

Quantification of Ocular Parameters To Create An Anatomical Eye Model for The Japanese Population

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Abstract

This prospective observational study aimed to evaluate the eye shape and visual function of Japanese people through a multicenter approach and to create a Japanese model eye. Uncorrected and corrected distance visual acuity (UDVA and CDVA, respectively) in the log minimum angle of resolution (logMAR), subjective and objective spherical equivalent values (SE) of ocular refraction, anterior and posterior corneal curvature (ACC and PCC, respectively), anterior and posterior corneal asphericity (ACA and PCA, respectively), central corneal thickness (CCT), anterior chamber depth (ACD), and ocular axial length (AL) were measured in the eyes of 250 participants (mean age = 46.5 ± 18.0 years, range: 20–90 years) across five institutions in Japan. The mean UDVA, CDVA, subjective SE, objective SE, ACC, PCC, ACA, PCA, CCT, ACD, and AL were 0.68, -0.08, -2.42 D, -2.66 D, 7.77 mm, 6.33 mm, -0.31, -0.39, 0.55 mm, 2.92 mm, and 24.78 mm, respectively. Age-related changes and sex-based differences were observed in the visual acuity, refraction, corneal shape, ACD, and AL. Although the sample size needs to be increased, the results of this study can be applied to the development of refractive correction methods and various vision-related fields.

Introduction

Gullstrand's eye model, a representative eye model created with reference to anatomical data, plays an important role in the optimal design of eyeglasses, contact lenses, intraocular lenses, and lasers for vision correction. While many historical eye models have been reported [1, 2], recent improvements in the measurement and evaluation techniques of the shape of the eye have made it possible to create models that are more accurate than the previously reported conventional models. In fact, in addition to Gullstrand's eye model, there are other models of the eye that take into account focal adjustment [3], age-related changes that reflect biometrics [4] among other parameters. Liou and Brennan proposed a new model that is closer to anatomical, biometric, and optical realities, including those previously reported [5]. Recently, in Europe, a study called Project Gullstrand - European Project for the Determination of Average Biometric Values of Human Eyes (Gullstrand) was conducted by the European Vision Institute Clinical Research Network and reported by Zocher et al. [6]. Furthermore, the Bigaussian model was reported by Rozema et al. in Europe [7].

While there is a famous eye model, refractive errors in Japanese and East Asian eyes are often myopic because of genetic and environmental influencing factors [8, 9]; this may require corrections to the eye model. In myopic eyes, the anterior chamber depth (ACD), which is the distance from the cornea to the lens, is deeper and the length of the ocular axial length (AL) is longer [10]. These findings suggest that the standard eye shapes are different from Japanese and East Asian eye shapes. Various studies have been conducted on this, including the Tajimi and Nagahama studies in Japan [11, 12] and the Liwan study in China [13]. We compared the present study with these previous studies [11, 13] and our eye model with other famous eye models, such as the Gullstrand [2], Navarro [3], and Liou and Brennan eye models [5]. This multicenter study was conducted at institutions belonging to the Japanese Society of Ophthalmology to obtain data on the average Japanese eye shape. The purpose of this project was to compile a database of the shape of the eyes of Japanese people and create a Japanese eye model, thereby allowing optimization of eyeglasses, contact lenses, intraocular lenses, and laser correction, and to apply this information to various fields.

Results

Two hundred and fifty eyes from 250 participants (mean age = 46.5 ± 18.0 years, range: 20–90 years) were included in this study (126 females and 124 males with mean ages of 46.74 ± 18.41 and 46.25 ± 17.56 years, respectively, $P = 0.905$) (Table 1). The descriptive statistics are shown in Table 1. While the mean log minimum angle of resolution (logMAR) value for best corrected distance visual acuity (CDVA) was -0.08 ± 0.09 , indicating good vision, the mean logMAR value for uncorrected distance visual acuity (UDVA) was 0.68 ± 0.53 , indicating a high degree of variability and a tendency for many participants to have insufficient vision. Owing to the variation in the normality of the various eye

