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JOURNAL: CONTACT LENS AND ANTERIOR EYE

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and Peter Campbell^b**

**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 $0.24 \pm 0.32D$, $0.46 \pm 0.27D$ and $-0.22 \pm 0.25D$ respectively for J0 and $-0.05 \pm 0.20D$, $0.01 \pm 0.16D$, and $-0.06 \pm 0.18D$ 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.

1 **Introduction**

2

3 Corneal astigmatism (CA) often exceeds the total astigmatic error, but a counterbalance between the
4 eye's internal and corneal optics helps to minimise the total refractive astigmatism (RA) (Park et al 2013;
5 Chen et al 2018). Corneal altering procedures such as refractive surgery and orthokeratology, or fitting
6 refractive solutions such as rigid lenses, may, therefore, disrupt this attenuation of corneal astigmatism
7 leading to treatment induced residual astigmatic error. To minimise the risk of such unsatisfactory
8 treatment outcomes, there is a clear benefit in defining and understanding internal and corneal astigmatic
9 error prior to surgical or other refractive interventions. Detailed study of astigmatism is timely given the
10 renewed and growing clinical interest in approaches such as orthokeratology which, while possibly fuelled
11 by an interest in myopia management, are also used to manage manifest refractive error (Morgan et al
12 2019).

13

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

23

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

31

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

36

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

44 **Materials and Methods**

45

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

48

49 *Refractive error, axial length, and keratometry measurements*

50

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

59

60 $MSE = S + (C/2)$

61

62 $J_0 = -C/2\cos(2\alpha)$

63

64 $J_{45} = -C/2\sin(2\alpha)$

65

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

68

69 Keratometry and axial length measurements were obtained using the Aladdin biometer (Topcon, Tokyo,
70 Japan). The Aladdin assumes a corneal refractive index of 1.3375, thus the refractive power of the
71 posterior cornea is already incorporated as the effective corneal refractive index (Topcon Europe Medical
72 BV, The Netherlands; Park et al 2013). As a result it was not possible to distinguish between anterior and
73 posterior corneal contributions. Corneal astigmatism was derived using the conventional rule of thumb
74 whereby each 0.1mm difference in corneal radii equates to 0.50D of cylindrical error (Keirl and Christie,
75 2007). Statistical analyses were also repeated by calculating astigmatism using refractive indices of
76 1.3375 and separately 1.336.

77

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

80

81 *Statistical analysis*

82

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

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

88

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

93

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

94

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

98 **Results**

99

100 *Participants*

101 Data from all participants found to have undergone refractive surgery were excluded from the analysis.
102 One-hundred and seventy-six young-adult participants were eligible for inclusion in the study (mean age
103 21.1±2.3 yrs; range 18-36 years, age data available for n=176) from the university student population.
104 Ethnicity data were available for the majority of subjects (n=172); ethnicity groupings were provided by
105 participants via questionnaire; the ethnicity options reflected those provided by the Office of National
106 Statistics UK,
107 (<https://www.ons.gov.uk/methodology/classificationsandstandards/measuringequality/ethnicgroupnationali>
108 [dentistryandreligion](https://www.ons.gov.uk/methodology/classificationsandstandards/measuringequality/ethnicgroupnationali)). The cohort was predominantly comprised of individuals who identified as being of
109 Indian or Pakistani ethnicities (please see Table 2 for full details).

