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TITLE: Characterisation of internal, refractive, and corneal astigmatism in a UK university student population

Abstract

Purpose

There is a clear benefit in defining internal (IA) and corneal astigmatic error (CA) prior to surgical and other refractive interventions, such as orthokeratology, to minimise risk of unsatisfactory refractive outcomes. Such data would also be of relevance to other areas of ophthalmic care such as spectacle dispensing and other types of rigid lens fitting. This study offers a detailed characterisation of astigmatic error in a group of university students and specifically investigates compensation of corneal astigmatism by the eye's internal optics.

Methods

For 176 young-adult participants, objective measurements of refractive error were obtained using the open-view Grand Seiko WAM-5500 autorefractor; corneal curvature and axial length were measured using the Aladdin biometer. Clinical measurements of corneal and refractive astigmatism were converted into vector components J0 and J45; followed by an assessment of corneal astigmatism compensation.

Results

Mean total refractive astigmatism (RA), CA, and IA were 0.24 ± 0.32D, 0.46 ± 0.27D and -0.22 ± 0.25D respectively for J0 and -0.05 ± 0.20D, 0.01 ± 0.16D, and -0.06 ± 0.18D for J45. Significant linear correlations were noted between RA, CA, and IA for both J0 and J45 ($P<0.01$). A significant linear regression was also noted between axial length and J45 RA and IA, but not CA. Levels of full compensation were low, 7% and 9% for J0 and J45 respectively, however, a complete absence of compensation was also uncommon particularly for J45 (2%).

Conclusions

In general, partial compensation for corneal astigmatism by the eye's internal optics is noted, but it is unclear whether this is an active compensatory mechanism. Further, larger scale, studies would be required to characterise differences in corneal astigmatic compensation with respect to ethnicity.

Highlights

- A complete absence of compensation for corneal astigmatism by the eye's internal optics is uncommon, especially for the J45 component. Nevertheless, full compensation for corneal astigmatism is also rare. The outcomes suggest that although compensatory mechanisms for corneal astigmatism may exist, they are generally imprecise.
- A weak, but significant correlation is noted for both axial length and MSE, with both internal and refractive (total) astigmatic components of J45, i.e. oblique astigmatism.
- This study presents new data on refractive error components: corneal, refractive and internal astigmatism, in a group of young UK based adults.

Introduction

Corneal astigmatism (CA) often exceeds the total astigmatic error, but a counterbalance between the eye's internal and corneal optics helps to minimise the total refractive astigmatism (RA) (Park et al 2013; Chen et al 2018). Corneal altering procedures such as refractive surgery and orthokeratology, or fitting refractive solutions such as rigid lenses, may, therefore, disrupt this attenuation of corneal astigmatism leading to treatment induced residual astigmatic error. To minimise the risk of such unsatisfactory treatment outcomes, there is a clear benefit in defining and understanding internal and corneal astigmatic error prior to surgical or other refractive interventions. Detailed study of astigmatism is timely given the renewed and growing clinical interest in approaches such as orthokeratology which, while possibly fuelled by an interest in myopia management, are also used to manage manifest refractive error (Morgan et al 2019).

The principal origin of internal astigmatism (IA) is thought to be the crystalline lens; however, smaller contributions may arise from other refractive media such as the vitreous or aqueous humour. Since internal astigmatism is difficult to measure, it is instead commonly accepted as the difference between refractive and corneal astigmatic error (Manny et al 2016). However, unless the refractive and corneal astigmatic axes coincide, internal astigmatism cannot be derived directly by subtracting corneal astigmatism from refractive astigmatism. Instead, Thibos et al (1997) advocate the application of Fourier analysis to convert refractive clinical data to vector notation. The vectorial approach permits statistical analysis of vector power components J0 and J45 which respectively represent the orthogonal and oblique astigmatic powers; hence both magnitude of power and axis orientation can be evaluated.