shape parameters, a non-parametric test was used. The mean and distribution results of the subjective and objective spherical equivalent values (SE) of ocular refraction revealed mild myopia and astigmatism (Tables 1). The spherical power (Sph), cylindrical power (Cyl), SE, power vector J180, and power vector J45 for differences between the subjective and objective measurements were 0.180 ± 0.463 D, 0.122 ± 0.329 D, 0.241 ± 0.469 D, -0.033 ± 0.222 , and 0.025 ± 0.154 , respectively (Table 1). The posterior corneal curvature (PCC) / anterior corneal curvature (ACC) and AL/ACC ratios were 0.82 ± 0.02 and 3.19 ± 0.17 , respectively. In the normality analyses, the hypothesis "This variable is normally distributed" was rejected for age, UDVA, CDVA, and all subjective and objective refractive parameters ($P < 0.05$), while AL, ACD, ACC, PCC, central corneal thickness (CCT), posterior corneal asphericity (PCA), PCC/ACC ratio, and AL/ACC ratio were accepted ($P > 0.05$).

Table 1
Descriptive statistics (n = 250)

Parameter	Mean	SD	Median	Min	Max
Age, years	46.50	17.96	45.00	20.00	90.00
UDVA, logMAR	0.68	0.53	0.70	-0.30	1.70
CDVA, logMAR	-0.08	0.09	-0.08	-0.30	0.30
Subjective Sph, D	-2.08	2.91	-1.88	-8.75	7.00
Subjective Cyl, D	-0.68	0.73	-0.50	-3.50	0.00
Subjective SE, D	-2.42	2.89	-2.25	-8.88	6.63
Subjective J180	-0.01	0.44	0.00	-1.72	1.25
Subjective J45	0.02	0.22	0.00	-0.87	1.15
Objective Sph, D	-2.26	3.08	-2.00	-9.50	7.25
Objective Cyl, D	-0.80	0.67	-0.63	-3.75	0.50
Objective SE, D	-2.66	3.05	-2.38	-9.75	6.88
Objective J180	0.02	0.47	0.04	-1.82	1.25
Objective J45	-0.01	0.23	0.00	-0.94	1.15
AL, mm	24.78	1.46	24.78	21.12	28.34
ACD, mm	2.92	0.41	2.94	1.82	3.95
ACC, mm	7.77	0.27	7.77	7.16	8.49
PCC, mm	6.33	0.27	6.33	5.63	7.09
CCT, mm	0.55	0.03	0.55	0.46	0.64
ACA	-0.31	0.13	-0.30	-0.91	0.00
PCA	-0.39	0.18	-0.39	-0.91	0.13
ACP, D	48.46	1.67	48.41	44.29	52.51
PCP, D	-6.33	0.27	-6.32	-7.11	-5.64
TCP, D	42.26	1.45	42.18	38.64	45.58

SD, standard deviation; Min, minimum; Max, maximum; UDVA, uncorrected distance visual acuity; logMAR, logarithm of minimum angle of resolution; CDVA, corrected distance visual acuity; Sph, sphere; Cyl, cylinder; SE, spherical equivalent; AL, axial length; ACD, anterior chamber depth from the posterior cornea to the anterior lens; ACC, anterior corneal curvature radius; PCC, posterior corneal curvature radius; CCT, central corneal thickness; ACA, anterior corneal asphericity; PCA, posterior corneal asphericity; ACP, anterior corneal power; PCP, posterior corneal power; TCP, total corneal power; D, diopter

Table 2

A comparison of the eye shape results between the present study and other eye models and studies [2, 3, 5]