110

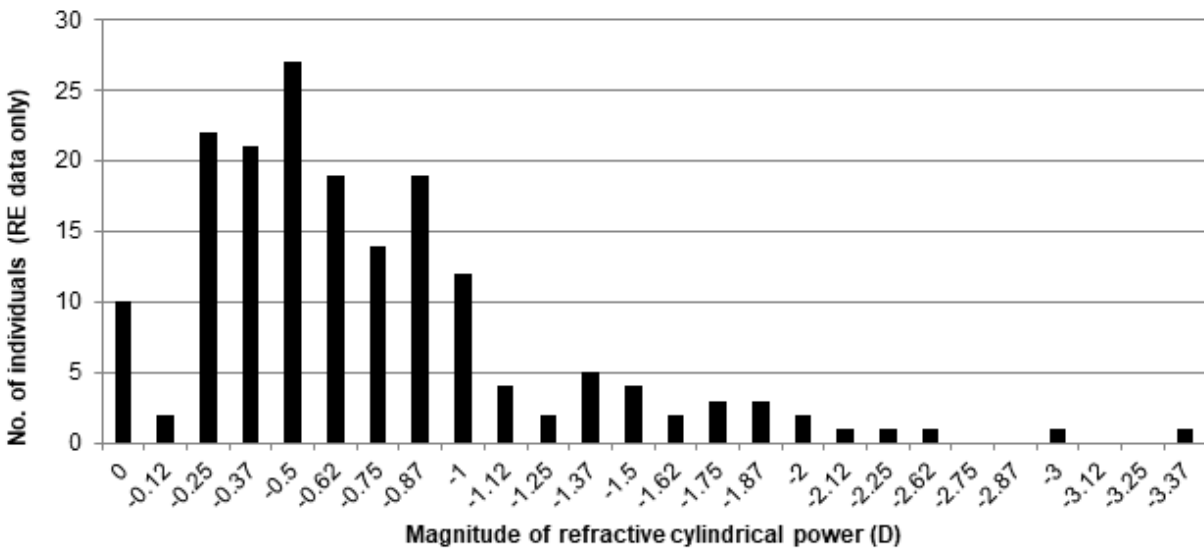
Ethnicity	Number of participants
Asian/Asian British	
Indian	55
Pakistani	39
Any other Asian background	32
Bangladeshi	17
Chinese	1
White	
Welsh/English/Scottish/Northern Irish/British	9
Any other white	2
Black/African/Caribbean/Black British	
African	7
Caribbean	2
Mixed/Multiple ethnic groups	
White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

