	max	min
1 mo to < 3 mos	m	5	11.00	0.55	11.60	10.40
	f	6	10.87	0.36	11.30	10.40
	m + f	11	10.93	0.44	11.60	10.40
3 mos to < 6 mos	m	17	11.66	0.30	12.10	11.00
	f	8	11.65	0.34	12.00	11.00
	m + f	25	11.66	0.31	12.10	11.00
6 mos to < 12 mos	m	16	11.76	0.44	12.50	11.00
	f	17	11.52	0.38	12.10	10.80
	m + f	33	11.64	0.43	12.50	10.80
1 yr to < 2 yrs	m	11	11.86	0.28	12.30	11.40
	f	8	11.75	0.26	12.10	11.40
	m + f	19	11.82	0.27	12.30	11.40
2 yrs to < 3 yrs	m	12	12.03	0.34	12.50	11.60
	f	9	11.69	0.26	12.00	11.40
	m + f	21	11.88	0.34	12.50	11.40
3 yrs to < 4 yrs	m	5	12.10	0.14	12.30	12.00
	f	11	11.84	0.35	12.30	11.10
	m + f	16	11.92	0.32	12.30	11.10
4 yrs to < 5 yrs	m	8	12.06	0.29	12.50	11.50
	f	13	11.75	0.41	12.40	11.10
	m + f	21	11.87	0.39	12.50	11.10

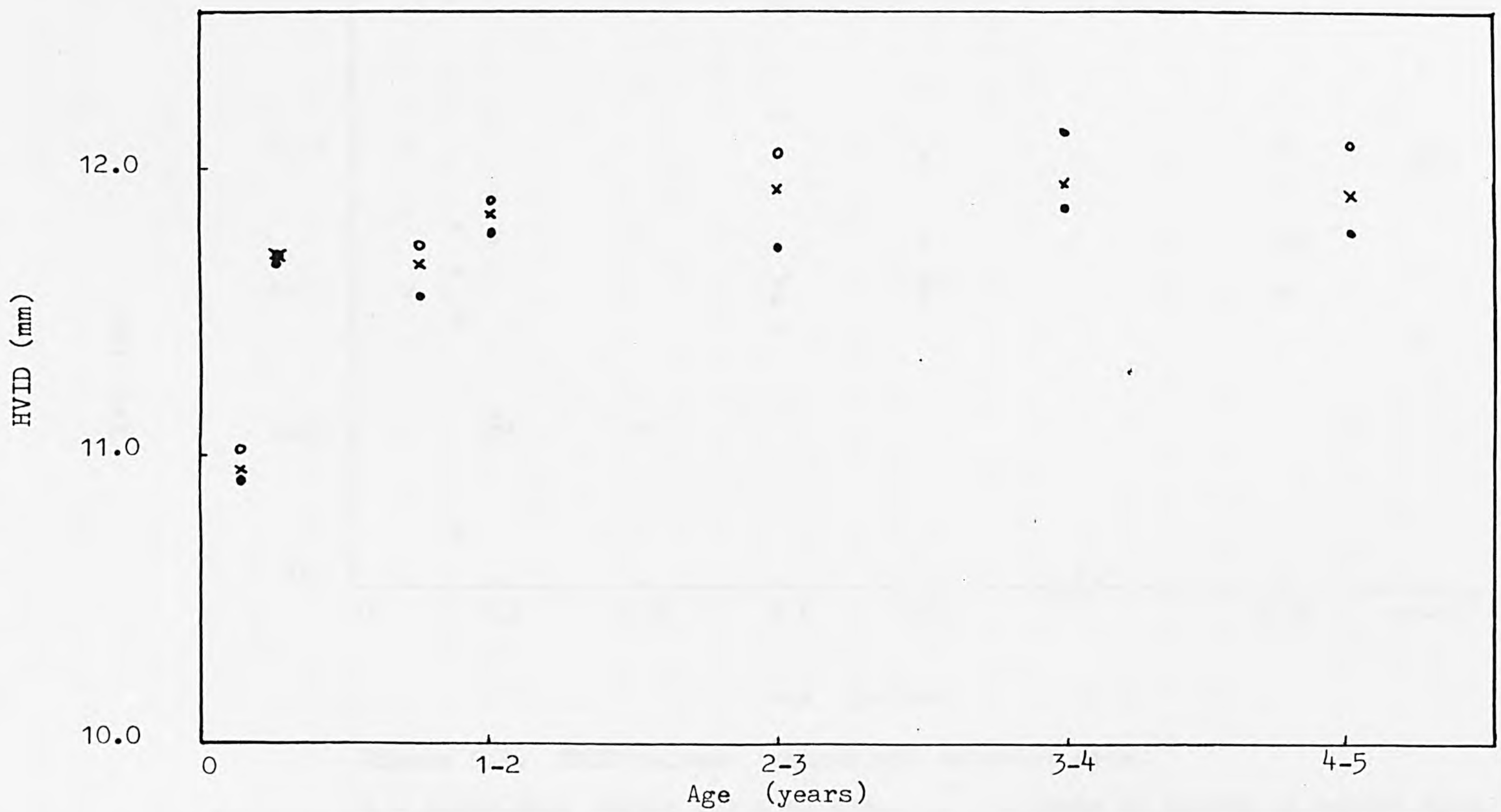


Figure 5.1. Variation of HVID with age: normal eyes.

o - males, ● - females, x - males and females.

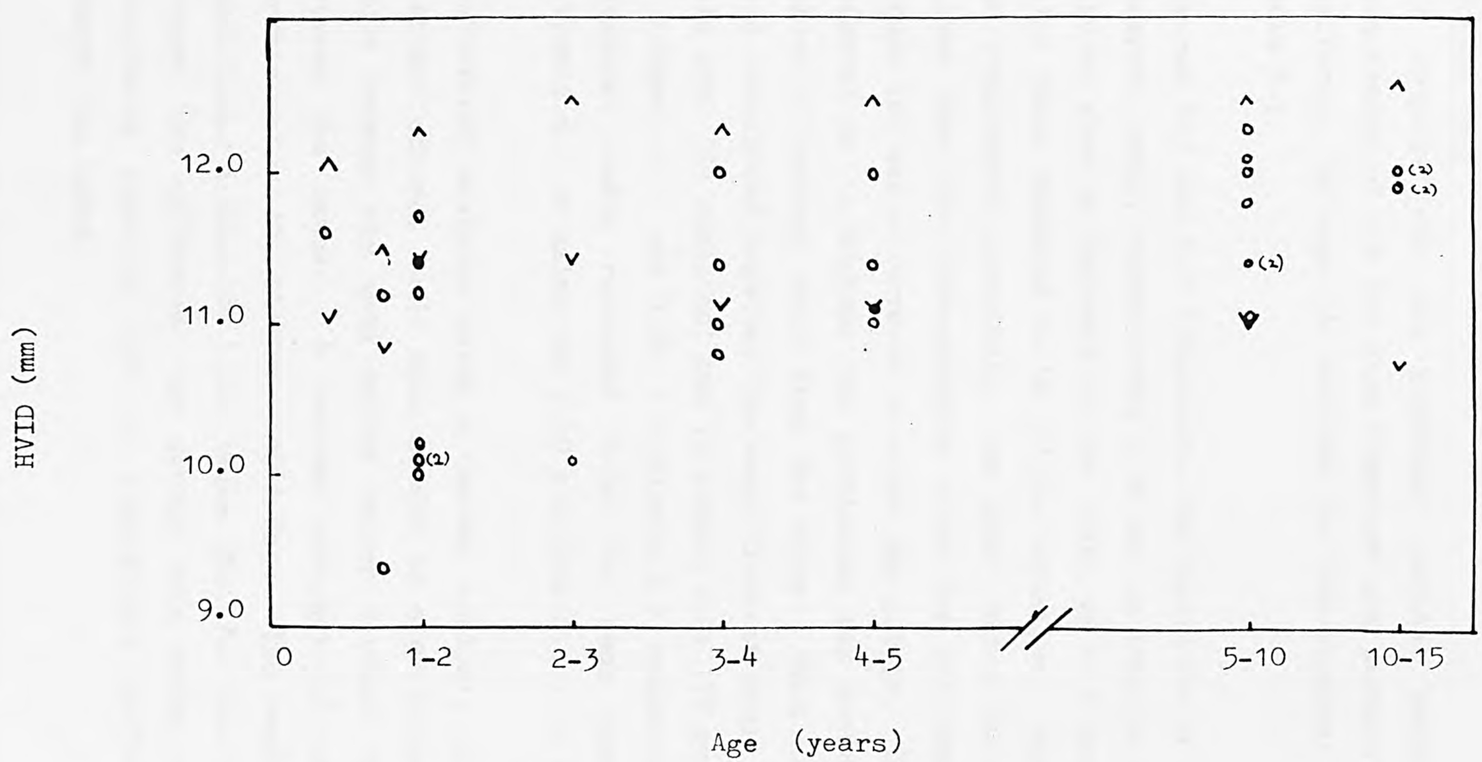


Figure 5.2. HVID values: congenital cataract eyes.
o - individual values for each eye, ^ v - range of values in normal eyes.

5.3 Corneal radii

Data from a total number of 151 normal eyes and 33 aphakic eyes were analysed.

5.3.1 Normal eyes

The results for the flattest corneal radii computed from measurement of the 2nd ring diameters are summarised in Table 5.2. Similarly, the same is recorded for the steepest corneal radii in Table 5.3.

Figures 5.3 and 5.4 illustrate the variation of the flattest and steepest radii, respectively with age as seen in this study. Both Figures show an increase in the radii up to 6 months of age after which there appeared to be little variation. When each age group was considered separately, the mean radius value for males was higher than the corresponding value for the females in some age groups but was vice-versa in other age groups. Thus, no trend was observed as to whether one particular sex tended to give larger values of corneal radii than the other. When all the age groups were considered together the mean flattest radii recorded from 79 male eyes (79 subjects) and 72 female eyes (72 subjects) were 7.66 ± 0.49mm(s.d.) and 7.61 ± 0.51mm(s.d.) respectively. The mean steepest radii recorded from the same eyes were 7.40 ± 0.47mm(s.d.) in males and 7.40 ± 0.52mm(s.d.) in females.

Statistical analysis using a two-way analysis of variance on the flattest corneal radii data showed no significant difference was found between the mean radius values between the age groups or between the sexes. A two-way analysis of variance was also carried out on the steepest radii data. The results showed just a significant difference (just below 5%), for the mean radii values between the different age groups when males and females were considered together but no significant difference was found between the sexes.

The degree of flattening observed along the horizontal meridian was noted over all the age groups for 123 eyes. For purposes of classification, these were divided into 6 groups as shown in Table 5.4. The diameters of cornea covered by rings 1, 2 and 3 of the photokeratoscope are 1.7mm, 3.5mm and 5.2mm respectively as

Table 5.2 Mean values of flattest corneal radii.

Age	Sex	No. of eyes	Flattest corneal radii (mm)			
			mean	s.d.	max	min
1 mo to < 3 mos	m	6	7.457	0.472	7.782	6.625
	f	6	7.197	0.585	7.989	7.847
	m + f	12	7.327	0.525	7.989	6.625
3 mos to < 6 mos	m	20	7.663	0.499	8.213	6.344
	f	8	7.807	0.139	8.009	7.584
	m + f	28	7.704	0.430	8.213	6.344
6 mos to < 12 mos	m	17	7.690	0.670	8.543	6.375
	f	17	7.501	0.540	8.426	6.695
	m + f	34	7.596	0.607	8.543	6.375
1 yr to < 2 yrs	m	11	7.610	0.310	7.973	6.935
	f	8	7.584	0.474	8.392	6.825
	m + f	19	7.599	0.375	8.392	6.825
2 yrs to < 3 yrs	m	12	7.739	0.355	8.412	7.232
	f	9	7.510	0.587	8.317	6.709
	m + f	21	7.641	0.470	8.412	6.709
3 yrs to < 4 yrs	m	5	7.623	0.482	8.327	7.140
	f	11	7.664	0.485	8.566	7.157
	m + f	16	7.651	0.468	8.566	7.157
4 yrs to < 5 yrs	m	8	7.755	0.528	8.359	6.908
	f	13	7.875	0.498	8.558	6.944
	m + f	21	7.829	0.500	8.558	6.944

Table 5.3 Mean values of steepest corneal radii.

Age	Sex	No. of eyes	Steepest corneal radii (mm)			
			mean	s.d.	max	min
1 mo to < 3 mos	m	6	7.147	0.294	7.312	6.605
	f	6	6.933	0.631	7.775	6.524
	m + f	12	7.040	0.482	7.775	6.524
3 mos to < 6 mos	m	20	7.379	0.514	7.898	6.140
	f	8	7.505	0.210	7.839	7.166
	m + f	28	7.415	0.448	7.898	6.140
6 mos to < 12 mos	m	17	7.371	0.619	8.233	6.223
	f	17	7.255	0.527	8.090	6.464
	m + f	34	7.313	0.569	8.233	6.223
1 yr to < 2 yrs	m	11	7.384	0.279	7.748	6.914
	f	8	7.480	0.481	8.271	6.743
	m + f	19	7.424	0.369	8.271	6.743
2 yrs to < 3 yrs	m	12	7.489	0.376	8.239	6.988
	f	9	7.286	0.556	8.235	6.621
	m + f	21	7.402	0.461	8.239	6.621
3 yrs to < 4 yrs	m	5	7.498	0.477	8.211	7.019
	f	11	7.506	0.493	8.436	6.804
	m + f	16	7.504	0.472	8.436	6.804
4 yrs to < 5 yrs	m	8	7.531	0.446	8.054	6.988
	f	13	7.664	0.512	8.449	6.683
	m + f	21	7.614	0.481	8.449	6.683

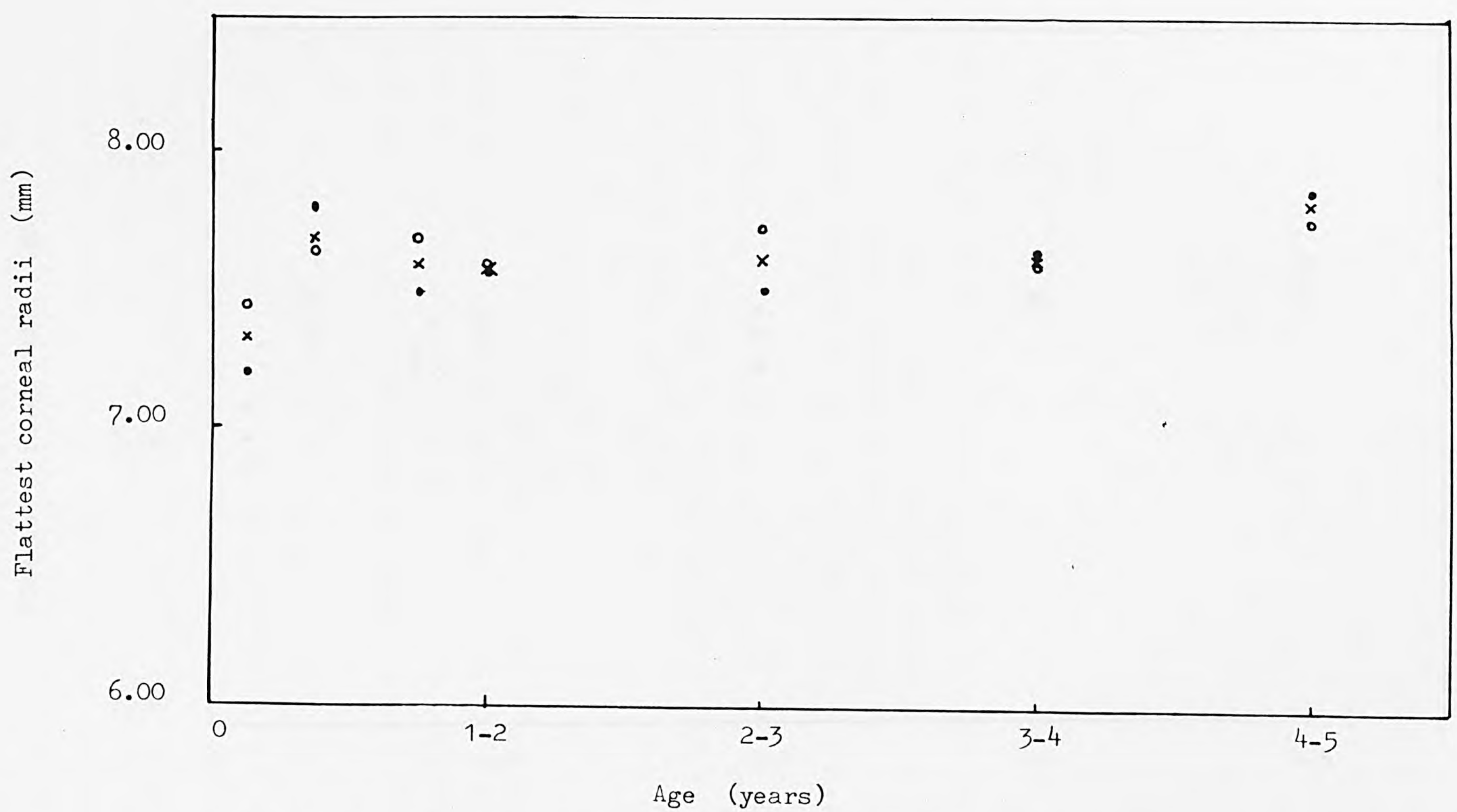


Figure 5.3. Variation of flattest corneal radii with age: normal eyes.
o - males, ● - females, x - males and females.

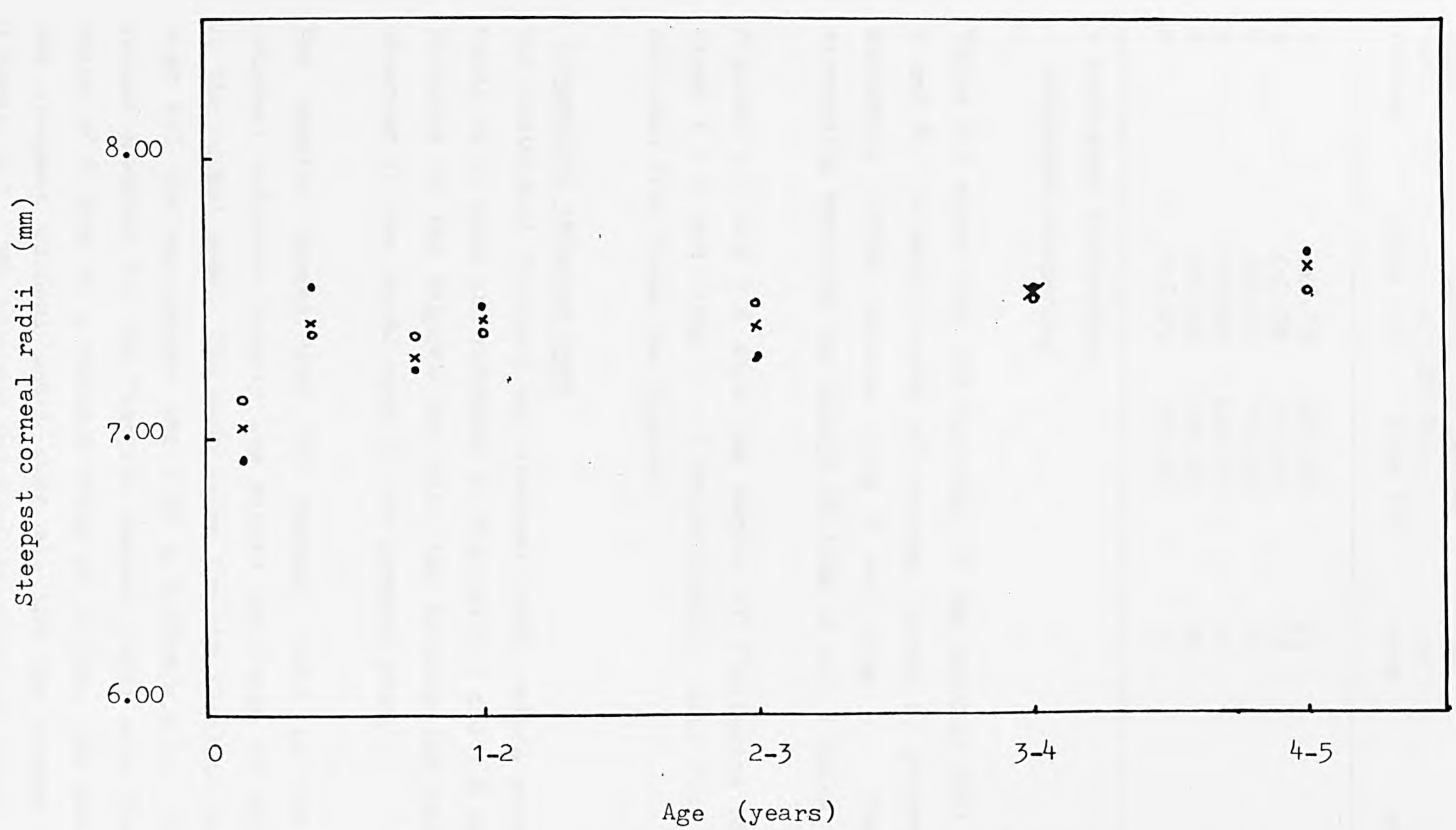


Figure 5.4. Variation of steepest corneal radii with age: normal eyes.
o - males, ● - females, x - males and females.

measured on a steel ball with a nominal radius of 7.50mm (see 4.10).

Table 5.4 Classification of corneas: normal eyes.

Type of cornea	Change in radius al 180 (mm) Ring 1-2	Ring 2-3	No. of eyes	% of total no. of eyes
A	⩽±0.05	⩽±0.05	15	12
B	⩽±0.05	>+0.05	22	18
C	⩽±0.05	>-0.05	0	0
D	>+0.05	⩽±0.05	42	34
E	>+0.05	>+0.05	39	32
F	>+0.05	>-0.05	5	4

+ indicates flattening

- indicates steepening

Table 5.4 shows that the majority of the corneas fell into groups D and E. A small number of corneas (group F) showed steepening exceeding 0.05mm between ring 2 and ring 3. The amount of steepening measured was always ⩽0.10mm in all 5 cases.

Figures 5.5 and 5.6 show the degree of flattening observed from rings 1 - 2 and rings 2 - 3 respectively. Data from group F was excluded from these two Figures.

5.3.2 Congenital cataract eyes

The individual flattest and steepest radii values recorded from a total of 33 eyes are recorded in Figures 5.7 and 5.8 respectively. Included in the Figures are also the minimum and maximum values observed in the normal eyes in the present study.

The results showed that the corneal radii in the congenital cataract subjects largely lay within the range of radii observed in the normal eyes. The mean value for the flattest corneal radii over all the age groups was 7.55 ± 0.48mm(s.d.). The range of values observed for the flattest corneal radii were from a minimum value of 6.50mm to a maximum value of 8.58mm. The mean value for the steepest corneal radii over all the age groups was 7.19 ± 0.45mm(s.d.). The minimum and maximum observed values were 6.12mm and 7.98mm, respectively.

The degree of flattening observed along the horizontal meridian was recorded over all the age groups for 19 aphakic eyes. They were also classified into the groups used for normal eyes (section 5.3.1). The proportion of aphakic eyes falling into each group is shown in Table 5.5.

Table 5.5 Classification of corneas: congenital cataract eyes.

Type of cornea	No. of eyes	% of total no. of eyes
A	3	16
B	3	16
C	0	0
D	7	37
E	6	32
F	0	0

The results on Table 5.5 shows that in common with the normal eyes, the majority of the corneas in the congenital cataract cases fell into groups D and E. The amounts of flattening observed from rings 1 - 2 and rings 2 - 3 on the aphakic eyes also fell into the range of values noted in the normal eyes (Figures 5.5 and 5.6).

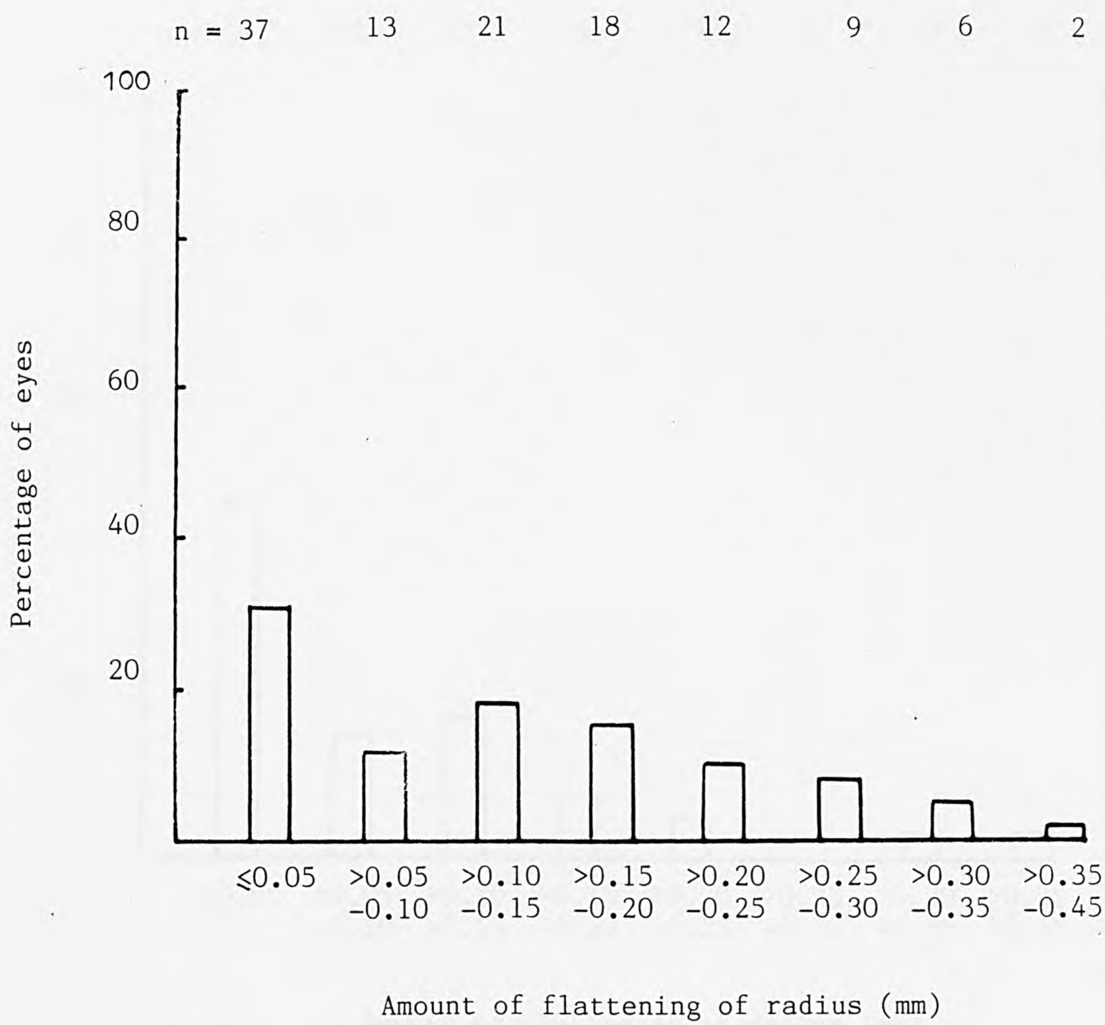


Figure 5.5. Degree of flattening of radius between rings 1 to 2 in 118 corneas. n = number of eyes showing the indicated amount of flattening.

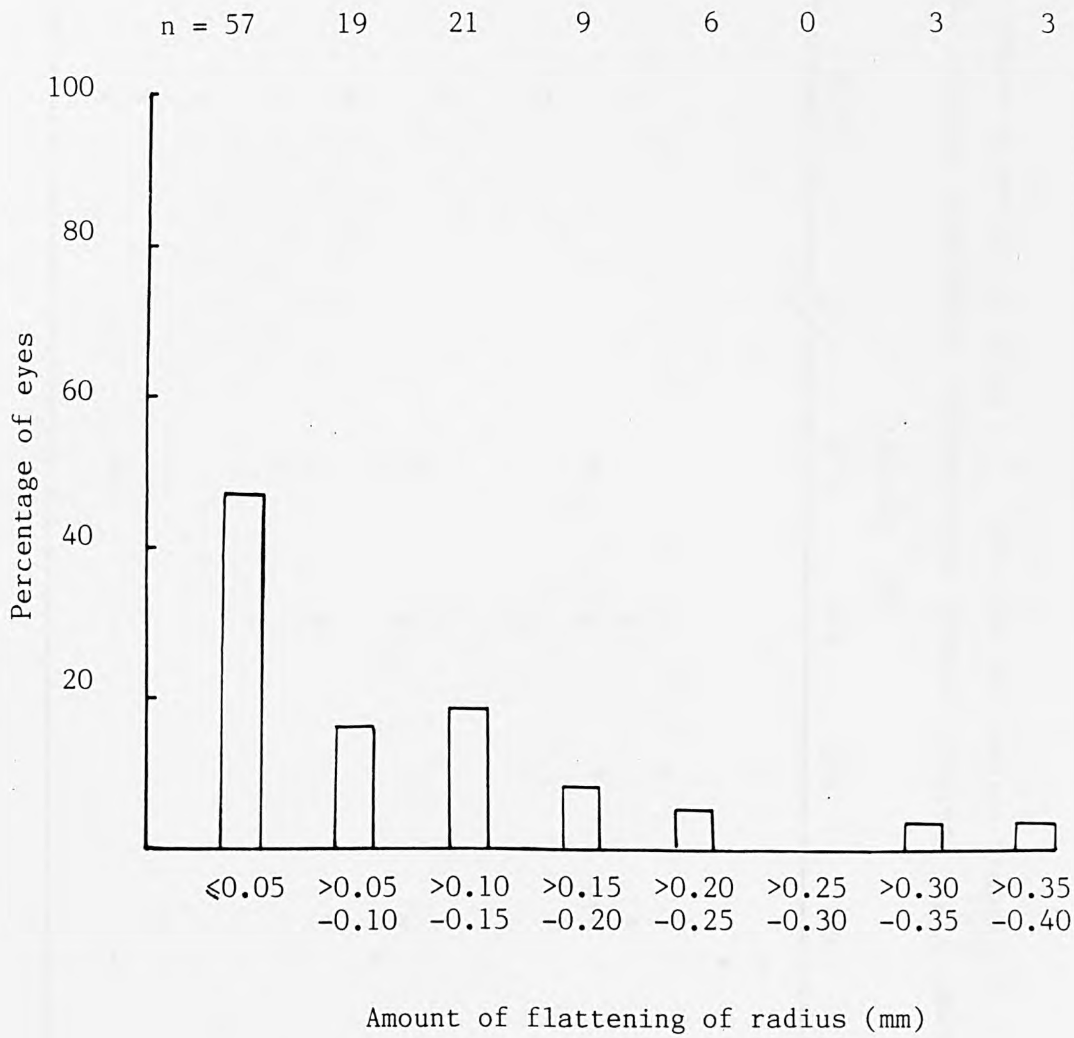


Figure 5.6. Degree of flattening of radius between rings 2 to 3 in 118 corneas. n = number of eyes showing the indicated amount of flattening.

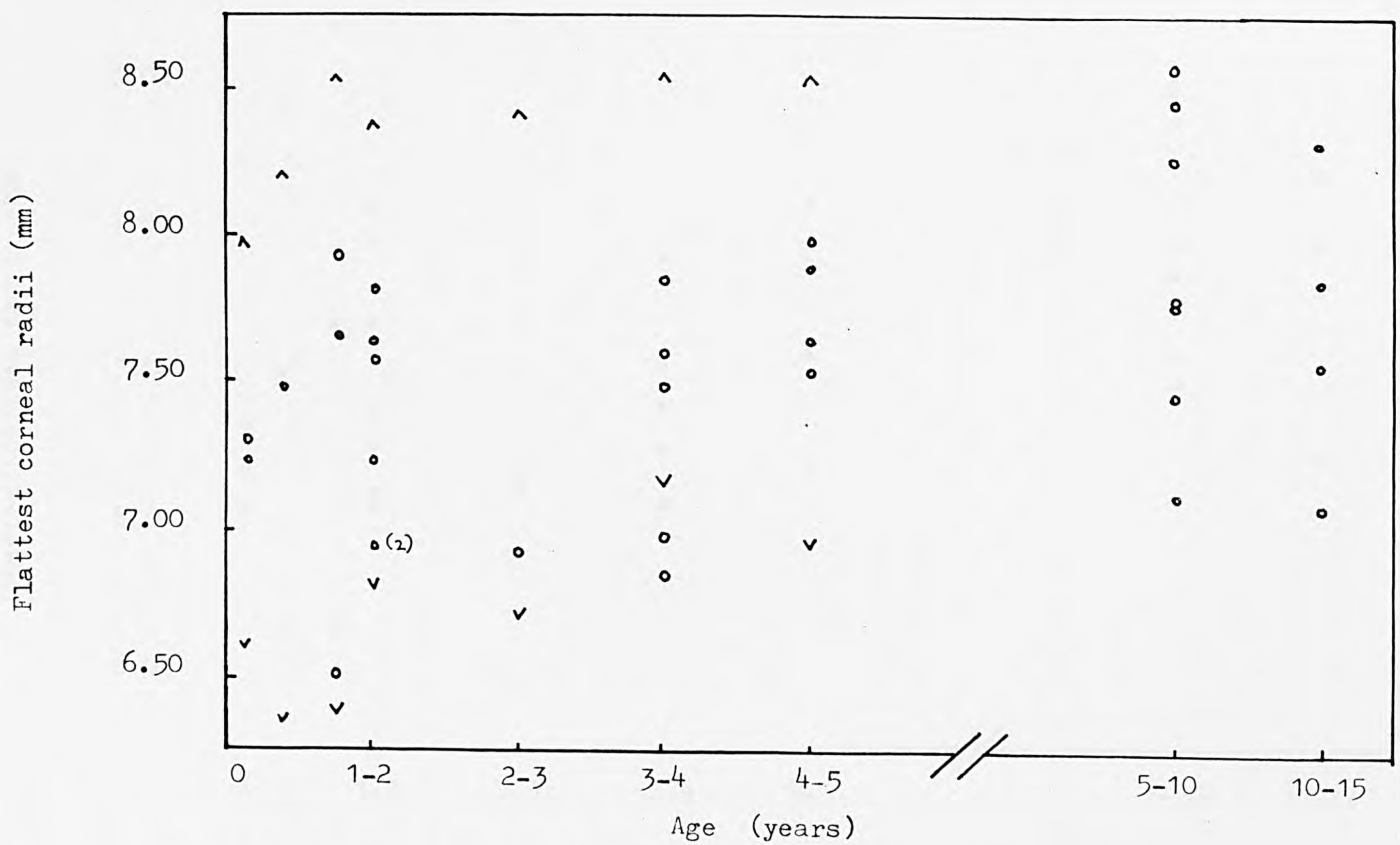


Figure 5.7. Flattest corneal radii values: congenital cataract eyes.
o - individual values for each eye, ^ v - range of values in normal eyes.