Parameter	Present study	Gullstrand's model	Navarro's model	Liou and Brennan's model* ¹	Nagahama study	Liwan eye study	German study* ²
Age, years (Min to Max)	46.5±18.0 (20–90)	n/a	n/a	n/a	57.6±12.4 (34–80)	64.4±9.6 n/a	42, 43 ⁴ (21–69)
ACC, mm	7.77±0.27	7.70	7.72	7.77	7.67±0.25	7.69 ^{2,3}	7.82±0.26
PCC, mm	6.33±0.27	6.80	6.50	6.40	n/a	n/a	6.47±0.25
CCT, mm	0.55±0.03	0.50	0.55	0.55	0.54±0.03	n/a	0.55±0.03
ACA	-0.30±0.13	n/a	-0.26	-0.18	n/a	n/a	0.38±0.19 ⁵
PCA	-0.39±0.18	n/a	0.00	-0.60	n/a	n/a	0.16±0.36 ⁵
ACD, mm	2.94±0.41	3.10	3.05	3.16	3.18±0.38	2.67 ²	2.83±0.37
AL, mm	24.78±1.46	24.39	24.00	23.97	24.09±1.37	23.11 ²	23.80±1.05
Min, minimum; Max, maximum; ACC, radius of the anterior corneal curvature; PCC, radius of the posterior corneal curvature; CCT, central corneal thickness; ACA, anterior corneal asphericity; PCA, posterior corneal asphericity; ACD, anterior chamber depth from the posterior cornea to the anterior lens; AL, axial length; n/a, not applicable							
The values in the table are expressed as means ± standard deviations. ¹ Merging multiple reports. The values in the table are means, except for ² . ² Median value (no mean and SD data available). ³ Estimated value calculated from the equivalent refractive index 1.3375; ⁴ 43 years in female, 42 years in male. ⁵ Eccentricity							

Table 3
A comparison of sex-based differences

Parameter	Female (n = 126)			Male (n = 124)			Mann–Whitney test
	Mean	SD	Median	Mean	SD	Median	p value
Age, years	46.74	18.41	45.00	46.25	17.56	45.00	0.905
UDVA, logMAR	0.61	0.55	0.70	0.75	0.51	0.82	0.030
CDVA, logMAR	-0.08	0.09	-0.08	-0.08	0.09	-0.08	0.715
Subjective Sph, D	-1.72	2.75	-1.00	-2.45	3.02	-2.75	0.024
Subjective Cyl, D	-0.62	0.70	-0.50	-0.74	0.75	-0.50	0.201
Subjective SE, D	-2.03	2.75	-1.50	-2.82	2.98	-2.75	0.014
Subjective J180	0.00	0.42	0.00	-0.03	0.47	0.00	0.468
Subjective J45	0.01	0.21	0.00	0.02	0.23	0.00	0.601
Objective Sph, D	-1.88	2.94	-1.25	-2.64	3.18	-3.00	0.032
Objective Cyl, D	-0.76	0.62	-0.50	-0.84	0.73	-0.75	0.440
Objective SE, D	-2.26	2.92	-1.81	-3.07	3.14	-3.13	0.020
Objective J180	0.01	0.43	0.06	0.03	0.51	0.00	0.752
Objective J45	0.00	0.23	0.00	-0.01	0.23	0.00	0.890
AL, mm	24.23	1.29	23.98	25.33	1.41	25.30	0.000
ACD, mm	2.82	0.38	2.88	3.01	0.41	3.03	0.000
ACC, mm	7.68	0.24	7.70	7.86	0.26	7.86	0.000
PCC, mm	6.24	0.25	6.23	6.42	0.25	6.41	0.000
CCT, mm	0.55	0.03	0.55	0.55	0.03	0.55	0.338
ACA	-0.34	0.14	-0.32	-0.29	0.12	-0.29	0.012
PCA	-0.39	0.17	-0.39	-0.39	0.19	-0.41	0.889
PCC/ACC ratio	0.81	0.02	0.81	0.82	0.02	0.82	0.085
AL/ACC ratio	3.16	0.15	3.15	3.23	0.18	3.21	0.001
ACP, D	49.01	1.55	48.83	47.90	1.59	47.87	0.000
PCP, D	-6.42	0.26	-6.43	-6.24	0.24	-6.24	0.000
TCP, D	42.72	1.35	42.58	41.78	1.40	41.70	0.000

SD, standard deviation; Min, minimum; Max, maximum; UDVA, uncorrected distance visual acuity; logMAR, Logarithm of minimum angle of resolution; CDVA, corrected distance visual acuity; Sph, sphere; Cyl, cylinder; SE, spherical equivalent; AL, Axial length; ACD, Anterior chamber depth from the posterior cornea to the anterior lens; ACC, anterior corneal radius of curvature; PCC, posterior corneal radius of curvature; CCT, central corneal thickness; ACA, anterior corneal asphericity; PCA, posterior corneal asphericity; ACP, anterior corneal power; PCP, posterior corneal power; TCP, total corneal power; D, diopter