111

112 **Table 2 Cohort ethnicity**

113

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



121

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

124

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

130

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

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

132

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

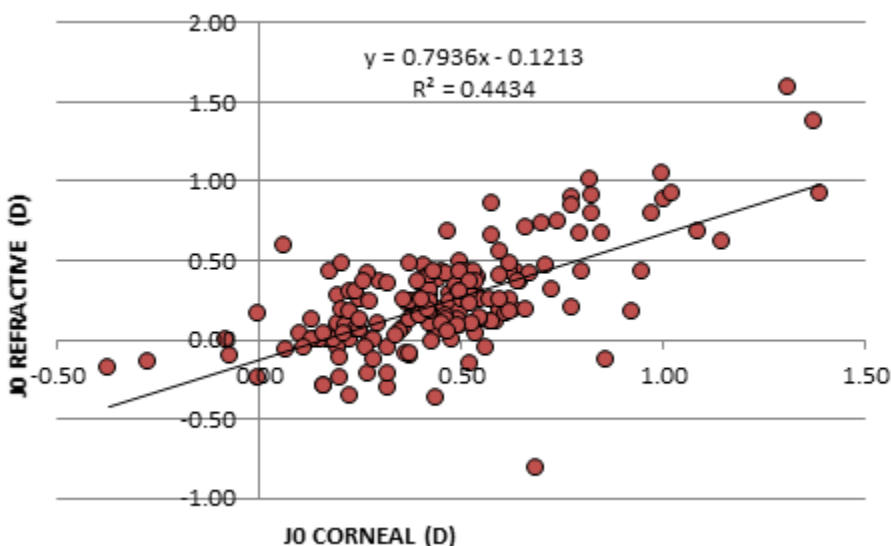
136

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

141

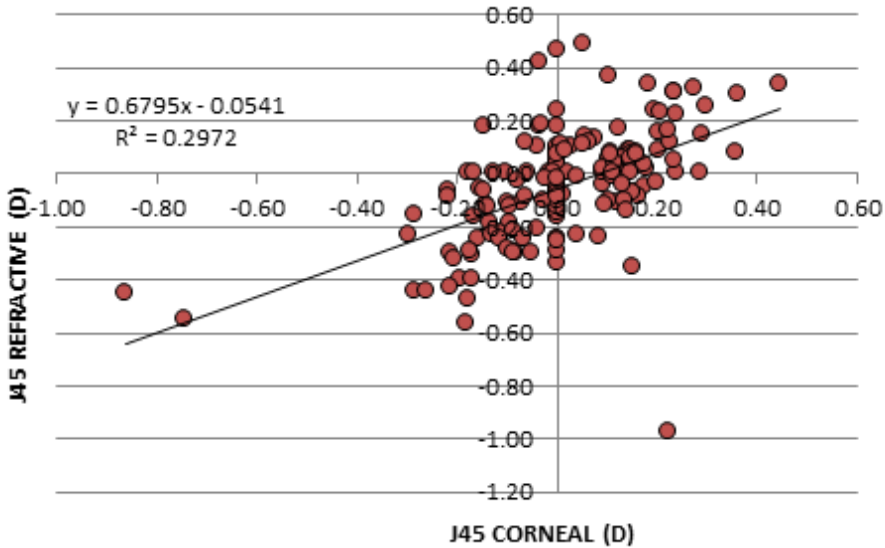
142 Paired sample t-tests showed significant differences between J0 IA, J0 CA, and J0 RA (all $p \leq 0.01$) and
 143 between J45 IA vs. J45 CA and J45 RA vs. J45 CA ($p \leq 0.01$ for both), but not between J45 IA and J45 RA
 144 ($p > 0.05$). Based on linear regression plots, approximately 33% of the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

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

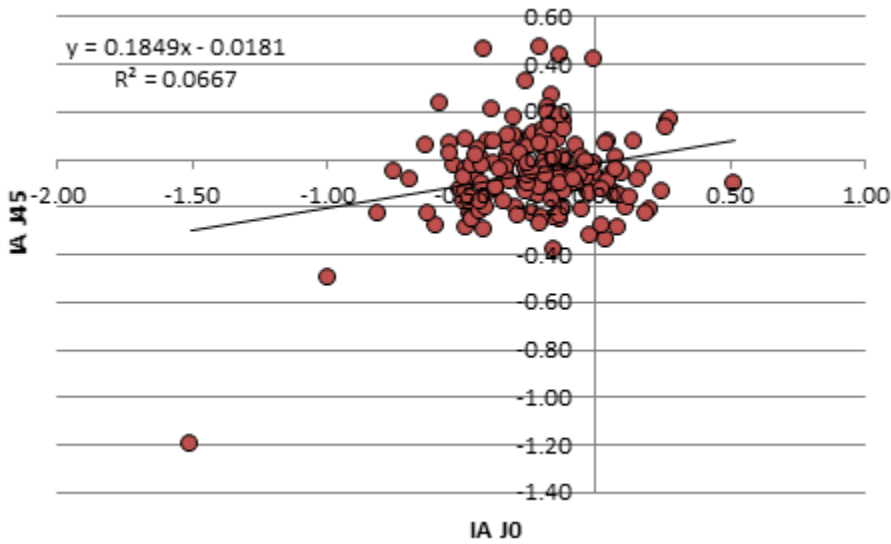


148

149 Fig 2 A Corneal and refractive J0 component. Mean values are clustered around 0.50D and 0.20D
150 for corneal and refractive respectively, indicating J0 is predominantly with-the-rule (WTR). 44% of
151 the variance in refractive J0 is accounted for by corneal astigmatism alone. Approximately 33% of
152 the variance in refractive J0 is accounted for by internal J0 alone.
153



154
155 Fig 2 B Corneal and refractive J45 component. Mean values are clustered around 0D for corneal
156 and refractive J45. Only 30% of the variance in refractive J45 astigmatism is accounted for by
157 corneal astigmatism. Approximately 41% of the variance in refractive J45 astigmatism may be
158 attributable to internal astigmatism alone.
159