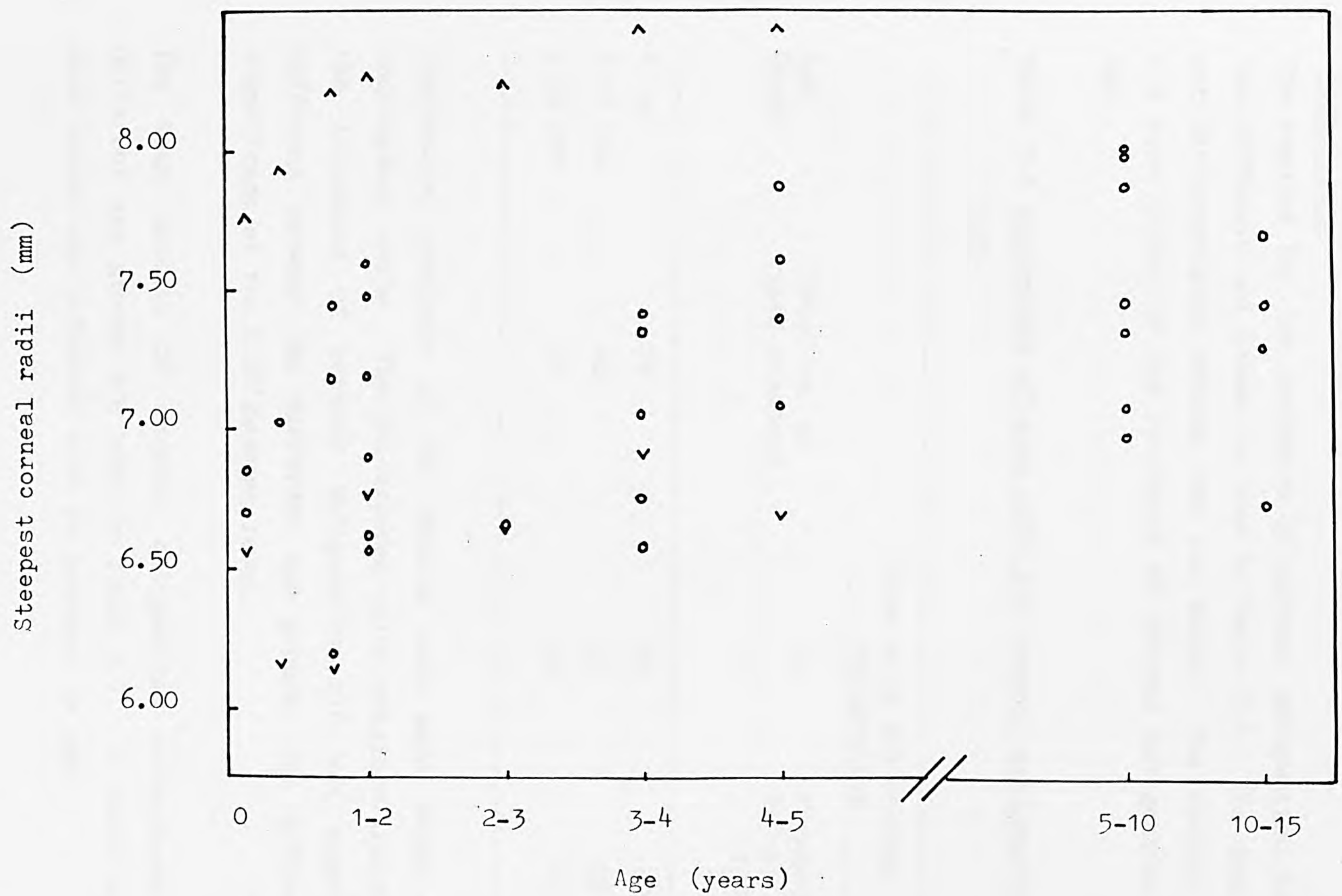


Figure 5.8. Steepest corneal radii values: congenital cataract eyes.
o - individual values for each eye, ^ v - range of values in normal eyes.

5.4 Corneal astigmatism

Data from a total number of 151 normal eyes and 33 aphakic eyes were analysed.

5.4.1 Normal eyes

The results for the incidence of corneal astigmatism $\geqslant$1D between the different age groups is seen in Table 5.6. The data here was not differentiated between the two sexes. The results in Table 5.6 show a drop of the incidence of corneal astigmatism $\geqslant$1D with age.

Table 5.6 Percentage of eyes with $\geqslant$1D corneal astigmatism: normal eyes.

Age Group	Total no. of eyes measured	Eyes with $\geqslant$1D corneal astigmatism: No.	Eyes with $\geqslant$1D corneal astigmatism: Percentage of total no. of eyes %
<1 yr	74	59	80
1-<3 yrs	40	23	58
3-<5 yrs	37	16	43

Statistical analysis of the results were made using a 2 x 3 contingency table. The chi-squared value obtained indicated that the incidence of corneal astigmatism $\geqslant$1D was significantly different between the different age groups. The difference was significant at the 0.04 percent level.

The mean amounts of corneal astigmatism encountered in the different age groups are seen in Table 5.7. A reduction in the mean values was indicated with an increase in age.

Table 5.7 Mean values of corneal astigmatism for various age groups: normal eyes.

Age Group	No. of eyes measured	Corneal astigmatism (D) mean value	s.d.	max. value
<1 yr	74	1.75	0.91	4.21
1-<3 yrs	40	1.25	0.91	4.22
3-<5 yrs	37	1.07	0.66	3.56

When the amount of corneal astigmatism ⩾1D for each eye was evaluated in each eye group, it was found that an appreciable drop in the proportion of eyes with ⩾2D of corneal astigmatism was seen with an increase in age. This is shown in Table 5.8 and Figure 5.9.

Table 5.8 Proportion of eyes with corneal astigmatism 1-<2D and ⩾2D: normal eyes.

Age group	Total no. of eyes	Eyes with corneal astigmatism 1-<2D: No. of eyes	1-<2D: % of total no.	⩾2D: No. of eyes	⩾2D: % of total no.
<1 yr	74	33	45	26	35
1-<3 yrs	40	16	40	7	18
3-<5 yrs	37	13	35	3	8

The data on eyes with ⩾1D corneal astigmatism was also classified into its distribution with regard to its direction. The corneal astigmatism was regarded as with- or against-the-rule if the steepest meridian was within ±15° of the vertical or horizontal respectively. All other cases were considered to have oblique corneal astigmatism. The results are shown on Table 5.9.

Table 5.9 Distribution of corneal astigmatism direction based on ±15° classification: normal eyes.

Age Group	Percentage distribution of corneal astigmatism (≥1D) direction: WTR	ATR	Oblique
<1 yr	31	5	64
1-<3 yrs	26	0	74
3-<5yrs	31	0	69

When the classification of the corneal astigmatism as being with- or against-the-rule was broadened to within ±30° of the vertical or horizontal as defined by Borish (1970:125), the distribution of the orientations of the corneal astigmatism altered to the results shown in Table 5.10.

Table 5.10 Distribution of corneal astigmatism direction based on ±30° classification: normal eyes.

Age Group	Percentage distribution of corneal astigmatism (≥1D) direction: WTR	ATR	Oblique
<1 yr*	58	14	29
1-<3 yrs	74	4	22
3-<5 yrs	81	0	19

*Percentages in this age group do not total 100% because of rounding up to the nearest 1%.

As can be seen from Table 5.9, a surprisingly high incidence of oblique astigmatism was observed amongst all 3 age groups. The incidence of with-the-rule astigmatism remained fairly constant between the 3 age groups whilst the incidence of against-the-rule astigmatism reduced with age.

When the broader classification of corneal astigmatism was used, the incidence of with-the-rule astigmatism rose with age whilst against-the-rule astigmatism still showed a decrease in frequency with age. The incidence of oblique astigmatism remained fairly constant for all 3 age groups.

5.4.2 Congenital cataract eyes

The individual amounts of corneal astigmatism recorded from the 33 eyes are recorded in Figure 5.10. 24 of the eyes (73%) showed corneal astigmatism values of between 1 to 3 D. 29 out of the 33 eyes (88%) had corneal astigmatism values below 3 D. The maximum corneal astigmatism value recorded was 4.26 D.

The eyes for all the age groups showing $\geqslant$1D corneal astigmatism were classified into whether the astigmatism was with-the-rule, against-the-rule or oblique based on the 15° and 30° basis (Table 5.11). Table 5.11 shows that the incidence of against-the-rule astigmatism amongst these eyes was low.

Table 5.11 Distribution of corneal astigmatism direction based on ±15° and ± 30° classification: congenital cataract eyes.

	Percentage distribution of corneal astigmatism ($\geqslant$1D) direction		
	WTR	ATR	Oblique
Based on ±15° basis	32	4	64
Based on ±30° basis*	61	4	36

*Percentages in this group do not total 100% because of rounding up to the nearest 1%.

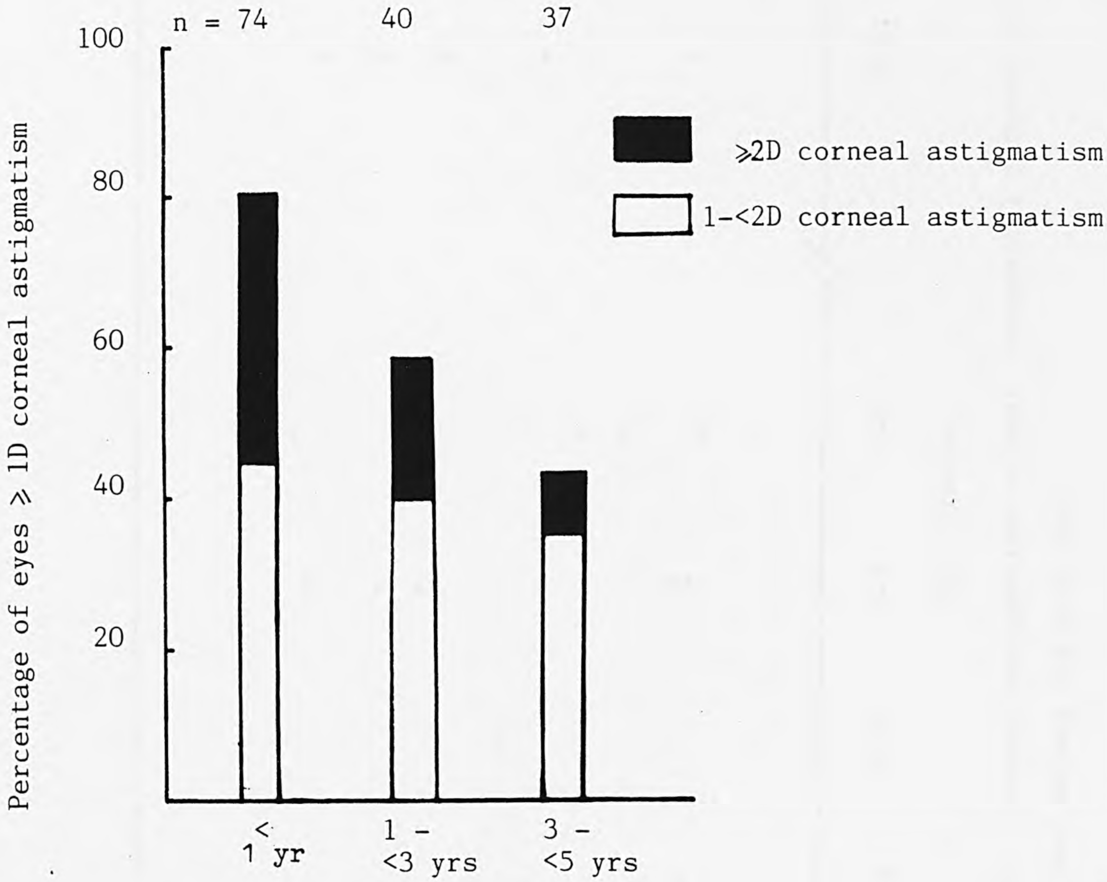


Figure 5.9. Incidence of corneal astigmatism at different ages. n = total number of eyes seen in each age group.

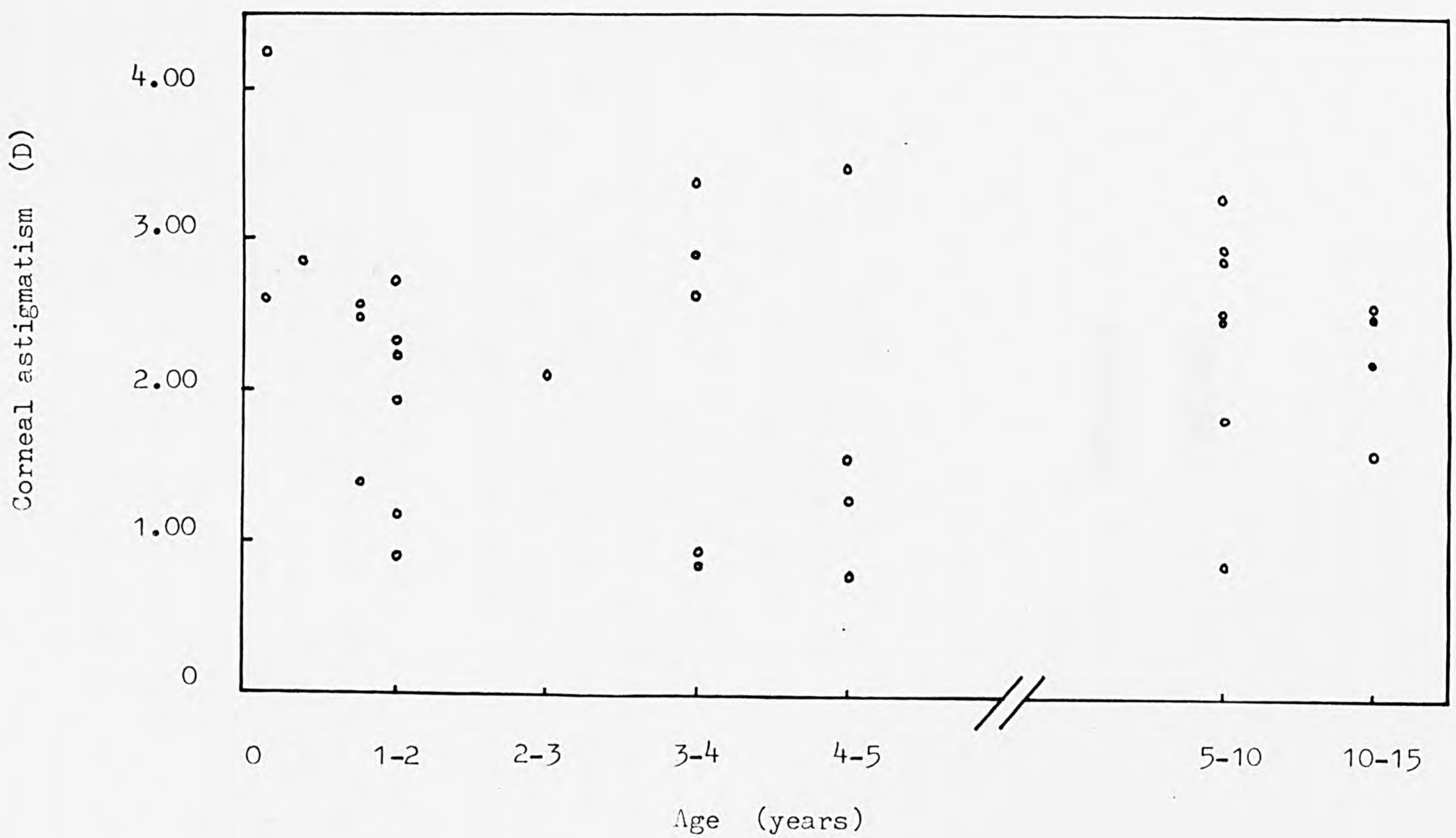


Figure 5.10. Corneal astigmatism values: congenital cataract eyes.
o - individual values for each eye.

CHAPTER 6

DISCUSSION

6.1 Growth of the eyeball.

In order to relate the corneal growth to growth of the eye as a whole, the latter aspect is first considered here.

The body as a whole increases about 20 times in weight from birth to adult size. In comparison, the eye only increases by a little less than 3 times in weight which makes it more similar to the brain which increases about 3 1/2 times in weight (Scammon and Wilmer, 1950).

The research of Sorsby et al. (1961) and Sorsby and Leary (1970) has thrown considerable light on our knowlege of ocular growth. Data from both studies led Sorsby and his co-workers to propose that the growth of the eye falls into 2 distinct phases:

(i) a period of rapid growth before the age of 3 years when the axial length increases by about 4mm from birth, followed by

(ii) a period of slower growth up to the age of 13 or 14 years when the axial length increases by about 1mm to reach adult dimensions.

It is of interest to note that Todd et al. (1940) who carried out measurements on the weight of cadavers' eyes, found a rapid increase in the weight of the eyeball during the first year of life suggesting a considerable rate of growth in this period.

Values obtained from anatomical measurements of cadaver material can be inaccurate because of post-mortem changes. Thus, it is ideal to be able to obtain measurements on the living eye. The technique of ultrasonography for the measurement of intraocular distances in vivo has allowed easier biometric measurement compared with phakometry (used by Sorsby et al. 1961 and Sorsby and Leary, 1970) due to the extensive mathematical procedures involved with the latter technique. Ultrasonic measurements of the depth of the anterior chamber, thickness of the crystalline lens and axial length of the eye have been shown to be in close agreement with the phakometric method (Leary et al., 1963; Sorsby et al., 1963; Kimura et al., 1969). Several biometric studies investigating ocular growth in the young eye have been conducted and mainly corroborate the findings of Sorsby et al. (1961) and Sorsby and Leary (1970).

In the full-term newborn, the axial length of the eye is on average about 17mm (Gernet, 1964; Luyckx, 1966; Grignolo and Rivara, 1968b; Larsen, 1971d; Blomdahl, 1979; Tatsugami et al., 1980; Yankov, 1982; Tane and Kohno, 1983; Gordon and Donzis, 1985). After birth the growth of the axial length falls into 3 phases:

(i) a period of rapid increase during the first 12-18 months of life. Gernet and Hollwich (1968) and Larsen (1971d) observed an increase of axial length of 3.7-3.8mm in 18 months whilst Tane and Kohno (1983) observed 3.75-3.93mm increase in the first year after birth. Gordon and Donzis (1985) also recorded the greatest increase of axial length (3.4mm) in their youngest age groups up to the age of 2 years in their cross-sectional study,

(ii) a slower phase from the first to 5 or 7 years of life. Larsen (1971d) recorded an increase of 1.1-1.2mm up to the age of 5 years. Tane and Kohno (1983) found an average increase of 1.58mm up to the age of 7 years,

(iii) and finally a slow juvenile phase up to the age of 13 to 15 years when an increase of 1.3-1.4mm is noted (Larsen, 1971d; Tane and Kohno, 1983). The axial lengths recorded on this age group had reached the values found in a group of 20 emmetropic adults aged 20-40 years (Larsen, 1971d).

When the depth of the anterior chamber (including corneal thickness) is considered, an average value at birth of 2.37-2.90mm is observed (Gernet, 1964; Luyckx, 1966; Larsen, 1971a; Blomdahl, 1979; Yankov, 1982; Tane and Kohno, 1983). This value is also observed to increase rapidly in the first year of life (0.9-1.0mm), followed by a slower increase of 0.3-0.4mm from 1-7 years of age and finally a slight increase of only about 0.1mm from the age of 8 to 13 years (Delmarcelle and Luyckx-Bacus, 1971; Larsen, 1971a; Tatsugami et al., 1980; Tane and Kohno, 1983). In the mature newborn, the average thickness of the crystalline lens has been recorded to be between 3.60 and 3.65mm (Gernet, 1964; Luyckx, 1966; Larsen, 1971b; Blomdahl, 1979; Yankov, 1982; Tane and Kohno, 1983). The anterio-posterior diameter decreases by about 0.3mm in the first year after birth and further reduces by about 0.2-0.3mm by the age of 11 to 13 years (Larsen, 1971b).

The vitreous length is on average about 10.22 to 11.28mm in the newborn (Luyckx, 1966; Larsen, 1971c; Blomdahl, 1979; Tatsugami et al. 1970; Yankov, 1982; Tane and Kohno, 1983). An increase in its length of about 2.91-3.31mm has been observed in the first 12-18 months of life, followed by an increase of 1.39-1.66mm up to the age of 7 years and a further 1.1mm up to the age of 15 years (Larsen, 1971c; Tatsugami et al., 1980; Tane and Kohno, 1983). Larsen (1971c) noted that beyond the second year of life, the longitudinal growth of the eye is almost exclusively due to the increase in vitreous length.

All the above data is in accordance with the older studies of Sorsby et al. (1961) and Sorsby and Leary (1970) and support the theory that postnatal growth of the ocular axial length is most rapid during the first 2 years of life, followed by a slower juvenile phase up to the age of 13 or 14 years.

Table 6.1 Collated data on corneal diameters in the newborn.

Investigator	Number of subjects	Mean value of corneal diameter ± s.d. (mm) Horizontal	Vertical
von Reuss (1881)	1(m) observations 3(f)	9.1	
Königstein (1884)	5 observations	10.0	
Schneller (1899)	16(m+f)	9.9	9.2
Seefelder (1908)	4(m+f) observations	10.4	
Grod (1910)	6(m) 4(f)	9.25 10.25	
Nussbaum (1912) cited from Scammon and Wilmer (1950)	3(m+f) observations	10.0	9.8
Kaiser (1925)	32(m) 23(f)	9.47 9.38	
Scammon and Armstrong (1925)	Computed values	9.80	9.00
Hymes (1929)	11(m) 6(f)	10.04±0.961 9.93±0.097	
Sorsby and Sheridan (1960)	13(m) Lived< 6(f) 24 hours 3(m) Lived 4(f) 1-6 days	9.8 ±0.33 10.1 ±0.33 9.25±0.404 10.1 ±0.301	10.4±0.35 10.7±0.29 10.1±0.51 10.6±0.301
Ellerbrock (1963)	NI	9.4	
Marshall and Grundle (1978)	NI	10.00	
Blomdahl (1979)	28(m+f)	9.8	
Yankov (1982)	100(m) from birth to 100(f) 5 days	9.44±0.33 9.32±0.34	8.96±0.31 8.83±0.34
Pfister and Breaud (1983)	NI	9.9	
Bahn et al. (1986)	3 observations (3,6, 21 days)	10.4 ±0.6	

(m) Male subjects

(f) Female subjects

NI Number of subjects not indicated

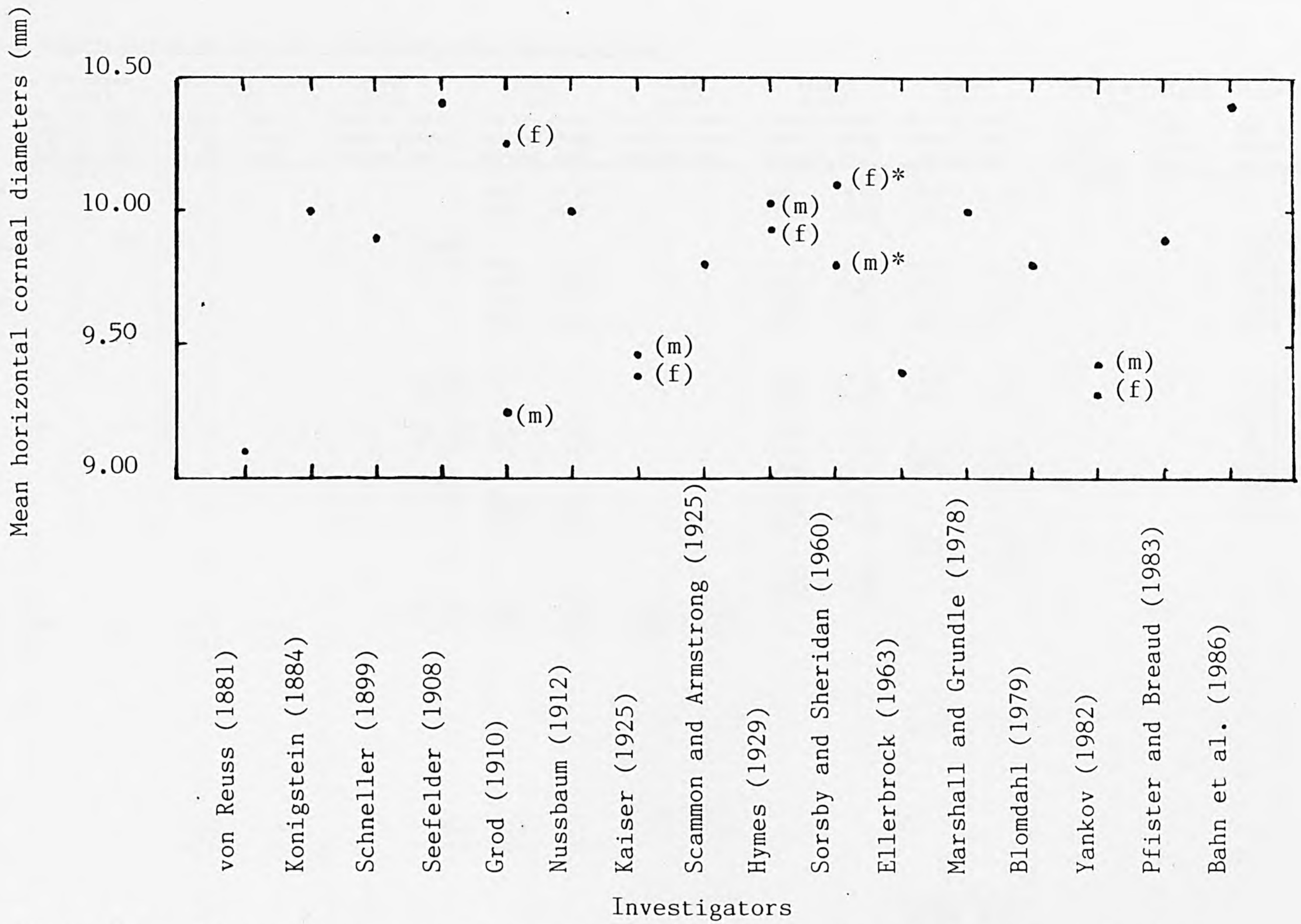


Figure 6.1. Horizontal corneal diameters in the newborn. Symbols: (m)-male subjects, (f)-female subjects, *-subjects lived < 24 hours.

Table 6.2 Collated data on the variation of horizontal corneal diameter with age.

Age	von Reuss (1881) No. of observations	von Reuss (1881) Mean value (mm)	Priestley Smith (1890) No. of observations	Priestley Smith (1890) Mean value (mm)	Greeff (1892) No. of observations†	Greeff (1892) Mean value (mm)	Grod (1910) No. of observations	Grod (1910) Mean value (mm)	Peter (1924) No. of observations	Peter (1924) Mean value (mm)	Kaiser (1925) No. of observations	Kaiser (1925) Mean value (mm)	Hymes (1929) No. of observations	Hymes (1929) Mean value (mm)	Gernet & Hollwich (1968) No. of observations	Gernet & Hollwich (1968) Mean value (mm)	Present study No. of observations	Present study Mean value (mm)
	(m+f)														(m+f)			
Newborn							6(m)	9.25			32(m)	9.47	11(m)	10.04				
							4(f)	10.25			23(f)	9.38	6(f)	9.93				
																	5(m)	11.00
½-6 mos.	13	9.3				9.0(m)											6(f)	10.87
						9.2(f)	10(m)	9.70			16(m)	10.85	12(m)	10.55			17(m)	11.66
							4(f)	10.00			15(f)	10.84	7(f)	10.37			8(f)	11.65
6-12mos.							2(m)	11.25			14(m)	11.46	3(m)	11.83			16(m)	11.76
							4(f)	10.00			15(f)	11.32	2(f)	10.95			17(f)	11.52
Years																		
1- 2						9.5(m)	4(m)	11.5			8(m)	11.45	3(m)	11.30	15	10.5	11(m)	11.86
						9.5(f)					12(f)	11.09	9(f)	11.33			3(f)	11.75
																	12(m)	12.03
2- 3	20	11.4				9.9(m)	4(m)	11.62			10(m)	11.42					9(f)	11.69
						10.3(f)	2(f)	11.75			10(f)	11.44	27(m)	11.33			5(m)	12.10
											9(m)	11.97	18(f)	11.69			11(f)	11.34
3- 4						11.4(m)					12(f)	11.43					8(m)	12.06
4- 5						11.0(f)	2(m)	11.5			11(m)	11.67					13(f)	11.75
							2(f)	12.0			20(f)	11.40						
													20(m)	11.73				
													23(f)	11.55				
5- 6											5(m)	11.58						
											14(f)	11.35						
6- 7						12.0(m)	2(m)	11.25	144(m)	11.72					66	11.7		
	31	11.6	54(m)	11.74		11.6(f)	3(f)	12.03	156(f)	11.58								
7- 8			40(f)	11.57														
8- 9																		
9-10																		
									140(m)	11.69			99(m)	11.75				
													102(f)	11.71				
10-11									152(f)	11.55								
11-12																		
12-13									124(m)	11.82								
			124(m)	11.70		11.6(m)	6(m)	11.3	112(f)	11.61								
13-14			132(f)	11.55		11.4(f)	4(f)	11.37										
14-15									82(m)	11.76								
									114(f)	11.55			64(m)	11.76				
													113(f)	11.79				
15-20	70	11.6																
													81(m)	11.83				
20-30			130(m)	11.73									77(f)	11.86				
			124(f)	11.70			2(m)	12.00										
30-39																		

† Total of 200 subjects from 1 - [illegible] years of age.

6.2 Growth of corneal diameters

Studies relating to corneal diameters are fairly substantial due to this dimension being easily accessible for measurement. The results from these studies relating to neonates have been collected and summarized in Table 6.1 and Figure 6.1. Data relating to older subjects are presented in Table 6.2.

6.2.1 Normal eyes

Von Reuss (1881) measured the horizontal diameter of the cornea in 184 cases comprising of living subjects and 10 infant cadavers. He used a pair of compasses and rule to perform the measurements.

Königstein (1884) reported an average transverse corneal diameter of about 10mm in the newborn eye after measuring 5 eyes. The range of values obtained was from 9.9 to 10.1mm.

Priestley Smith (1890) conducted his measurements with a keratometer on both eyes of 500 living subjects. He stated that his measurements were correct to the nearest 0.5mm. The subjects studied ranged in age from 5 to 90 years.

Greeff (1892) as cited by Scammon and Armstrong (1925) and Hymes (1929) observed the corneal diameter in 200 living subjects using a Horstmann pupillometer and claimed that he was unable to vouch for the accuracy of his measurements to within ±1mm.

Schneller (1899) measured 32 corneas of 16 newborn infant cadavers and mean horizontal and vertical diameters of 9.9mm and 9.2mm were found.

Seefelder (1908) examined 4 neonates and reported an average transverse corneal diameter of 10.4mm.

Grod (1910) employed compasses to measure the horizontal corneal diameters in fresh cadavers whose age at death ranged fom the newborn to over 60 years.

Nussbaum (1912) gave a mean value of 10.0mm for the transverse corneal diameter measured on 3 newborn infants (cited by Scammon and Wilmer, 1950).
Peter (1924) reported data on the horizontal visible iris diameters gathered from 1,024 normal eyes. The subjects, 245 boys and 267 girls ranged in age from 5 to 16 years. Peter expressed difficulty in distinguishing the exact limbal margin as it was not distinct especially in individuals with lightly-coloured irides. In the present study, this difficulty was not present except in cases when 1 or 2 of the electronic flash guns did not work at the time of photography giving a very faint limbal margin in the negatives. These cases were not included for measurement with regard to the HVID. Measurements were made by Peter with a Wesseley Keratometer and an accuracy of ±1/8mm was claimed. In young children, local anaesthesia was administered before measurements were taken with the lids retracted using hooks. A difference of 0.25 to 0.5mm in the horizontal diameters were found between the right and left eyes in 34 of the children.

Scammon and Armstrong (1925) computed values of 9.8 and 9.00mm for the horizontal and vertical diameters respectively, in the newborn. These values were based on measurements made on human cadavers. A steel vernier caliper with which readings could be made to the nearest 0.1mm was used for the measurements.

Kaiser (1925) also obtained results on the transverse corneal diameters in living subects from birth up to 6 years of age. The author designed an instrument called a "Mikrometer" which had a 2cm long scale with graduations of 0.1mm. This enabled readings to be made correct to the nearest 0.05mm. A photograph of this instrument reduced by 1 1/2 times its actual size was included in the paper. Kaiser noted that it was easier to distinguish the limbal margin in neonates and older infants than in adults. The present author did not find any difference in this respect.

Hymes (1929) examined a sample of 320 males and 362 females using a Wesseley Keratometer. Measurements of the horizontal corneal diameters of both eyes for each subject were made and an average value was obtained from both values. The investigator found it necessary to anaesthetize the eyes of newborn infants and to retract their lids with a lid speculum. In most of the newborn subjects, fixation forceps were used to hold the eyeball in a suitable position before the corneal measurements could be taken. Hymes produced a table of data on horizontal corneal diameters from past researchers which was as an exact copy of a table produced in an earlier paper by Scammon and Armstrong (1925) but Hymes made no mention of this in his report.

Sorsby and Sheridan (1960) measured the transverse and vertical corneal diameters in 77 eyes of 48 cadavers of newborn infants. These included both premature babies and full-term babies up to 6 days old. The corneal diameters (both horizontal and vertical) were found to be larger in females than in males for both the premature and full-term subjects. There is some discrepancy in the reported results as in the table of their results and the summary, it was stated that the horizontal corneal diameters were shorter than their vertical counterparts. However, in another part of the text the horizontal corneal diameter was stated to be larger than the vertical in all cases. This latter statement appears to be a printing error as Sorsby (1973) in a separate article reported that in the 1960 study, the vertical diameter was recorded as larger compared with the horizontal.

Ellerbrock (1963) gave a value of 9.4mm for the corneal diameter in neonates.

Gernet and Hollwich (1968) compared the ocular dimensions including corneal diameters of glaucomatous and normal healthy eyes.

Marshall and Grindle (1978) stated that the horizontal corneal diameter at birth was 10mm which lengthened to 11.7mm by 1 year of age.

Blomdahl (1970) published the results of measurements taken on 28 full-term newborn (14 boys and 14 girls). An average value of 9.8mm (range 9.00 to 10.5mm) was recorded for the horizontal corneal diameter. Calipers were used for the measurement.

Yankov (1982) conducted measurements on the horizontal and vertical corneal diameters of full-term newborn infants using compasses. Readings were made correct to the nearest 0.5mm. In total, both eyes of 100 male and 100 female infants were measured during the first five days following birth. On the basis of these results, Yankov concluded that the diameter of the cornea in neonates is 25 percent less than that in adults.

Pfister and Breaud (1983) reported an average horizontal diameter of 9.9mm in neonates in their study on newborn donor corneas for penetrating keretoplasty.

Bahn et al. (1986) measured the diameters of 3 corneas from a cornea eye bank. The corneas had been taken from infants aged 3, 6 and 21 days at the time of death. An average of the horizontal and vertical diameters was calculated to be 10.4 ± 0.6mm(s.d.). Similar measurements made on 4 adult corneas gave a mean value of 11.00 ± 1.2mm(s.d.). Bahn et al. claimed that these measurements obtained on eye bank corneas did not differ from those made on living eyes.

The results of the present study are in good agreement with the older studies by Grod (1910), Kaiser (1925) and Hymes (1929) which show that most of the postnatal growth of the horizontal corneal diameter takes place in the first year of life. The mean HVID value of 11.9mm (males and females considered together) had been reached by the age of 1 to 2 years in this study and no obvious increase was apparent after this age. The most dramatic increase in HVID was noted in the first 6 months of life. This finding was also noted by Hymes (1929). Grod (1910) and Kaiser (1925) recorded slower rates of growth during this period (Figure 6.2). Priestley Smith (1890) and Peter (1924) who studied subjects aged 5 years and older were also of the opinion that adult values of corneal diameters were reached by the age of 5 years.