A comparison between these results and results from the previous reports is presented in Table 2. Compared to the Gullstrand's model eye, the posterior surface of the cornea was 0.5 mm steeper and the cornea was 0.05 mm thicker. In the Liou and Brennan's model eye, the anterior corneal asphericity (ACA) and PCA were -0.18 and -0.60, respectively, while in this study, the ACA and PCA were -0.12 and 0.21, respectively; the corneal radius of curvature and thickness were almost the same. Compared to that in the Nagahama study [11], the ACC was 0.10 mm flatter and the ACD was 0.24 mm shallower. Compared to that in the German study [6], the ACC and PCC were 0.05 mm and 0.14 mm steeper, respectively and the ACD was 0.13 mm deeper. In addition, the AL in the present study was longer than that of any ocular model [2, 3, 5] and ALs reported in the previous studies [6, 11, 13].

With respect to age-related changes, the visual acuity (UDVA, adjusted $R^2 = 0.041$, $P < 0.001$; CDVA, adjusted $R^2 = 0.437$, $P < 0.001$) and many ocular shape parameters were correlated with age (Figures 1–3).

Concerning visual acuity, the UDVA improved with age ($P = 0.000$ for both subjective SE and objective SE, Figure 1), although there was a large variability. The CDVA decreased slightly with age ($P = 0.000$, Figure 1). For refraction, both subjective SE and objective SE changed to the positive side with age ($P = 0.000$, Figure 1). Furthermore, the J180 shifted to the minus side with increasing age, i.e., from with-the-rule astigmatism to against-the-rule astigmatism ($P = 0.000$ for both subjective J180 and objective J180, Figure 1). For J45, there was a trend towards greater variability with age; while no age-related changes were observed in the objective values ($P = 0.067$), a positive change toward 135° was noted in the subjective values ($P = 0.013$, Table 3). Furthermore, the observation test power (OTP) was almost equal to 1 (Figure 1).

Ocular biometry shows that the corneal shape is slightly steeper (ACC, adjusted $R^2 = 0.107$, $P < 0.001$; PCC, adjusted $R^2 = 0.083$, $P < 0.001$) and more oblate (ACA, adjusted $R^2 = 0.021$, $P = 0.028$; PCA, adjusted $R^2 = 0.178$, $P < 0.001$) with age (Figure 2). The parameters that did not differ significantly were the CCT (adjusted $R^2 = 0.001$, $P = 0.244$), PCC/ACC ratio ($P = 0.447$), and AL/ACC ratio (adjusted $R^2 = 0.020$, $P = 0.074$).

Furthermore, the OTP in the univariate general linear model was almost equal to 1 (Figures 1 and 2).

Regarding sex-based differences, male participants had a slightly worse UDVA compared to that of female participants ($P = 0.03$) due to negative shifts in the subjective and objective SE ($P = 0.014$, $P = 0.020$, respectively; Figure 1 and Table 3).

Regarding ocular parameters, male participants had a slightly longer ocular AL ($P < 0.001$), deeper ACD ($P < 0.001$), flatter corneal shape (ACC, $P < 0.001$; PCC, $P < 0.001$), and different ACA (positive side) as compared those of the female participants ($P = 0.012$; Figure 2 and Table 3). The anterior corneal power (ACP) and total corneal power (TCP) were significantly more refractive, and the posterior corneal power (PCP) was significantly more negative in female participants than in male participants ($P = 0.000$ for ACP, TCP, and PCP; Figure 3 and Table 3). The parameters that did not differ significantly were the CDVA ($P = 0.715$), subjective and objective Cylinder (subjective Cyl, $P = 0.201$; objective Cyl, $P = 0.440$), J180 (subjective J180, $P = 0.468$; objective J180, $P = 0.752$), J45 (subjective J45, $P = 0.601$; objective J45, $P = 0.890$), CCT ($P = 0.338$), PCA ($P = 0.889$), and PCC / ACC ratio ($P = 0.085$) (Table 3).

Table 4 compares the refractive error by age and sex between Japanese and German participants, as reported by Zocher et al. [6]. The P-values in the Kruskal–Wallis test for the refraction values by age groups for female participants were < 0.001 for the sphere values and 0.002 for the spherical equivalent values; for male participants P-values were 0.014 for the sphere values and 0.055 for the spherical equivalent values. Both groups shifted toward hyperopia with increasing age; Japanese participants showed more myopia as compared to the German participants (Table 4).