Further characterisation of astigmatic error can be achieved through determining the amount of corneal astigmatism compensation (Manny et al 2016; Park et al 2013; Muftuoglu et al 2008; Liu et al 2017). Based on work by Muftuoglu et al (2008) and others, Park et al (2013) proposed a detailed system of calculating and classifying corneal astigmatism 'compensation factor', (CF). For a perfect optical system, full compensation would be achieved with zero refractive (total) astigmatism. However, Park et al (2013) reported 'under compensation' of corneal astigmatism as the most common form of CF in young adults (aged 19-46 years old) (see Methods, Table 1).

While the primary focus for many studies investigating astigmatism in children is to garner clues about refractive developmental processes, particularly predictions of myopia development; in adults, characterising astigmatism may have a clinical relevance in relation to predicting visual outcomes for refractive and other corneal altering therapies such as orthokeratology.

Previous reports have provided valuable datasets which characterise astigmatism for various age groups and ethnicities (e.g. Fuller et al 1995; Hunyh et al 2006; Namba et al 2018; Mohammadpour et al 2016; Park et al 2013; Saw et al 2006; Ip et al 2008; Mandel et al 2010; Remon et al 2009; Huynh et al 2006; Liu et al 2011; Tong et al 2001; Shanker and Bobier 2004; Fuller et al 1995). The principal aim of this study was to characterise and understand the interrelationships between corneal, refractive, and internal astigmatism, in a cohort of young UK based optometry students i.e. individuals of an age where refractive surgery or alternative such as orthokeratology may be a consideration.

Materials and Methods

Ethical approval was provided by the internal university departmental ethics committee; all aspects of the research were carried out in accordance with the tenets of the Declaration of Helsinki.

Refractive error, axial length, and keratometry measurements

Non-cycloplegic objective measurements of refractive error were obtained using the infra-red open-view Grand Seiko WAM-5500 autorefractor (Ryusyo Industrial Co. Ltd, Osaka,Japan). Vertex distance was set to 12mm and autorefractor output increments to 0.12D. Negative cylindrical clinical notation of refractive error was then converted into individual dioptric power vectors using the vectorial method proposed by Thibos et al (1997) and described by many others (e.g. Miller, 2009; Dunne et al 1994; Humphrey 1976; Keating 1981; Harris 1988; Barnes 1984): MSE, which represents the spherical equivalent; J0 and J45 which respectively indicate the orthogonal (90 and 180 degree) and oblique (45 and 135 degree) axes of the Jackson Cross Cylinder. The following formulas were used to generate vectorial components:

$$MSE = S + (C/2)$$

$$J_0 = -C/2\cos(2\alpha)$$

$$J_{45} = -C/2\sin(2\alpha)$$

MSE represents the spherical equivalent (Mean Spherical Error), and C represents the cylindrical power, and α represents the axis in radians.

Keratometry and axial length measurements were obtained using the Aladdin biometer (Topcon, Tokyo, Japan). The Aladdin assumes a corneal refractive index of 1.3375, thus the refractive power of the posterior cornea is already incorporated as the effective corneal refractive index (Topcon Europe Medical BV, The Netherlands; Park et al 2013). As a result it was not possible to distinguish between anterior and posterior corneal contributions. Corneal astigmatism was derived using the conventional rule of thumb whereby each 0.1mm difference in corneal radii equates to 0.50D of cylindrical error (Keirl and Christie, 2007). Statistical analyses were also repeated by calculating astigmatism using refractive indices of 1.3375 and separately 1.336.

Internal astigmatism (IA) was calculated for each of the power vector components (J0 and J45) by subtracting corneal astigmatism (CA) from (total) refractive astigmatism (RA).

Statistical analysis

All statistical analyses were undertaken using commercially available software (SPSS, IBM, UK). Linear regression analyses and scatterplots were used to investigate the relationship between IA, CA, RA, M and axial length

Student's paired t-tests were used to check for differences between IA, CA, and RA for vector components J0 and J45.

Using a method proposed by Muftuoglu et al (2008) 'compensation factor' (CF) was calculated; this refers to the ratio describing amount of compensation of corneal astigmatism by refractive astigmatism. To help provide a detailed characterisation of the astigmatic error, CF type was assigned according to the classification system proposed by Park et al (2013) (see Table 1 for details).