It is interesting to note that the mean value of 11.9mm recorded in this study at which the corneal diameters appear to stabilize is very similar to the adult values recorded by other investigators (Table 6.2). The corneal values on subjects up to 5 years of age measured by Greeff (1892) were smaller compared with

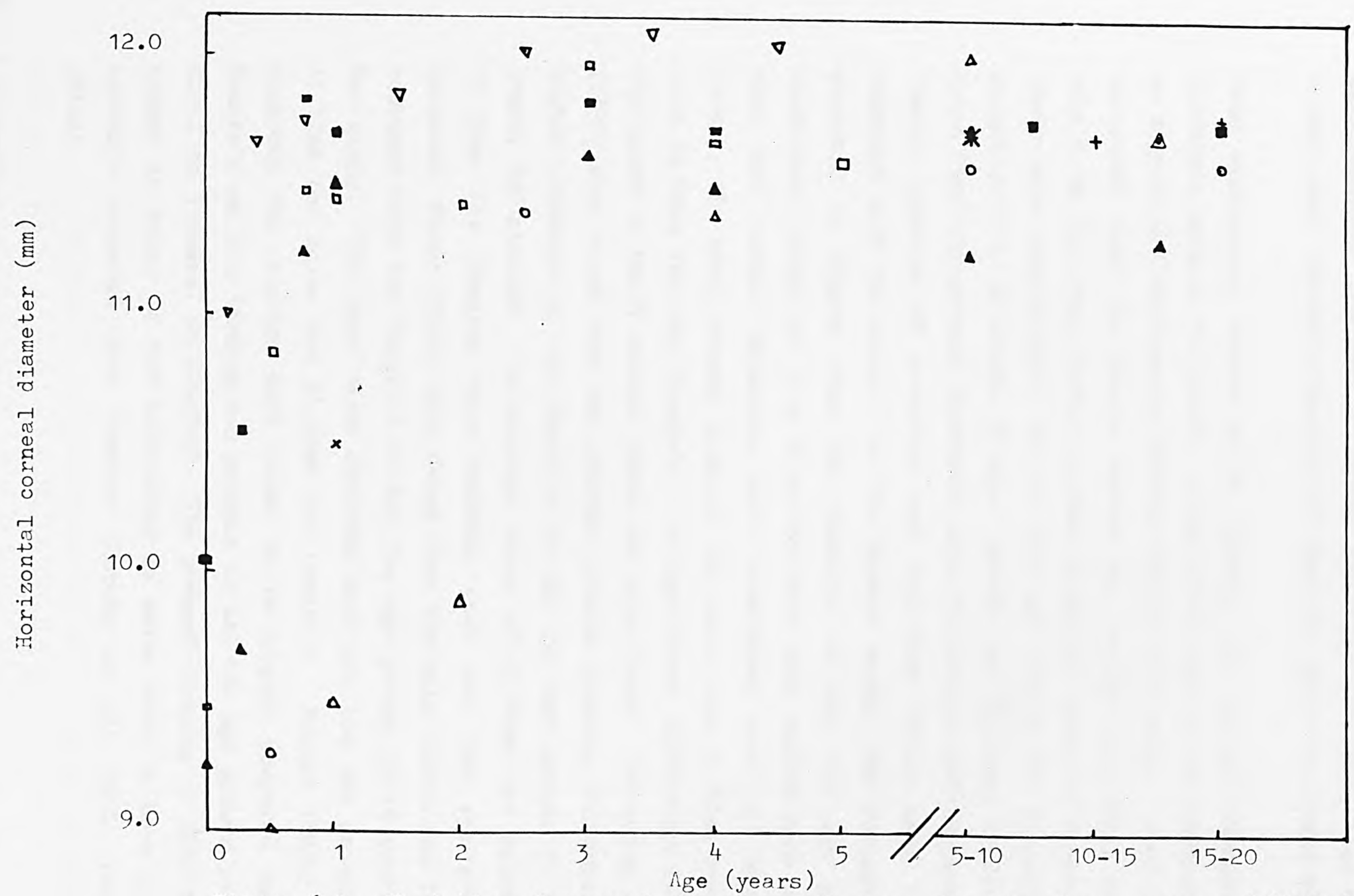


Figure 6.2. Variation of corneal diameter with age. Results of o von Reuss (1881)-(m+f), ● Priestley Smith (1890) - (m), △ Greeff (1892) - (m), ▲ Grod (1910) - (m), + Peter (1924) - (m), ▫ Kaiser (1925) - (m), ■ Hymes (1929) - (m), × - Gernet and Hollwich (1968) - (m+f), ▽ Present study - (m).

the present results and also those of the other investigators. This may be due to the low accuracy he obtained in his measurements. The data of Gernet and Hollwich (1968) also showed a very small corneal diameter (10.5mm) for the 1 to 2-year-olds.

Some discrepancy exists as to whether the corneal diameter is different between the sexes. Hymes (1929) was of the opinion that no significant difference existed between the sexes. Grod (1910) concluded that the female cornea was larger than that of the male's as the mean female corneal diameters were no larger than their male counterparts in all the age groups he investigated except at 6 to 12 months of age. Sorsby and Sheridan (1970) also found that the corneal diameters (both horizontal and vertical) in female cadavers of premature and full-term babies were larger compared with the males. In the present study, the average male diameter is higher than the female's in all the age groups considered except at 3 to 6 months when both values were equal. When the corneal diameters were considered over all the age groups, the mean corneal diameter for males was 11.80mm compared with 11.60mm for the female's. A significant difference between the sexes at the 5 percent level was also found. Priestley Smith (1890) also noted that the average corneal diameter for males was higher compared to the female's in all the age groups (5 to 90 years) he studied. An average value of 11.65mm for males and 11.54mm for females were recorded over all the age groups. Likewise, Peter (1924) also found that the male cornea was larger compared with the female's in all the age groups (5-16 years) of her study. The mean value recorded over all the age groups was 11.74mm for males and 11.60mm for female's. Kaiser (1925) also regarded the average male value to be higher compared to the female's as this finding was present in all the age groups (except for 2 to 3 years) he studied. The present finding of HVID being larger in males is not surprising as males tend to have bigger eyeballs compared with females (Sorsby et al. 1961; Larsen, 1971d).

6.2.2 <u>Congenital cataract eyes.</u>

Our knowledge of corneal dimensions including corneal diameters in congenital cataract cases is relatively sparse. Most of the data reported on congenital cataract cases had been collected whilst fitting these subjects with contact lenses following cataract extraction. The results from various researchers who have attempted measurements on corneal diameters in these cases are presented in Table 6.3. Fuller details of their work now follows.

Enoch (1972) observed that corneal diameters in 16 uniocular and binocular congenital cataract cases aged from birth to 14 years were only slightly lower compared to normal children of the same age. He did not give any actual figures for normal diameter values but he stated that 3 out of the 16 eyes measured had a corneal diameter of less than 10mm. Their tendency towards a steeper corneal curvature was noted by Enoch but only 1 of these had a relatively extreme corneal curvature value (see 6.3.2).

Enoch and Rabinowicz (1976) found that both eyes of a healthy neonate born with a unilateral cataract had corneal diameters of 9.5mm in both the horizontal and vertical meridians. The measurements were taken just prior to surgery when the infant was 4 days old.

Ellis (1977) noted the rate of enlargement of the horizontal diameter of the cornea in a 3-month-old congenital cataract baby. The diameters in both the cataractous and normal eye increased from 9.00mm at the age of 3 months to reach 11.5mm at the age of 10 months. In contrast, he found that in another case of a monocular congenital cataract subject (aphakic) examined initially at 2 3/4 years, the corneal diameters in both eyes were similar to those in adults and remained relatively static.

Enoch et al. (1979) recorded the horizontal and vertical corneal diameters of a 6 month old monocular congenital cataract case just prior to cataract surgery. A further note of the horizontal diameters were noted when the subject was 1 year old. It was interesting to find that the horizontal corneal diameter remained smaller in the aphakic eye compared with the normal eye at the age of 1 year.

Jacobson et al. (1981) measured the corneal diameters in 3 newborn infants (2 with bilateral congenital cataracts and 1 with a unilateral cataract).

Pratt-Johnson and Tillson (1985) noted that in bilateral congenital cataract cases, the corneal diameters were usually equal in both eyes. No actual figures were given.

Moore (1987) observed the corneal diameters of 14 infants born with monocular congenital cataracts ranging in age from 1.3 to 1.6 months (mean age 3.7 months). All of these infants were normal full-term babies with one exception who had respiratory and cardiac problems at birth. One of the infants had persistent hyperplastic primary vitreous but no other infants in the study had associated ocular or systemic abnormalities. The corneal diameters in the eyes with cataracts ranged from 9.5 to 11.75mm with no relationship found with age. Microcornea (defined as the horizontal visible corneal diameter in the aphakic eye being 1mm or more smaller than that of the normal eye) was detected in 6 of the 14 infants, and a further 2 infants developed this in the following year. The corneal diameters were monitored over a 3-year period, and these were observed to increase in each eye of all the infants over time. Moore found that in several of the aphakic eyes, the rate of growth was apparently less than that of the normal eye. No actual figures were given to illustrate this point.

Robb et al. (1987) observed that the aphakic eyes in 8 subjects (aged between 3.5 to 8.3 years) born with monocular congenital cataracts had horizontal corneal diameters 0.25 to 1.00mm smaller than their normal eyes. This was a generalized statement and no actual figures of diameters were given.

Pollard (1987) measured the corneal diameters in 3 congenital cataract cases aged 1 week, 2 weeks and 3 weeks old.

The range of corneal diameters observed in 30 binocular congenital cataract eyes (aged 2 months to 15 years) in this study ranged from 9.40mm to 12.30mm. 10 out of the 19 eyes belonging to subjects up to 5 years of age had HVID values which fell below the minimum values observed in normal eyes of the same age group (Figure 5.2).

These results are in agreement with those of Enoch's (1972) study who had also found that the corneal diameters in the congenital cataract cases were lower compared with those in normal children. The tendency for smaller corneal diameters to be found in eyes with congenital cataracts have also been noted by Enoch et al. (1979), Moore (1987), Robb et al. (1987) and Pollard (1987). Their studies of monocular congenital cataract cases where comparisons with the normal eye could be made showed the corneal diameter to be smaller in the eye with the cataract. In contrast, Ellis (1977) and Jacobson et al. (1981) recorded equal corneal diameters in both the normal and cataractous eye in 3 monocular congenital cataract cases.

The present study also showed that for aphakic children aged from 5 to 15 years, the HVID values recorded fell within the range of values recorded by Hymes (1929) on normal eyes belonging to subjects of the same age groups.

Only one eye in this study had a corneal diameter below 10.00mm. This belonged to a 9-month-old infant who had the steepest corneal curvature recorded in the whole sample of 33 eyes. However, when all the eyes were surveyed as a whole, the size of the corneal diameter was seen not to be a reliable indicator of the corneal curvature.

Table 6.3 Collated data on corneal diameters in congenital cataract cases.

Age	Enoch and Rabinowicz (1976) No. of eyes	Enoch and Rabinowicz (1976) Mean value (mm)	Ellis* (1977) No. of eyes	Ellis* (1977) Mean value (mm)	Enoch et al. (1979) No. of eyes	Enoch et al. (1979) Mean value (mm)	Jacobson et al.* (1981) No. of eyes	Jacobson et al.* (1981) Individual values (mm)	Moore* (1987) No. of eyes	Moore* (1987) Mean value (mm)	Robb et al. (1987) No. of eyes	Robb et al. (1987) Mean value (mm)	Pollard (1987) No. of eyes	Pollard (1987) Mean value (mm)
Months														
0- 3	1°† (4days)	9.5(c)(h&v) 9.5(n)(h&v)					1°† (birth, rubella)	8(c)	14°‡	range from 9.5-11.75(c)			1°‡ (7days)	10(c)(h)
							1°† (3days)	10(c)					1°‡ (2wks)	9(c)•,10(n)•
							1°† (5days)	10(c),10(n)					1•† (3wks)	8(c)(h) bilateral microphthalmia
3- 6			1°† (3mos)	9.0(c) 9.0(n)										
6- 9			1°‡ (7mos)	10.5(c) 11.0(n) same eye	1°† (6.5mos)	10.25,10.00(c) (h) (v) 10.75,10.25(n) (h) (v)								
9-12			1°‡ (10mos)	11.5(c) 11.5(n)		same eye								
Years														
1- 2					1°‡ (1yr)	11.25(c) (h) 11.75(n) (h)					9°‡ (3.5-8.3yrs)	(c) had HVID 0.25-1.0 mm smaller than normal eye		
2- 3			1°‡ (2¾yrs)	12.00(c) 12.00(n)										

o Monocular congenital cataract case.
• Binocular congenital cataract case.
† Measurements taken before cataract surgery.
‡ Measurements taken after cataract surgery (i.e. aphakic eye).
(c) Eye with cataract or which had cataract before removal.
(n) Normal eye of the same subject with (c).
(h) Horizontal corneal diameter.
(v) Vertical corneal diameter.

* These authors did not specify whether they measured the horizontal or vertical corneal diameters.

6.3 Growth of corneal radii

6.3.1 Normal eyes

The anterior corneal curvature in newborn babies and its post-natal changes recorded by various investigators are summarized and presented in Tables 6.4, 6.5 and Figures 6.3 and 6.4. The methods used for taking these measurements have been discussed in section 3.11. Table 6.5 does not include data evaluated by Fledelius (1976) on 10-year-old children. Mean keratometric values of 7.90±0.27mm(s.d.) and 7.78±0.23mm(s.d.) were found in 113 male subjects and 124 female subjects respectively.

All the previous data indicate steeper corneas in the premature and newborn compared with adult corneas. It is suggested that adult values are reached by as early as 6 months (Molnar 1970; Gordon and Donzis, 1985). York and Mandell (1969) deduced that central corneal radii values are stabilised by the time the baby reaches its first year of life. The result of Yamamoto et al. (1981a), suggested that adult values are present by the age of 2 years. Ehlers et al. (1976) estimated that mature values are attained by the third year of life. Fledelius and Stubgaard (1986) who recorded keratometric readings on a sample of 454 subjects aged 5 to 80 years concluded that adult radii values had already been reached by the age of 5 years.

The present results on subjects aged from 1 month to 5 years showed an increase in the mean flattest and steepest corneal radii up to 6 months of age (Figures 5.3 and 5.4) after which there appeared to be little variation with age. However, statistical analysis of the results showed no significant change with age. (The variation in the steepest corneal radii with age was significant just below the 5 percent level.) This unexpected finding is most probably due to the fact that this was a cross-sectional study as Sorsby et al. (1961) also noted that the average values of corneal radii in the vertical meridian showed little variation between the ages of 3 and 13 years in their cross-sectional study. However, in their follow-up longitudinal study, the cornea was shown to flatten with increase in axial length.

Table 6.4 Collated data on the anterior corneal radius in the newborn.

Investigator	Number of subjects	Mean value of corneal radius±s.d.(mm)
Gerson (1810) cited from Merkel and Orr (1891)	NI	6.35
Donders (1864) cited from Scammon and Wilmer (1950)	4 observations	6.67
von Hasner (1873) cited from von Reuss (1881)	1	6.06
Dickinson (1876) cited from Borish (1970:72)	NI (premature)	6.81
Merkel and Orr (1891)	NI	7.3
Axenfeld (1897) cited from von Pflugk (1909)	NI	7.0 - 7.29
de Vries (1901) cited from Sorsby et al. (1961)	NI	6.6 - 7.2
Tscherning (1904:33)	NI	7.2
von Pflugk (1909)	5 (7 observations)	7.0
Ellerbrock (1963)	NI	6.6
Gernet (1964)	2	6.4 individual 7.2 values
Rivara and Gemme (1965)	1 (1 mth premature) 1 full-term	5.73 6.43
Mandell (1967)	5 (aged 4-15 days after birth)	6.87±0.20
Grignolo and Rivara (1968b)	11 (3 mths premature) 20 (2 mths premature) 17 (1 mth premature) 18 full-term	5.44 5.70 6.34 6.21
Molnar (1970)	16 premature 8 full-term	6.25±0.17 6.86±0.25
Ehlers et al. (1976)	6 premature 19 full-term	6.35±0.09 s.e.m. 7.11±0.07 s.e.m.
Lotmar (1976) on re-measurement of von Pflugk's (1909) photographs	5 (7 observations)	7.26±0.2
Blomdahl (1979)	15 full-term	7.0 (range 6.4-7.4)
Yamamoto et al. (1981a)	64 premature 20 full-term	6.65±0.24 7.02±0.12

cont. Table 6.4

Investigator	Number of subjects	Mean value of corneal radius±s.d.(mm)
Yankov (1982)	100 (males) full- 100 (females) term	6.70±0.09 6.60±0.09
Donzis et al. (1985)	6 premature (gestational age at birth from 28-34 wks)	6.09 (range 5.49-6.52)
Gordon and Donzis (1985)	11 observations (30-35 wks) gestational ages at birth	6.30±0.30
	14 observations (35-39 wks)	6.42±0.24
	10 observations (39-41 wks)	6.59±0.15
Inagaki et al.(1985)	22 observations (gestational age at birth from 37-43 wks)	7.05±0.23 (range 6.63-7.47)
Inagaki (1986)	7 premature (mean gestational age at birth 36-42 wks)	6.82±0.24 (range 6.41-7.15)
	11 full-term	7.18±0.19 (range 6.88-7.39)
Insler et al. (1987)	19 (gestational age at birth from 34-41.5 wks)	7.15

NI Number of subjects not indicated.

s.e.m. Standard error of the sample mean.

Table 6.5 Collated data on the variation of anterior corneal radius with age.

Age	von Reuss (1881) No. of subjects (m+f)	von Reuss (1881) Mean value (mm)	Scammon and Armstrong No. of subjects (m+f)	Scammon and Armstrong Mean value* (mm)	Sorsby et al. (1961) No. of subjects	Sorsby et al. (1961) Mean value** ± s.d. (mm)	Grignolo & Rivara (1968b) No. of subjects (m+f)	Grignolo & Rivara (1968b) Mean value (mm)	Gernet & Hollwich (1968) No. of eyes (m+f)	Gernet & Hollwich (1968) Mean value (mm)	York & Mandell (1969) No. of subjects (m+f)	York & Mandell (1969) Mean† value (mm)	Woodruff (1969, 1971) No. of subjects (m+f)	Woodruff (1969, 1971) Mean† value (mm)
Newborn							18	6.21						
Months			4	6.67			58 (½ - 2½ mos)	6.44			10	6.96		
1- 3	1	6.59												
3- 6	2	7.02					63 (2½ - 9 mos)	6.59						
6-12	5	7.42	4	7.43							3	7.60		
Years							37 (10-18 mos)	6.92						
1- 2	3	7.58	3	7.58					15	7.61	5	7.49		
2- 3	1	7.21	6	7.40			35 (19-36 mos)	7.83			3	7.53	113	7.70
3- 4	3	7.47			53(m) 36(f)	7.92±0.30 7.71±0.27					5	7.45	152	7.64
4- 5	2	7.61			52(m) 50(f)	7.89±0.28 7.76±0.22	24	7.98			3	7.40	177	7.73
5- 6	7	7.33	9	7.41	54(m) 55(f)	7.79±0.34 7.72±0.22					6	7.42	131	7.74
6- 7	8	7.43	17	7.45	51(m) 51(f)	7.79±0.28 7.72±0.30	26	7.95	6	7.72			58	7.75
7- 8	9	7.48			60(m) 55(f)	7.83±0.26 7.71±0.23								
8- 9	9	7.49	18	7.48	56(m) 58(f)	7.94±0.28 7.71±0.25	39	7.85						
9-10	15	7.40			47(m) 52(f)	7.89±0.26 7.79±0.26								
10-14	49	7.50	25	7.50	255(m) 326(f)	7.90 7.74								
14-20	15	7.73	33	7.70	92(m) (19-20 yrs)	7.83								
20-40			319	7.89										

Age	Molnar (1970) No. of subjects (m+f)	Molnar (1970) Mean value ± s.d. (mm)	Ehlers et al. (1976) No. of subjects (m+f)	Ehlers et al. (1976) Mean ‡ value ± s.e.m. (mm)	Yamamoto et al. (1981a) No. of eyes (m+f)	Yamamoto et al. (1981a) Mean value ± s.d. (mm)	Gordon & Donzis (1985) No. of eyes (m+f)	Gordon & Donzis (1985) Mean value ± s.d. (mm)	Fledelius & Stubgaard (1986) No. of subjects	Fledelius & Stubgaard (1986) Mean value ± s.d. (mm)	Inagaki (1986) No. of ° subjects (m+f)	Inagaki (1986) Mean value ± s.d. (mm)
Newborn	8	6.86±0.25	19	7.11±0.07	20	7.02±0.12	10	6.59±0.15			(2wks)	6.89±0.32
Months	(8-30 days)	7.23±0.38									8 (4wks)	7.34±0.36
1- 3	(1-6 mos)	7.23±0.03									(8wks)	7.57±0.35
3- 6							11	7.43±0.22			(12wks)	7.66±0.31
6-12	51 (6-12 mos)	7.41±0.24										
Years												
1- 2	39	7.55±0.03 7.74±0.24			29	7.80	8 8	7.48±0.16 7.62±0.05				
2- 3			10	7.73±0.09	44	7.73	8	7.69±0.09				
3- 4					54	7.72	5	7.78±0.13				
4- 5					38	7.75	9	7.69±0.16				
5- 6			15	7.81±0.09	48	7.76	5	7.74±0.11	20(m) 19(f)	7.90±0.22 7.69±0.19		
6- 7					27	7.75	10	7.60±0.29				
7- 8					30	7.70						
8- 9					23	7.76			30(m) 34(f)	8.00±0.19 7.73±0.22		
9-10												
10-14			11	8.01±0.95	16	7.86	7	7.72±0.13	28(m) 31(f)	7.98±0.23 7.79±0.31		
14-20							6	7.72±0.20	43(m) 46(f)	7.99 7.81		
20-40							36	7.72±0.22	52(m) 48(f) (20-30 yrs)	7.91 7.73		

* Collated values based on older studies by other researchers.

° Longitudinal study involving 8 subjects (16 eyes).

** Values for vertical meridian.

† Values for flattest meridian.

‡ Values for horizontal meridian.

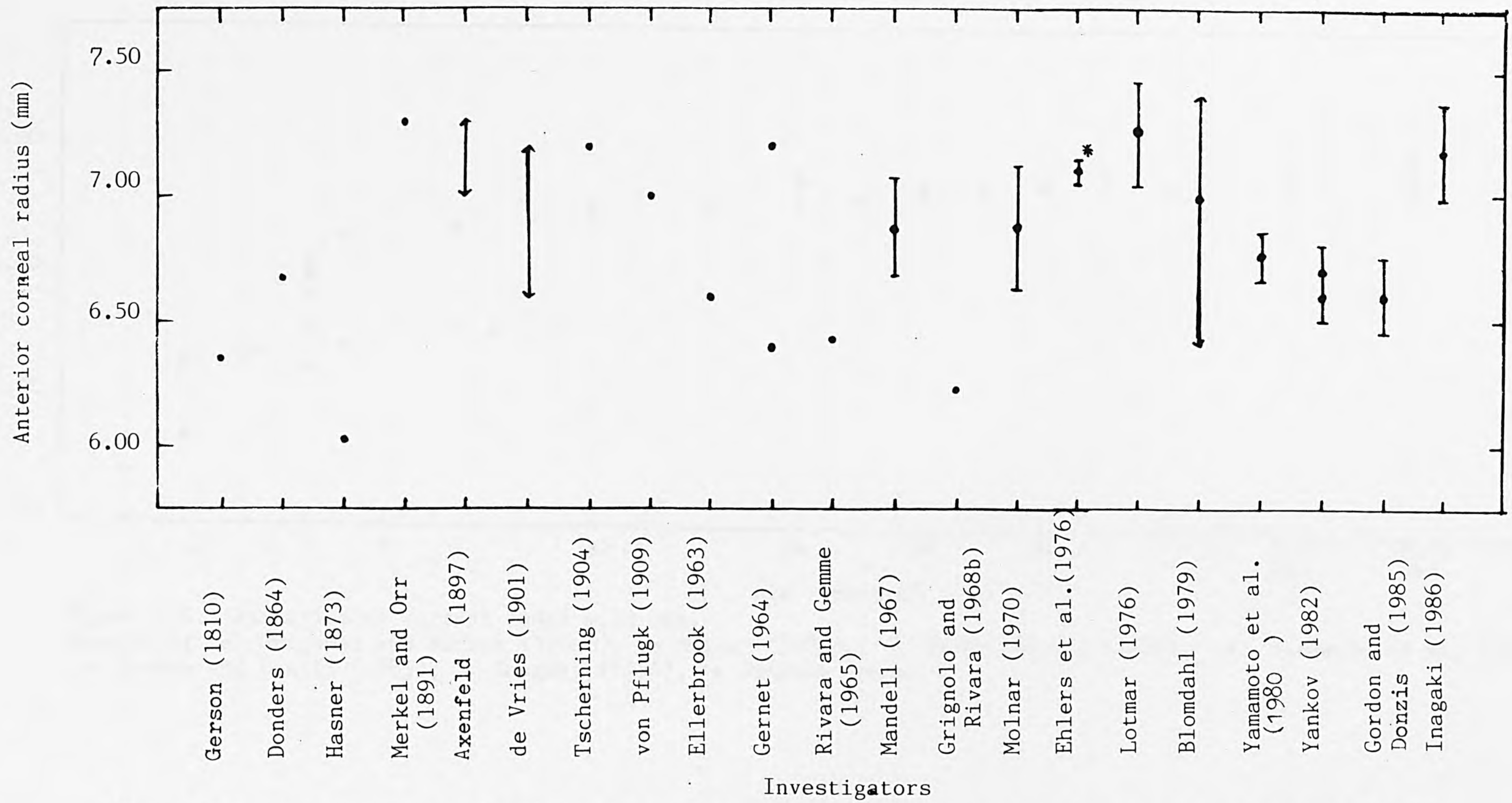


Figure 6.3. Anterior corneal radius in the full-term newborn. Symbols: • -mean or individual values, ⌶ -mean value ± s.d., ↕ -range of values, *-mean value ± s.e.m., (m)-male subjects, (f)-female subjects.

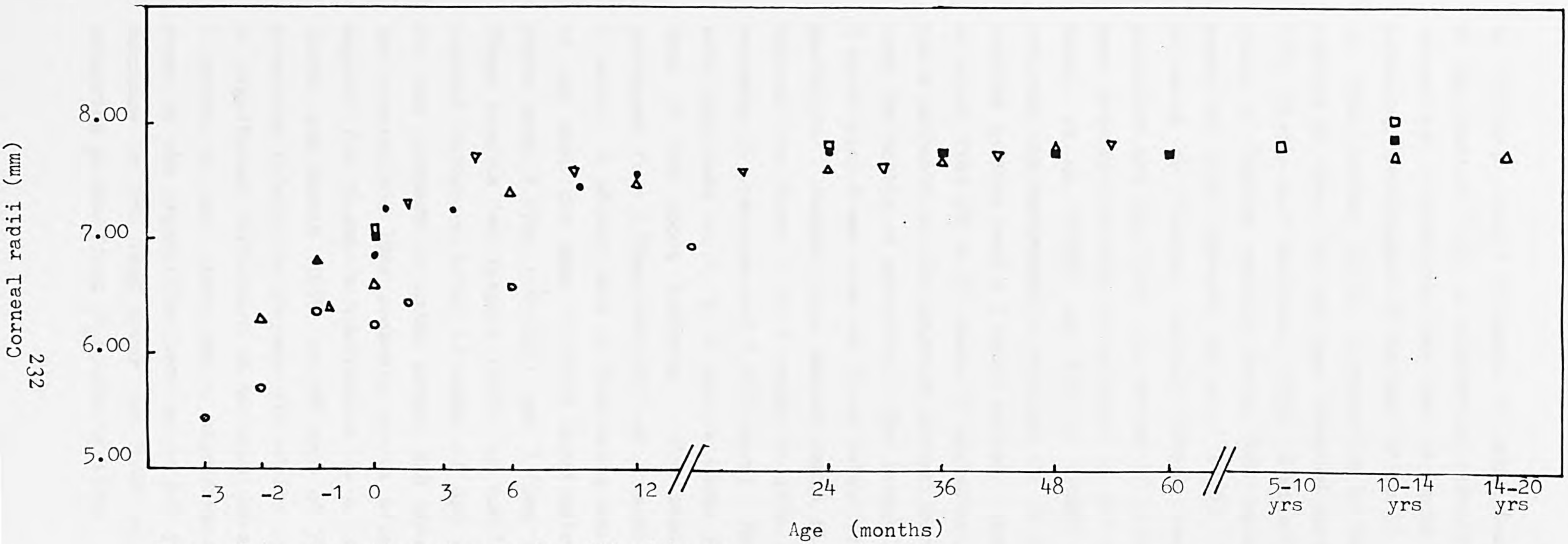


Figure 6.4. Variation of corneal radii with age.
Results of o Grignolo and Rivara (1968b), ● Molnar (1970), □ Ehlers et al. (1976), ■ Yamamoto et al. (1981a), △ Gordon and Donzis (1985), ▲ Inagaki (1986), ▽ Present study.

As the axial length increases by about 4mm from birth to 3 years of age (section 6.1), a substantial reduction in the powers of the cornea and crystalline lens has to occur to compensate for the potential development of between 12 to 15 D of myopia (Sorsby et al. 1961; Sorsby, 1973). A reduction in the corneal power of baby rabbits by about 20D has been observed during their first year of life (Sorsby and Sheridan, 1953) Similarly, kitten corneas were found to flatten rapidly (about 40D) between the first 3 to 14 weeks of life (Freeman et al., 1978). The human cornea is believed to flatten rapidly during the last few months of gestation and the first few months of life. This occurrence has been demonstrated most effectively in the longitudinal studies of Donzis et al. (1985) and Inagaki (1986). Donzis et al. (1985) recorded the keratometric readings on 12 eyes of 6 premature but healthy infants over a 3 month period. These babies ranged in age at birth from 28 to 34 weeks of gestation. In all these eyes, a rapid decrease in the anterior corneal curvature was noted in the last few months of gestation. The larger reduction (8D) over the 3 month period was observed in an infant first seen at 28 weeks of gestation. Inagaki also showed rapid flattening of the cornea between the first 2 to 4 weeks of life in a study involving 8 neonates (5 premature and 3 full-term). Keratometric measurements were performed at 2, 4, 8 and 12 weeks following birth on both eyes of the above subjects. The mean corneal radius value increased from 6.89mm (+49.01D) at 2 weeks to 7.34mm (+45.98D) at 4 weeks. A slower rate of flattening was observed after 8 weeks of age when the mean recorded keratometric values at 8 and 12 weeks were 7.57mm (+44.60D) and 7.66mm (+44.05D) respectively. These results led Inagaki (1986) to conclude that the change in corneal curvature after 12 weeks of age would hardly compensate for the increase in axial length and therefore, compensation by the crystalline lens probably occurs after this age. There is support for Inagaki's conclusions as a cross-sectional study by Gordon and Donzis (1985) on 148 eyes of 79 subjects ranging from premature infants to 36-year old adults, showed whilst there was no significant difference in the mean keratometric readings after 6 months of age, there was a significant decrease in the mean power of the crystalline lens up to 6-7 years of age. The mean decrease in the lens power was 8.0D with the greatest change occurring in the first 18 months of life.

The results of the present study did not show any clear trend as to whether the average male and female corneal radii were higher for one sex than the other. This applied to all the age groups examined. The mean flattest radii recorded over all the eyes from 79 males and 72 females were 7.66±0.49mm(s.d.) and 7.61±0.51mm(s.d.) respectively. The mean steepest corneal radii values recorded from the same subjects were 7.40±0.4mm(s.d.) for males and 7.40±0.52mm(s.d.) for females. Statistical analysis of the results showed no significant differences between the two sexes for the flattest and steepest corneal radii values. Although the differences in corneal radii between the two sexes were not significant in this study, others believe that the male cornea tends to have the flatter corneal curvature (Donders, 1864b; Lyle, 1965; Woodruff 1969, 1971).

Corneal radii values have been found to vary between difference races (Amano and Tanaka, 1968; Nakajima, 1971). Also children born prematurely tend to have steeper corneal radii compared with those born at full-term (Fledelius, 1981). These 2 possible influences on corneal curvature are not relevant for the results of the present study on normal eyes as all the subjects were Caucasian in origin and full-term at birth. Possible influences of diurnal variation on the corneal curvatures recorded in this study cannot be ruled out as subjects were photographed at different times of day (Rengstorff, 1968; Reynolds and Poynter, 1970; Rengstorff, 1972; Kiely et al., 1982a).

The results of the present study and those studies mentioned above suggest that corneal radii values reach adult levels by 1 year of age with the most rapid changes occurring before the age of 6 months. However, the need for more longitudinal studies involving larger numbers of subjects below the age of 3 years is clearly indicated to give a more definitive picture of corneal changes which take place before that age. Also the data on corneal curvature would be more useful and easier for comparison between different studies if the keratometric readings were recorded as they were observed along the principal meridians instead of being reported as the mean readings between the flattest and steepest meridians as the majority of investigators mentioned in this section tended to do.

The photokeratoscope as used in this study was centred with respect to the subjects' pupil. This axis is typically displaced from the visual axis (Bennett and Rabbetts, 1984: 229-231). Also, the corneal apex is often displaced from the visual axis (Ludlam and Wittenberg, 1966b; Mandell and St. Helen, 1969). These factors were not taken into account in this study.

The degree of radius change along the horizontal meridian (canthus line) was investigated in 123 eyes from 3 areas covering approximately 1.7mm, 3.5mm and 5.2mm diameters on the cornea. The majority of corneas measured showed between 0.10 to 0.30mm flattening in radii between these first and third areas. The author is aware of the inaccuracies involved by analysing the corneal radii in this way as an assumption was made that the areas reflected by each ring had symmetrical radii of curvature.

6.3.2 Congenital cataract eyes.

Most of the data on anterior corneal curvature in congenital cataract cases has also mainly been collected whilst fitting aphakic infants or children with contact lenses. More recently, the introduction of epikeratophakia to correct aphakia in pediatric patients has generated more information on the central corneal curvature due to the need to measure the anterior corneal radii before and after this refractive surgery procedure. The results of the various researchers who have attempted measurements of congenital cataract cases are presented in Table 6.6.

Nakajima (1969) reported an average anterior corneal radius of 7.2±0.5mm(s.d.) in a sample of 23 eyes belonging to Japanese congenital cataract subjects. No indication was given as to whether the cataracts had been removed from these eyes or to the age of the subjects. As the data was presented in the same table as another sample of normal eyes of males aged 10-14 years who had a mean corneal radius of 7.7±0.1mm(s.d.), it may be reasonable to deduce that the population with congenital cataracts were probably of this same age group or even older.

Shapiro (1970) recorded the flattest and steepest corneal radii in 3 congenital cataract cases (2 bilateral and 1 uniocular).

Table 6.6 Collated data on anterior corneal radii in congenital cataract cases.