Table 4

Comparison of the subjective refractive error by age groups and sexes between Japanese and German participants [6]

Age group	n		Sph, D				SE, D				
	Japanese	German	Japanese		German		Japanese		German		
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Female											
20–29 years	25	24	-1.88 ± 2.27		-0.85 ± 1.64		-2.07 ± 2.30		-0.99 ± 1.64		
30–39 years	25	19	-2.96 ± 2.72		-1.34 ± 2.06		-3.13 ± 2.78		-1.63 ± 2.17		
40–49 years	26	32	-2.23 ± 2.71		-0.86 ± 1.93		-2.47 ± 2.82		-1.13 ± 2.00		
50–59 years	21	19	-2.20 ± 2.71		0.91 ± 1.22		-2.66 ± 2.76		0.74 ± 1.17		
60–69 years	9	16	-0.58 ± 2.67		0.63 ± 1.94		-0.89 ± 2.66		0.24 ± 2.18		
Over 70 years	20	0	0.70 ± 2.04		n/a		0.11 ± 2.04		n/a		
Total	126	110	-1.72 ± 2.75		-0.42 ± 1.95		-2.03 ± 2.75		-0.66 ± 2.02		
Male											
20–29 years	25	24	-3.26 ± 2.22		-1.07 ± 1.39		-3.46 ± 2.28		-1.46 ± 1.46		
30–39 years	25	19	-3.47 ± 3.25		-1.62 ± 2.29		-3.84 ± 3.16		-2.00 ± 2.35		
40–49 years	25	32	-1.85 ± 3.35		-0.24 ± 2.13		-2.11 ± 3.35		-0.56 ± 2.11		
50–59 years	21	19	-2.88 ± 2.66		0.16 ± 2.36		-3.25 ± 2.67		-0.13 ± 2.41		
60–69 years	10	16	-1.45 ± 2.67		1.07 ± 1.66		-1.99 ± 2.86		0.68 ± 1.76		
Over 70 years	18	0	-0.79 ± 3.09		n/a		-1.47 ± 2.98		n/a		
Total	124	110	-2.45 ± 3.02		-0.47 ± 2.15		-2.82 ± 2.75		-0.81 ± 2.18		
Sph, sphere; SE, spherical equivalent; D, diopter; n/a, not applicable											

Discussion

We conducted a multicenter study on visual function and eye shape to create a Japanese myopic eye model. Results showed that the values of refraction were slightly myopic, and there were age-related changes and sex-based differences in many parameters.

The results of the descriptive statistics regarding refraction showed the low myopia, which could be related to the higher myopia rate among East Asians. Morgan et al. [8] showed that myopia was common among East Asians and reported that 80–90% of middle school graduates were affected. It has also been reported that the curvature of the corneal radius flattens with increasing myopia [15]. Compared to the other model eyes [2, 3, 5, 6, 11], in this study the anterior surface of the cornea was similar, the posterior surface was slightly steeper, and the asphericity was on the positive side. This may be due to the unique structure of the Japanese eye, where only the AL of the eye is slightly longer. In fact, this result was similar to the result of the large-scale Nagahama study conducted by Nakao et al. [11]. The results of the present study showed that the AL was about 0.7 mm longer than that in the Nagahama Study [11], about 1.7 mm longer than that in the Liwan Eye study [13], and about 1.0 mm more myopic than that in the above-mentioned German study [6]; however, the difference in Nagahama study and Liwan eye study may be because our study also included people in their 20s. The shallower ACD of our model, as compared to that of some previous models [1–3, 5, 11], could be due to the higher average age of the participants and the inclusion of older individuals.