CF value	Compensation type in relation to corneal astigmatism	Meaning
<-0.1	Same axis augmentation	Total astigmatism increases to values greater than CA, CA axis is maintained.
-0.1 to 0.1	No compensation	
0.1 to 0.9	Under compensation	Total astigmatism decreases to values less than CA, but CA axis remains the same
0.9 to 1.1	Full compensation	
1.1 to 2	Over compensation	Amount of total astigmatism decreases to values smaller than CA, axis is also changed to opposite angle
>2	Opposite axis augmentation	Total astigmatism greater than CA and axis opposite angle

Table 1 Classification of compensation factor (CF) according to methodology proposed by Park et al (2013). CF is derived using the formula CF= (CA-RA)/CA after Muftuoglu et al (2008) for both J0 and J45.

Results

Participants

Data from all participants found to have undergone refractive surgery were excluded from the analysis. One-hundred and seventy-six young-adult participants were eligible for inclusion in the study (mean age 21.1±2.3 yrs; range 18-36 years, age data available for n=176) from the university student population. Ethnicity data were available for the majority of subjects (n=172); ethnicity groupings were provided by participants via questionnaire; the ethnicity options reflected those provided by the Office of National Statistics UK, (https://www.ons.gov.uk/methodology/classificationsandstandards/measuringequality/ethnicgroupnationalidentityandreligion). The cohort was predominantly comprised of individuals who identified as being of Indian or Pakistani ethnicities (please see Table 2 for full details).

Ethnicity	Number of participants
Asian/Asian British Indian	55
Pakistani	39
Any other Asian background	32
Bangladeshi	17
Chinese	1
White Welsh/English/Scottish/Northern Irish/British	9
Any other white	2
Black/African/Caribbean/Black British African	7
Caribbean	2
Mixed/Multiple ethnic groups White and Asian	1
Other ethnic group Arab	6
Any other ethnic group	1
No response given	4

Table 2 Cohort ethnicity

Mean (± standard deviation) axial length was 24.05±1.33mm (range 20.26-29.44). Average spherical and cylindrical component powers were -1.16±2.63D (range-15.25 to +10.25D) and -0.77 ±0.54D (range -3.37 to 0D) respectively for n=176 based on Grand Seiko autorefractor readings. Using ≥0.75D as the definition of corneal astigmatism, 42.9% of the participants were found to be astigmatic (vd=12mm). The mode cylinder value was -0.50D, which accounted for approximately 15% of all those included in the study. See Figure 1 for detailed frequency distribution of cylindrical error magnitude (expressed in negative cylindrical notation).