Age	Shapiro (1970) No. of eyes ‡	Shapiro (1970) Individ. values (mm)	Enoch (1972) No. of eyes o•†‡	Enoch (1972) Mean value (mm)	Ellis (1977) No. of eyes o	Ellis (1977) Mean value (mm)	Enoch & Rabinowicz (1974); Enoch et al. (1979) No. of eyes	Enoch & Rabinowicz (1974); Enoch et al. (1979) Mean value (mm)	Levinson (1980) No. of eyes o•□‡	Levinson (1980) Mean value (mm)	Arffa et al. (1985) No. of eyes o†‡T	Arffa et al. (1985) Mean value ± s.d. (mm)	Pratt-Johnson & Tillson (1985) No. of eyes o•†‡	Pratt-Johnson & Tillson (1985) Individ. values (mm)	Morgan et al. (1986) No. of eyes †‡	Morgan et al. (1986) Mean value ± s.d. (mm)	Kelley et al. (1986) No. of eyes o‡	Kelley et al. (1986) Individ. values (mm) along flattest meridian.	Morgan et al. (1987) No. of eyes o•‡	Morgan et al. (1987) Mean value ± s.d. (mm)	Moore et al. (1987) No. of eyes o‡	Moore et al. (1987) Mean value ± s.d. (mm)	Pollard (1987) No. of eyes	Pollard (1987) Individ. values (mm)
Months																								
0- 3							1°† (4days)	7.5(c) 7.5(n)													10 (3.70mos)	7.40±0.39 (range 6.82-7.85)	1°‡	7.50/7.34(c)
3- 6					1† (3mos)	7.20(c) 7.20(n)			10 ages NI	radii between 7.30-7.86	19	7.11±0.48	2°† (5mos)	2 infants 7.58, 7.94 (c) (c)	21°•✱ (5.1±28 mos s.d.)	7.12±0.48								
6- 9					1‡ (7mos) same infant	7.55(c) 7.70(n)	1°† (6.5mos)	7.8(c) 7.68(n)	1	6.36			2°‡ (6mos)	7.34R&L					47✱ (7.6±0.51 mos s.e.m.)	7.17±0.08				
9-12					1‡ (10mos)	7.70(c) 7.80(n)	same infant						1°† (7mos)	8.04(c)			1 (9mos)	7.55						
Years																								
1- 2	1° 1• same infant 1°	7.68/7.34(c) 8.11/7.71(c) 7.74/7.34(c) 8.25/7.67(c)	16 (3mos -13yrs)	most radii between 7.4-7.6			1°‡ (1yr)	8.10(c) 7.92(n)			19	7.22±0.52			17°✱ (16.8±2.6 mos s.d.)	7.13±0.49	1 (1yr)	7.91	44✱ (18.2±0.58 mos s.e.m.)	7.41±0.10				
2- 3					1‡ (2½yrs)	7.65(c) 7.60(n)					12	7.44±0.65			14°✱ (35.2±10.0 mos s.d.)	7.22±0.40	2 (2.5yrs)	8.04, 7.54						
3- 4											28	7.78±0.40							98✱ (4.2±0.19 yrs s.e.m.)	7.54±0.06				
4- 5											(upper age limit NI)				18°•✱✱ (53.1±17.0 mos s.d.)	7.8±0.31								
5-10																	1(5yrs) 1(6yrs)	7.58 8.23						
10-15																	1(14yrs)	8.88						

o Monocular congenital cataract cases.
• Binocular congenital cataract cases.
✱ Dense congenital cataract cases.
✱✱ Incomplete congenital cataract cases.
(c) Eye with cataract or which had cataract before removal.
(n) Normal eye of same subject with (c).
□ Did not specify whether cataracts were congenital or traumatic in origin.
T Traumatic cataract cases included.
† Measurements taken before cataract removal.
‡ Measurements taken after cataract removal.

Enoch (1972) measured the anterior corneal curvature in 16 eyes belonging to subjects (aged from birth to 14 years) born with congenital cataracts. These were a mixture of uniocular and binocular cataract cases. Some of the measurements were done post-cataract removal in the office whilst the remainder were carried out in the operating room under general anaesthesia, presumably before the cataract was removed. The majority of the corneal radii fell between 7.4 to 7.6mm (with a range in values from 6.9-8.3mm). As was mentioned earlier (section 6.2.2), the 3 eyes which had microcorneas (less than 10mm in diameter) tended to have steeper curvatures, but only 1 of these was found to have a relatively extreme value of corneal curvature.

Enoch and Rabinowicz (1976) found the corneal radii (along the flattest meridian) in a 4-day-old neonate with a uniocular congenital cataract to be equal in both the cataractous and the normal eye. The corneal radii were approximately 7.5mm in both eyes and the measurements were taken prior to surgery. The eye of the infant with the cataract was normal otherwise in all other respects.

Ellis (1977) presented 3 case histories of contact lens fitting on uniocular aphakic children, 2 of whom were congenital cataract cases. The first was interesting in that a follow-up of about 7 months on the corneal curvature changes on both the cataractous and normal eye was made. The second case was a uniocular aphakic (born with a congenital cataract) examined at 2 3/4 years old.

Enoch et al. (1979) measured the central corneal radii in both eyes of a uniocular congenital cataract subject aged 6 1/2 months just prior to cataract surgery. The radii were also noted later when the child was 1 year old.

Levinson (1980) published corneal radii readings of 11 eyes in 7 infants (no ages given) following cataract removal. The subjects appeared to be a mixture of monocular and binocular cataract cases but no indication was made as to whether these were congenital cataract cases. In 10 of the 11 eyes observed, the radii lay between 7.30 and 7.8mm. The remaining eye showed a steeper value of 6.36mm.

Jacobson et al. (1981) performed keratomety on 4 infants with congenital cataracts (2 bilateral and 2 unilateral cases) but no figures were given in their paper.
Arffa et al. (1985) recorded the keratometric readings on monocular congenital and traumatic cataract cases prior to and post-epikeratophakia surgery. Some of these were already aphakic at the time of the refractive surgery whilst those who were phakic underwent a combined lensectomy/capsulectomy and epikeratophakia procedure. Unfortunately, no distinction was made in the keratometric data presented between the traumatic and congenital cataract cases. The upper age limit of the sample was also not given.

Pratt-Johnson and Tillson (1985) presented 3 unilateral and 1 bilateral congenital cataract cases who were fitted with hard contact lenses following removal of their cataracts.

Morgan et al. (1986) published the keratometric readings of congenital cataract cases prior to epikeratophakia surgery. The subjects were all below 8 years of age and all the eyes included in the data were aphakic at the time of measurement. The patients had been sub-divided into those with uniocular dense congenital cataracts, incomplete congenital cataracts (form vision experienced prior to development of the cataract), and bilateral congenital cataracts. The brand of the keratometer used in this study was not indicated and as the keratometric measurements were published as power readings, a refractive index of 1.336 was used to convert them into radii values for comparison. The value of 1.336 was selected as this research was an extension of the earlier study by Arffa et al. (1985) who stated that they used an American Optical Ophthalmometer for their measurements. (Table 6.6 does not include the mean keretometric value of 7.71±0.49mm (s.d.) recorded on 6 bilateral congenital cataract eyes in subjects with a mean age of 31.0±21.9 months (s.d.)

Kelley et al. (1986) reported on the corneal radii measurements on 7 unilateral aphakic patients who had had congenital cataracts removed. The radii were recorded pre-epikeratophakia surgery. Again, the measurements were given as corneal power readings with no brand name of the keratometer given. A refractive index of 1.336 was used to correct the measurements to radii values.

Morgan et al. (1987) published the results of a nationwide study of epikeratophakia for aphakia in pediatric patients aged 8 years old and younger. Pre-epikeratophakia keratometric readings were noted. Here similar to the earlier study by Morgan et al. (1986), the patients were similarly divided into those with dense congenital cataracts and those with incomplete congenital cataracts. No differentiation was made between uniocular and binocular cataract cases in the presentation of the results. A refractive index of 1.336 was also assumed here by the author to convert the published corneal power readings into radii values as the brand of keratometer used was not given. It is also doubtful whether the same keratometer brand was used in all cases as this study was nationwide and involved 97 ophthalmic surgeons. (In order to prevent confusion, Table 6.6 does not include the mean keratometric value of 7.48±0.07mm.s.d. found in 59 eyes with incomplete congenital cataracts after cataract surgery. Their mean age was 3.6±0.31 years s.e.m.)

Moore (1987) presented a study on mensuration data on infants with uniocular congenital cataracts. The corneal curvature was measured using a Bausch and Lomb keratometer at the time of contact lens fitting on the aphakic eye of 10 infants. An average of 2 to 3 measurements were taken of the flattest meridian in each eye and these were usually made by 2 observers who obtained similar results. The mean corneal radius recorded in the flattest meridian was 7.40±0.39mm(s.d.) with the minimum value being 6.82mm and the maximum value being 7.85mm. Measurements of the phakic eye were not included in the study.

Pollard (1987) also reported that keratometry was performed on 3 congenital cataract subjects (2 uniocular, 1 binocular). However, actual corneal powers were only reported in both principal meridians for 1 of these cases.

The results of the present study show that the majority of corneal radii (flattest and steepest) observed in the binocular congenital cataract cases lie within the range of values observed amongst normal eyes (Figures 5.7 and 5.8). This finding is similar to the studies listed earlier in this section. The mean value for the flattest corneal radii in the present study for all the subjects was 7.55±0.48mm(s.d.). This result is very similar to that of Enoch's (1972) study who observed that the majority of corneal radii fell between 7.4 and 7.6mm with a range from 6.9 to 8.3mm. The range of values for the flattest corneal radii in the present study was from 6.50 to 8.6mm.

As was mentioned earlier in section 6.2.2, 1 eye in this study had a corneal diameter which fell below 10.00mm. This eye also showed the minimum values for the flattest and steepest corneal radii in the whole sample of 33 eyes. Its radius in the flattest and steepest meridia were 6.50mm and 6.20mm, respectively. Enoch (1972) who had noted 3 corneas with a diameter below 10.00mm in his sample found that although these cases tended to have steeper corneal curvatures, only 1 of these had a relatively extreme radius value (corneal radius = 6.9mm). A survey of all the eyes in the present sample showed that the size of the corneal diameter was not a reliable indicator of corneal radii. This finding is similar to those of Moore's (1987) study which also showed that some eyes with microcorneas had the flattest corneal curvatures recorded in the group.

An attempt was also made in the present study to measure the amount of flattening of radii along the horizontal meridian in 19 eyes. Subject to the same inaccuracies as outlined in section 6.3.1, the degree of flattening observed in these aphakic eyes were of similar amounts to those seen in normal eyes.

6.4 Variation of corneal astigmatism with age

6.4.1 Normal eyes

A review of the investigations relating to the measurement of corneal astigmatism in under 6-year-olds revealed that only very few such studies have been carried out in the past (York and Mandell, 1969; Woodruff, 1969, 1971; Blomdahl, 1979; Howland, 1982a, b; Howland and Sayles, 1985). These previous reports have already been described in section 2.7.

The present findings in this study of a high incidence of corneal astigmatism >1D in under 3-year-olds (Table 5.6) confirm the results of Howland and Sayles (1985) who also had found the same phenomenon. Both the present study and that of Howland and Sayles also show that this high incidence drops with age. This decrease in the frequency of corneal astigmatism ⩾1D with age was shown to be highly significant in this study. Table 6.7 allows a comparison to be made between the present results and those recorded by Howland and Sayles (1985).

Table 6.7 Incidence of corneal astigmatism ⩾1D: Howland and Sayles (1985) and present study.

Age Group	Howland and Sayles (1985) Total no. measured: No. of eyes	No. of subjects	%⩾ID corneal astigmatism	Present Study Total no. measured: No. of eyes	No. of subjects	% ⩾ID corneal astigmatism
0-1	44	28	48	74	74	80
1-3	99	53	21	40	40	58
3-5	18	9	0	37	37	43

Table 6.7 shows that the estimates of the frequency of corneal astigmatism ⩾ID tend to be higher compared with those found by Howland and Sayles. It must be pointed out that only 1 eye from each subject investigated in the present study was used but

Howland and Sayles often used data from both eyes of the same subject in their analysis.
The incidence of corneal astigmatism in the age group under 1-year-old in the present study of 80% is also higher compared with Blomdahl's (1979) estimate of 66% in 15 neonates. However, when the results for the under 1-year-olds in the present study were broken up into small age groups, the results which emerged were interesting.

Table 6.8 Incidence of corneal astigmatism ≥1D in under 1-year-olds: present study.

Age Group (mos.)	Total no. of eyes	Percentage of total no. of eyes ≥1D corneal astigmatism
1-<3	12	67
3-<6	28	82
6-<12	34	82

Table 6.8 shows that the incidence of corneal astigmatism >1D for those under 3 months is similar to that found by Blomdahl. Also this incidence appears to peak at 3 to 12 months of age. Although the numbers of eyes investigated for the above age groups are not large enough to make generalized statements, this "peak" seen at 3 - <12 months in the present study may explain why Mohindra et al. (1978) noted that the incidence of refractive astigmatism in under 1-year-olds was maximum between the ages of 11 to 20 weeks.

The results of York and Mandell (1969) on corneal toricity found in under 6-year-olds do not show any particular trend with age and the number of subjects they investigated were too small to allow comparison with results in this study (see Table 2.7).

The findings in the present study and Howland and Sayles (1985) both contradict those reported by Woodruff (1969, 1971) who showed an increase in the incidence of corneal astigmatism ≥0.87D from 2 to 6 years of age. Woodruff's results are shown in Table 2.9.

When the present results for age 3-<5 years was compared with those in school-aged children, they were found to be similar to Lyle's (1965) study. Lyle reported an incidence of 53% with $\geqslant$0.87D and 23% with $\geqslant$1.25D of corneal astigmatism in 10 eyes of subjects aged under 10 years. The corresponding values in the present study were 54% with $\geqslant$0.87D and 32% with $\geqslant$1.25D. However, it must be noted that Lyle's subjects were not from a random sample as they were from records obtained from optometry clinics. The estimates of the present study for 3 to <5-year-olds and Lyle's (1965) study are higher than those of other reports given on school-aged children (Castrèn, 1955; Anstice, 1971; Lyle, 1972; Fledelius, 1976). These studies have also been described in section 2.7. The lower estimates reported by the above authors may be rather conservative as a recent study by Guillon et al. (1986) on 220 adult eyes (110 subjects) showed that the incidence of corneal astigmatism $\geqslant$1D was in the region of 30 to 35%.

The mean amounts of corneal astigmatism recorded for the different age groups in this investigation were found to decrease with age. Howland and Sayles (1985) also noted a similar finding. The results from both studies are incorporated into Table 6.9 for comparison.

Table 6.9 Mean values of corneal astigmatism: Howland and Sayles (1985) and present study.

Age Group (yrs)	Mean corneal astigmatism values ±s.e.m. (D) Howland and Sayles (1985)	Present Study
0-1	0.93 ± 0.10	1.75 ± 0.11
1-2	0.55 ± 0.05	1.05 ± 0.17
2-3	0.70 ± 0.11	1.43 ± 0.22
3-5	0.30 ± 0.05	1.07 ± 0.18

The values recorded by Howland and Sayles are lower than those for the present study for all age groups. This may be due to the fact that the former was only recording the corneal astigmatism in the same direction as the refractive astigmatism measured by photorefraction. Howland and Sayles were primarily interested in correlating the amounts of corneal astigmatism with the amounts of total astigmatism recorded by photorefraction for each subject. Blomdahl's (1979) data from 15 neonate eyes showed a mean corneal astigmatism value of 1.07D. The estimate for under 1-year-olds in the present sample was 1.75D. Blomdahl used a lid speculum to retract the lids of his infants and this may have had an influence on the amounts of corneal astigmatism he recorded (Wilson et al., 1982; Inagaki et al., 1985).

Lyle (1965) recorded a mean corneal astigmatism of about 1.00 ± 0.80D(s.d.) in under 10-year-olds. Guillon et al. (1986) reported that the mean keratometric power difference between the flattest and steepest meridian found in their adult sample was 0.96 ± 0.81D(s.d.). The present corresponding results for the 3- to 5-year-old age group was 1.07 ± 0.66D(s.d.) which is very similar to those recorded by Lyle and Guillon et al.

The most common orientations of corneal astigmatism present in under 5-year-olds are still relatively unknown.

Blomdahl (1979) reported incidences of 44% with-the-rule and 56% oblique corneal astigmatism (≥1D) in 15 eyes (15 neonates). No against-the-rule corneal astigmatism was found in all the subjects. The present study recorded that the incidences of corneal astigmatism (≥1D) in the under 1-year-old age group was 31% with-the-rule, 5% against-the-rule and 64% oblique. These findings of a high percentage of oblique corneal astigmatism are surprising as these are not reflected in refractive studies on infants and young children who have mainly reported high incidences of with- or against-the-rule refractive astigmatism (Table 2.1 and Section 2.3). However, this puzzle may be due to the reason suggested by Howland and Sayles (1984) who found that cylinder axes tended to be judged as being closer to the vertical or horizontal "by eye" than they really were if no angular scale was used. These errors would result in reporting of higher numbers of with-the-rule and against-the-rule cases.

The classification of whether a refractive or corneal astigmatism is taken to be with- or against-the-rule is mainly taken as to whether the flattest meridian within ±15 degrees of the horizontal or vertical by most of the investigators listed in Table 2.1 and Section 2.3. This is a fairly narrow division and Borish (1970:125) broadens this classification to within ±30 degrees. This results in findings of a decrease in the incidence of oblique astigmatism (Table 5.10) for the present results.

However, using either classification, the incidence of against-the-rule corneal astigmatism which was highest for the under 1-year-olds in this study showed a reduction with age. An increase in with-the-rule astigmatism was seen with age when the broader classification was used (Table 5.9 and 5.10). This decrease in against-the-rule and increase in with-the-rule corneal astigmatism may explain the same phenomenon seen in refractive astigmatism (Gwiazda et al., 1984b).

Guillon et al. (1986) reported the following incidences of corneal astigmatism in their adult sample taking all values into account: 85.5% with-the-rule, 10.5% against-the-rule, and 4.0% oblique. These results are similar to those recorded in the present study on 3 to <5-year-olds which showed that in eyes with ≥1D corneal astigmatism, 81% were with-the-rule, 0% against-the-rule and 19% oblique.

The overall results of the present study on corneal astigmatism support the view held by Howland (1982a, b) and Howland and Sayles (1985) that the major component of total astigmatism observed in infants under 3 years of age is corneal in nature as the time course of corneal astigmatism as found in this study and that of total astigmatism recorded by many investigators (Chapter 2) are similar over the first 5 years of life.

6.4.2 Congenital cataract eyes

Both Enoch (1972) and Moore (1987) recorded that the refractive and corneal astigmatism values measured on congenital cataract eyes were low. Enoch found that only 3 out of the 16 eyes he measured had corneal astigmatism values greater than 1D. Moore reported that none of the 14 monocular congenital cataract infants (28 eyes) in his study had over 1.25 D of refractive or corneal astigmatism. He also noted that since there was little difference

between fellow (normal) eyes in the incidence or amount of astigmatism postoperatively, surgery would not appear to induce corneal astigmatism.
The results of the present study dispute the findings of Enoch and Moore as the majority of the eyes measured had corneal astigmatism values of between 1 to 3D. These findings are more similar to those recorded by Shapiro (1970) on a small number of eyes whose measurements of the flattest and corneal radii values gives corneal astigmatism values in the order of 2D (Table 6.6).

It could be argued that the higher amounts of corneal astigmatism detected in this study could be due to poor centration of the photokeratoscope but only photographs which were in focus and well-centred with respect to the subject's pupil were used for measurement.

CHAPTER 7

SUMMARY

AND

CONCLUSIONS

A photokeratoscope was calibrated and used in the present study for the measurement of the HVID, flattest and steepest corneal radii and amounts of corneal astigmatism in a cross-sectional study of normal and binocular congenital cataract eyes.

In the sample of normal eyes, a significant increase in HVID with age was found. This increase was most dramatic up to the age of 6 months after which there was little apparent change up to the age of 5 years. This result confirmed those of previous studies indicating that growth of the horizontal corneal diameter is completed by the first year of postnatal life in contrast to the rest of the eye which continues to grow throughout childhood. A significant difference in the mean HVID values between the sexes was also demonstrated with the male cornea being larger in diameter compared to the female's. The mean values of the flattest and steepest corneal radii showed an increase with age up to 6 months but this change was not significant. No significant difference between the sexes was shown in relation to corneal radii. The incidence of corneal astigmatism $\geqslant$1D in subjects up to the age of 5 years was seen to drop very significantly with age. The mean amounts of corneal astigmatism detected also decreased with age. The decreases in the incidence of corneal astigmatism $\geqslant$1D and the mean values of corneal astigmatism noted in this study parallel those observed in refractive (total) astigmatism over the first 3 to 5 years of life by a large number of investigators, hence confirming the results of Howland (1982a, b) and Howland and Sayles (1985) that a major cause of total astigmatism observed under 3 years of age is corneal in origin.

Although the number of congenital cataract cases investigated in the present study was small, the following trends in corneal dimensions were observed. The HVID in these aphakic eyes tended to be smaller than those observed in normal eyes of the same age group up to the age of 5 years. This difference was not apparent after that age until 15 years of age. The flattest and steepest corneal radii values mainly fell within the ranges observed in normal eyes. Most of the observed corneal astigmatism values (88% of eyes) fell below 3D with the majority of these lying between 1-3D.

Longitudinal studies of corneal radii and crystalline lens power on large samples under 5 years of age are necessary in order to understand the extent these 2 factors play in compensating for the large increase in axial length which occurs up to 2 years of age. Similar studies on corneal and total astigmatism and their long-term effects on vision are also indicated in view of the potential danger of meridonial amblyopia. More studies on corneal dimensions are still needed on larger samples of congenital cataract eyes to aid in the design of contact lenses which at present is the favoured method of optical correction following cataract removal.

APPENDIX A

TERMINOLOGY RELATING TO CORNEAL TOPOGRAPHY

Terminology relating to corneal topography

Efforts to record and analyse the corneal contour have been attempted by many researchers over the past two centuries. As a result, various theories have been put forward to describe the shape of the average cornea. The range from a spherical optic cap with a flattening periphery to complex mathematical curves (Ronchi and Stefanacci, 1975).

More recently, the trend is towards approximating the corneal profile to conic sections (Noto, 1961; Wesley, 1969; Holden, 1970; Townsley, 1970; Garner, 1970; Mandell and St. Helen, 1971; Bibby, 1976a; Chandler et al., 1979; Wechsler and Miller, 1981; Kiely et al., 1982b, 1984; Edmund and Sjøntoft, 1985; Guillon et al., 1986).

A comprehensive treatment of conic sections has been developed by Bennett (1968-1969, 1988) on an idea originally proposed by Baker (1943). The notation used by Bennett can be used to describe any conic section which is symmetrically placed with its vertex placed at the origin of the co-ordinate system and gives the relationship between the x and y values for any point of the curve by :

$$y^2 = 2r_o x - px^2$$

where r_o = radius of curvature at the apex

p = a parameter indicating the degree of peripheral flattening

This "p-value" is a number and can have different values each identifying one particular conic:

p-value	conic
>1	prolate (steepening) ellipse
=1	circle
+ve<1	oblate (flattening) ellipse
0	parabola
-ve	hyperbola

Figure A1. illustrates the influence of the p-value in determining the conic.

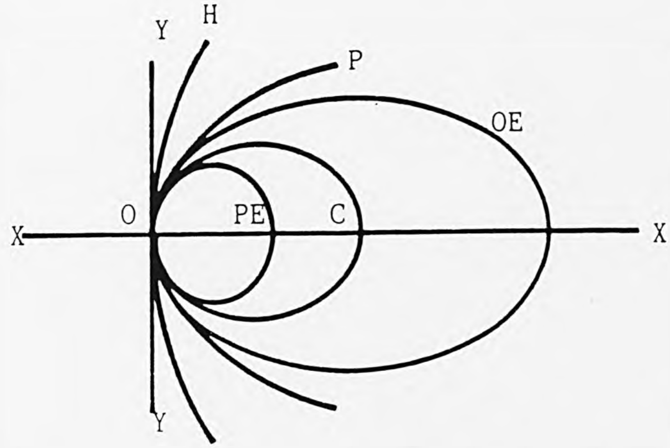


Figure A1. The influence of the p-value in differentiating between various conicoids all with the same vertex radius. (After Bennett, 1968-1969.). Symbols: PE - prolate ellipse ($p>1$), C - circle ($p=1$), OE - oblate ellipse (p+ve<1), P - parabola ($p=o$), H - hyperbola (p-ve).

Another term which is applicable to all conic sections and often used to describe the flattening of the periphery is the eccentricity (e). The p-value is related to eccentricity by the following relationship:

$$p = 1-e^2$$

The reader is referred to the papers by Bennett (1968-1969, 1988) and Burek (1987) if more information about conics is required.

Confusion is present in many of the studies relating to corneal topography due to the loose use of the term "shape factor". This term has been used by various researchers to denote different parameters like e (Townsley, 1970), e^2 (in the Wesley-Jessen System 2000 photokeratoscope and the Humphrey Auto-Keratometer), and the p-value (Chandler et al., 1979; Knoll, 1986; Guillon et al., 1986; Young, 1987; Douthwaite, 1987a). To add to this muddle, Kiely et al. (1982b, 1984) used the term "asphericity" denoted by the letter Q to mean the parameter $-e^2$ in their corneal topography studies.

APPENDIX B

BASIC DATA RELATING TO THE PHOTOKERATOSCOPE: ITS CALIBRATION AND ACCURACY

Table B1. Results of experiment to assess camera magnification.

	1st Film		2nd Film	
	1st Negative	2nd Negative	1st Negative	2nd Negative
Separation of 10.0 mm on scale as measured on negatives (each negative measured twice)	5.01, 5.00	5.00, 5.00	5.00, 5.01	4.99, 5.00

Average separation of 10.0 mm on scale as measured on the negatives = 5.00 mm

Therefore the scale is reduced to $\frac{5.00}{10.0}$ = 0.5 its actual size by the camera.

Thus the camera magnification is 0.5.

Table B2. Measured ring diameters when distance between photokeratoscope and steel ball varied.

	Photokeratoscope too near steel ball			Correct position	Photokeratoscope too far from steel ball		
Error in working distance (mm)	3.0	2.0	1.0	0.0	1.0	2.0	3.0
1st ring diameter (mm)	0.94	0.91	0.90	0.87	0.85	0.82	0.78
	0.92	0.91	0.89	0.87	0.86	0.83	0.77
	0.92	0.90	0.89	0.88	0.85	0.83	0.79
	0.92	0.90	0.91	0.87	0.86	0.82	0.79
	0.93	0.905	0.89	0.865	0.84	0.83	0.78
	0.93	0.91	0.89	0.87	0.86	0.82	0.78
Mean 1st ring diameter (mm)	0.9250	0.9058	0.8950	0.8708	0.8533	0.8250	0.7817
Standard deviation (mm)	0.0084	0.0049	0.0076	0.0049	0.0082	0.0055	0.0075
2nd ring diameter (mm)	1.84	1.80	1.78	1.74	1.72	1.68	1.62
	1.84	1.80	1.78	1.745	1.71	1.69	1.63
	1.83	1.79	1.77	1.75	1.70	1.69	1.64
	1.84	1.795	1.78	1.74	1.71	1.69	1.63
	1.85	1.80	1.77	1.74	1.71	1.68	1.63
	1.83	1.78	1.77	1.74	1.70	1.70	1.64
Mean 2nd ring diameter (mm)	1.8383	1.7942	1.7750	1.7425	1.7083	1.6883	1.6300
Standard deviation (mm)	0.0075	0.0080	0.0055	0.0068	0.0075	0.0075	0.0063
3rd ring diameter (mm)	2.72	2.67	2.64	2.61	2.56	2.53	2.46
	2.71	2.68	2.63	2.61	2.56	2.52	2.47
	2.71	2.68	2.64	2.62	2.57	2.53	2.47
	2.72	2.69	2.64	2.61	2.55	2.52	2.47
	2.71	2.68	2.65	2.62	2.56	2.51	2.46
	2.72	2.68	2.64	2.61	2.56	2.52	2.48
Mean 3rd ring diameter (mm)	2.7150	2.6800	2.6383	2.6133	2.5600	2.5217	2.4683
Standard deviation (mm)	0.0055	0.0063	0.0041	0.0052	0.0063	0.0075	0.0075

Table B3. Measured ring diameters for different steel ball radii.

Notional radius of steel ball (mm)	5.00	5.50	6.00	6.50
Diameter of 1st ring (mm)	0.56, 0.56, 0.56, 0.56, 0.55, 0.55	0.64, 0.63, 0.63, 0.63, 0.64, 0.63.	0.70, 0.70, 0.70, 0.70, 0.70, 0.69.	0.75, 0.75, 0.755, 0.755, 0.75, 0.75.
Mean diameter of 1st ring (mm)	0.5567	0.6333	0.6983	0.7517
Standard deviation (mm)	0.0052	0.0052	0.0041	0.0026
Diameter of 2nd ring (mm)	1.14, 1.14, 1.13. 1.14, 1.14, 1.14.	1.275, 1.27 , 1.28, 1.28, 1.28, 1.27.	1.39, 1.40, 1.395, 1.40, 1.405, 1.40.	1.50, 1.50, 1.51, 1.51, 1.50, 1.51.
Mean diameter of 2nd ring (mm)	1.1383	1.2758	1.3983	1.5050
Standard deviation (mm)	0.0041	0.0049	0.0052	0.0055
Diameter of 3rd ring (mm)	1.74, 1.75, 1.73. 1.75, 1.74, 1.74.	1.90, 1.90, 1.91. 1.92 1.905, 1.905.	2.08, 2.085, 2.08, 2.08, 2.08, 2.08,	2.26, 2.26, 2.26, 2.27, 2.27, 2.26.
Mean diameter of 3rd ring (mm)	1.7417	1.9067	1.0808	2.2633
Standard deviation (mm)	0.0075	0.0075	0.0020	0.0052

Cont. Table B3.

Notional radius of steel ball (mm)	7.00	7.50	8.00	9.00
Diameter of 1st ring (mm)	0.81, 0.81, 0.82, 0.81, 0.82, 0.81.	0.87, 0.87, 0.88, 0.87, 0.865, 0.87.	0.94, 0.94, 0.95 0.93, 0.94, 0.93.	1.00, 1.01, 1.00, 1.00, 0.99, 1.00.
Mean diameter of 1st ring (mm)	0.8133	0.8708	0.9383	1.0000
Standard deviation (mm)	0.0052	0.0049	0.0075	0.0063
Diameter of 2nd ring (mm)	1.61, 1.61, 1.61, 1.62, 1.61, 1.605.	1.74, 1.745, 1.75, 1.74, 1.74, 1.74.	1.86, 1.85, 1.86, 1.86, 1.87, 1.86.	1.97, 1.98, 1.98, 1.99, 1.97, 1.98.
Mean diameter of 2nd ring (mm)	1.6108	1.7425	1.8600	1.9783
Standard deviation (mm)	0.0049	0.0042	0.0063	0.0075
Diameter of 3rd ring (mm)	2.405, 2.42, 2.415 2,425, 2.415,2,415	2.61, 2.61, 2.62, 2.61, 2.61, 2.62.	2.81, 2.80, 2.81, 2.80, 2.79, 2.80	3.00, 3.00, 2.99, 3,00, 3.01, 3.00.
Mean diameter of 3rd ring (mm)	2.4158	2.6133	2.8017	3.0000
Standard deviation (mm)	0.0066	0.0052	0.0075	0.0063

Table B4. Diameters of steel balls measured with micrometer.

Nominal diameter of steel ball (mm)	Measured diameters (mm)	Mean diameter (mm)	Standard deviation (mm)
10.00	10.01	10.003	0.0067
	10.00		
	10.00		
	10.00		
	10.01		
	10.01		
	10.01		
	10.00		
	9.99		
	10.00		
11.00	11.00	11.000	0.0067
	11.00		
	10.99		
	11.00		
	11.01		
	11.00		
	11.00		
	10.99		
	11.00		
	11.01		
12.00	11.99	11.998	0.0092
	12.00		
	12.00		
	12.00		
	12.01		
	11.99		
	12.00		
	12.01		
	11.98		
	12.00		
13.00	13.02	13.003	0.0082
	13.00		
	13.01		
	13.00		
	13.00		
	13.01		
	13.00		
	12.99		
	13.00		
	13.00		
14.00	14.00	14.002	0.0092
	14.00		
	14.02		
	14.00		
	13.99		
	14.00		
	14.01		
	14.00		

cont. Table B4.

Nominal diameter of steel ball (mm)	Measured diameters (mm)	Mean diameter (mm)	Standard deviation (mm)
	14.01		
	13.99		
15.00	15.00	14.997	0.0067
	14.99		
	14.99		
	15.00		
	15.01		
	15.00		
	15.00		
	14.99		
	15.00		
	14.99		
16.00	15.98	15.995	0.0097
	16.00		
	15.99		
	15.99		
	16.00		
	15.98		
	16.00		
	16.01		
	16.00		
	16.00		
17.00	17.00	16.999	0.0074
	17.01		
	17.00		
	17.00		
	16.99		
	17.01		
	17.00		
	16.99		
	17.00		
	16.99		

Fitting of regression lines between ring diameters and steel ball radii

Computer programme used : Hewlett Packard 85 Standard Pac.