With regards to age-related changes, previous reports have shown that refractive values become hyperopic with increasing age [16]. In addition, the corneal radius of curvature becomes slightly steeper and the asphericity changes slightly [4]. Dubbelman et al. [17] showed that the corneal radius of curvature does not change with age in either the anterior or posterior surfaces, while the asphericity changes slightly. The AL of the eye is slightly reduced [18], and the lens are reported to experience steepening and have a decreased refractive index [19]. In this study, the refraction values became more hyperopic, the corneal radius of curvature became steeper, and the ocular AL became shorter with age, each with statistically significant correlations. Therefore, these age-related changes were similar to those in Nagahara's study for refraction [11] and in Navarro's study for the corneal radius of curvature [4]. The decrease in the ACD with increasing age appears to be mainly due to an increase in the lens thickness, which was in line with the findings of a previous report [20]. Although the age-related changes in the eye shape were similar to those previously reported [4, 11, 20], the average height difference between 20-year-olds was about 10 cm higher than that between 80-year-olds [21], which may have affected the difference in the ocular AL. Zocher et al. [6] reported that there is a relationship between height and ocular AL; the regression equation is 0.0393 mm longer per 1 cm of the height.

Regarding sex-based differences, Roters et al. [22] reported that women have a slightly shorter ocular AL and ACD than men. Dubbelman et al. [17] reported that the anterior and posterior corneal surfaces of men were flatter than those of women. For all other parameters, including asphericity and trends with age, no sex-based differences have been observed. The results of the present study showed sex-based differences in the SE, corneal shape, ocular AL, and ACD. These differences between men and women could be related to a correlation between height and ocular shape [23, 24]. This is consistent with the results of previous studies. A comparison of the results between the present study and those obtained by Zocher et al. [6] regarding age- and sex-based differences showed that the results of this study were on the myopic side for all ages. The male eye showed more myopic refraction and an elongated myopic eye shape than the female eye.

Thus, race, age, and sex differences need to be considered when using an eye model to optimize refractive correction. The most commonly used eye models include the Gullstrand's eye model and the LeGrand's precision eye model, which are spherical proximal axis models [1]. The Navarro's eye model is an aspheric model that can consider the effects of off-axis aberration and more closely resembles the shape of the human eye [3]. The Liou and Brennan eye model takes into account the distribution of the lens' refractive index [5]. The Arizona eye model by Schwiegerling can control the

accommodation level with longitudinal chromatic aberration of the eye and longitudinal spherical aberration [25]. Furthermore, Atchison and Thibos have reviewed, in detail, the eye models reported in the past [26]. As biometric techniques develop, new ocular models are emerging, and the role of these models will become increasingly important in elucidating the functional role of ocular structures and in developing new refractive correction methods. Eye models based on biometric data should also be actively applied to the development of corrective methods (which are applicable to the majority of cases) and to the selection of appropriate corrective methods that are customizable, in order to meet the needs of individual patients and address the individual differences in refraction.

A possible limitation of this study was the inclusion of some variability due to differences in the autorefractometers used at the five different institutions. However, the trend of the objective refractive data was similar to that of the subjective data, and we believe that the study conclusion would remain unchanged. In addition, the results provided in this study are from a sample size of 250, which is not sufficient to reflect the whole of Japan. However, we believe that the reliability of the results can be ensured, because the measurements were conducted by specialists using instruments with high accuracy and reproducibility. Further studies are needed that address the limitations. The study findings on the model should be interpreted as being reflective of the characteristics of the Japanese eye rather than of the Japanese population. In addition, it would be desirable to examine the statistical differences between the present model eyes and the model eyes reported previously; however, due to the unavailability of raw data, only simple comparisons of the means and medians were made rather than of the statistical tests of differences. Due to racial, regional, and chronological biases, caution should be exercised in interpreting the data, and it is important to conduct future studies to compare the data statistically.

In conclusion, we have obtained eye shape data that are representative of the Japanese population, although the limitations of the study described above must be considered and interpreted with caution. The results can be used to optimize standard optical designs and laser treatments, such as new eyeglasses, contact lenses, and intraocular lenses, for the Japanese and East Asian population. The model eye can be applied to other fields such as oncology or fields related to vision, such as electronic displays and lighting, and to provide comparative data when epidemiological studies are conducted in the future. In the future, it is important to collect data from a larger sample size and to also investigate data outside the scope of this study, including eyes with intense myopia and diseases, to compare with the data from other countries.