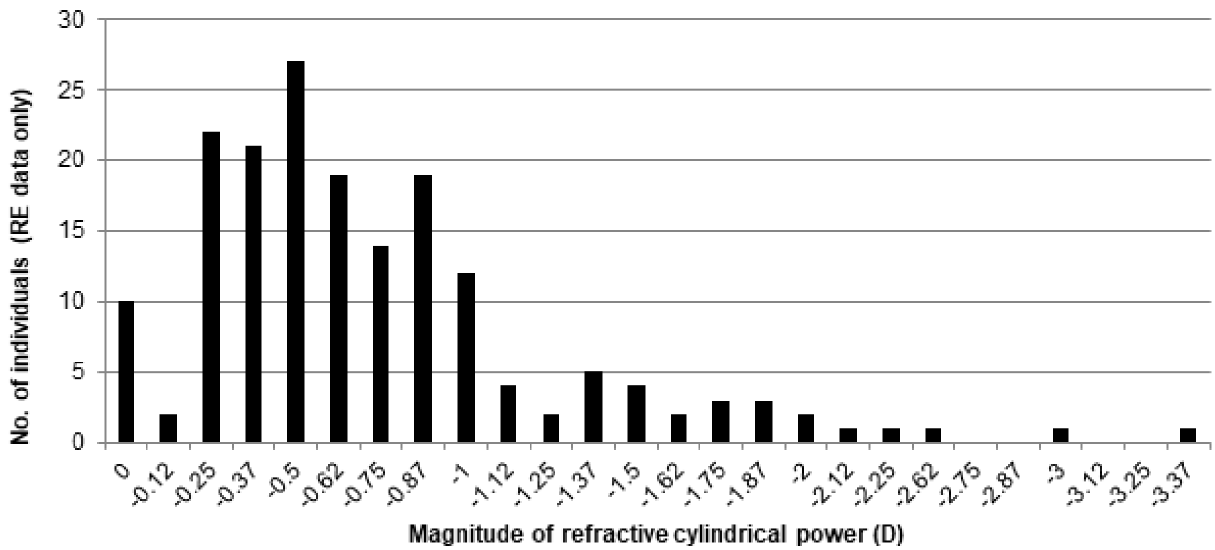


Figure 1 Magnitude of refractive cylindrical error (as derived from autorefractor readings), vertex distance 12mm

Using vectorial analysis as outlined above vertex distance corrected refractive (autorefractor) readings and corneal measurements were converted into vector components (see Table 3). The difference between the respective refractive and corneal values represented the magnitude of internal (or residual) astigmatism. Detailed analysis was then undertaken using methods proposed by Muftuoglu et al and Park et al (see Figure 4).

Power vector	Magnitude in D
M (Spherical equivalent)	-1.43 ± 2.53D
Refractive Astigmatism (RA)	
J0 RA	0.24 ± 0.32D
J45 RA	-0.05 ± 0.20D

Corneal Astigmatism (CA)	
J0 CA	0.46 ± 0.27D
J45 CA	0.01 ± 0.16D
Internal Astigmatism (IA)	
J0	-0.22 ± 0.25D
J45	-0.06 ± 0.18D

Table 3 Average vertex distance corrected vector powers (in D±standard deviation)

The J0 component was generally found to be with-the-rule (WTR) and the J45 data tended to cluster around zero. A positive powered J45 would indicate the negative cyl axis to be around 45° and negative values indicate the cyl axis is around 135° (Chen et al 2018).

There were significant linear correlations between J0 IA, CA, and RA (all p≤0.01) and also between J45 IA, RA, and CA (all p≤0.01). The negative correlations noted between internal and corneal astigmatism, for both J45 and J0 components, may suggest the presence of a compensatory mechanism for corneal astigmatism.

Paired sample t-tests showed significant differences between J0 IA, J0 CA, and J0 RA (all p≤0.01) and between J45 IA vs. J45 CA and J45 RA vs. J45 CA (p≤0.01 for both), but not between J45 IA and J45 RA (p>0.05). Based on linear regression plots, approximately 33% of the variance in J0 RA was accounted for by J0 IA and 44% by J0 CA. Similarly, for J45 approximately 41% of the variance in J45 RA was accounted for by J45 IA and 30% by J45 CA.

Figures 2 A-C illustrate mean values for J0 and J45 for corneal, refractive, and internal astigmatism.

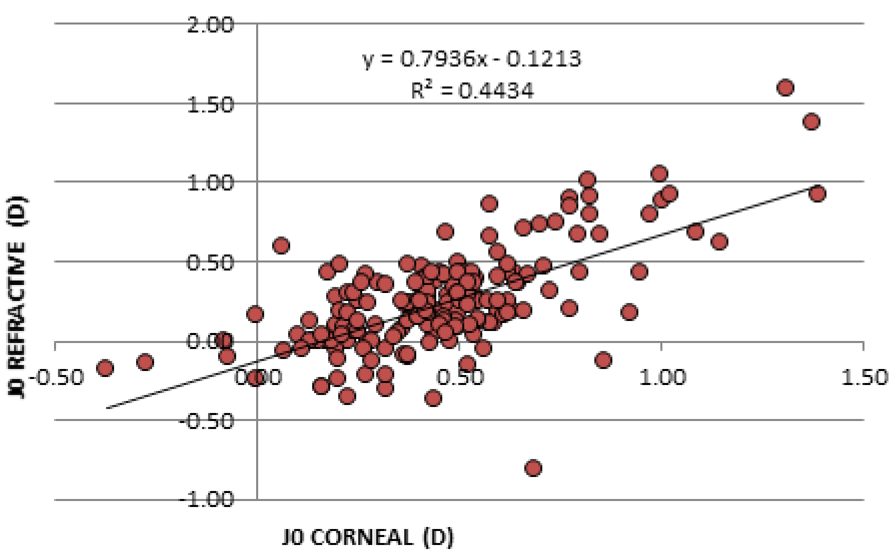


Fig 2 A Corneal and refractive J0 component. Mean values are clustered around 0.50D and 0.20D for corneal and refractive respectively, indicating J0 is predominantly with-the-rule (WTR). 44% of the variance in refractive J0 is accounted for by corneal astigmatism alone. Approximately 33% of the variance in refractive J0 is accounted for by internal J0 alone.