160

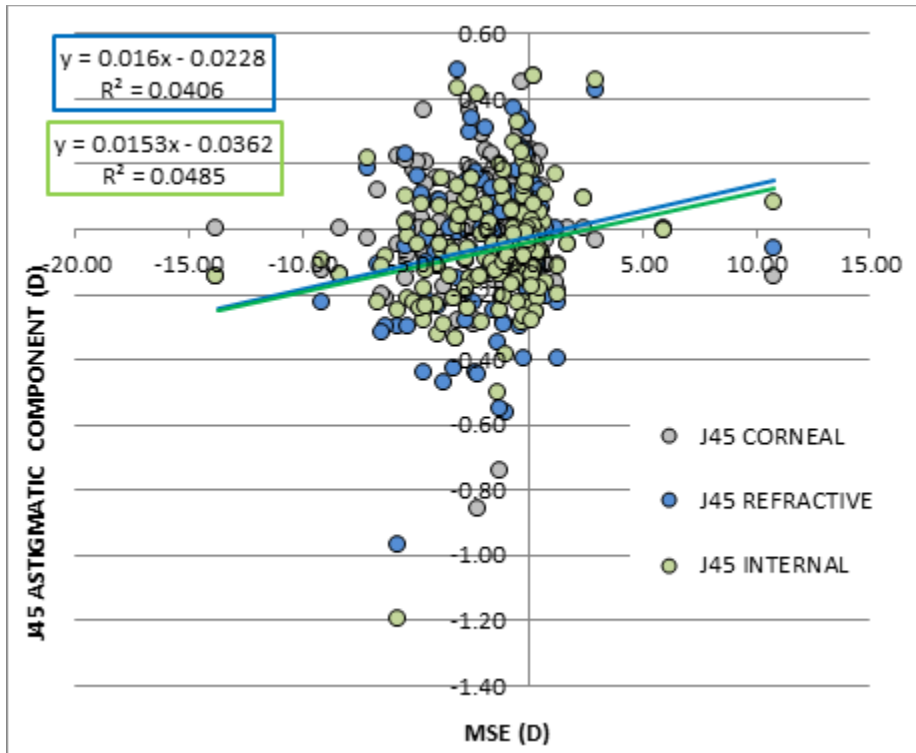
161 **Fig 2 C Internal astigmatism J0 and J45 components. While J45 is clustered around zero; J0 is**
162 **clustered about a mean of approximately -0.20D indicating a tendency towards against the rule**
163 **(ATR) astigmatism.**

164

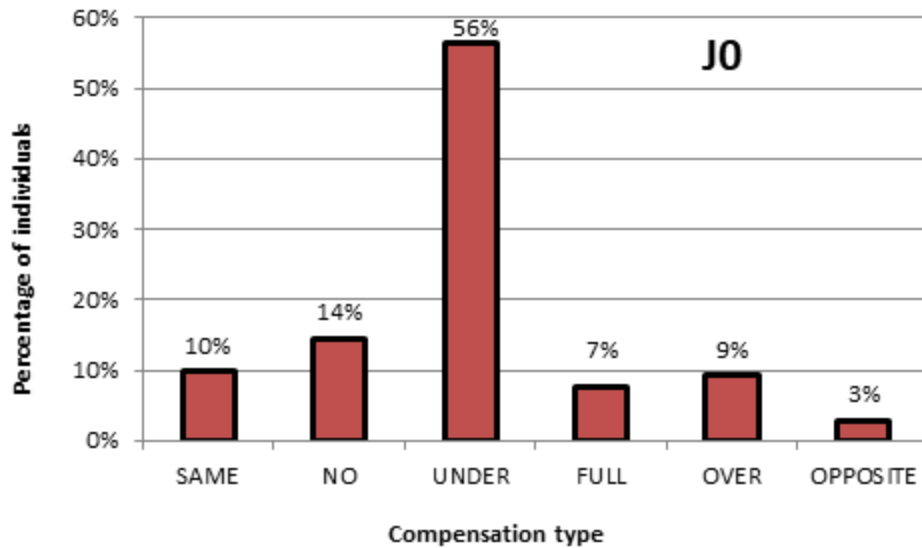
165 ***Associations between power vector components, axial length and MSE***