X = measured ring diameters on negatives
Y = radii of steel balls

Curve fitting for ring 1

I	X(I)	Y(I)
1	0.5567	5.0000
2	0.6333	5.5000
3	0.6983	6.0000
4	0.7517	6.5000
5	0.8133	7.0000
6	0.8708	7.5000
7	0.9383	8.0000
8	1.0000	8.5000

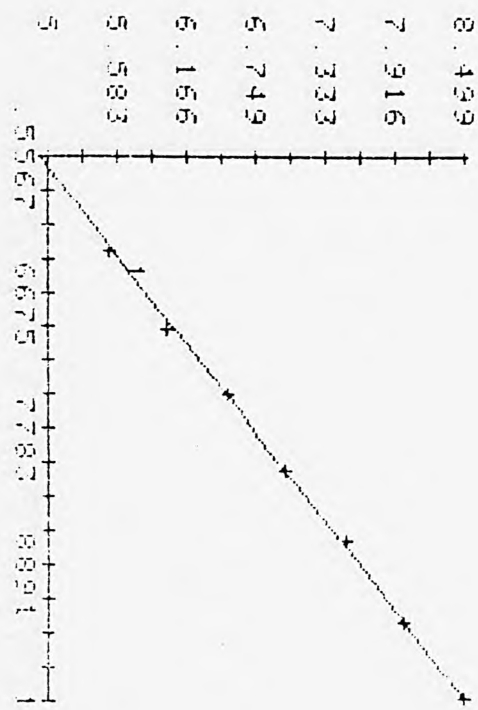
LABEL DELETED AT .6121
LABEL DELETED AT .7229
LABEL DELETED AT .8338
LABEL DELETED AT .9446

AOV: LINEAR REG:CODE 1

SOURCE/DF		SS	MS	F
TOTAL	7	10.5		
REG	1	10.5	10.5	999.9
RESID	6	0.0	0.0	

R SQUARE = 0.999

YHAT = 0.444 + 8.055 X

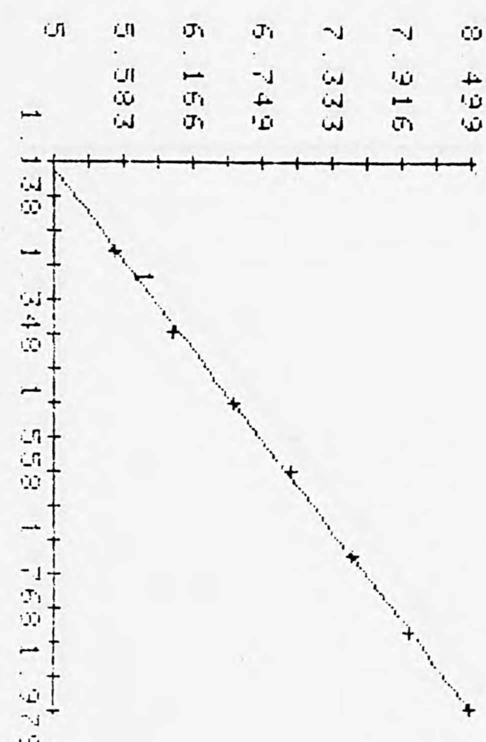


Curve fitting for ring 2

```
   I        X(I)        Y(I)
   1       1.1383      5.0000
   2       1.2758      5.5000
   3       1.3983      6.0000
   4       1.5050      6.5000
   5       1.6108      7.0000
   6       1.7425      7.5000
   7       1.8600      8.0000
   8       1.9783      8.5000
LABEL DELETED AT      1.2433
LABEL DELETED AT      1.4533
LABEL DELETED AT      1.6633
LABEL DELETED AT      1.8733
```

```
  AOV: LINEAR REG:CODE 1
SOURCE/DF     SS      MS      F
TOTAL  7     10.5
REG    1     10.5    10.5 999.9
RESID  6      0.0     0.0
R SQUARE =        0.999

YHAT =     0.148 +     4.222 X
```



Curve fitting for ring 3

I	X(I)	Y(I)
1	1.7417	5.0000
2	1.9067	5.5000
3	2.0808	6.0000
4	2.2633	6.5000
5	2.4158	7.0000
6	2.6133	7.5000
7	2.8017	8.0000
8	3.0000	8.5000

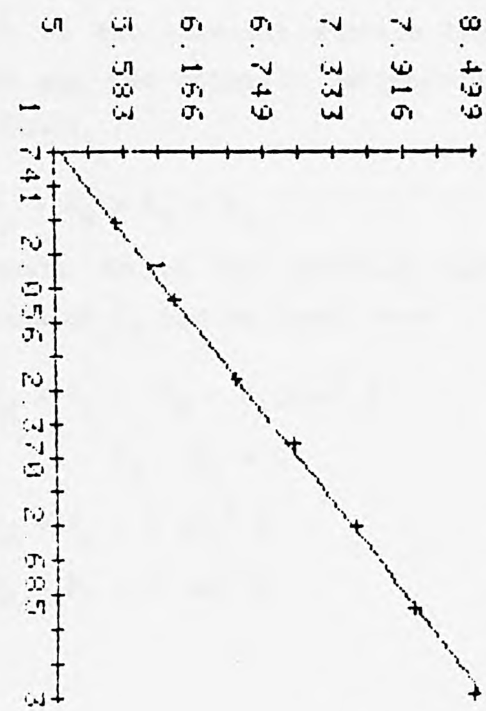
LABEL DELETED AT 1.8990
LABEL DELETED AT 2.2136
LABEL DELETED AT 2.5281
LABEL DELETED AT 2.8427

AOV: LINEAR REG:CODE 1

SOURCE/DF		SS	MS	F
TOTAL	7	10.5		
REG	1	10.5	10.5	999.9
RESID	6	0.0	0.0	

R SQUARE = 0.999

YHAT = 0.183 + 2.791 X



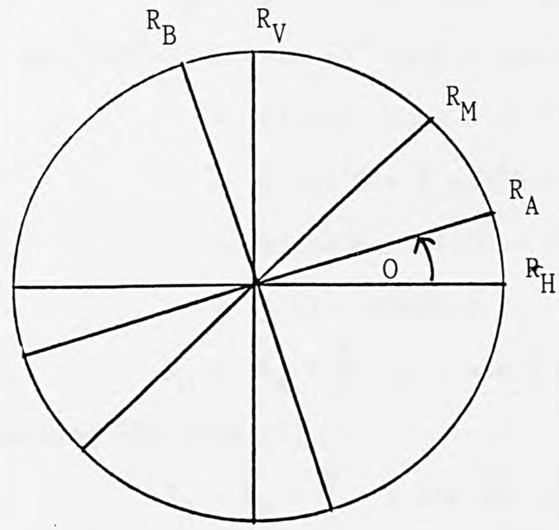


Figure B1. Diagram illustrating the principal meridia of the toroidal surface.

R_A and R_B are the principal meridians of curvature of the toroidal surface. R_A lies at Θ degrees in standard axis notation. R_H, R_M, and R_V are the known curvatures in the horizontal, 45^o, and vertical meridians respectively. It is required to find R_A, R_B, and Θ.

It is a property of the toroidal surface that the sum of the curvature in <u>any</u> two mutually perpendicular meridians is a constant. Hence,

$$R_A + R_B = R_H + R_V \qquad (1)$$

Also, the curvature $R\phi$ in any meridian making an angle ϕ with the meridian of R_A can be found from

$$R_\phi = R_A + (R_B - R_A)\sin^2 \phi \qquad (2)$$

For brevity, let $\quad R_B - R_A = D \qquad (3)$

so that $\quad R_\phi = R_A + D \sin^2 \phi \qquad (4)$

We thus obtain $R_H = R_A + D \sin^2 \Theta \qquad (5)$

$$R_V = R_A + D\sin^2(90 - \Theta)$$

$$= R_A + D\cos^2\Theta \qquad (6)$$

and $$R_M = R_A + D\sin^2(45^o - \Theta) \qquad (7)$$

Now, $$\sin^2(45^o - \Theta) = [\sin 45^o \cos\Theta - \cos 45^o \sin\Theta]^2$$

$$= (1/\surd 2)\ \cos\Theta - (1/\surd 2\ \ \sin\Theta)\ ^2$$

$$= \tfrac{1}{2}\cos^2\Theta + \tfrac{1}{2}\sin^2\Theta - \sin\ \ \cos\Theta$$

$$= \tfrac{1}{2}(\cos^2\Theta + \sin^2\Theta - 2\sin\Theta\cos\Theta)$$

$$= \tfrac{1}{2}(1 - \sin 2\Theta)$$

Hence, $$R_M = R_A + \frac{D}{2}(1 - \sin 2\Theta) \qquad (8)$$

Subtracting (8) from (5),

$$R_H - R_M = \frac{D}{2}\quad 2\sin 2\Theta - 1 + \sin 2\Theta$$

$$= \frac{D}{2}(\sin 2\Theta - \cos 2\Theta) \text{ since}$$

$$1 - 2\sin^2\Theta = \cos 2\Theta \qquad (9)$$

Subtracting (8) from (6),

$$R_V - R_M = \frac{D}{2}(2\cos^2\Theta - 1 + \sin 2\Theta)$$

$$= \frac{D}{2}(\sin 2\Theta + \cos 2\Theta) \text{ since}$$

$$2\cos^2\Theta - 1 = \cos 2\Theta \qquad (10)$$

Dividing (9) by (10)

$$\frac{R_H - R_M}{R_V - R_M} = \frac{\sin 2\Theta - \cos 2\Theta}{\sin 2\Theta + \cos 2\Theta} \qquad (11)$$

Cross multiplied, equation (11) can be reduced to

$$\sin 2\Theta\,(R_H - R_V) = \cos 2\Theta\,(2R_M - R_H - R_V)$$

whence $$\tan 2\Theta = \frac{2R_M - (R_H + R_V)}{R_H - R_V} \qquad (12)$$

from which Θ is determined.

Then, from (5) and (6), $$R_H - R_V = D(\sin^2\Theta - \cos^2\Theta)$$

$$= -D\cos 2\Theta$$

whence $$D = \frac{R_V - R_H}{\cos 2\Theta} \qquad (13)$$

Then, from (5)

$$R_A = R_H - D \sin^2 \Theta \qquad (14)$$

Finally, R_B can be obtained from either (1) or (3), giving

$$R_B = R_H + R_V - R_A = R_A + D \qquad (15)$$

In the special case where $R_H = R_V$, equation (13) becomes indeterminate (o/o). The procedure is then as follows:

$$\Theta = 45^o \qquad \text{(from eq. 12)}$$

$$R_A = R_M \qquad \text{(from eq. 8)}$$

$$R_B = R_H + R_V - R_A \qquad \text{(eq. 15)}$$

Computer programme for locating principal meridia.

For use on BBC microcomputer.

```
>L.
   10 INPUT M,H,V
   20 T=(2*M-H-V)/(H-V)
   30 S=ATN(T)
   40 W=COS(S)
   50 D=(V-H)/W
   60 J=H-(D*SIN(S/2)^2)
   70 L=1000/J
   80 A=337.5/L
   90 K=J+D
  100 N=1000/K
  110 B=337.5/N
  120 C=B-A
  130 PRINT "DEG= ";DEG(S/2):PRINT"L= ";L:PRINT"N= ";N:PRINT"A= ";A:PRINT"B= ";B
:PRINT"C= ";C
  140 GOTO 10
  150 END
```

Table B5. Dimensions of negative just after development and after a one year span.

	Dimension of negative (mm)			
	Longitudinal		Transverse	
	Observed values	Mean	Observed values	Mean
Just after development	136.06, 136.05, 136.06	136.057	25.30, 25.325, 25.315	25.313
1 year after development	136.05, 136.05, 136.04	136.047	25.31, 25.30 25.30	25.303

Table B6. 1 Photokeratograph of a 7.50 mm radius steel ball measured 10 times.

Ring No.	Measurements on 1 photokeratograph (mm)	Mean diameter (mm)	Standard deviation (σ_{n-1})	
			Diameter (mm)	Radius (mm)
1	0.88, 0.87, 0.87, 0.88, 0.87 0.87, 0.87, 0.87, 0.86, 0.87.	0.8710	0.0057	0.0459
2	1.75, 1.75, 1.74, 1.75, 1.74, 1.74, 1.74, 1.74 1.75, 1.73,	1.7430	0.0067	0.0283
3	2.61, 2.61, 2.62, 2.62, 2.60, 2.62, 2.63, 2.61, 1.62, 2.62.	2.6160	0.0084	0.0234

Table B7. 1 Photokeratograph of an adult cornea measured 10 times.

Ring No.	Measurements on 1 photokeratograph (mm)	Mean diameter (mm)	Standard deviation (σ_{n-1})	
			Diameter (mm)	Radius (mm)
1	0.93, 0.92, 0.93, 0.93, 0.94, 0.92, 0.93, 0.92, 0.93, 0.93.	0.9280	0.0063	0.0508
2	1.86, 1.86, 1.86, 1.87, 1.86, 1.865, 1.86, 1.86, 1.86, 1.87.	1.8625	0.0043	0.0182
3	2.84, 2.85, 2.84, 2.84, 2.84, 2.86, 2.84, 2.84, 2.85, 2.86.	2,8460	0.0084	0.0234

Table B8. 10 photokeratographs of a steel ball (7.50 mm radius), each measured twice.

Ring No.	Negative No.										Mean diameter (mm)	Standard deviation (σn-1)	
	1	2	3	4	5	6	7	8	9	10		Diameter (mm)	Radius (mm)
1	0.86 0.87	0.87 0.87	0.87 0.87	0.865 0.86	0.87 0.87	0.86 0.86	0.87 0.86	0.88 0.87	0.86 0.86	0.865 0.87	0.8665	0-0056	0.0451
2	1.745 1.74	1.73 1.74	1.73 1.74	1.74 1.74	1.74 1.75	1.74 1.73	1.74 1.74	1.75 1.75	1.75 1.74	1.74 1.74	1.7408	0.0061	0.0259
3	2.62 2.62	2.62 2.61	2.60 2.61	2.60 2.61	2.62 2.61	2.62 2.62	2.62 2.615	2.61 2.62	2.62 2.62	2.62 2.62	2.6153	0.0068	0.0190

Table B9. 10 photokeratographs of an adult cornea, each measured twice.

Ring No.	Negative No.										Mean diameter (mm)	Standard deviation ($\sigma n-1$)	
	1	2	3	4	5	6	7	8	9	10		Diameter (mm)	Radius (mm)
1	0.92	0.93	0.94	0.93	0.92	0.93	0.93	0.935	0.93	0.93	0.9303	0.0057	0.0462
	0.93	0.93	0.93	0.93	0.92	0.94	0.93	0.93	0.94	0.93			
2	1.86	1.86	1.855	1.87	1.85	1.86	1.86	1.87	1.86	1.86	1.8593	0.0061	0.0259
	1.85	1.86	1.86	1.86	1.85	1.86	1.87	1.86	1.85	1.86			
3	2.85	2.84	2.84	2.84	2.85	2.84	2.84	2.83	2.84	2.85	2.8410	0.0066	0.0185
	2.85	2.83	2.84	2.835	2.85	2.845	2.84	2.84	2.83	2.84			

Table B10. Comparison of corneal astigmatism from 2 photokeratographs of an adult cornea.

Negative No.	Ring 2 mean diameters (mm)			Data computed from ring 2			
	al 180	al 90	al 45	flattest radii (mm)	steepest radii (mm)	amount of astigmatism (D)	direction of flattest meridian (degrees)
1	1.8567	1.8700	1.8433	8.1059	7.9260	0.945	126
2	1.8600	1.8700	1.8400	8.1481	7.9132	1.230	128

Table B11. Corneal data collected on 10 adults.

Subject No.	HVID (mm) photok. method	HVID (mm) ruler method	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Data computed from ring 2: flattest radii (mm)	Data computed from ring 2: steepest radii (mm)	Data computed from ring 2: amount of astig-matism (D)	Data computed from ring 2: direction of flattest meridian (degrees)	Keratometric values: flattest radii (mm)	Keratometric values: steepest radii (mm)	Keratometric values: amount of astig-matism (D)	Keratometric values: direction of flattest meridian (degrees)
1	11.40	11.50	1.7767	1.7267	1.7333	7.675	7.414	1.550	162	7.658	7.383	1.641	180
2	11.90	12.00	1.8567	1.8700	1.8433	8.106	7.926	0.945	126	8,173	7.990	0.945	125
3	12.10	12.00	1.6333	1.6333	1.6700	7.199	6.895	2.063	45	7.270	7.000	1.790	35
4	12.00	12.00	1.7733	1.7400	1.7533	7.711	7.629	0.470	165	7.690	7.585	0.608	175
5	12.00	12.00	1.8100	1.7567	1.7833	7.790	7.565	1.289	180	7.783	7.550	1.338	180
6	12.10	12.00	1.8533	1.8067	1.8333	7.974	7.775	1.084	4	7.950	7.727	1.225	180
7	11.60	11.50	1.9000	1.8600	1.8667	8.187	7.985	1.044	163	8.092	7.918	0.916	175
8	11.70	11.50	1.7800	1.7500	1.7833	7.700	7.501	1.165	25	7.683	7.477	1.210	10
9	12.20	12.00	1.7800	1.7733	1.7533	7.751	7.550	1.163	139	7.727	7.547	1.042	150
10	11.90	12.00	1.9500	1.8933	1.9033	8.404	8.120	1.405	164	8.373	8.073	1.498	175

Fitting of regression lines between photokeratoscopic and keratometric values

Computer programme used : Hewlett Packard 85 General Statistics Pac.

X = keratometric values
Y = photokeratoscopic values

Flattest corneal radii

	X(I)	Y(I)
1	7.6500	7.6750
2	8.1730	8.1060
3	7.2700	7.1990
4	7.6900	7.7110
5	7.7330	7.7900
6	7.9500	7.5740
7	8.0920	8.1370
8	7.6830	7.7000
9	7.7270	7.7510
10	8.3730	8.4040

MAXIMUM DEGREE REGRESSION= 1

BASIC STATISTICS
****
MEANS,VARIANCES,CORRELATION
X MEAN= 7.8339
VAR(X)= .0991
Y MEAN= 7.8457
VAR(Y)= .1123

MINIMUM	MAXIMUM
7.2700	8.3730
7.1990	8.4040

RXY = .9910

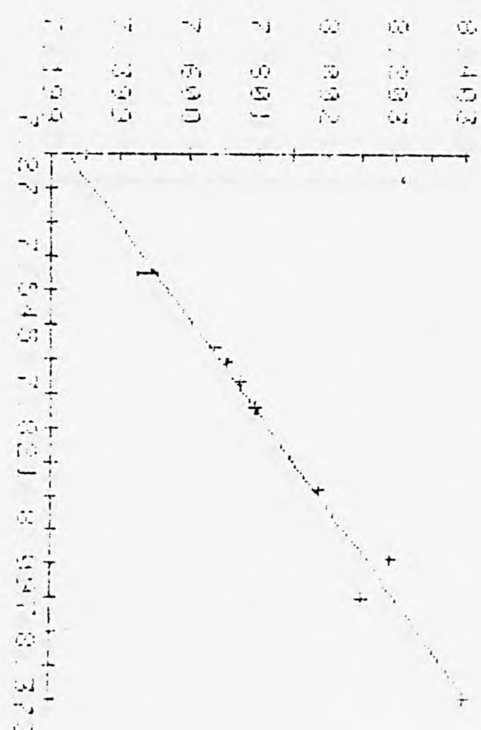
LABEL DELETED AT 7.4079
LABEL DELETED AT 7.6836
LABEL DELETED AT 7.9594
LABEL DELETED AT 8.2351

ROW LINEAR REG CODE 1

SOURCE/DF	SS	MS	F
TOTAL 9	1.0		
REG 1	1.0	1.0	440.3
RESID 8	0.0	0.0	

R SQUARE = 0.982

YHAT = -0.423+ 1.055 X



Steepest corneal radii

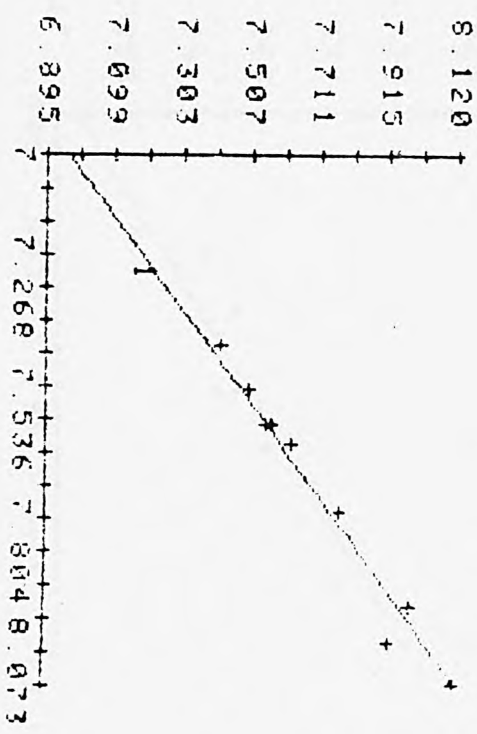
I	X(I)	Y(I)
1	7.3830	7.4140
2	7.9900	7.9260
3	7.0000	6.8950
4	7.5850	7.6290
5	7.5500	7.5650
6	7.7270	7.7750
7	7.9180	7.9850
8	7.4770	7.5010
9	7.5470	7.5500
10	8.0730	8.1200

```
MAXIMUM DEGREE REGRESSION=  1

BASIC STATISTICS
********************************
MEANS,VARIANCES,CORRELATION
X MEAN=      7.6250
VAR(X)=       .1016
Y MEAN=      7.6360
VAR(Y)=       .1210
    MINIMUM        MAXIMUM
     7.0000        8.0730
     6.8950        8.1200
RXY =          .9905


LABEL DELETED AT          7.1341
LABEL DELETED AT          7.4024
LABEL DELETED AT          7.6706
LABEL DELETED AT          7.9389
   AOV: LINEAR REG CODE 1
SOURCE/DF       SS       MS       F
TOTAL  9        1 1
REG    1        1.1       1.1  413.0
RESID  8        0.0       0.0
R SQUARE =          0.981

YHAT =     -0.603+      1.081 X
```



Corneal astigmatism

I	X(I)	Y(I)
1	1.6410	1.5500
2	0.9450	0.9450
3	1.7900	2.0630
4	0.6080	0.4700
5	1.3380	1.2890
6	1.2250	1.0840
7	0.9160	1.0440
8	1.2100	1.1650
9	1.0420	1.1630
10	1.4980	1.4050

MAXIMUM DEGREE REGRESSION= 1

BASIC STATISTICS
****
MEANS, VARIANCES, CORRELATION
X MEAN= 1.2213
VAR(X)= .1297
Y MEAN= 1.2178
VAR(Y)= .1725

MINIMUM	MAXIMUM
.6080	1.7900
.4700	2.0630

RXY = .9486

LABEL DELETED AT .7558
LABEL DELETED AT 1.0513
LABEL DELETED AT 1.3468
LABEL DELETED AT 1.6423

AOV: LINEAR REG:CODE 1

SOURCE/DF		SS	MS	F
TOTAL	9	1.6		
REG	1	1.4	1.4	71.9
RESID	8	0.2	0.0	

R SQUARE = 0.900

YHAT = -0.118+ 1.094 X

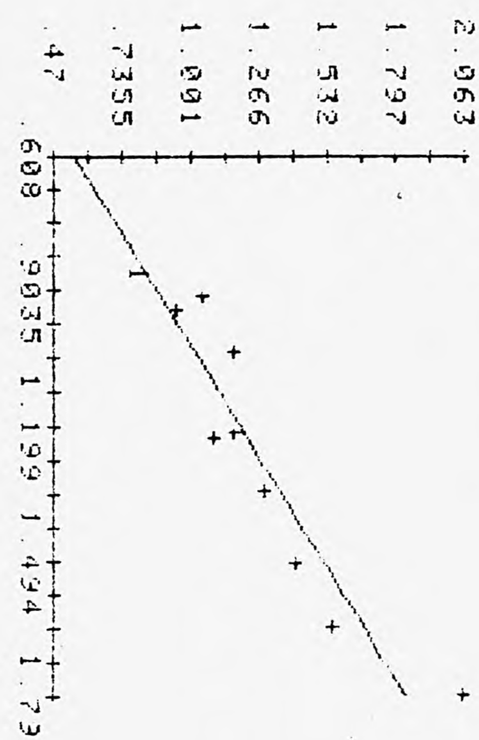


Table B12. 1 photokeratograph of an adult cornea measured 10 times : HVID.

Measurements on negative (mm)	Mean value (mm)	s.d. (mm)	Actual HVID (mm)	Actual s.d. (mm)
6.00, 6.00, 5.90, 6.10, 6.00, 6.10, 6.00, 6.00, 6.00, 5.90	6.00	0.07	12.00	0.14

APPENDIX C

RADIATION FROM INSTRUMENT

The potential damaging effects of radiation on the eye.

Apart from the skin, the eye is the only organ or tissue in the body which is particularly sensitive to the non-ionizing wavelengths of radiant energy. In recent years, it has become apparent that retinae of experimental animals are susceptible to photochemical injury at light levels well below those necessary for photocoagulation (Noell et al., 1966; Ham et al., 1976; Kuwabara and Gorn, 1968; Lawwill et al., 1977). Therefore, it was necessary to examine the photokeratoscope in view of this potential hazard.

Lerman (1980) considered the morphology and chemical composition of the transparent parts of the eye and predicted which specific areas of the electromagnetic spectrum would reach the retina. The cornea filters out all u-v radiation below 295nm. The relative spectral transmission and absorption of the human cornea with respect to age is shown in Figure C1. The transmission of visible and u-v radiation between 300 to 400nm decreases with age. The aqueous humour also transmits most of the u-v radiation from 295 to 400nm into the interior of the eye. Transmission studies on normal human lenses ranging in age from 6 months to 82 years reveal that a relatively high percentage (over 75%) of u-v radiation is transmitted in 6-month to 8-year-old lenses. This transmission drops markedly to 20% or less in lenses over 25 years of age (Figure C2). These data parallel the relative lack of fluorescent pigment in young lenses and the increase in these pigments with lenticular aging. As these fluorescent pigments increase in concentration, there is a concomitant decrease in the transmission of u-v light between 300 to 400nm as well as an increase in the colour of the lens nucleus. The increase in the yellow colouration of the lens nucleus may account for the decrease in transmission of visible light as the lens ages. Although it is not yet fully understood, the yellow pigment of the aging lens is thought to be a photochemical production of other molecules which absorb in the u-v region (280 to 315nm) (Marshall, 1984). Examination of the morphology and chemical composition of the vitreous humour shows that it should transmit all visible radiation. The vitreous has chromophores capable of absorbing u-v radiation but most of this is already filtered out by the cornea

and the lens (Lerman, 1980). Thus, considering the transmissions of all the above portions of the eye, a significant amount of radiation between 400 to 1400nm falls upon the retina.
The generally held view was that only thermal injury to the retina was of any consequence until it was shown that non-thermal injury to the retina was possible in primates. Levels of retinal illumination hundreds or even thousands of times below thermal injury thresholds could be hazardous especially if the illumination source emitted short wavelengths that is, blue-violet light(Lawwill et al., 1977; Ham et al., 1980).

As presently understood, visible light levels which cause retinal hazards are quite discomforting to stare at. The blink response of the eye is 0.2 seconds and the normal response when an extremely bright light source is encountered is to blink and avoid staring at it (Sliney, 1983). Applying this to the photokeratoscope, the duration of the flash is 275 μ seconds which is well within the blink reflex and all the light emitted will possibly enter the eye.

From Figure C2, it is apparent that in the aphakic eye, a significant protective filter is lost on lens removal, which results in the retina receiving a large increase in radiant exposure to short wavelength radiation between 350 and 400mm. This wavelength is potentially the most dangerous for inducing retinal damage (see later). However, for the young aphakic, Lerman (1980) implies that the danger of retinal damage is less compared to that of an adult as the repair mechanisms in a young retina are superior. Also, as most aphakic infants and children are fitted with soft contact lenses, the transmission spectrum of the contact lens is similar to that of the young crystalline lens up to 8 years of age, so that one may reasonably assume that this age group is fairly well protected. However, this study would involve measurements of corneal curvature on aphakic infants and children which requires photographs to be taken without the contact lenses in the eye, thus removing the protection afforded by these lenses.

The mechanisms by which excessive light causes damage to the eye may involve interactions of heat, thermoacoustic (mechanical) transients and photochemical processes (Marshall, 1984).

Thermal damage is currently exploited in all types of retinal photocoagulation therapy. If enough light is absorbed by a system, the molecules experience an increase in vibration and hence an increased heat content. Thermal injury results when sufficient radiant energy has been absorbed within a tissue to create and sustain, (at least for some seconds), a considerable increase in normal tissue temperature. This increase needs to be in the order of 10-25°C before permanent harmful changes occur within exposed cells (Ham et al., 1980; Marshall, 1984). Thermal injury requires retinal levels exceeding $1W/cm^2$ and is not normally a hazard (Sliney and Wolborsht, 1980).

Thermoacoustic injury occurs when so much light is absorbed within a system in such a very short time that the thermal energy cannot be removed by conduction or reradiation. This causes rapid state changes and the increase in volume associated with the instantaneous gas phase cannot be contained by the system. A micro-explosion occurs within the absorbing tissue creating a second abrupt change in volume.

Photochemical damage is of most potential danger to the retina, as it is produced by absorbed power levels much below those required to produce thermal damage. Here, injury is due to photochemical reactions in which single photons have sufficient quantum energy to convert individual absorbing molecules into others, which may be harmful to the cell. Photochemical damage is more pronounced for the shorter or blue wavelengths of the spectrum.

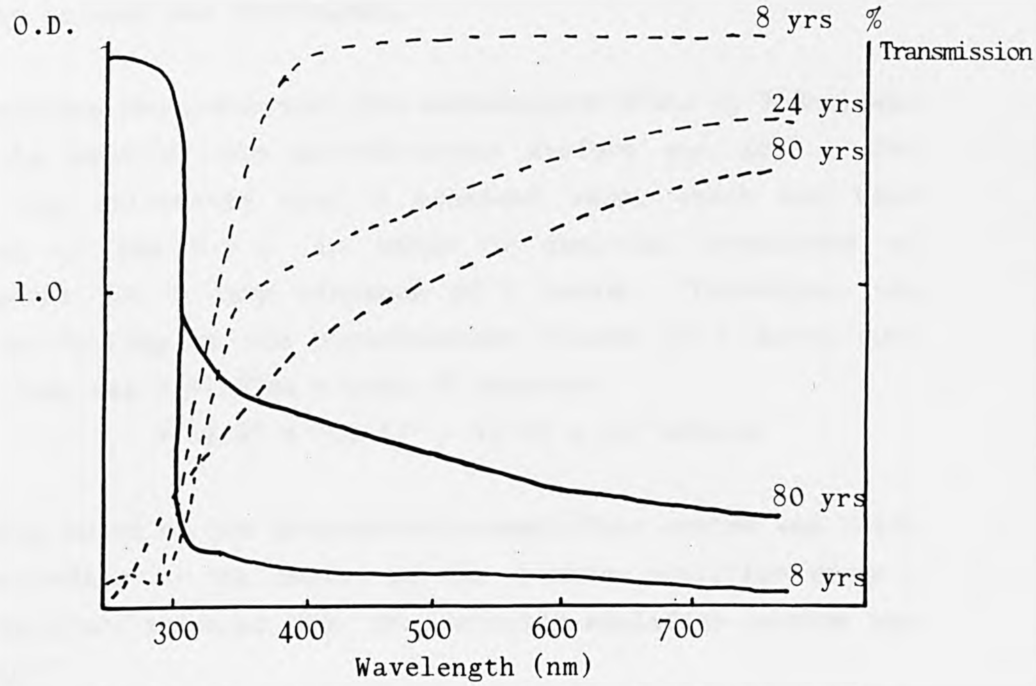


Figure C1. Absorption (solid line) and transmission (dotted line) of the human cornea. (After Lerman, 1980:58.)

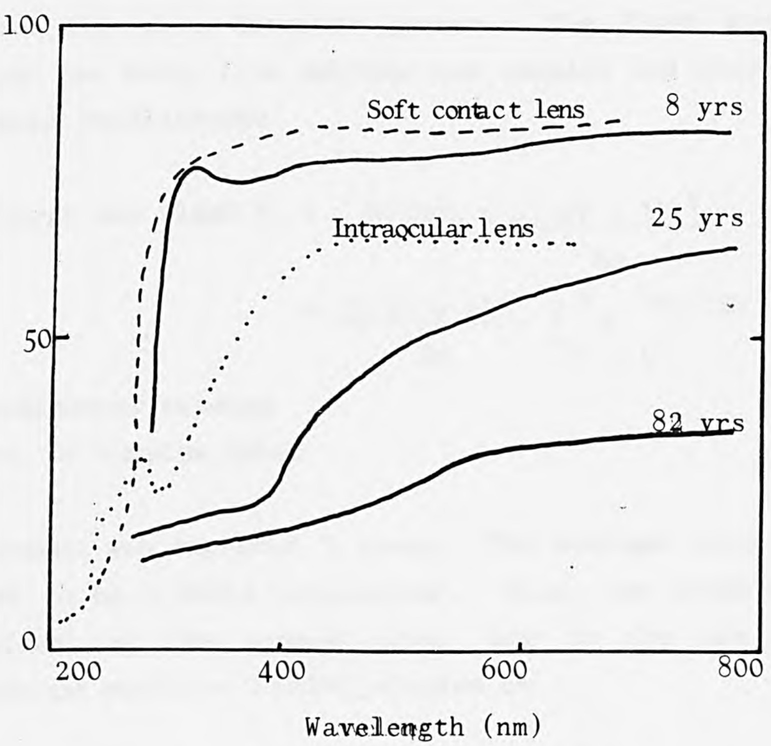


Figure C2. The relative spectral transmission of the crystaline lens as a function of age. (After Lerman, 1980:153, 167.)

Radiation measurements of photokeratoscope.

To assess the irradiation hazard from the use of electronic flash guns in the photokeratoscope, the total radiant exposure when the instrument is used was determined.

A flat response photodetector (for wavelengths 390nm to 760nm) was used. The area of the photodetector surface was $1cm^2$. The detector was calibrated with a standard lamp, which had been calibrated at the N.P.L. in terms of spectral irradiance at $17.67mW/m^2/nm$ for a lamp distance of 1 metre. Therefore, the total flux falling on the photodetector placed at 1 metre away from the lamp was = 17.67mW x area of detector

$$= 17.67 \times (10^{-2})^2 = 17.67 \times 10^{-4}\text{mWatts}$$

The reading noted on the photodetector-amplifier system was Xo(Xo varied according to the choice of the optimum amplifier range.) The calibration constant for the detector-amplifier system was

$$\frac{17.67 \times 10^{-4}}{Xo}$$

The photokeratoscope was then mounted at its normal working distance form the photo-detector system. The flash guns were triggered and the total flux emitted was sampled and stored in a digital storage oscilloscope.

The total energy per flash E_t = $R(t)dt \times \frac{17.67 \times 10^{-4}}{Xo}$
$mJoules/cm^2$

$$= \frac{17.67 \times 10^{-4}}{Xo} \sum_{i=0}^{N} \Delta T R(i \Delta T)$$

where R = radiometer reading

i = no. of samples taken

This measurement was repeated 3 times. The average value for E_t was measured to be 0.06012 $mJoules/cm^2$. Thus, the total radiant energy incident at the corneal surface due to the use of the photokeratoscope would be 0.06012 $mJoules/cm^2$.

Choice of filter.

Following consultations with Prof. J. Marshall on the total radiant energy incident at the corneal plane, the use of a filter over all the electronic flash guns was advised to prevent any risk occurring from the blue light component. Several filters were assessed and Kodak Wratten filter number 12 was selected as being the most suitable as it cut off all radiation at wavelengths of 500nm and below (Figure C3).

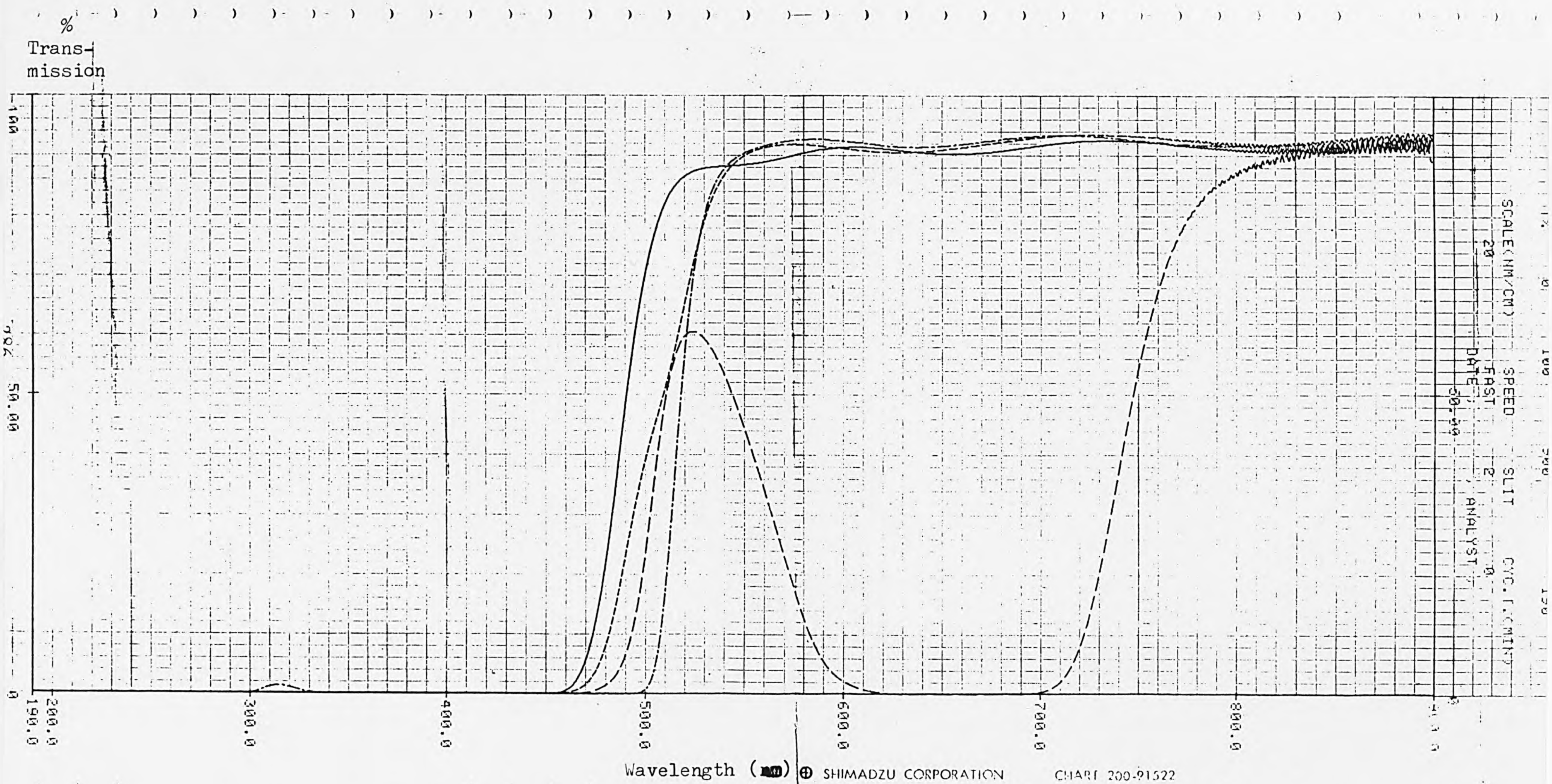


Figure C3. Transmission curves of Kodak Wratten filters. ___ No. 8, --- No. 9, - . - No. 12, _ _ No. 58.