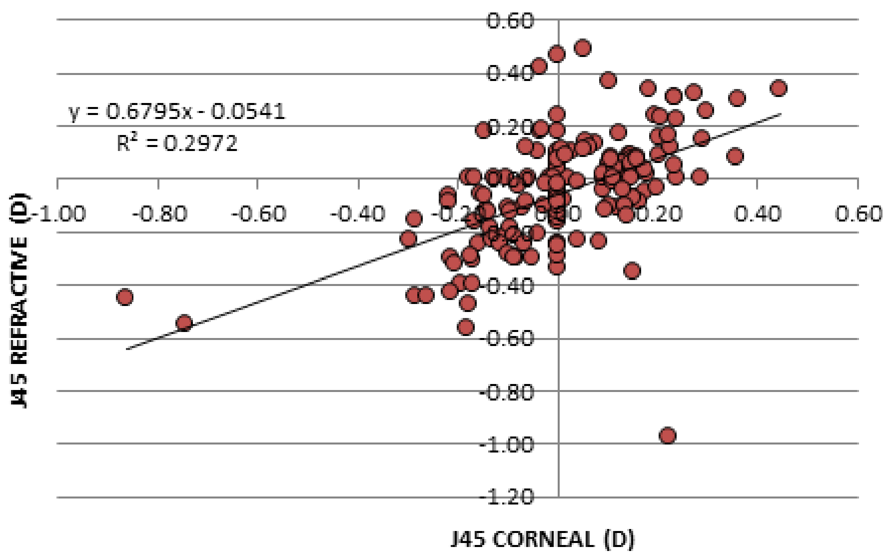


Fig 2 B Corneal and refractive J45 component. Mean values are clustered around 0D for corneal and refractive J45. Only 30% of the variance in refractive J45 astigmatism is accounted for by corneal astigmatism. Approximately 41% of the variance in refractive J45 astigmatism may be attributable to internal astigmatism alone.