166

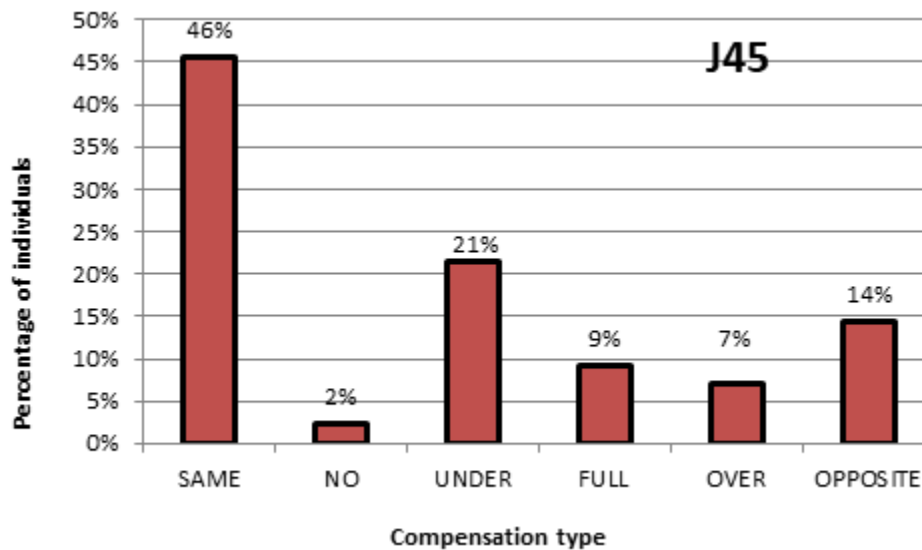
167 As expected there was a significant relationship between increase in axial length and mean myopic
168 spherical error ($p < 0.001$). Linear regression showed both J45 IA and J45 RA to be significantly negatively
169 correlated with axial length ($p < 0.01$) and positively correlated with MSE ($p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



171



189



190

191 **Figure 4 Distribution of compensation factor types for J0 and J45**

192

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

196

197 **Discussion**

198

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

203 common compensation type for the J0 component, and the most common compensation types for the
204 J45 component were axis augmentation (same and opposite) and under compensation.

205
206 Cross-sectional data alone cannot, however, establish whether there is an *active* compensatory
207 mechanism. Significant negative linear correlations between internal and corneal power vectors and
208 analysis of compensation factors seldom showed 'no compensation' of corneal astigmatism, particularly
209 for the J45 component. Nevertheless, full compensation of corneal astigmatism was also uncommon,
210 thus the imbalance between internal and corneal optics rendered many eyes astigmatic.

211
212 In line with previous reports of internal (or residual) astigmatic error (e.g. Park et al 2013; Manny et al
213 2016; Remon et al 2009) the mean J0 component of internal astigmatism was found to be against-the-
214 rule. Previous studies are, however, equivocal with respect to the refractive and corneal J0 component.
215 With some reports finding against-the-rule (ATR) astigmatism (Park et al 2013) and others reporting with-
216 the-rule (WTR) astigmatism (Remon et al 2009). Such differences may arise from variance in cohort age
217 groups; ethnicity; or the methodologies employed e.g. the assumptions made and methodology used to
218 estimate posterior corneal astigmatism. In this study, predominantly positive values were noted for both
219 refractive and corneal J0 indicating with-the-rule (WTR) astigmatism.

220
221 It has been hypothesised that an increased axial length may cause misalignment of internal optics (e.g.
222 lens tilt) thereby inducing internal astigmatic refractive error (Park et al 2013). Data from the present study
223 where correlations between axial length and internal astigmatism were noted, albeit only for the J45 and
224 not J0 component, would appear to support this theory. It is, however, unclear whether there is an
225 association between longitudinal changes in axial length and internal astigmatism; reports both appear to
226 support (Wu et al 2018) and reject such associations (Manny et al 2016). That only oblique, and not
227 orthogonal, astigmatism correlated with axial length, may reflect the asymmetric changes in ocular
228 structures with eye growth.