APPENDIX D

BASIC DATA ON NORMAL EYES

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Table D1(a). Age 1-<3 months : HVID and ring diameters.

Subject No.	Sex	Age mos	Age wks	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
1	m	2	3	L	5.50	11.00	missing		1.7267	1.7333	1.8033	7.4381	7.4660	7.7615	0.8567	7.3447
4	f	2	0	L	5.20	10.40	2.4667	7.0676	1.6067	1.6033	1.6067	6.9315	6.9171	6.9315	0.7867	6.7809
10	m	2	3	R	limbus not distinct		2.7967	7.9886	1.7767	1.7200	1.7933	7.6492	7.4098	7.7193	0.8933	7.6395
11	m	1	2	R	5.25	10.50	2.5500	7.3000	1.7033	1.7667	1.7033	7.3393	7.6070	7.3393	0.8433	7.2368
12	f	2	2	L	5.60	11.20	2.3133	6.6394	1.5167	1.6067	1.5867	6.5515	6.9315	6.8470	0.7600	6.5658
16	f	2	2	R	5.20	10.40	2.3200	6.6581	1.5433	1.5600	1.5000	6.6638	6.7343	6.4810	0.7533	6.5118
19	f	1	3	L	5.30	10.60	2.7233	7.7837	1.8067	1.8200	1.8567	7.7759	7.8320	7.9870	0.8767	7.5058
21	m	2	0	R	5.20	10.40	2.5100	7.1859	1.6567	1.6433	1.6433	7.1426	7.0860	7.0860	0.8067	6.9420
23	m	1	2	L	5.80	11.60	2.6967	7.7095	1.7833	1.7500	1.7300	7.6771	7.5365	7.4521	0.8933	7.6395
27	f	1	3	L	5.50	11.00	2.3000	6.6023	1.5067	1.4533	1.4867	6.5093	6.2838	6.4248	0.7300	6.3242
31	m	2	3	R	5.75	11.50	2.3367	6.7047	1.5333	1.5300	1.5300	6.6216	6.6077	6.6077	0.7533	6.5118
42	f	2	2	R	5.65	11.30	2.7400	7.8303	1.8233	1.8067	1.8167	7.8460	7.7759	7.8181	0.8967	7.6669

Table D1(b). Age 1-< 3 months: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
1	m	7.7619	7.1660	3.616	46	+0.094	-
4	f	6.9345	6.9141	0.143	23	+0.151	+0.136
10	m	7.7563	7.3120	2.644	29	+0.010	+0.339
11	m	7.6649	7.2862	2.288	113	+0.103	-0.039
12	f	6.9625	6.5241	3.257	75	-0.014	+0.088
16	f	6.9349	6.4784	3.429	131	+0.152	-0.006
19	f	7.9893	7.6269	2.007	50	+0.270	-0.008
21	m	7.1544	7.0744	0.534	158	+0.201	-0.043
23	m	7.7824	7.4377	2.010	147	+0.038	+0.032
27	f	6.5134	6.2800	1.926	8	+0.185	+0.093
31	m	6.6245	6.6048	0.152	158	+0.110	+0.083
42	f	7.8467	7.7751	0.396	6	+0.179	-0.016

Table D2(a). Age 3-<6 months : HVID and ring diameters.

Subject No.	Sex	Age		Eye	HVID		Ring 3		Ring 2						Ring 1	
		mos	wks		mean diameter on negative (mm)	actual diameter (mm)	mean diameter (mm) al 180	computed radius (mm) al 180	mean diameter (mm) al 180	al 90	al 45	computed radius (mm) al 180	al 90	al 45	mean diameter (mm) al 180	computed radius (mm) al 180
1	m	5	3	L	limbus not distinct		missing		1.7767	1.7567	1.7500	7.6492	7.5648	7.5365	0.8900	7.6130
2	m	5	0	R	5.95	11.90	2.7867	7.9607	1.8433	1.8033	1.7933	7.9304	7.7615	7.7193	0.9067	7.7475
3	m	4	3	L	5.50	11.00	2.4367	6.9838	1.5867	1.4600	1.5133	6.8470	6.3121	6.5372	0.7667	6.6198
5	m	4	1	R	6.00	12.00	2.8433	8.1187	1.7967	1.7267	1.7467	7.7337	7.4381	7.5226	0.8933	7.6395
8	m	4	3	L	limbus not distinct		missing		1.8367	1.9067	1.8867	7.9025	8.1981	8.1136	0.8867	7.5864
9	f	5	3	R	5.80	11.60	2.7633	7.8954	1.7833	1.7467	1.7667	7.6771	7.5226	7.6070	0.8867	7.5864
10	m	5	1	R	5.90	11.80	2.8033	8.0070	1.8200	1.7567	1.7867	7.8320	7.5648	7.6914	0.8900	7.6130
11	m	4	1	R	5.85	11.70	2.4567	7.0396	1.6433	1.6267	1.6133	7.0860	7.0159	6.9594	0.7967	6.8614
12	f	4	1	R	5.85	11.70	2.7700	7.9141	1.7600	1.6633	1.7000	7.5787	7.1705	7.3254	0.8667	7.4253
15	m	4	2	L	5.80	11.60	2.6067	7.4583	1.7367	1.7000	1.7567	7.4803	7.3254	7.5648	0.8567	7.3447
18	f	4	3	R	5.70	11.40	2.7167	7.7653	1.7967	1.6967	1.7600	7.7337	7.3115	7.5787	0.8867	7.5864

continued.....
Table D2(a). Age 3-<6 months : HVID and ring diameters.

Subject No.	Sex	Age mos	Age wks	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
21	m	5	3	R	6.05	12.10	2.5733	7.3651	1.6900	1.6567	1.7067	7.2832	7.1426	7.3537	0.8267	7.1031
24	m	4	2	R	5.90	11.80	2.8433	8.1187	1.8900	1.8467	1.8433	8.1276	7.9448	7.9304	0.9300	7.9352
25	m	4	3	L	5.90	11.80	2.6800	7.6629	1.7833	1.7133	1.7267	7.6771	7.3816	7.4381	0.8700	7.4519
27	m	4	3	L	5.80	11.60	2.7233	7.7837	1.7833	1.8100	1.7633	7.6771	7.7898	7.5927	0.8967	7.6669
29	m	4	2	R	5.90	11.80	2.8967	8.2677	1.9167	1.9067	1.9000	8.2403	8.1981	8.1698	0.9300	7.9352
31	f	5	3	L	5.50	11.00	2.6967	7.7095	1.7867	1.7800	1.8367	7.6914	7.6632	7.9025	0.8967	7.6669
32	m	3	1	R	5.55	11.10	2.2633	6.4999	1.4633	1.4233	1.4567	6.3261	6.1572	6.2982	0.7300	6.3242
34	m	3	3	L	5.80	11.60	2.8867	8.2398	1.8833	1.8433	1.8833	8.0993	7.9304	8.0993	0.9533	8.1228
38	f	3	1	R	6.00	12.00	2.7633	7.8953	1.8400	1.7867	1.8000	7.9165	7.6914	7.7476	0.9167	7.8280
39	f	5	3	R	6.00	12.00	2.7500	7.8583	1.8067	1.7433	1.7500	7.7759	7.5082	7.5365	0.8933	7.6395
42	m	5	3	R	5.60	11.20	missing		1.6433	1.6600	1.6333	7.0860	7.1565	7.0438	0.7967	6.8614

continued....
Table D2(a). Age 3-<6 months : HVID and ring diameters.

Subject No.	Sex	Age mos	Age wks	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
43	m	4	1	L	5.85	11.70	2.7900	7.9699	1.7767	1.8267	1.8467	7.6492	7.8603	7.9448	0.8900	7.6130
45	f	4	2	L	5.80	11.60	2.8200	8.0536	1.8600	1.8233	1.8333	8.0009	7.8460	7.8882	0.9133	7.8006
48	m	4	3	L	5.80	11.60	2.7467	7.8490	1.8333	1.8667	1.8100	7.8882	8.0292	7.7898	0.9067	7.7475
49	f	3	1	R	5.95	11.90	2.7500	7.8583	1.8000	1.7733	1.8067	7.7476	7.6349	7.7759	0.8700	7.4519
51	m	5	0	L	5.95	11.90	missing		1.7433	1.7467	1.7567	7.5082	7.5226	7.5648	0.8700	7.4519
52	m	5	2	R	limbus not distinct		missing		1.7200	1.6367	1.6733	7.4098	7.0581	7.2127	0.8567	7.3636

Table D2(b). Age 3-< 6 months: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2: Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	Change in radius al 180 from rings 1 - 2 (mm)	2 - 3 (mm)
1	m	7.6902	7.5251	0.963	150	+0.036	-
2	m	8.0013	7.6948	1.680	152	+0.183	+0.030
3	m	6.8491	6.3104	4.207	177	+0.227	+0.137
5	m	7.7462	7.4265	1.876	169	+0.094	+0.385
8	m	8.2125	7.8892	1.684	78	+0.316	-
9	f	7.6775	7.5222	0.908	3	+0.091	+0.218
10	m	7.8321	7.5647	1.523	179	+0.219	+0.175
11	m	7.1513	6.9531	1.345	145	+0.225	-0.046
12	f	7.5836	7.1661	2.593	174	+0.153	+0.335
15	m	7.5835	7.2291	2.181	32	+0.136	-0.022
18	f	7.7430	7.3031	2.625	8	+0.147	+0.032
21	m	7.3712	7.0599	2.019	32	+0.180	+0.082
24	m	8.1777	7.8975	1.464	155	+0.192	-0.009
25	m	7.7031	7.3577	2.057	164	+0.225	-0.014
27	m	7.8899	7.5823	1.735	124	+0.010	+0.106
29	m	8.2734	8.1656	0.539	147	+0.305	+0.027
31	f	7.9030	7.4641	2.512	43	+0.024	+0.018
32	m	6.3441	6.1402	1.767	17	+0.002	+0.174
34	m	8.1352	7.8963	1.255	23	-0.024	+0.140
38	f	7.9297	7.6790	1.389	167	+0.088	-0.021
39	f	7.8134	7.4736	1.964	161	+0.136	+0.082

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Table D2(b).

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
42	m	7.2079	7.0364	1.141	123	+0.225	-
43	m	7.9740	7.5446	2.409	60	+0.036	+0.321
45	f	8.0085	7.8387	0.913	168	+0.200	+0.053
48	m	8.1483	7.7765	1.980	124	+0.141	-0.039
49	f	7.7934	7.5909	1.156	28	+0.296	+0.111
51	m	7.5653	7.4661	0.593	49	+0.056	-
52	m	7.4107	7.0574	2.280	177	+0.046	-

Table D3(a). Age 6-<12 months : HVID and ring diameters.

Subject No.	Sex	Age		Eye	HVID		Ring 3		Ring 2						Ring 1	
		mos	wks		mean diameter on negative (mm)	actual diameter (mm)	mean diameter (mm) al 180	computed radius (mm) al 180	mean diameter (mm) al 180	al 90	al 45	computed radius (mm) al 180	al 90	al 45	mean diameter (mm) al 180	computed radius (mm) al 180
5	m	7	1	R	5.70	11.40	2.3233	6.6673	1.4867	1.4433	1.4667	6.4248	6.2417	6.3404	0.7467	6.4587
6	f	9	0	R	5.70	11.40	2.4333	6.9743	1.6300	1.5633	1.5700	7.0299	6.7483	6.7765	0.7800	6.7269
7	m	7	1	R	6.15	12.30	too faint		1.9067	1.8533	1.8833	8.1981	7.9726	8.0993	0.9633	8.2034
8	m	6	2	R	5.85	11.70	3.0067	8.5747	1.9733	1.8600	1.8767	8.4793	8.0009	8.0714	0.9867	8.3919
9	m	10	2	R	5.70	11.40	2.5233	7.2255	1.6600	1.6400	1.6133	7.1565	7.0721	6.9594	0.8133	6.9951
10	m	9	1	L	5.80	11.60	2.9700	8.4723	1.9167	1.8600	1.8733	8.2403	8.0009	8.0571	0.9400	8.0157
12	m	6	3	L	5.70	11.40	2.6667	7.6258	1.7133	1.6100	1.6800	7.3816	6.9454	7.2410	0.8567	7.3447
14	f	6	1	L	5.80	11.60	2.9067	8.2956	1.9267	1.9133	1.9600	8.2825	8.2260	8.4231	0.9667	8.2308
16	m	8	1	R	5.80	11.60	2.6800	7.6629	1.7433	1.7467	1.7300	7.5082	7.5226	7.4521	0.8800	7.5324
17	f	8	0	R	5.85	11.70	2.7300	7.8024	1.8067	1.7900	1.8033	7.7759	7.7054	7.7615	0.9100	7.7741
19	m	9	0	L	5.75	11.50	2.5467	7.2908	1.6667	1.5433	1.6167	7.1848	6.6638	6.9737	0.8267	7.1031
21	f	6	1	R	5.90	11.80	2.8767	8.2119	1.8800	1.8767	1.8500	8.0854	8.0714	7.9587	0.9267	7.9086

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Table D3(a). Age 6-<12 months : HVID and ring diameters.

Subject No.	Sex	Age mos	Age wks	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
24	f	10	0	R	5.50	11.00	2.4067	6.9000	1.5767	1.5633	1.5500	6.8048	6.7483	6.6921	0.7900	6.8075
25	m	9	3	R	6.00	12.00	2.8267	8.0723	1.8700	1.8267	1.8267	8.0431	7.8603	7.8603	0.9300	7.9352
26	f	6	0	L	5.65	11.30	2.5067	7.1792	1.6400	1.5800	1.5800	7.0721	6.8188	6.8188	0.7867	6.7809
27	f	9	0	R	5.60	11.20	2.4300	6.9651	1.6033	1.6067	1.5900	6.9171	6.9315	6.8610	0.7600	6.5658
28	f	10	2	L	6.00	12.00	too faint		1.7267	1.7700	1.7267	7.4381	7.6209	7.4381	0.8500	7.2908
31	f	7	1	R	5.90	11.80	2.8567	8.1560	1.8767	1.8467	1.8167	8.0714	7.9448	7.8181	0.9267	7.9086
36	m	6	2	R	limbus not distinct		2.6467	7.5699	1.7700	1.7167	1.7033	7.6209	7.3959	7.3393	0.8800	7.5324
37	m	10	1	L	6.05	12.10	2.7700	7.9141	1.8200	1.7833	1.8167	7.8320	7.6771	7.8181	0.9033	7.7201
40	f	7	2	R	5.80	11.60	2.6767	7.6537	1.7600	1.7267	1.7300	7.5787	7.4381	7.4521	0.8567	7.3447
41	f	10	2	R	5.60	11.20	too faint		1.6500	1.5700	1.5667	7.1143	6.7765	6.7625	0.7767	6.7003
42	m	8	1	L	6.00	12.00	2.7467	7.8490	1.8200	1.8667	1.8167	7.8320	8.0292	7.8181	0.9233	7.8812

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Table D3(a). Age 6-<12 months : HVID and ring diameters.

Subject No.	Sex	Age mos	Age wks	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
43	m	7	2	R	5.50	11.00	2.4700	7.0768	1.6167	1.6067	1.6000	6.9737	6.9315	6.9032	0.8067	6.9420
45	f	11	2	L	6.00	12.00	2.7300	7.8024	1.7767	1.7867	1.7700	7.6492	7.6914	7.6209	0.8933	7.6395
49	m	8	1	R	6.25	12.50	missing		1.8100	1.7467	1.7867	7.7898	7.5226	7.6914	0.8933	7.6395
50	f	9	2	R	5.85	11.70	2.4567	7.0396	1.6100	1.6000	1.6033	6.9454	6.9032	6.9171	0.7767	6.7003
51	f	7	1	R	5.50	11.00	2.5767	7.3746	1.6867	1.6500	1.6667	7.2692	7.1143	7.1848	0.8500	7.2908
53	m	8	0	L	6.10	12.20	2.9500	8.4165	1.9467	1.8000	1.8367	8.3670	7.7476	7.9025	0.9733	8.2839
54	m	9	2	R	6.15	12.30	2.9367	8.3793	1.9167	1.9867	1.9400	8.2403	8.5358	8.3387	0.9500	8.0963
55	f	8	1	R	6.05	12.10	2.9167	8.3235	1.9167	1.8467	1.8733	8.2403	7.9448	8.0571	0.9500	8.0963
56	f	9	3	R	5.40	10.80	2.3467	6.7326	1.5500	1.4967	1.5167	6.6921	6.4671	6.5515	0.7700	6.6464
57	f	7	0	R	5.80	11.60	2.5767	7.3746	1.7000	1.7067	1.6667	7.3254	7.3537	7.1848	0.8067	6.9420
61	m	7	2	R	5.60	11.20	2.3067	6.6210	1.4500	1.4633	1.4400	6.2699	6.3261	6.2277	0.7033	6.1091

Table D3(b). Age 6-< 12 months: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
5	m	6.4253	6.2412	1.549	3	-0.034	+0.243
6	f	7.0705	6.7112	2.555	161	+0.303	-0.056
7	m	8.1992	7.9716	1.175	4	-0.005	-
8	m	8.5342	7.9527	2.892	163	+0.087	+0.095
9	m	7.2816	6.9541	2.183	143	+0.161	+0.069
10	m	8.2560	7.9862	1.381	166	+0.225	+0.232
12	m	7.3979	6.9310	3.073	10	+0.037	+0.244
14	f	8.4256	8.0895	1.664	40	+0.052	+0.013
16	m	7.5802	7.4517	0.768	132	-0.024	+0.155
17	f	7.7817	7.6996	0.462	15	+0.002	+0.027
19	m	7.1919	6.6577	3.765	6	+0.082	+0.106
21	f	8.2019	7.9585	1.259	137	+0.177	+0.126
24	f	6.8676	6.6877	1.322	144	-0.003	+0.095
25	m	8.0821	7.8235	1.380	158	+0.108	+0.029
26	f	7.1269	6.7685	2.507	158	+0.291	+0.107
27	f	6.9892	6.8606	0.905	132	+0.351	+0.048
28	f	7.6599	7.4014	1.539	113	+0.147	-
31	f	8.2171	7.8085	2.149	144	+0.163	+0.085
36	m	7.7174	7.3073	2.454	152	+0.089	-0.051
37	m	7.8555	7.6547	1.127	20	+0.112	+0.082

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Table D3(b).

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
40	f	7.5988	7.4189	1.077	161	+0.234	+0.075
41	f	7.1999	6.7007	3.492	156	+0.414	-
42	m	8.0821	7.7823	1.609	114	-0.049	+0.017
43	m	7.0069	6.8990	0.754	147	+0.032	+0.103
45	f	7.7246	7.6167	0.619	124	+0.010	+0.153
49	m	7.7951	7.5176	1.598	8	+0.150	-
50	f	6.9466	6.9020	0.314	171	+0.245	+0.094
51	f	7.2695	7.1141	1.014	178	-0.022	+0.105
53	m	8.4023	7.7176	3.563	167	+0.083	+0.050
54	m	8.5434	8.2332	1.488	99	+0.144	+0.139
55	f	8.2441	7.9413	1.561	174	+0.144	+0.083
56	f	6.6952	6.4641	1.802	173	+0.046	+0.041
57	f	7.5017	7.1842	1.988	132	+0.383	+0.049
61	m	6.3751	6.2225	1.299	124	+0.161	+0.351

Table D4(a). Age 1-<2 yrs : HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
4	f	1	6	R	6.00	12.00	2.3733	6.8069	1.5800	1.5633	1.5667	6.8188	6.7483	6.7626	0.7800	6.7269
5	m	1	3	R	5.85	11.70	2.5200	7.2163	1.6733	1.6300	1.6300	7.2127	7.0299	7.0299	0.8167	7.0225
6	m	1	11	R	6.00	12.00	2.6533	7.5884	1.7200	1.6933	1.6767	7.4098	7.2971	7.2270	0.8567	7.3447
7	m	1	2	L	5.75	11.50	2.6700	7.6350	1.7933	1.7500	1.7500	7.7193	7.5365	7.5365	0.8733	7.4784
9	f	1	8	L	6.05	12.10	too faint		1.8467	1.8400	1.8400	7.9448	7.9165	7.9165	0.9233	7.8812
14	f	1	6	L	6.00	12.00	missing		1.9267	1.9500	1.9300	8.2825	8.3809	8.2965	0.9467	8.0697
17	f	1	6	R	5.70	11.40	2.5933	7.4209	1.7167	1.7100	1.7133	7.3959	7.3676	7.3816	0.8567	7.3447
18	m	1	1	L	6.15	12.30	2.8000	7.9978	1.8033	1.7067	1.7600	7.7615	7.3537	7.5787	0.8833	7.5590
19	m	1	10	L	5.70	11.40	2.5933	7.4209	1.7333	1.6900	1.7233	7.4660	7.2832	7.4238	0.8600	7.3713
21	m	1	0	R	6.00	12.00	too faint		1.7933	1.7700	1.7733	7.7193	7.6209	7.6349	0.9000	7.6935
24	f	1	4	R	5.75	11.50	2,7100	7.7466	1.8133	1.8267	1.8133	7.8038	7.8603	7.8038	0.8800	7.5324
26	f	1	1	R	5.80	11.60	2.6033	7.4488	1.7100	1.6833	1.6933	7.3676	7.2549	7.2971	0.8600	7.3713

continued.
Table D4(a). Age 1-<2 yrs : HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
28	m	1	5	R	6.00	12.00	2.6633	7.6163	1.7600	1.7633	1.7600	7.5787	7.5927	7.5787	0.8733	7.4784
31	m	1	0	R	5.95	11.90	2.8000	7.9978	1.8533	1.8000	1.8267	7.9726	7.7476	7.8603	0.9333	7.9617
34	m	1	3	L	6.05	12.10	2.7233	7.7837	1.7600	1.7333	1.6967	7.5787	7.4660	7.3115	0.8800	7.5324
35	f	1	3	R	5.80	11.60	2.6600	7.6071	1.7333	1.6800	1.7033	7.4660	7.2410	7.3393	0.8400	7.2102
39	f	1	4	R	5.90	11.80	2.5833	7.3930	1.7133	1.6900	1.6900	7.3816	7.2832	7.2832	0.8233	7.076
41	m	1	5	L	6.00	12.00	missing		1.8233	1.8267	1.8533	7.8460	7.8603	7.9726	0.8933	7.6395
42	m	1	0	R	5.80	11.60	missing		1.6033	1.6067	1.6033	6.9171	6.9315	6.9171	0.7967	6.8614

Table D4(b). Age 1-< 2yrs: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
4	f	6.8245	6.7426	0.600	165	+0.092	-0.012
5	m	7.2517	6.9932	1.721	158	+0.190	+0.004
6	m	7.4958	7.2156	1.749	147	+0.065	+0.179
7	m	7.7583	7.4997	1.500	158	+0.241	-0.084
9	f	7.9507	7.9106	0.215	158	+0.064	-
14	f	8.3923	8.2714	0.588	108	+0.213	-
17	f	7.3959	7.3676	0.175	180	+0.051	+0.025
18	m	7.7633	7.3521	2.432	4	+0.203	+0.236
19	m	7.4791	7.2707	1.293	14	+0.095	-0.045
21	m	7.7307	7.6099	0.693	162	+0.026	-
24	f	7.8721	7.7921	0.440	113	+0.271	-0.057
26	f	7.3693	7.2533	0.733	173	-0.004	+0.081
28	m	7.5955	7.5758	0.116	113	+0.100	+0.038
31	m	7.9726	7.7476	1.230	1	+0.011	+0.025
34	m	7.7525	7.3047	2.669	142	+0.046	+0.205
35	f	7.4667	7.2403	1.413	177	+0.256	+0.141
39	f	7.4023	7.2631	0.873	158	+0.306	+0.011
41	m	7.9729	7.7370	1.291	47	+0.206	-
42	m	6.9345	6.9142	0.143	113	+0.056	-

Table D5(a). Age 2- <3 yrs : HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
3	m	2	1	R	5.95	11.90	2.6800	7.6629	1.7833	1.8067	1.7900	7.6771	7.7759	7.7054	0.9000	7.6935
4	f	2	6	L	6.00	12.00	missing		1.8733	1.8600	1.8600	8.0571	8.0009	8.0009	0.9333	7.9617
5	f	2	2	L	6.00	12.00	2.7200	7.7745	1.8100	1.7833	1.7467	7.7898	7.6771	7.5226	0.8900	7.6130
7	m	2	9	R	6.00	12.00	2.6100	7.4675	1.7133	1.7000	1.7167	7.3816	7.3254	7.3959	0.8633	7.3979
12	m	2	2	L	5.90	11.80	2.6333	7.5325	1.7167	1.6800	1.6833	7.3959	7.2410	7.2549	0.8500	7.2908
13	m	2	1	R	6.15	12.30	2.7200	7.7745	1.7933	1.6833	1.6767	7.7193	7.2549	7.2270	0.9000	7.6935
17	f	2	6	L	5.90	11.80	blocked by tear meniscus		1.8433	1.7300	1.7400	7.9304	7.4521	7.4943	0.9267	7.9086
18	f	2	8	R	5.75	11.50	too faint		1.5533	1.5500	1.5500	6.7060	6.6921	6.6921	0.7333	6.3507
19	f	2	3	R	5.70	11.40	2.4433	7.0023	1.6000	1.5333	1.5700	6.9032	6.6216	6.7765	0.7600	6.5658
20	m	2	10	R	5.90	11.80	missing		1.8033	1.8000	1.7767	7.7615	7.7476	7.6492	0.9133	7.8006
22	m	2	0	R	limbus not distinct		missing		1.6333	1.6700	1.6700	7.0438	7.1987	7.1987	0.8067	6.9420

continued...
Table D5(a). Age 2- <3 yrs : HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
24	m	2	7	L	6.15	12.30	2.9200	8.3327	1.9400	1.9333	1.9167	8.3387	8.3104	8.2403	0.9667	8.2308
25	f	2	6	L	6.00	12.00	2.9233	8.3419	1.9300	1.9200	1.9167	8.2965	8.2542	8.2403	0.9567	8.1502
26	m	2	8	R	6.20	12.40	2.6533	7.5884	1.7600	1.7200	1.7333	7.5787	7.4098	7.4660	0.8767	7.5058
27	f	2	4	L	5.80	11.60	too faint		1.7100	1.6767	1.7033	7.3676	7.2270	7.3393	0.8300	7.1297
29	f	2	6	L	5.75	11.50	too faint		1.6700	1.6267	1.6667	7.1987	7.0159	7.1848	0.8133	6.9951
30	f	2	9	L	5.70	11.40	2.4933	7.1418	1.6200	1.6133	1.6267	6.9876	6.9594	7.0159	0.7900	6.8075
33	m	2	0	R	5.85	11.70	2.6000	7.4396	1.6900	1.6300	1.6867	7.2832	7.0299	7.2692	0.8167	7.0225
36	m	2	6	L	6.20	12.40	2.8233	8.0628	1.8800	1.8433	1.8333	8.0854	7.9304	7.8882	0.9100	7.7741
37	m	2	5	L	5.80	11.60	2.8200	8.0536	1.8467	1.7933	1.8200	7.9448	7.7193	7.8320	0.9133	7.8006
38	m	2	9	L	6.25	12.50	too faint		1.8400	too faint	1.8133	7.9165	-	7.8038	0.9200	7.8546
41	m	2	6	L	5.80	11.60	missing		1.7933	1.8200	1.7800	7.7193	7.8320	7.6632	0.9000	7.6935

Table D5 (b). Age 2-< 3 yrs: Principal corneal radii, corneal astigatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
3	m	7.7802	7.6729	0.606	101	-0.016	-0.014
4	f	8.0688	7.9894	0.416	158	+0.095	-
5	f	7.9633	7.5157	2.524	142	+0.177	-0.015
7	m	7.4045	7.3030	0.634	28	-0.016	+0.086
12	m	7.4190	7.2189	1.261	160	+0.105	+0.137
13	m	7.8468	7.1458	4.219	156	+0.026	+0.055
17	f	8.0046	7.3877	3.521	160	+0.022	-
18	f	6.7089	6.6892	0.148	158	+0.355	-
19	f	6.9043	6.6206	2.094	4	+0.337	+0.099
20	m	7.8631	7.6490	1.201	137	-0.039	-
22	m	7.2317	7.0125	1.459	68	+0.102	-
24	m	8.4116	8.2392	0.840	140	+0.108	-0.006
25	f	8.3165	8.2345	0.404	151	+0.146	+0.045
26	m	7.5832	7.4056	1.067	171	+0.073	+0.010
27	f	7.3797	7.2155	1.041	16	+0.238	-
29	f	7.2282	6.9881	1.604	20	+0.204	-
30	f	7.0183	6.9292	0.618	36	+0.180	+0.154
33	m	7.3282	6.9884	2.239	21	+0.261	+0.156
36	m	8.1532	7.8662	1.510	151	+0.311	-0.023
37	m	7.9448	7.7193	1.241	180	+0.144	+0.109
41	m	7.9043	7.6504	1.417	122	+0.026	-

Table D6(a). Age 3-<4 yrs : HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
3	f	3	0	L	6.00	12.00	2.8000	7.9978	1.8600	1.8500	1.8433	8.0009	7.9587	7.9304	0.9167	7.8280
5	f	3	6	R	6.15	12.30	2.8933	8.2582	1.9300	1.8967	1.9300	8.2965	8.1559	8.2965	0.9200	7.8546
6	f	3	0	L	5.75	11.50	2.5333	7.2534	1.6600	1.6433	1.6533	7.1565	7.0860	7.1282	0.8400	7.2102
7	f	3	11	L	6.00	12.00	2.6433	7.5605	1.7167	1.7000	1.7300	7.3959	7.3254	7.4521	0.8233	7.0757
8	m	3	6	R	6.00	12.00	2.6400	7.5512	1.7233	1.6900	1.7200	7.4238	7.2832	7.4098	0.8600	7.3713
10	f	3	6	R	5.80	11.60	2.5033	7.1697	1.6600	1.6600	1.6533	7.1565	7.1565	7.1282	0.8300	7.1205
11	f	3	2	R	5.85	11.70	2.6200	7.4954	1.7433	1.7000	1.6967	7.5082	7.3254	7.3115	0.8567	7.3447
13	f	3	6	L	5.95	11.90	2.6533	7.5884	1.7300	1.7533	1.7667	7.4521	7.5504	7.6070	0.8800	7.5324
14	m	3	1	L	6.10	12.20	too faint		1.6500	1.6333	1.6533	7.1143	7.0438	7.1282	0.8267	7.1031
15	f	3	0	R	5.55	11.10	2.4867	7.1234	1.6433	1.5800	1.6267	7.0860	6.8188	7.0159	0.8033	6.9146
16	m	3	6	R	6.15	12.30	2.9533	8.4257	1.9267	1.9200	1.9367	8.2825	8.2542	8.3247	0,9600	8.1768
17	f	3	8	R	6.15	12.30	2.7567	7.8769	1.8300	1.7967	1.8100	7.8746	7.7337	7.7898	0.9200	7.8546

continued
Table D6(a). Age 3-<4 yrs: HVID and ring diameters.