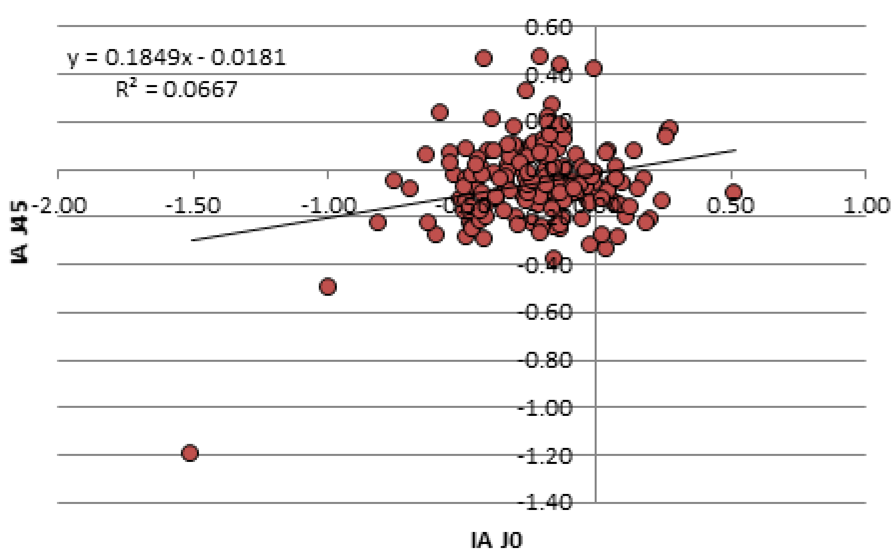
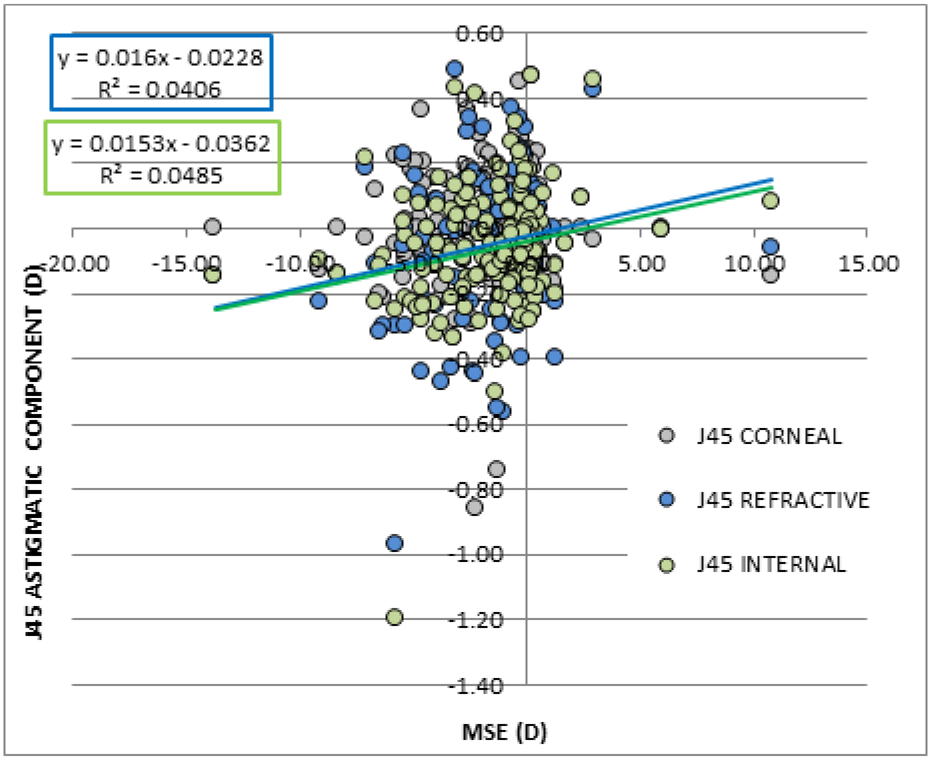


Fig 2 C Internal astigmatism J0 and J45 components. While J45 is clustered around zero; J0 is clustered about a mean of approximately -0.20D indicating a tendency towards against the rule (ATR) astigmatism.

Associations between power vector components, axial length and MSE

As expected there was a significant relationship between increase in axial length and mean myopic spherical error ($p<0.001$). Linear regression showed both J45 IA and J45 RA to be significantly negatively correlated with axial length ($p<0.01$) and positively correlated with MSE ($p<0.01$), however, J45 CA and J0 components did not show any significant correlation with either axial length or MSE ($p>0.05$).