229
230 Previous studies have remarked on differences in astigmatism between ethnicities (Mandel et al 2010;
231 Saw et al 2006; Ip et al 2008; Huynh et al 2006; Fozailoff et al 2011). The present data set was not,
232 however, large enough to justify meaningful comparisons of astigmatic compensation between different
233 ethnic groups.

234
235 In summary, there appears to be some attenuation of corneal astigmatism by the eye's internal optics,
236 however, in most cases this is partial and not complete compensation. Larger scale studies may help to
237 provide detailed characterisation of astigmatism with respect to ethnicity and help mitigate the risk of
238 unwanted residual astigmatism following corneal reshaping therapies.

239

240 **REFERENCES**

- 241 1. Barnes DA. Astigmatic decomposition: an alternative subjective refraction test employing
242 conventional instrumentation. *Ophthalmic and Physiological Optics*. 1984 Oct 1;4(4):359-64.
- 243 2. Chen Z, Liu L, Pan C, Li X, Pan L, Lan W, Yang Z. Ocular residual and corneal astigmatism in a
244 clinical population of high school students. *PloS one*. 2018 Apr 9;13(4):e0194513.
- 245 3. Dunne M, Elawad ME, Barnes DA. A study of the axis of orientation of residual astigmatism. *Acta*
246 *ophthalmologica*. 1994 Aug 1;72(4):483-9.
- 247 4. Fozailoff A, Tarczy-Hornoch K, Cotter S, Wen G, Lin J, Borchert M, Azen S, Varma R. Prevalence
248 of astigmatism in 6-to 72-month-old African American and Hispanic children: the Multi-ethnic
249 Pediatric Eye Disease Study. *Ophthalmology*. 2011 Feb 1;118(2):284-93.
- 250 5. Fuller JR, Baxter LA, Harun S, Levy IS. Astigmatism in Bangladeshi and white school entrants in
251 East London: a prospective comparative study. *Eye*. 1995 Nov 1;9(6):794-6.
- 252 6. Harris WF. Squaring the sphero-cylinder, the equivalent of squaring the refractive power matrix.
253 *Ophthalmic and Physiological Optics*. 1988 Oct 1;8(4):458-9.
- 254 7. Humphrey WE. A remote subjective refractor employing continuously variable sphere-cylinder
255 corrections. *Optical Engineering*. 1976 Aug;15(4):154286.
- 256 8. Huynh SC, Kifley A, Rose KA, Morgan I, Heller GZ, Mitchell P. Astigmatism and its components in
257 6-year-old children. *Investigative ophthalmology & visual science*. 2006 Jan 1;47(1):55-64.
- 258 9. Huynh SC, Kifley A, Rose KA, Morgan IG, Mitchell P. Astigmatism in 12-year-old Australian
259 children: comparisons with a 6-year-old population. *Investigative ophthalmology & visual science*.
260 2007 Jan 1;48(1):73-82.
- 261 10. Ip JM, Huynh SC, Robaei D, Kifley A, Rose KA, Morgan IG, Wang JJ, Mitchell P. Ethnic differences
262 in refraction and ocular biometry in a population-based sample of 11–15-year-old Australian
263 children. *Eye*. 2008 May;22(5):649.
- 264 11. Keating MP. A system matrix for astigmatic optical systems. *American Journal of Optometry and*
265 *Physiological Optics*. 1981 Nov 1;58(11):919-29.
- 266 12. Keating MP. A system matrix for astigmatic optical systems: II. Corrected systems including an
267 astigmatic eye. *Optometry & Vision Science*. 1981 Nov 1;58(11):919-29.