Subject No.	Sex	Age		Eye	HVID		Ring 3		Ring 2						Ring 1	
		yrs	mos		mean diameter on negative (mm)	actual diameter (mm)	mean diameter (mm) al 180	computed radius (mm) al 180	mean diameter (mm) al 180	mean diameter (mm) al 90	mean diameter (mm) al 45	computed radius (mm) al 180	computed radius (mm) al 90	computed radius (mm) al 45	mean diameter (mm) al 180	computed radius (mm) al 180
18	f	3	1	R	6.00	12.00	2.9400	8.3885	1.9667	1.9900	1.9667	8.4514	8.5498	8.4514	0.9800	8.1800
20	f	3	1	R	5.90	11.80	2.6533	7.5884	1.7200	1.7200	1.7167	7.4098	7.4098	7.3959	0.8633	7.3979
21	m	3	2	L	6.00	12.00	missing		1.8100	1.8233	1.8000	7.7898	7.8460	7.7476	0.9100	7.7741
23	m	3	8	L	6.00	12.00	missing		1.6900	1.6900	1.6967	7.2832	7.2832	7.3115	0.8333	7.1562

Table D6(b). Age 3-< 4 yrs: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
3	f	8.0341	7.9262	0.572	147	+0.173	-0.003
5	f	8.3262	8.1273	0.992	23	+0.442	-0.038
6	f	7.1572	7.0853	0.479	6	-0.054	+0.097
7	f	7.4589	7.2647	1.210	34	+0.320	+0.165
8	m	7.4442	7.2637	1.127	19	+0.053	+0.127
10	f	7.1850	7.1282	0.375	135	+0.036	+0.013
11	f	7.5581	7.2785	1.715	155	+0.163	-0.013
13	f	7.6183	7.3871	1.387	58	+0.018	+0.136
14	m	7.1398	7.0190	0.813	27	+0.011	-
15	f	7.1018	6.8042	2.079	13	+0.171	+0.037
16	m	8.3265	8.2110	0.570	38	+0.106	+0.143
17	f	7.8743	7.7337	0.779	175	+0.020	+0.002
18	f	8.5656	8.4360	0.605	113	+0.271	-0.063
20	f	7.4238	7.3959	0.172	135	+0.012	+0.179
21	m	7.8947	7.7423	0.842	124	+0.016	-
23	m	7.3115	7.2551	0.359	45	+0.127	-

Table D7(a). Age 4- <5 yrs: HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
3	m	4	6	R	6.05	12.10	2.8500	8.1374	1.8933	1.7667	1.8733	8.1415	7.6070	8.0571	0.9500	8.0963
4	f	4	0	L	6.05	12.10	2.8200	8.0536	1.8700	1.7867	1.8300	8.0431	7.6914	7.8743	0.9300	7.9352
5	f	4	2	R	5.70	11.40	too faint		1.6600	1.6133	1.6633	7.1565	6.9594	7.1705	0.8267	7.1031
6	f	4	0	R	6.00	12.00	too faint		1.8533	1.8067	1.8367	7.9726	7.7759	7.9025	0.9233	7.8812
7	m	4	6	R	6.00	12.00	2.4333	6.9743	1.5767	1.6000	1.5933	6.8048	6.9032	6.8749	0.7600	6.5658
8	m	4	6	L	5.75	11.50	2.6900	7.6908	1.7833	1.7500	1.7500	7.6771	7.5365	7.5365	0.8667	7.4253
9	m	4	8	R	6.00	12.00	2.7133	7.7558	1.7900	1.7900	1.7767	7.7054	7.7054	7.6492	0.8867	7.5864
10	m	4	9	R	6.05	12.10	too faint		1.9333	1.8800	1.9333	8.3104	8.0854	8.3104	0.9600	8.1768
11	m	4	1	L	6.25	12.50	2.8900	8.2490	1.9167	1.8800	1.8800	8.2403	8.0854	8.0854	0.9733	8.2839
12	f	4	11	L	5.95	11.90	3.0233	8.6210	1.9800	1.9167	1.9500	8.5076	8.2043	8.3809	0.9667	8.2308
13	f	4	0	R	5.75	11.50	2.6800	7.6629	1.7733	1.7467	1.7700	7.6349	7.5226	7.6209	0.8600	7.3713
14	f	4	9	R	6.00	12.00	2.6300	7.5233	1.7467	1.7167	1.7200	7.5226	7.3959	7.4098	0.8533	7.3173

Continued
Table D7(a). Age 4- <5 yrs: HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
15	f	4	4	L	5.55	11.10	2.4433	7.0023	1.5967	1.5600	1.6033	6.8893	6.7343	6.9171	0.7700	6.6464
16	f	4	4	R	5.70	11.40	2.7433	7.8396	1.8400	1.8300	1.7967	7.9165	7.8743	7.7337	0.9067	7.7475
18	f	4	7	R	5.80	11.60	2.9867	8.5189	1.9900	1.9433	1.9567	8.5498	8.3526	8.4092	0.9900	8.4185
19	f	4	2	L	6.00	12.00	2.7900	7.9699	1.7633	1.7367	1.7633	7.5927	7.4803	7.5927	0.8600	7.3713
20	f	4	11	L	5.60	11.20	2.7133	7.7558	1.7867	1.7700	1.7867	7.6914	7.6209	7.6914	0.8800	7.5394
22	m	4	10	R	6.00	12.00	2.6967	7.7095	1.7867	1.7800	1.7867	7.6914	7.6632	7.6914	0.8967	7.6669
24	f	4	6	R	6.10	12.20	2.9800	8.5002	1.9867	1.9667	1.9800	8.5358	8.4514	8.5076	0.9700	8.2574
25	m	4	4	L	6.15	12.30	2.5400	7.2721	1.6533	1.6200	1.6367	7.1282	6.9876	7.0581	0.8067	6.9420
27	f	4	3	R	6.20	12.40	2.7900	7.9699	1.8267	1.8633	1.8433	7.8603	8.0149	7.9304	0.9200	7.8546

Table D7(b). Age 4-< 5 yrs: Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
3	m	8.2054	7.5521	3.558	18	+0.045	-0.004
4	f	8.0435	7.6911	1.922	2	+0.108	+0.011
5	f	7.2090	6.9104	2.023	24	+0.053	-
6	f	7.9770	7.7717	1.118	8	+0.091	-
7	m	6.9076	6.8005	0.770	78	+0.239	+0.170
8	m	7.7069	7.5080	1.160	158	+0.252	+0.014
9	m	7.7624	7.6492	0.643	135	+0.119	+0.050
10	m	8.3586	8.0403	1.599	23	+0.134	-
11	m	8.2731	8.0540	1.110	158	-0.044	+0.009
12	f	8.5079	8.2400	1.290	2	+0.277	+0.113
13	f	7.6493	7.5086	0.827	19	+0.264	+0.028
14	f	7.5398	7.3794	0.973	161	+0.205	+0.001
15	f	6.9436	6.6832	1.894	27	+0.243	+0.113
16	f	8.0653	7.7324	1.802	139	+0.169	-0.077
18	f	8.5582	8.3446	1.009	169	+0.131	-0.031
19	f	7.6163	7.4575	0.944	23	+0.221	+0.377
20	f	7.7062	7.6065	0.574	23	+0.159	+0.064
22	m	7.6973	7.6573	0.229	23	+0.024	+0.018
24	f	8.5382	8.4491	0.417	9	+0.278	-0.036
25	m	7.1282	6.9876	0.953	180	+0.186	+0.145
27	f	8.0151	7.8601	0.831	92	+0.006	+0.110

APPENDIX E

BASIC DATA ON CONGENITAL CATARACT EYES

Table E1(a). HVID and ring diameters.

Subject No.	Sex	Age		Eye	HVID		Ring 3		Ring 2						Ring 1	
		mos	wks		mean diameter on negative (mm)	actual diameter (mm)	mean diameter (mm) al 180	computed radius (mm) al 180	mean diameter (mm) al 180	al 90	al 45	computed radius (mm) al 180	al 90	al 45	mean diameter (mm) al 180	computed radius (mm) al 180
Age Group <1yr																
2 Cof's syndrome	f	2	3	R	limbus not distinct		2.5733	7.3651	1.6367	1.6200	1.6733	7.0581	6.9876	7.2127	0.8000	6.8880
5	f	10	1	R	limbus not distinct		too faint		1.7667	1.7413	1.7300	7.6071	7.5082	7.4521	0.8600	7.3713
7	f	9	0	L	4.70	9.40	missing		1.5033	1.4333	1.4700	6.4949	6.1994	6.3543	0.7433	6.4313
8 Middle-Eastern	m	2	3	R	limbus not distinct		2.5000	7.1605	1.6733	1.5667	1.5700	7.2127	6.7626	6.7765	0.8400	7.2102
15 Asian	m	7	3	R	5.60	11.20	2.7610	7.8890	1.8200	1.7167	1.7633	7.8320	7.3959	7.5927	0.9067	7.7475
20	f	5	0	L	5.80	11.60	too faint		1.7233	1.6400	1.7133	7.4238	7.0721	7.3816	0.8700	7.4519

continued...
Table E1(a). HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
Age Group 1 - <2 yrs																
1 Asian	m	1	11	R	5.10	10.20	2.6400	7.5512	1.7533	1.6700	1.7267	7.5504	7.1987	7.4381	0.8800	7.5324
2	m	1	2	L	5.05	10.10	2.6633	7.6163	1.7700	1.7333	1.7500	7.6209	7.4660	7.5365	0.8900	7.6130
4	m	1	8	L	5.85	11.70	2.5400	7.2721	1.6733	1.6000	1.6233	7.2127	6.9032	7.0016	0.8200	7.0491
5	m	1	4	R	5.70	11.40	2.7267	7.7932	1.8100	1.7667	1.7767	7.7898	7.6070	7.6492	0.8767	7.5058
6	m	1	6	L	5.60	11.20	2.4133	6.9185	1.5833	1.5400	1.6000	6.8327	6.6499	6.9032	0.7900	6.8075
7	m	1	6	L	5.05	10.10	2.3800	6.8256	1.5800	1.5667	1.5433	6.8188	6.7626	6.6638	0.7600	6.5658
11 rubella	m	1	7	L	5.00	10.00	2.5600	7.3280	1.6867	blocked by top eyelid		7.2692	-	-	0.8200	7.0491

continued...
Table E1(a). HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
Age Group 2 - <3 yrs																
6	m	2	0	R	limbus not distinct		2.7167	7.7653	1.7467	block-ed by top lid	1.7667	7.5226	-	7.6070	0.8500	7.2908
9 poly-syndactyly	f	2	5	R	5.05	10.10	2.3567	6.7605	1.5700	1.5700	1.5367	6.7765	6.7765	6.6359	0.7800	6.7269
Age Group 3 - <4 yrs																
2 West Indian	f	3	7	L	5.70	11.40	2.3733	6.8069	1.5833	1.5000	1.5233	6.8327	6.4810	6.5794	0.7800	6.7269
7 rubella	f	3	3	L	5.40	10.80	2.3767	6.8164	1.5800	1.5733	1.5633	6.8188	6.7905	6.7483	0.7833	6.7535
11	m	3	8	R	5.50	11.00	2.5067	7.1792	1.6000	1.5433	1.6100	6.9032	6.6638	6.9454	0.8000	6.8880
12	m	3	9	L	6.00	12.00	too faint	1.8233	1.7267	1.7500	7.8460	7.4381	7.5365	0.09167	7.8280	
15	f	3	3	R	limbus not	2.5833	7.3930	1.7267	1.6733	1.6433	7.4681	7.2127	7.0860	0.8500	7.2908	

continued...
Table E1(a). HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
Age Group 4 - <5 yrs																
5 Lowe's Syndrome	m	4	0	R	5.55	11.10	too faint	1.8100	1.8467	1.8500	7.7898	7.9448	7.9587	0.9033	7.7201	
7	f	4	9	L	5.70	11.40	2.7267	7.7932	1.7700	1.6433	1.6867	7.6209	7.0860	7.2692	0.8633	7.3979
8 rubella	f	4	6	R	5.50	11.00	2.6300	7.5233	1.7467	1.7200	1.7400	7.5226	7.4098	7.4943	0.8700	7.4519
9	f	4	10	R	6.00	12.00	2.7330	7.7558	1.7933	1.8033	1.7667	7.7193	7.7615	7.6070	0.8833	7.5590
Age Group 5 - <15 yrs																
1	f	5	10	L	5.70	11.40	2.4900	7.1326	1.6300	1.6333	1.6167	7.0299	7.0438	6.9737	0.8033	6.9146
2	m	5	11	R	5.90	11.80	2.5633	7.3372	1.7000	1.6667	1.7267	7.3254	7.1848	7.4381	0.8567	7.3447
3	f	5	2	R	6.00	12.00	2.7300	7.8024	1.8067	1.7100	1.7733	7.7759	7.3676	7.6349	0.9100	7.7741
4 Asian	m	8	8	R	5.70	11.40	2.9367	8.3793	1.9467	1.8267	1.9333	8.3670	7.6803	8.3104	0.9700	8.2574

continued...
Table E1(a). HVID and ring diameters.

Subject No.	Sex	Age yrs	Age mos	Eye	HVID mean diameter on negative (mm)	HVID actual diameter (mm)	Ring 3 mean diameter (mm) al 180	Ring 3 computed radius (mm) al 180	Ring 2 mean diameter (mm) al 180	Ring 2 mean diameter (mm) al 90	Ring 2 mean diameter (mm) al 45	Ring 2 computed radius (mm) al 180	Ring 2 computed radius (mm) al 90	Ring 2 computed radius (mm) al 45	Ring 1 mean diameter (mm) al 180	Ring 1 computed radius (mm) al 180
8 Negro	m	14	10	L	5.95	11.90	2.6900	7.6908	1.7833	1.7633	1.7300	7.6771	7.5927	7.4521	0.8933	7.6395
12 Cerebral Palsy	m	13	2	L	6.00	12.00	2.5467	7.2908	1.6400	1.5567	1.6067	7.0721	6.7204	6.9315	0.8100	6.9686
13 Galacto-saemia	f	11	3	L	6.00	12.00	2.6700	7.6350	1.7500	1.7000	1.7067	7.5365	7.3254	7.3537	0.8767	7.5058
15	f	8	4	L	6.05	12.10	2.7300	7.8024	1.7500	1.7833	1.8000	7.5365	7.6771	7.7476	0.8733	7.4784
16	f	8	1	R	5.50	11.00	2.9967	8.5468	1.9567	1.8933	1.9900	8.4092	8.1415	8.5498	0.9600	8.1768
17	m	13	0	L	5.95	11.90	2.9333	8.3698	1.9300	1.8333	1.8500	8.2965	7.8882	7.9587	0.9567	8.1502
18	m	9	4	R	6.15	12.30	2.8900	8.2490	1.9100	1.8033	1.8667	8.2120	7.7615	8.1415	0.9500	8.0963

Table E1(b). Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
Age Group < 1 yr.							
2	f	7.2162	6.8394	2.577	40	+0.170	+0.307
5	f	7.6767	7.4415	1.390	147	+0.236	-
7	f	6.4953	6.1990	2.484	2	+0.064	-
8	m	7.3022	6.6858	4.261	159	+0.027	-0.052
15	m	7.8326	7.3954	2.547	178	+0.085	+0.057
20	f	7.4725	7.0285	2.853	19	-0.028	-
Age Group 1-< 2 yrs.							
1	m	7.5634	7.1869	2.338	11	+0.018	+0.001
2	m	7.6212	7.4657	0.922	178	+0.008	-0.005
4	m	7.2220	6.8946	2.219	171	+0.164	+0.059
5	m	7.8022	7.5953	1.1782	166	+0.284	+0.003
6	m	6.9288	6.5613	2.7288	30	+0.025	+0.086
7	m	6.9254	6.6609	1.935	141	+0.253	+0.007
11	m	-	-	-	-	+0.220	+0.059

Continued
Table E1(b). Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of astigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
Age Group 2- < 3 yrs.							
6	m	-	-	-	-	+0.232	+0.243
9	f	6.9232	6.6359	2.110	135	+0.050	-0.016
Age Group 3- < 4 yrs.							
2	f	7.4867	7.3476	0.854	23	+0.106	-0.026
7	f	6.8636	6.7465	0.853	142	+0.065	-0.002
11	m	6.9874	6.5872	2.934	27	+0.015	+0.276
12	m	7.8712	7.4156	2.635	167	+0.018	-
15	f	7.6043	7.0630	3.401	147	+0.147	-0.045
Age Group 4- < 5 yrs.							
5	m	7.9880	7.7487	1.3044	65	+0.070	-
7	f	7.6322	7.0763	3.4734	172	+0.223	+0.172
8	f	7.5294	7.4032	0.764	13	+0.071	+0.001
9	f	7.8802	7.6054	1.547	131	+0.160	+0.037

Continued
Table E1(b). Principal corneal radii, corneal astigmatism and radius change along the horizontal.

Subject No.	Sex	Data computed from ring 2				Change in radius al 180 from rings	
		Flattest radius (mm)	Steepest radius (mm)	Amount of atigmatism (D)	Direction of flattest meridian (std. notation) (degrees)	1 - 2 (mm)	2 - 3 (mm)
Age Group 5- < 15 yrs.							
1	f	7.1015	6.9733	0.873	132	+0.115	+0.103
2	m	7.4521	7.0669	2.469	34	-0.019	+0.012
3	f	7.1388	6.7993	2.361	26	+0.002	+0.027
4	m	8.4414	7.7957	3.311	19	+0.110	-0.012
8	m	7.8313	7.4476	2.221	143	+0.038	+0.014
12	m	7.0767	6.7162	2.560	6	+0.104	+0.219
13	f	7.5621	7.3013	1.594	162	+0.031	+0.098
15	f	7.7650	7.4536	1.816	58	+0.058	+0.266
16	f	8.5836	7.9844	2.951	32	+0.232	+0.138
17	m	8.3369	7.8520	2.500	164	+0.146	+0.073
18	m	8.2124	7.8317	1.998	2	+0.116	+0.037

APPENDIX F

STATISTICAL ANALYSIS OF RESULTS

General notes

a) All tests were carried out on HVID, flattest corneal radii and steepest corneal radii using the "Statgraphics" statistical package. The chi-square contingency table test on the incidence of corneal astigmatism with age was carried out using the Hewlett Packard 85 General Statistics package.

b) For data on HVID, flattest and steepest corneal radii, the codes used for the age groups were:

0 - 1 - < 3 months

1 - 3 - < 6 months

2 - 6 - <12 months

3 - 1 - < 2 years

4 - 2 - < 3 years

5 - 3 - < 4 years

6 - 4 - < 5 years

The codes used for the sexes were:-

1 - males

2 - females

File A:CORNEA

2-WAY ANALYSIS OF VARIANCE FOR HVID

Input Data

row	age	sex	diam
1	0	1	11.0
2	0	1	10.5
3	0	1	10.4
4	0	1	11.6
5	0	1	11.5
6	0	2	10.4
7	0	2	11.2
8	0	2	10.7
9	0	2	10.6
10	0	2	11.0
11	0	2	11.3
12	1	1	11.9
13	1	1	11.0
14	1	1	12.0
15	1	1	11.8
16	1	1	11.7
17	1	1	11.6
18	1	1	12.1
19	1	1	11.8
20	1	1	11.8
21	1	1	11.6
22	1	1	11.8
23	1	1	11.1
24	1	1	11.6
25	1	1	11.2
26	1	1	11.7
27	1	1	11.6
28	1	1	11.9
29	1	2	11.6
30	1	2	11.7
31	1	2	11.4
32	1	2	11.0
33	1	2	12.0
34	1	2	12.0
35	1	2	11.6
36	1	2	11.9
37	2	1	11.4
38	2	1	12.3
39	2	1	11.7
40	2	1	11.4
41	2	1	11.6
42	2	1	11.4
43	2	1	11.6
44	2	1	11.5
45	2	1	12.0
46	2	1	12.1
47	2	1	12.0
48	2	1	11.0
49	2	1	12.5
50	2	1	12.2
51	2	1	12.3
52	2	1	11.2
53	2	2	11.4
54	2	2	11.6
55	2	2	11.7
56	2	2	11.8
57	2	2	11.0

58	2	2	11.3
59	2	2	11.2
60	2	2	12.0
61	2	2	11.8
62	2	2	11.6
63	2	2	11.2
64	2	2	12.0
65	2	2	11.7
66	2	2	11.0
67	2	2	12.1
68	2	2	10.8
69	2	2	11.6
70	3	1	11.7
71	3	1	12.0
72	3	1	11.5
73	3	1	12.3
74	3	1	11.4
75	3	1	12.0
76	3	1	12.0
77	3	1	11.9
78	3	1	12.1
79	3	1	12.0
80	3	1	11.6
81	3	2	12.0
82	3	2	12.1
83	3	2	12.0
84	3	2	11.4
85	3	2	11.5
86	3	2	11.6
87	3	2	11.6
88	3	2	11.8
89	4	1	11.9
90	4	1	12.0
91	4	1	11.8
92	4	1	12.3
93	4	1	11.6
94	4	1	11.8
95	4	1	12.3
96	4	1	12.4
97	4	1	11.7
98	4	1	12.4
99	4	1	11.6
100	4	1	12.5
101	4	2	12.0
102	4	2	12.0
103	4	2	11.8
104	4	2	11.5
105	4	2	11.4
106	4	2	12.0
107	4	2	11.6
108	4	2	11.5
109	4	2	11.4
110	5	1	12.0
111	5	1	12.2
112	5	1	12.3
113	5	1	12.0
114	5	1	12.0

File A:CORNEA

row	age	sex	diam
115	5	2	12.0
116	5	2	12.3
117	5	2	11.5
118	5	2	12.0
119	5	2	11.6
120	5	2	11.7
121	5	2	11.9
122	5	2	11.1
123	5	2	12.3
124	5	2	12.0
125	5	2	11.8
126	6	1	12.1
127	6	1	12.0
128	6	1	11.5
129	6	1	12.0
130	6	1	12.1
131	6	1	12.5
132	6	1	12.0
133	6	1	12.3
134	6	2	12.1
135	6	2	11.4
136	6	2	12.0
137	6	2	11.9
138	6	2	11.5
139	6	2	12.0
140	6	2	11.1
141	6	2	11.4
142	6	2	11.6
143	6	2	12.0
144	6	2	11.2
145	6	2	12.2
146	6	2	12.4

Analysis of Variance for A:CORNEA.diam

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	10.527980	7	1.5039971	12.098	.0000
A:CORNEA.age	9.301404	6	1.5502341	12.470	.0000
A:CORNEA.sex	1.466062	1	1.4660624	11.793	.0008
2-FACTOR INTERACTIONS	.4285243	6	.0714207	.574	.7501
A:CORNEA.aA:CORNEA.s	.4285243	6	.0714207	.574	.7501
RESIDUAL	16.410071	132	.1243187		
TOTAL (CORR.)	27.366575	145			

0 missing values have been excluded.

Table of means for A:CORNEA.diam

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A:CORNEA.age						
0	11	10.927273	.1314886	.1063095	10.716935	11.137610
1	25	11.656000	.0616658	.0705177	11.516478	11.795522
2	33	11.636364	.0742154	.0613778	11.514925	11.757802
3	19	11.815789	.0617783	.0808894	11.655747	11.975832
4	21	11.880952	.0751567	.0769411	11.728721	12.033184
5	16	11.918750	.0807356	.0881472	11.744347	12.093153
6	21	11.871429	.0853962	.0769411	11.719197	12.023660
A:CORNEA.sex						
1	74	11.800000	.0500647	.0409876	11.718904	11.881096
2	72	11.616667	.0496466	.0415530	11.534452	11.698881
A:CORNEA.age by A:CORNEA.sex						
0 1	5	11.000000	.2469818	.1576824	10.688019	11.311981
0 2	6	10.866667	.1452966	.1439437	10.581868	11.151465
Total	146	11.709589	.0291804	.0291804	11.651854	11.767324

Table of means for A:CORNEA.diam

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
1	1	17	11.658824	.0737936	.0855153	11.489628	11.828019
1	2	8	11.650000	.1195229	.1246589	11.403357	11.896643
2	1	16	11.762500	.1110086	.0881472	11.588097	11.936903
2	2	17	11.517647	.0932404	.0855153	11.348452	11.686843
3	1	11	11.863636	.0834187	.1063095	11.653299	12.073974
3	2	8	11.750000	.0925820	.1246589	11.503357	11.996643
4	1	12	12.025000	.0970200	.1017836	11.823617	12.226383
4	2	9	11.688889	.0873124	.1175295	11.456352	11.921426
5	1	5	12.100000	.0632456	.1576824	11.788019	12.411981
5	2	11	11.836364	.1064064	.1063095	11.626026	12.046701
6	1	8	12.062500	.1016603	.1246589	11.815857	12.309143
6	2	13	11.753846	.1135756	.0977905	11.560364	11.947329
Total		146	11.709589	.0291804	.0291804	11.651854	11.767324

Multiple range analysis for A:CORNEA.diam by A:CORNEA.a - age (m+f)

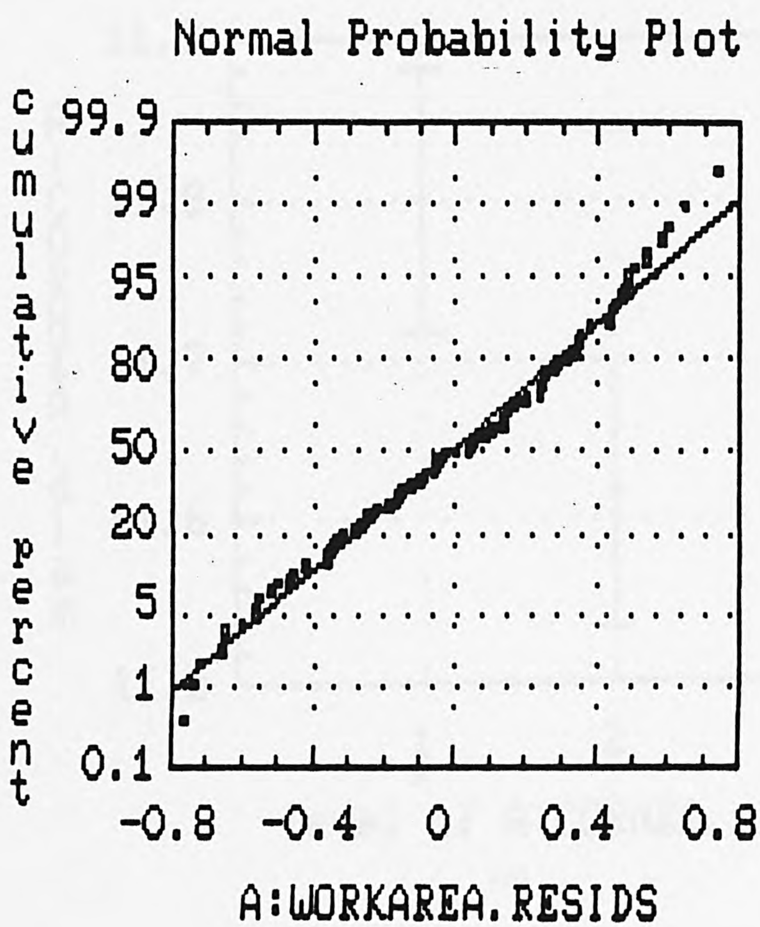
Method: 95 Percent Confidence Intervals

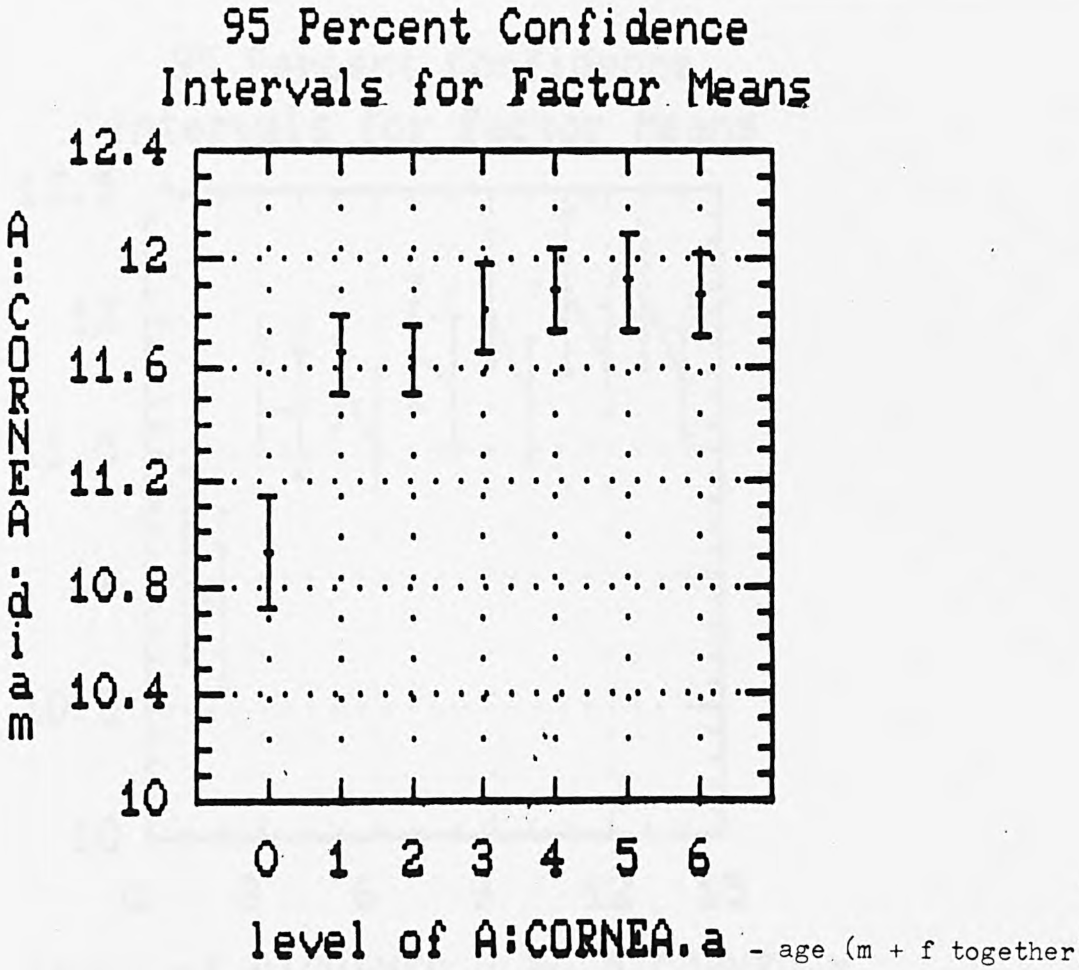
Level	Count	Average	Homogeneous Groups
0	11	10.927273	*
2	33	11.636364	*
1	25	11.656000	*
3	19	11.815789	*
6	21	11.871429	*
4	21	11.880952	*
5	16	11.918750	*

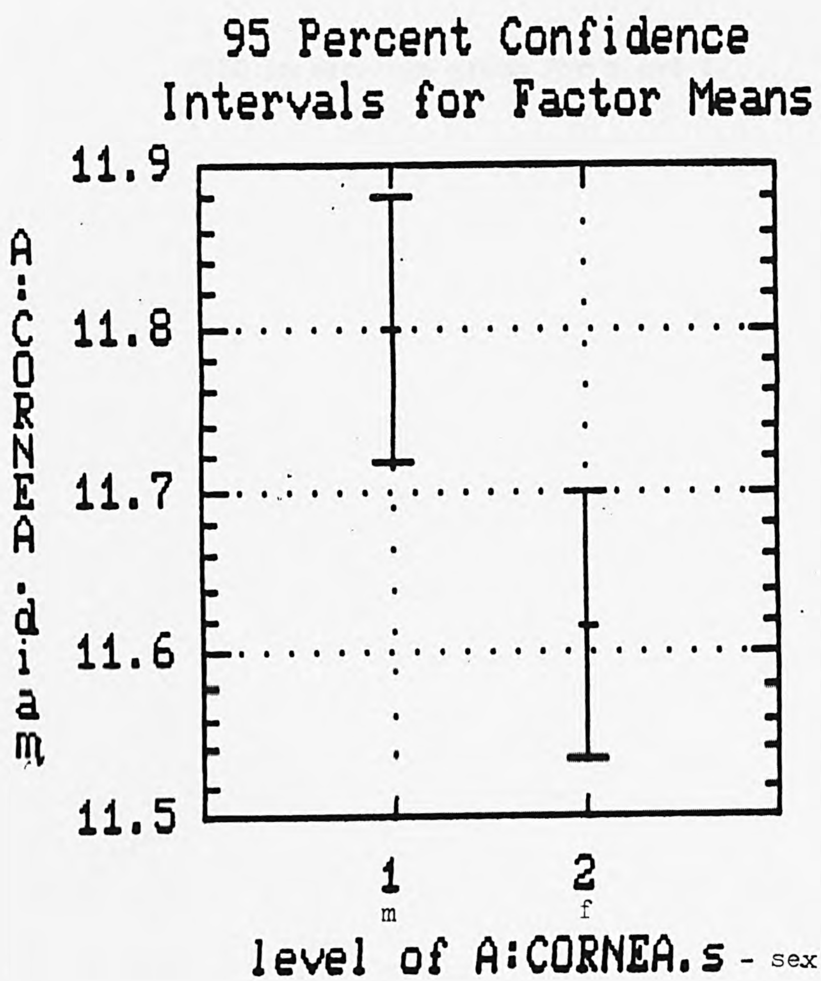
Multiple range analysis for A:CORNEA.diam by A:CORNEA.s - sex (all ages)

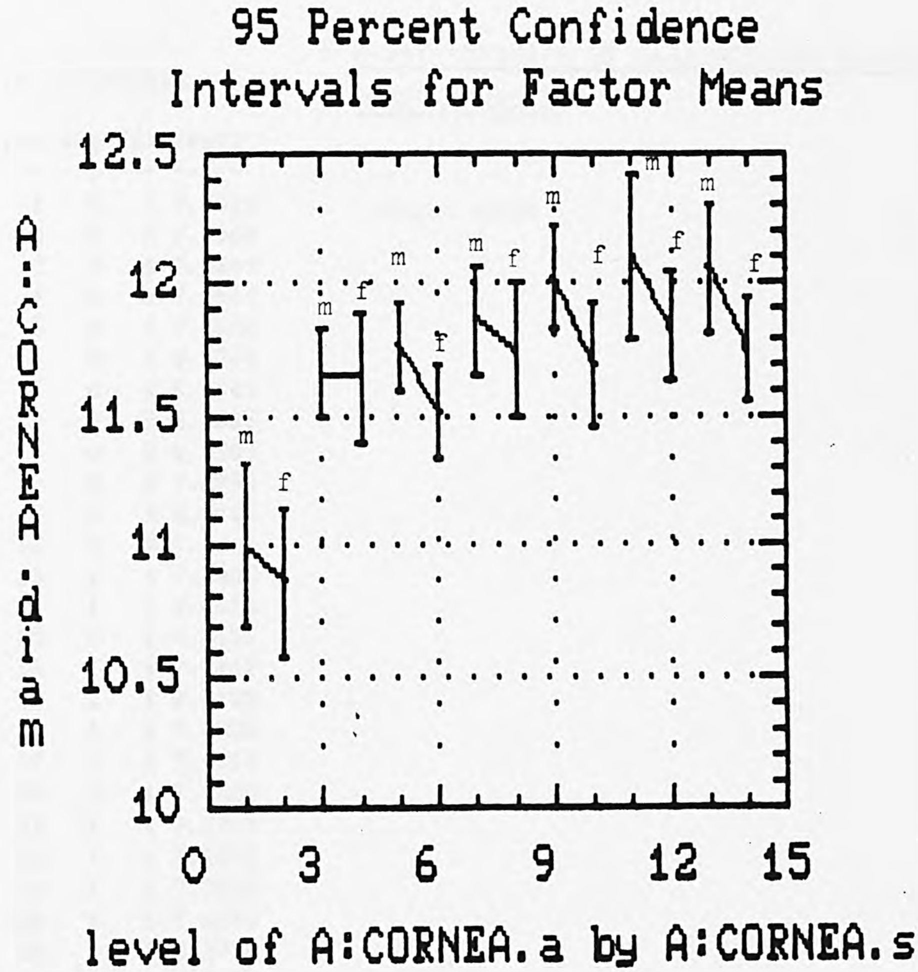
Method: 95 Percent Confidence Intervals

Level	Count	Average	Homogeneous Groups
2	72	11.616667	*
1	74	11.800000	*




95 Percent Confidence
Intervals for Factor Means
A:CORNEA.diam
12.4
12
11.6
11.2
10.8
10.4
10
0
1
2
3
4
5
6
level of A:CORNEA.a - age (m + f together)


95 Percent Confidence
Intervals for Factor Means
A:CORNEA.diam
11.9
11.8
11.7
11.6
11.5
1
m
2
f
level of A:CORNEA.s - sex



HVID in each age group for m and f.

2-WAY ANALYSIS OF VARIANCE FOR FLATTEST CORNEAL RADII.