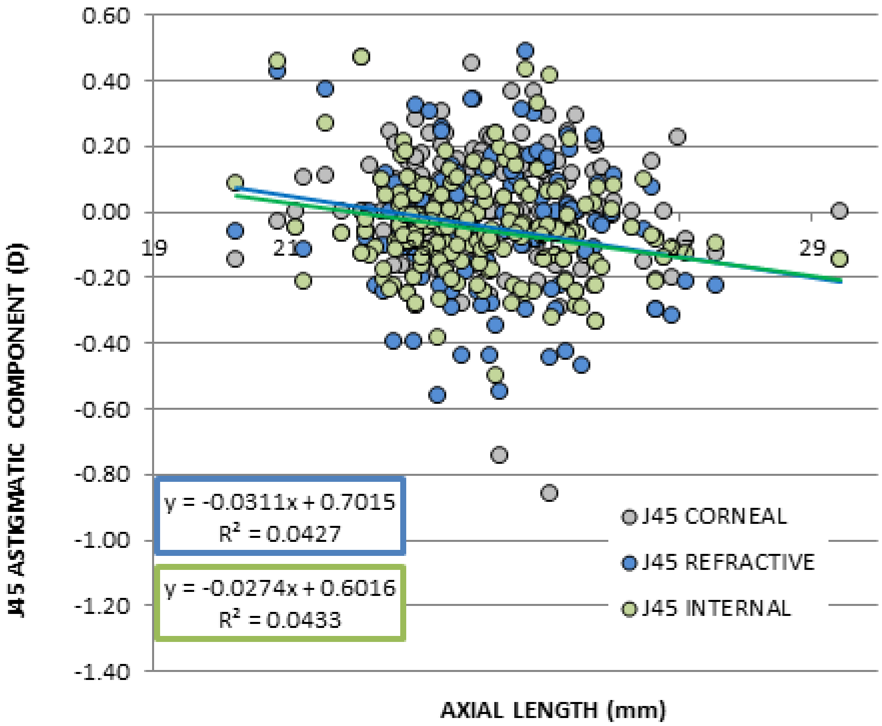
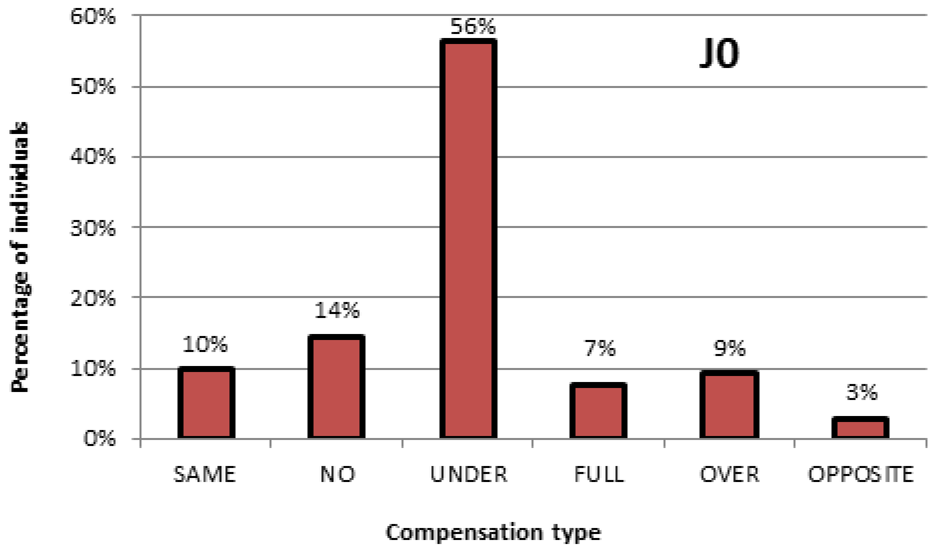


Figure 3 MSE and J45 astigmatic components. Significant linear relationships were noted between MSE and IA and RA J45, but not CA J45

Compensation Factor (CF)

Several compensation types were identified, levels of 'full compensation' were similar for J0 and J45 (7% and 9% respectively). There was, however, a noticeable difference in the percentage of 'no compensation' for J0 relative to J45 (14% vs. 2%). For J0, most participants showed under compensation, indicating total refractive astigmatism (RA) decreased to less than corneal astigmatism, but that the corneal axis remained the same. For J45, the majority of participants fell into the same axis augmentation group, whereby total astigmatism increased greater than corneal astigmatism, whilst corneal axis was maintained. Figure 4 shows compensation factor types for both J0 and J45, (in n=2 for J0 and n=3 for J45, CF was not determined as the denominator was zero). Overall, 63% of J0 astigmatism was fully or partially compensated, compared to 30% of J45 astigmatism.