- 268 13. Keirl A, Christie C. Clinical optics and refraction: A guide for optometrists, contact lens opticians
269 and dispensing opticians. Elsevier Health Sciences; 2007.
- 270 14. Liu YC, Chou P, Lin PY, Chen SJ, Liu JH, Liu CJ, Hsu WM, Cheng CY. Power Vector Analysis of
271 Refractive, Corneal and Lenticular Astigmatism in an Elderly Chinese Population: The Shihpai Eye
272 Study. *Investigative Ophthalmology & Visual Science*. 2011 Apr 22;52(14):2514-.
- 273 15. Liu Y, Cheng Y, Zhang Y, Zhang L, Zhao M, Wang K. Evaluating internal and ocular residual
274 astigmatism in Chinese myopic children. *Japanese journal of ophthalmology*. 2017 Nov
275 1;61(6):494-504.
- 276 16. Mandel Y, Stone RA, Zadok D. Parameters associated with the different astigmatism axis
277 orientations. *Investigative ophthalmology & visual science*. 2010 Feb 1;51(2):723-30.
- 278 17. Manny RE, Deng L, Gwiazda J, Hyman L, Weissberg E, Scheiman M, Fern KD, COMET Study
279 Group. Internal Astigmatism in Myopes and Non-myopes: Compensation or Constant?. *Optometry
280 & Vision Science*. 2016 Sep 1;93(9):1079-92.
- 281 18. Miller JM. Clinical applications of power vectors. *Optometry & Vision Science*. 2009 Jun
282 1;86(6):599-602.
- 283 19. Mohammadpour M, Heidari Z, Khabazkhoob M, Amouzegar A, Hashemi H. Correlation of major
284 components of ocular astigmatism in myopic patients. *Contact Lens and Anterior Eye*. 2016 Feb
285 29;39(1):20-5. Artal et al
- 286 20. Morgan PB, Efron N, Woods CA, Santodomingo-Rubido J, International Contact Lens Prescribing
287 Survey Consortium. International survey of orthokeratology contact lens fitting. *Contact Lens and
288 Anterior Eye*. 2019 Aug 1;42(4):450-4.
- 289 21. Muftuoglu O, Erdem U. Evaluation of internal refraction with the optical path difference scan.
290 *Ophthalmology*. 2008 Jan 31;115(1):57-66.
- 291 22. Namba H, Kawasaki R, Sugano A, Nishi K, Murakami T, Nishitsuka K, Kato T, Kayama T,
292 Yamashita H. Cross-Sectional and Longitudinal Investigation of the Power Vector in Astigmatism:
293 The Yamagata Study (Funagata). *Cornea*. 2018 Jan 1;37(1):53-8.
- 294 23. Park CY, Oh JH, Chuck RS. Predicting ocular residual astigmatism using corneal and refractive
295 parameters: a myopic eye study. *Current eye research*. 2013 Aug 1;38(8):851-61.

- 296 24. Remón L, Benlloch J, Furlan WD. Corneal and refractive astigmatism in adults: a power vectors
297 analysis. *Optometry & Vision Science*. 2009 Oct 1;86(10):1182-6.
- 298 25. Saw SM, Goh PP, Cheng A, Shankar A, Tan DT, Ellwein LB. Ethnicity-specific prevalences of
299 refractive errors vary in Asian children in neighbouring Malaysia and Singapore. *British journal of*
300 *ophthalmology*. 2006 Oct 1;90(10):1230-5.
- 301 26. Shankar S, Bobier WR. Corneal and lenticular components of total astigmatism in a preschool
302 sample. *Optometry & Vision Science*. 2004 Jul 1;81(7):536-42.
- 303 27. Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the
304 description and statistical analysis of refractive error. *Optometry & Vision Science*. 1997 Jun
305 1;74(6):367-75.
- 306 28. Tong L, Carkeet A, Saw SM, Tan DT. Corneal and refractive error astigmatism in Singaporean
307 schoolchildren: a vector-based Javal's rule. *Optometry & Vision Science*. 2001 Dec 1;78(12):881-7.
- 308 29. Tong L, Saw SM, Lin Y, Chia KS, Koh D, Tan D. Incidence and progression of astigmatism in
309 Singaporean children. *Investigative ophthalmology & visual science*. 2004 Nov 1;45(11):3914-8.
- 310 30. Wu L, Weng C, Xia F, Wang X, Zhou X. Internal Astigmatism and Its Role in the Growth of Axial
311 Length in School-Age Children. *Journal of Ophthalmology*. 2018;2018.