File A:FLATCORN

Input data

row	AGE	SEX	RADII
1	0	1	7.7619
2	0	1	7.7563
3	0	1	7.6649
4	0	1	7.1544
5	0	1	7.7824
6	0	1	6.6245
7	0	2	6.9345
8	0	2	6.9625
9	0	2	6.9349
10	0	2	7.9893
11	0	2	6.5134
12	0	2	7.8467
13	1	1	7.6902
14	1	1	8.0013
15	1	1	6.8491
16	1	1	7.7462
17	1	1	8.2125
18	1	1	7.8321
19	1	1	7.1513
20	1	1	7.5835
21	1	1	7.3712
22	1	1	8.1777
23	1	1	7.7031
24	1	1	7.8899
25	1	1	8.2734
26	1	1	6.3441
27	1	1	8.1352
28	1	1	7.2079
29	1	1	7.9740
30	1	1	8.1483
31	1	1	7.5653
32	1	1	7.4107
33	1	2	7.6775
34	1	2	7.5836
35	1	2	7.7430
36	1	2	7.9030
37	1	2	7.9297
38	1	2	7.8134
39	1	2	8.0085
40	1	2	7.7934
41	2	1	6.4253
42	2	1	8.1992
43	2	1	8.5342
44	2	1	7.2816
45	2	1	8.2560
46	2	1	7.3979
47	2	1	7.5802
48	2	1	7.1919
49	2	1	8.0821
50	2	1	7.7174
51	2	1	7.8555
52	2	1	8.0821
53	2	1	7.0069
54	2	1	7.7951
55	2	1	8.4023
56	2	1	8.5434
57	2	1	6.3751

File A:FLATCORN

row	AGE	SEX	RADII
58	2	2	7.0705
59	2	2	8.4256
60	2	2	7.7817
61	2	2	8.2019
62	2	2	6.8676
63	2	2	7.1269
64	2	2	6.9892
65	2	2	7.6599
66	2	2	8.2171
67	2	2	7.5988
68	2	2	7.1999
69	2	2	7.7246
70	2	2	6.9466
71	2	2	7.2695
72	2	2	8.2441
73	2	2	6.6952
74	2	2	7.5017
75	3	1	7.2517
76	3	1	7.4958
77	3	1	7.7583
78	3	1	7.7633
79	3	1	7.4791
80	3	1	7.7307
81	3	1	7.5955
82	3	1	7.9726
83	3	1	7.7525
84	3	1	7.9729
85	3	1	6.9345
86	3	2	6.8245
87	3	2	7.9507
88	3	2	8.3923
89	3	2	7.3959
90	3	2	7.8721
91	3	2	7.3693
92	3	2	7.4667
93	3	2	7.4023
94	4	1	7.7802
95	4	1	7.4045
96	4	1	7.4190
97	4	1	7.8468
98	4	1	7.8631
99	4	1	7.2317
100	4	1	8.4116
101	4	1	7.5832
102	4	1	7.3282
103	4	1	8.1532
104	4	1	7.9448
105	4	1	7.9043
106	4	2	8.0688
107	4	2	7.9633
108	4	2	8.0046
109	4	2	6.7089
110	4	2	6.9043
111	4	2	8.3165
112	4	2	7.3797
113	4	2	7.2282
114	4	2	7.0183

File A:FLATCORN

row	AGE	SEX	RADII
115	5	1	7.4442
116	5	1	7.1398
117	5	1	8.3265
118	5	1	7.8947
119	5	1	7.3115
120	5	2	8.0341
121	5	2	8.3262
122	5	2	7.1572
123	5	2	7.4589
124	5	2	7.1850
125	5	2	7.5581
126	5	2	7.6183
127	5	2	7.1018
128	5	2	7.8743
129	5	2	8.5656
130	5	2	7.4238
131	6	1	8.2054
132	6	1	6.9076
133	6	1	7.7069
134	6	1	7.7624
135	6	1	8.3586
136	6	1	8.2731
137	6	1	7.6973
138	6	1	7.1282
139	6	2	8.0435
140	6	2	7.2090
141	6	2	7.9770
142	6	2	8.5079
143	6	2	7.6493
144	6	2	7.5398
145	6	2	6.9436
146	6	2	8.0653
147	6	2	8.5582
148	6	2	7.6163
149	6	2	7.7062
150	6	2	8.5382
151	6	2	8.0151

Analysis of Variance for A:FLATCORN.RADII

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2.2697593	7	.3242513	1.290	.2595
A:FLATCORN.AGE	2.1687364	6	.3614561	1.438	.2043
A:FLATCORN.SEX	.1281883	1	.1281883	.510	.4839
2-FACTOR INTERACTIONS	.8438084	6	.1406347	.560	.7618
A:FLATCORNA:FLATCORN	.8438084	6	.1406347	.560	.7618
RESIDUAL	34.426199	137	.2512861		
TOTAL (CORR.)	37.539767	150			

0 missing values have been excluded.

Table of means for A:FLATCORN.RADII

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A:FLATCORN.AGE						
0	12	7.3271417	.1514984	.1447084	7.0409270	7.6133563
1	28	7.7042536	.0812192	.0947339	7.5168821	7.8916250
2	34	7.5955000	.1040544	.0859696	7.4254632	7.7655368
3	19	7.5989842	.0861376	.1150025	7.3715239	7.8264445
4	21	7.6411048	.1025409	.1093892	7.4247468	7.8574627
5	16	7.6512500	.1169917	.1253211	7.4033809	7.8991191
6	21	7.8289952	.1090515	.1093892	7.6126373	8.0453532
A:FLATCORN.SEX						
1	79	7.6641937	.0550936	.0563989	7.5526438	7.7757435
2	72	7.6124069	.0605388	.0590769	7.4955603	7.7292536
A:FLATCORN.AGE by A:FLATCORN.SEX						
0 1	6	7.4574000	.1928967	.2046485	7.0526314	7.8621686
0 2	6	7.1968833	.2387294	.2046485	6.7921147	7.6016520
Total	151	7.6395007	.0407940	.0407940	7.5588154	7.7201859

Table of means for A:FLATCORN.RADII

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
1	1	20	7.6633500	.1116150	.1120906	7.4416491	7.8850509
1	2	8	7.8065125	.0492572	.1772308	7.4559726	8.1570524
2	1	17	7.6897765	.1624941	.1215793	7.4493081	7.9302449
2	2	17	7.5012235	.1309480	.1215793	7.2607551	7.7416919
3	1	11	7.6097182	.0933522	.1511430	7.3107767	7.9086596
3	2	8	7.5842250	.1677536	.1772308	7.2336851	7.9347649
4	1	12	7.7392167	.1025073	.1447084	7.4530020	8.0254313
4	2	9	7.5102889	.1957748	.1670948	7.1797967	7.8407811
5	1	5	7.6233400	.2157796	.2241812	7.1799382	8.0667418
5	2	11	7.6639364	.1461012	.1511430	7.3649949	7.9628778
6	1	8	7.7549375	.1867142	.1772308	7.4043976	8.1054774
6	2	13	7.8745692	.1380165	.1390313	7.5995831	8.1495554
Total		151	7.6395007	.0407940	.0407940	7.5588154	7.7201859

Multiple range analysis for A:FLATCORN.RADII by A:FLATCORN - age (m+f)

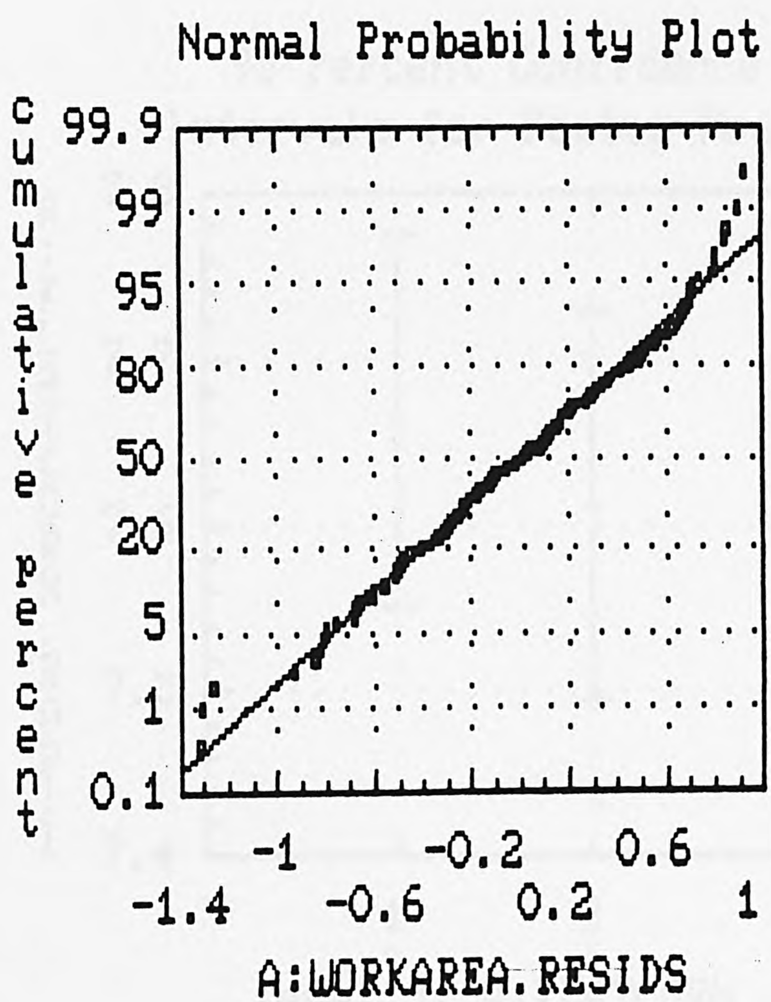
Method: 95 Percent Confidence Intervals

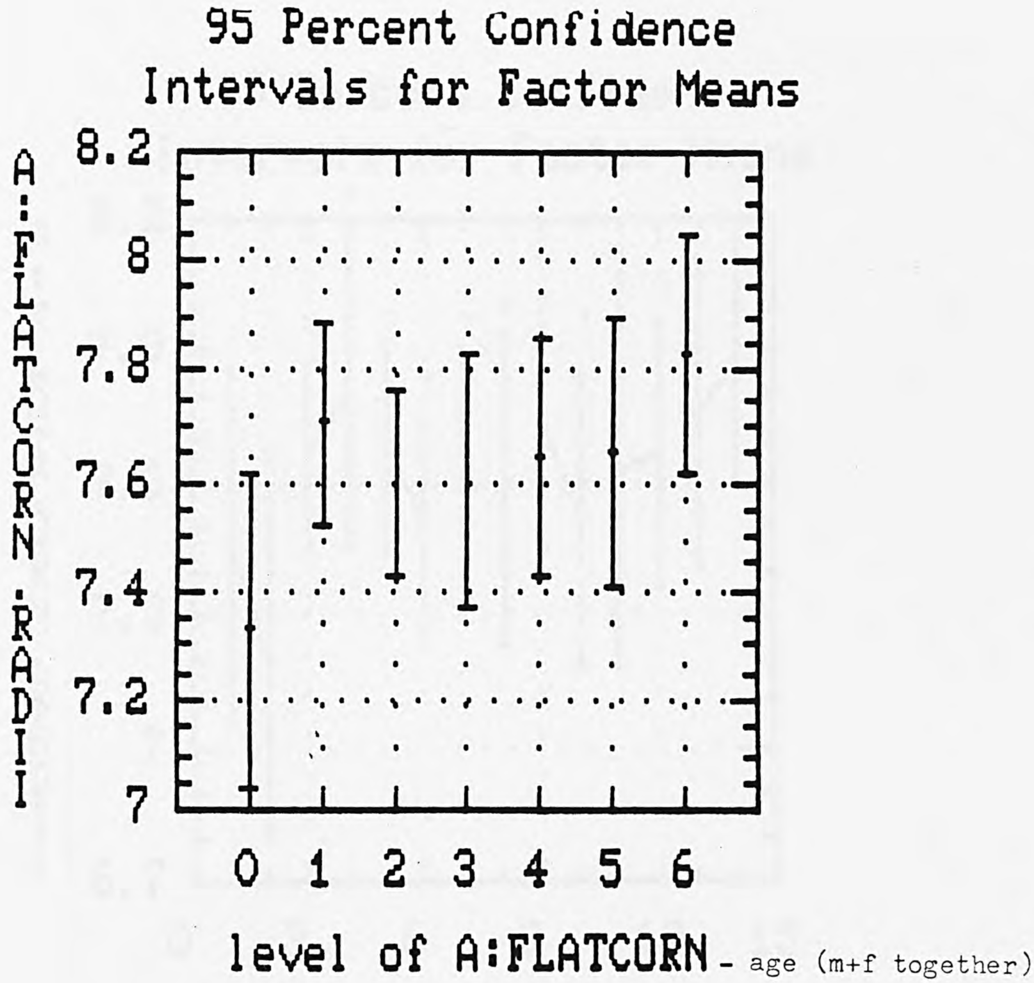
Level	Count	Average	Homogeneous Groups
0	12	7.3271417	*
2	34	7.5955000	*
3	19	7.5989842	*
4	21	7.6411048	*
5	16	7.6512500	*
1	28	7.7042536	*
6	21	7.8289952	*

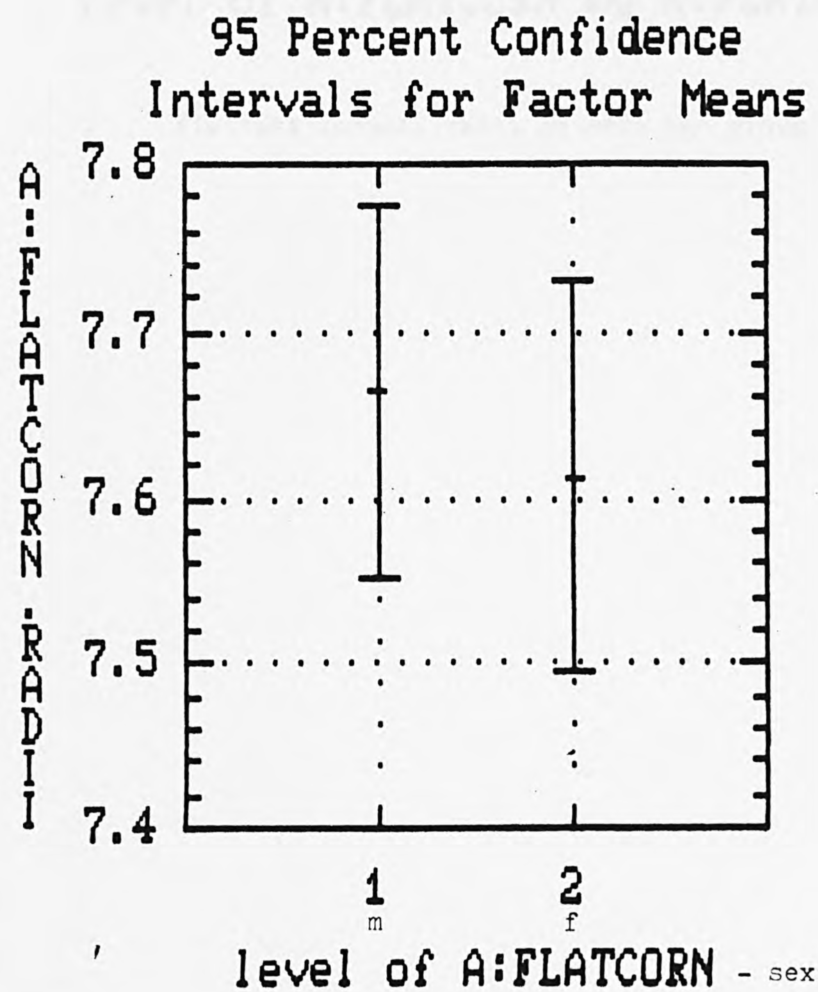
Multiple range analysis for A:FLATCORN.RADII by A:FLATCORN - sex (all ages)

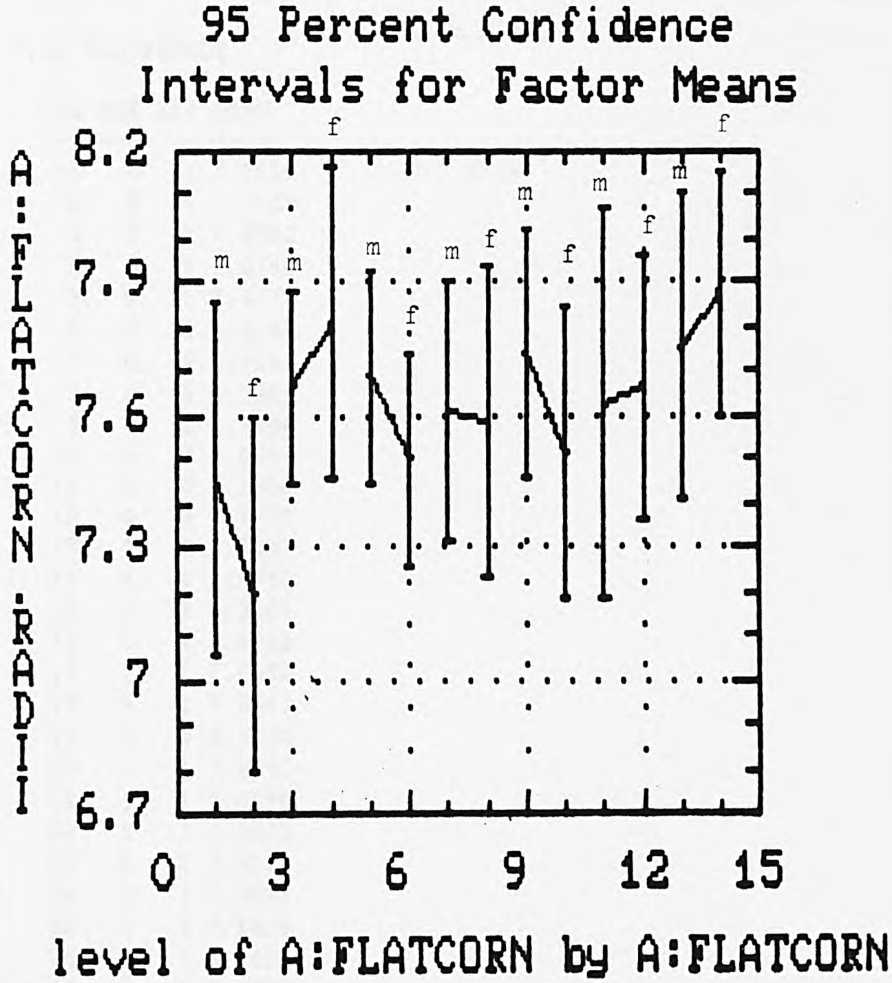
Method: 95 Percent Confidence Intervals

Level	Count	Average	Homogeneous Groups
2	72	7.6124069	*
1	79	7.6641937	*




95 Percent Confidence
Intervals for Factor Means
A:FLATCORN.RADII
8.2
8
7.8
7.6
7.4
7.2
7
0 1 2 3 4 5 6
level of A:FLATCORN - age (m+f together)


95 Percent Confidence
Intervals for Factor Means
A:FLATCORN.RADII
7.8
7.7
7.6
7.5
7.4
1
m
2
f
level of A:FLATCORN - sex



Flattest corneal radii in each age group for m + f.

2-WAY ANALYSIS OF VARIANCE FOR STEEPEST CORNEAL RADII.

File A:STEEPCOR

Input data

row	AGE	SEX	DATA
1	0	1	7.1660
2	0	1	7.3120
3	0	1	7.2862
4	0	1	7.0744
5	0	1	7.4377
6	0	1	6.6048
7	0	2	6.9141
8	0	2	6.5241
9	0	2	6.4784
10	0	2	7.6269
11	0	2	6.2800
12	0	2	7.7751
13	1	1	7.5251
14	1	1	7.6948
15	1	1	6.3104
16	1	1	7.4265
17	1	1	7.8892
18	1	1	7.5647
19	1	1	6.9531
20	1	1	7.2291
21	1	1	7.0599
22	1	1	7.8975
23	1	1	7.3577
24	1	1	7.5823
25	1	1	8.1656
26	1	1	6.1402
27	1	1	7.8963
28	1	1	7.0364
29	1	1	7.5446
30	1	1	7.7765
31	1	1	7.4661
32	1	1	7.0574
33	1	2	7.5222
34	1	2	7.1661
35	1	2	7.3031
36	1	2	7.4641
37	1	2	7.6790
38	1	2	7.4736
39	1	2	7.8387
40	1	2	7.5909
41	2	1	6.2412
42	2	1	7.9716
43	2	1	7.9527
44	2	1	6.9541
45	2	1	7.9862
46	2	1	6.9310
47	2	1	7.4517
48	2	1	6.6577
49	2	1	7.8235
50	2	1	7.3073
51	2	1	7.6547
52	2	1	7.7823
53	2	1	6.8990
54	2	1	7.5176
55	2	1	7.7176
56	2	1	8.2332
57	2	1	6.2225

File A:STEEL.COR

row	AGE	SEX	DATA
58	2	2	6.7112
59	2	2	8.0895
60	2	2	7.6996
61	2	2	7.9585
62	2	2	6.6877
63	2	2	6.7685
64	2	2	6.8606
65	2	2	7.4014
66	2	2	7.8085
67	2	2	7.4189
68	2	2	6.7007
69	2	2	7.6167
70	2	2	6.9020
71	2	2	7.1141
72	2	2	7.9413
73	2	2	6.4641
74	2	2	7.1842
75	3	1	6.9932
76	3	1	7.2156
77	3	1	7.4997
78	3	1	7.3521
79	3	1	7.2707
80	3	1	7.6099
81	3	1	7.5758
82	3	1	7.7476
83	3	1	7.3047
84	3	1	7.7370
85	3	1	6.9142
86	3	2	6.7426
87	3	2	7.9106
88	3	2	8.2714
89	3	2	7.3676
90	3	2	7.7921
91	3	2	7.2533
92	3	2	7.2403
93	3	2	7.2631
94	4	1	7.6729
95	4	1	7.3030
96	4	1	7.2189
97	4	1	7.1458
98	4	1	7.6490
99	4	1	7.0125
100	4	1	8.2392
101	4	1	7.4056
102	4	1	6.9884
103	4	1	7.8662
104	4	1	7.7193
105	4	1	7.6504
106	4	2	7.9894
107	4	2	7.5157
108	4	2	7.3877
109	4	2	6.6892
110	4	2	6.6206
111	4	2	8.2345
112	4	2	7.2155
113	4	2	6.9881
114	4	2	6.9292

File A:STEEPCOR

row	AGE	SEX	DATA
115	5	1	7.2637
116	5	1	7.0190
117	5	1	8.2110
118	5	1	7.7423
119	5	1	7.2551
120	5	2	7.9262
121	5	2	8.1273
122	5	2	7.0853
123	5	2	7.2647
124	5	2	7.1282
125	5	2	7.2785
126	5	2	7.3871
127	5	2	6.8042
128	5	2	7.7337
129	5	2	8.4360
130	5	2	7.3959
131	6	1	7.5521
132	6	1	6.8005
133	6	1	7.5080
134	6	1	7.6492
135	6	1	8.0403
136	6	1	8.0540
137	6	1	7.6573
138	6	1	6.9876
139	6	2	7.6911
140	6	2	6.9104
141	6	2	7.7717
142	6	2	8.2400
143	6	2	7.5086
144	6	2	7.3794
145	6	2	6.6832
146	6	2	7.7324
147	6	2	8.3446
148	6	2	7.4575
149	6	2	7.6065
150	6	2	8.4491
151	6	2	7.8601

Analysis of Variance for A:STEEPCOR.DATA

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2.9798934	7	.4256991	1.788	.0943
A:STEEPCOR.AGE	2.9795585	6	.4965931	2.086	.0587
A:STEEPCOR.SEX	.0191969	1	.0191969	.081	.7799
2-FACTOR INTERACTIONS	.6679757	6	.1113293	.468	.8313
A:STEEPCORA:STEEPCOR	.6679757	6	.1113293	.468	.8313
RESIDUAL	32.612341	137	.2380463		
TOTAL (CORR.)	36.260210	150			

0 missing values have been excluded.

Table of means for A:STEEPCOR.DATA

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
A:STEEPCOR.AGE						
0	12	7.0399750	.1392361	.1408446	6.7614025	7.3185475
1	28	7.4146821	.0845896	.0922044	7.2323136	7.5970507
2	34	7.3126882	.0975384	.0836741	7.1471915	7.4781850
3	19	7.4242895	.0845431	.1119319	7.2029025	7.6456765
4	21	7.4019571	.1005278	.1064685	7.1913761	7.6125382
5	16	7.5036375	.1179586	.1219750	7.2623866	7.7448884
6	21	7.6135048	.1049744	.1064685	7.4029237	7.8240858
A:STEEPCOR.SEX						
1	79	7.3998759	.0523605	.0548930	7.2913046	7.5084473
2	72	7.3968944	.0615495	.0574996	7.2831677	7.5106212
A:STEEPCOR.AGE by A:STEEPCOR.SEX						
0 1	6	7.1468500	.1198222	.1991843	6.7528889	7.5408111
0 2	6	6.9331000	.2576339	.1991843	6.5391389	7.3270611
Total	151	7.3984543	.0397047	.0397047	7.3199234	7.4769852

Table of means for A:STEEPCOR.DATA

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
1 1	20	7.3786700	.1148353	.1090977	7.1628886	7.5944514
1 2	8	7.5047125	.0741116	.1724987	7.1635322	7.8458928
2 1	17	7.3708176	.1500251	.1183331	7.1367699	7.6048654
2 2	17	7.2545588	.1277274	.1183331	7.0205111	7.4886066
3 1	11	7.3836818	.0842051	.1471073	7.0927223	7.6746413
3 2	8	7.4801250	.1701587	.1724987	7.1389447	7.8213053
4 1	12	7.4892667	.1084858	.1408446	7.2106941	7.7678392
4 2	9	7.2855444	.1854976	.1626333	6.9638766	7.6072123
5 1	5	7.4982200	.2134700	.2181955	7.0666573	7.9297827
5 2	11	7.5061000	.1485633	.1471073	7.2151405	7.7970595
6 1	8	7.5311250	.1577026	.1724987	7.1899447	7.8723053
6 2	13	7.6642000	.1420504	.1353191	7.3965562	7.9318438
Total	151	7.3984543	.0397047	.0397047	7.3199234	7.4769852

Multiple range analysis for A:STEEPCOR.DATA by A:STEEPCOR - age (m+f)

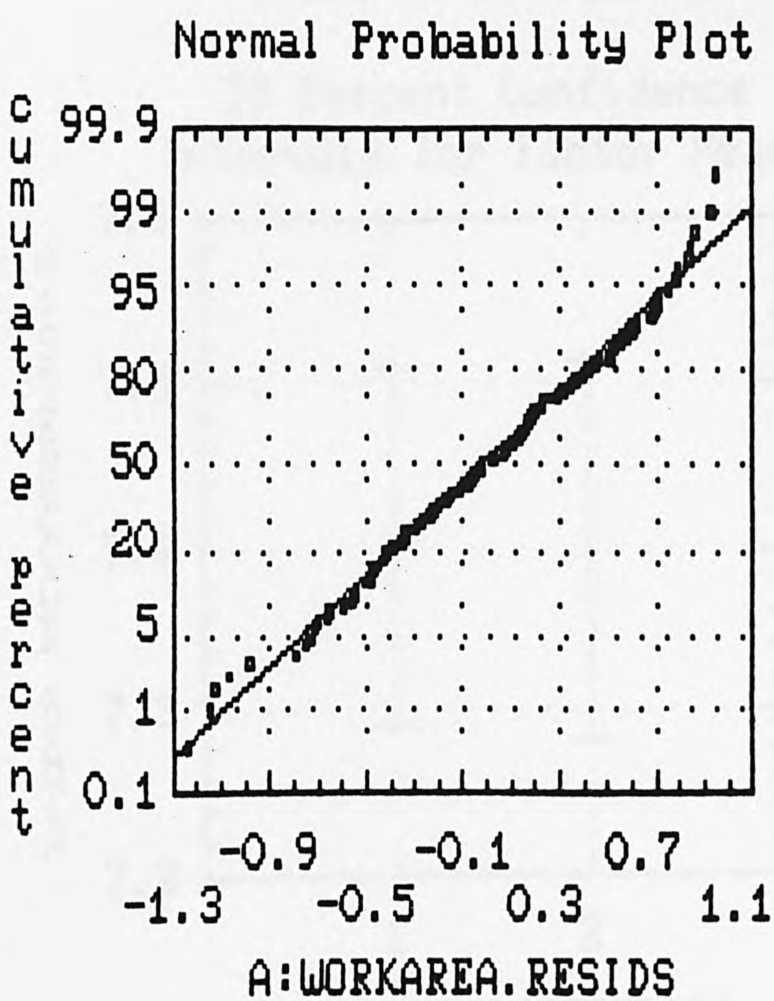
Method: 95 Percent Confidence Intervals

Level	Count	Average	Homogeneous Groups
0	12	7.0399750	*
2	34	7.3126882	**
4	21	7.4019571	**
1	28	7.4146821	**
3	19	7.4242895	**
5	16	7.5036375	**
6	21	7.6135048	*

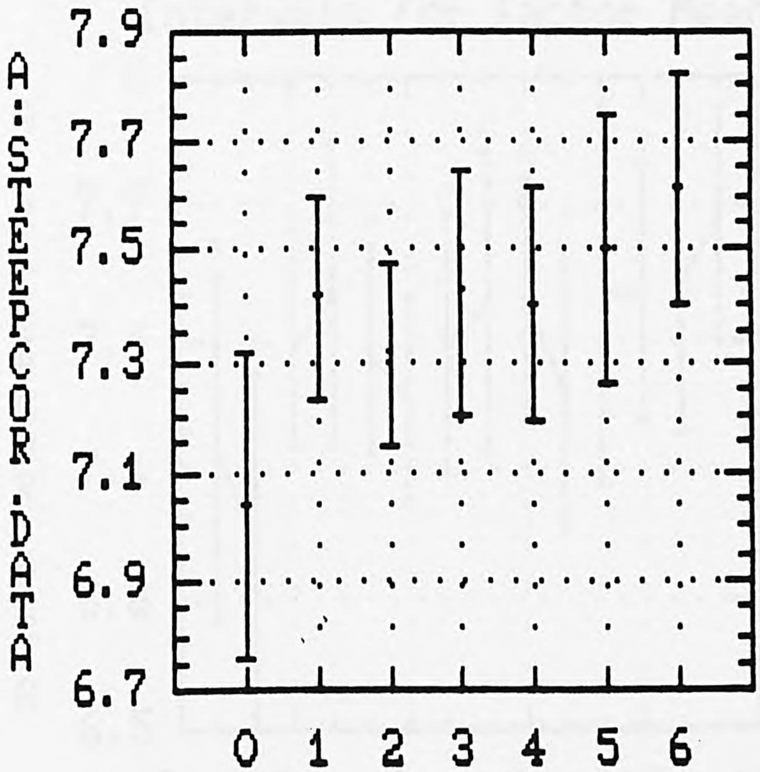
Multiple range analysis for A:STEEPCOR.DATA by A:STEEPCOR - sex (all ages)

Method: 95 Percent Confidence Intervals

Level	Count	Average	Homogeneous Groups
2	72	7.3968944	*
1	79	7.3998759	*

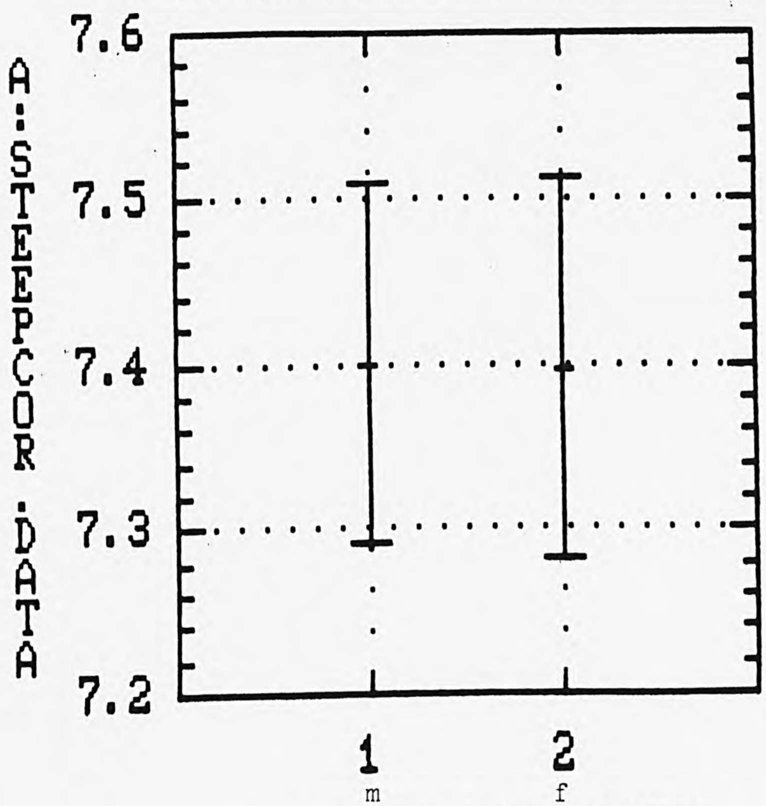


95 Percent Confidence
Intervals for Factor Means

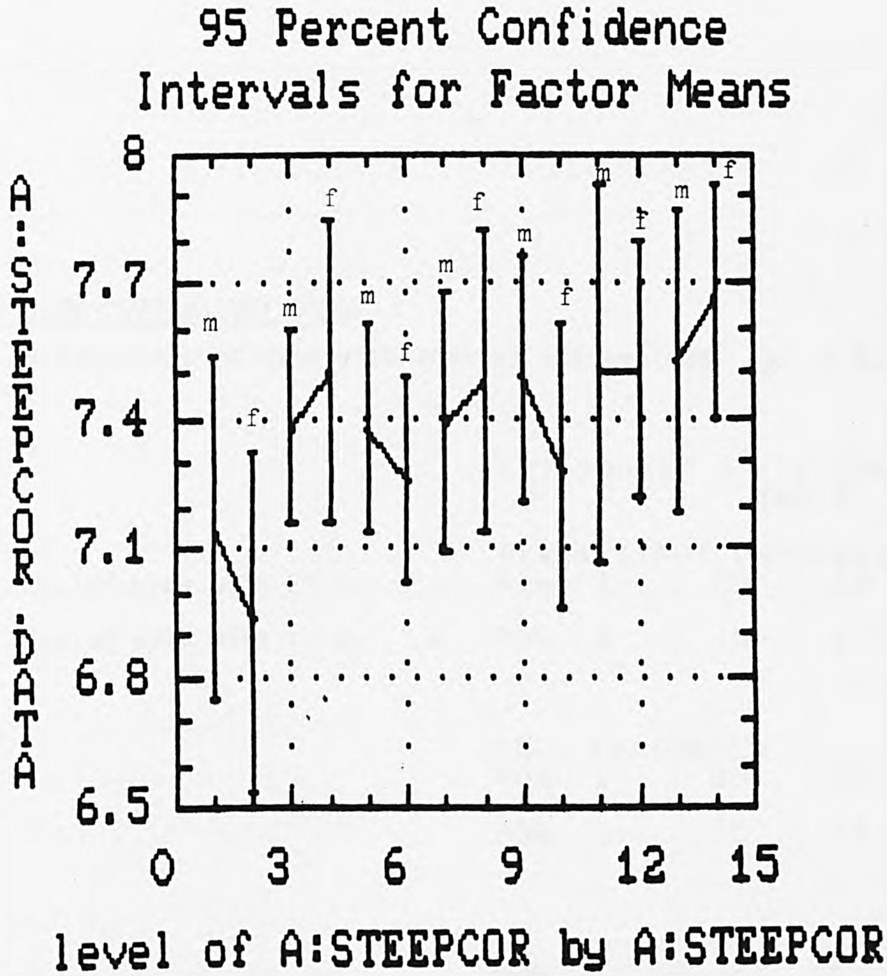


level of A:STEEPCOR - age (m+f together)

95 Percent Confidence
Intervals for Factor Means



level of A:STEEPCOR - sex



Steepest corneal radii in each age group for m + f.

CHI-SQUARE CONTINGENCY TABLE

Data on incidence of eyes with corneal astigmatism $\geqslant$ 1 D.

CHI-SQUARE R X C CONTINGENCY TABLE

******INPUT DATA******

No. of eyes with $\geqslant$1 D. -	ROW 1:	59	23	16
No. of eyes with $<$1 D. -	ROW 2:	15	17	21

CELL FREQUENCY

ROW 1:	59	23	16
ROW 2:	15	17	21

ROW 1:	59	23	16
ROW 2:	15	17	21

TOTALS:

	COLUMN	TOTAL
Age $<$ 1 yr -	C(1) =	74
Age 1- $<$ 3 yrs -	C(2) =	40
Age 3- $<$ 5 yrs -	C(3) =	37

ROW	TOTAL
R(1) =	98
R(2) =	53

OVERALL= 151

EXPECTED FREQUENCY

ROW 1:

48.03
25.96
24.01

ROW 2:

25.97
14.04
12.99

OF EXP. FREQ. <=2 = 0
% EXP. FREQ. <=5 = 0.00%
CHI-SQUARE = 15.7237
CONTINGENCY COEFFICIENT = .3071
DF= 2
PROB CHI-SQUARE > 15.7237 = .0004

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