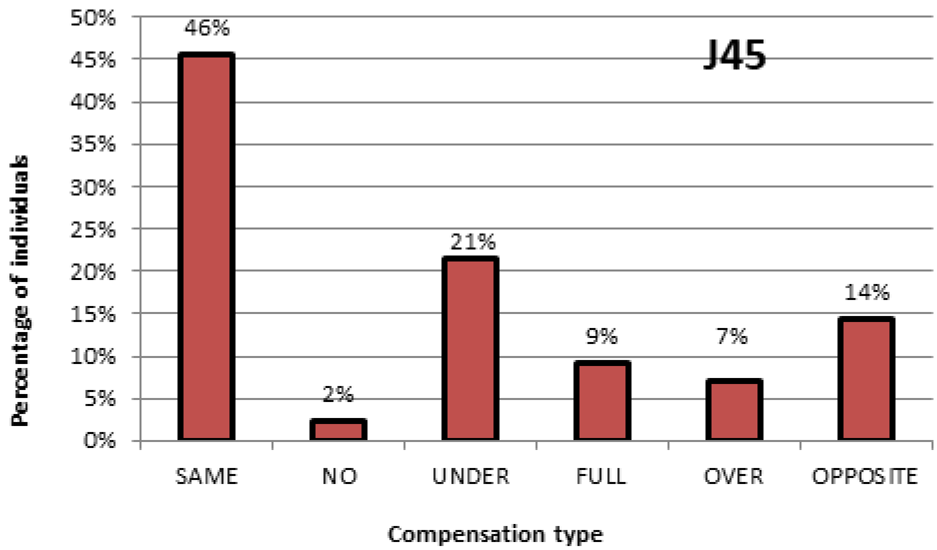


Figure 4 Distribution of compensation factor types for J0 and J45

All aforementioned analyses (intercorrelations, t-tests, and correlations with MSE and AL) were repeated by calculating astigmatism using refractive indices 1.3375 and separately 1.336; the outcomes remained the same. Patterns of compensation factors were also retained

Discussion

This study presents new data on refractive error components: corneal, refractive and internal astigmatism, in a group of young UK based adults. In general, the data support the presence of a compensatory mechanism for corneal astigmatism by the eye's internal optics. The findings from this study were similar to those of Park et al (2013) where 'under compensation' was reported as the most common compensation type for the J0 component, and the most common compensation types for the J45 component were axis augmentation (same and opposite) and under compensation.

Cross-sectional data alone cannot, however, establish whether there is an *active* compensatory mechanism. Significant negative linear correlations between internal and corneal power vectors and analysis of compensation factors seldom showed ‘no compensation’ of corneal astigmatism, particularly for the J45 component. Nevertheless, full compensation of corneal astigmatism was also uncommon, thus the imbalance between internal and corneal optics rendered many eyes astigmatic.

In line with previous reports of internal (or residual) astigmatic error (e.g. Park et al 2013; Manny et al 2016; Remon et al 2009) the mean J0 component of internal astigmatism was found to be against-the-rule. Previous studies are, however, equivocal with respect to the refractive and corneal J0 component. With some reports finding against-the-rule (ATR) astigmatism (Park et al 2013) and others reporting with-the-rule (WTR) astigmatism (Remon et al 2009). Such differences may arise from variance in cohort age groups; ethnicity; or the methodologies employed e.g. the assumptions made and methodology used to estimate posterior corneal astigmatism. In this study, predominantly positive values were noted for both refractive and corneal J0 indicating with-the-rule (WTR) astigmatism.

It has been hypothesised that an increased axial length may cause misalignment of internal optics (e.g. lens tilt) thereby inducing internal astigmatic refractive error (Park et al 2013). Data from the present study where correlations between axial length and internal astigmatism were noted, albeit only for the J45 and not J0 component, would appear to support this theory. It is, however, unclear whether there is an association between longitudinal changes in axial length and internal astigmatism; reports both appear to support (Wu et al 2018) and reject such associations (Manny et al 2016). That only oblique, and not orthogonal, astigmatism correlated with axial length, may reflect the asymmetric changes in ocular structures with eye growth.

Previous studies have remarked on differences in astigmatism between ethnicities (Mandel et al 2010; Saw et al 2006; Ip et al 2008;Huynh et al 2006;Fozailoff et al 2011). The present data set was not, however, large enough to justify meaningful comparisons of astigmatic compensation between different ethnic groups.

In summary, there appears to be some attenuation of corneal astigmatism by the eye’s internal optics, however, in most cases this is partial and not complete compensation. Larger scale studies may help to provide detailed characterisation of astigmatism with respect to ethnicity and help mitigate the risk of unwanted residual astigmatism following corneal reshaping therapies.

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