Methods

This was a multicenter, prospective observational study and a cross-sectional survey involving five institutions: Osaka University, Kitasato University, Keio University, Juntendo University, and the University of Tsukuba. A target of 250 eyes was set, and 250 participants were enrolled between October 18, 2016 and March 31, 2019. The inclusion criteria were as follows: measurement of one healthy eye (left or right eye, randomly determined), subjective and objective SEs of -10.0 D to +10.0 D, absence of corneal or retinal lesions, no ocular disease other than cataracts, and residents of Japan. The exclusion criteria were as follows: presence of lesions, no ocular diseases, no previous ophthalmic surgery, no amblyopia, refractive error greater than ± 10.0 D, no systemic diseases (e.g., diabetes and multiple sclerosis), women who were more than five months pregnant prior to testing, and hard contact lens wearers. This study was approved by the Institutional Review Board at five institutions: Osaka University, Kitasato University, Keio University, Juntendo University, and the University of Tsukuba, and have been performed in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants after explanation of the study.

The UDVA and CDVA in the logMAR unit, subjective manifest refraction (spherical and minus cylindrical powers and axis), and objective refraction (spherical and minus cylindrical powers and axis) were evaluated using the autorefractometer. The AL was evaluated using optical low-coherence reflectometry (IOLMaster 500 or 700, Carl Zeiss

Meditec AG, Jen, Germany). The radii of the ACC and PCC, ACA and PCA, CCT, and ACD expressed as the distance from the posterior surface of the cornea to the front surface of the lens were estimated using the Pentacam HR (Oculus, Wetzlar, Germany) with rotating Scheimpflug photography. The SE and power vectors, J180 and J45, were calculated from the subjective manifest refraction and objective refraction as follows (equation 1) [14]:

$$\begin{aligned}
 SE &= SE + \left(\frac{Cyl}{2}\right) \\
 J180 &= \left(-\frac{Cyl}{2}\right) \cos 2\alpha \\
 J45 &= \left(-\frac{Cyl}{2}\right) \sin 2\alpha
 \end{aligned}
 \tag{1}$$

where, Sph is the sphere power, Cyl is the minus cylinder power, and α is the minus cylinder axis.

The total corneal power (TCP) was calculated using the follow formula (equation 2):

$$TCP = ACP + PCP - \left(\frac{CCT}{n_2}\right) \left(\frac{n_2-n_1}{ACC}\right) \left(\frac{n_3-n_2}{PCC}\right)
 \tag{2}$$

where, ACP is the anterior corneal power; PCP is the posterior corneal power; CCT is the central corneal thickness; ACC is the radius of the anterior corneal curvature; PCC is the radius of the posterior corneal curvature; and n_1 , n_2 , and n_3 are the refractive indices of air (1.000), cornea (1.376), and aqueous humor (1.336), respectively. The PCC/ACC ratio and the AL / ACC ratio were also calculated.

These measurements were performed under non-mydratic and non-cycloplegic conditions.

Statistical analyses were performed using the IBM SPSS Statistics software (version 25.0, SPSS, Inc., Chicago, IL, USA) and Microsoft® Excel® for Office 365 (Microsoft Co., Ltd, Redmond, WA, USA). Descriptive statistics (mean, standard deviation, median, minimum value, maximum value, and percentage) were computed and tests of normality, Shapiro-Wilk test, was performed. A regression analysis of age for each parameter was performed to assess changes associated with age. Regression equations were either linear or curve estimations based on the height of the adjusted coefficient of determination. To know if the amount of data was sufficient, we calculated the OTP using $\alpha = 0.05$. The OTP takes a value between 0 and 1; the closer the value is to 1, the more likely that the analysis of variance (ANOVA) is based on sufficient data.

Non-parametric analyses using the Mann–Whitney U test (for two groups) and the Kruskal–Wallis test (for independent samples) were performed to evaluate the sex-based differences in each parameter between the age groups. Furthermore, an ANOVA and the Games–Howell post-hoc test for multiple comparisons were performed to compare the parameters between the refractive data groups. A P value of less than 0.05 was considered statistically significant.

In addition, the results of this study were compared with those of previous reports and eye models [2, 3, 5, 6, 11].

Declarations

Data Availability: The datasets generated and analyzed in this study have not been made public in view of the ethics application, but will be discussed by the board of directors upon formal request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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Figures

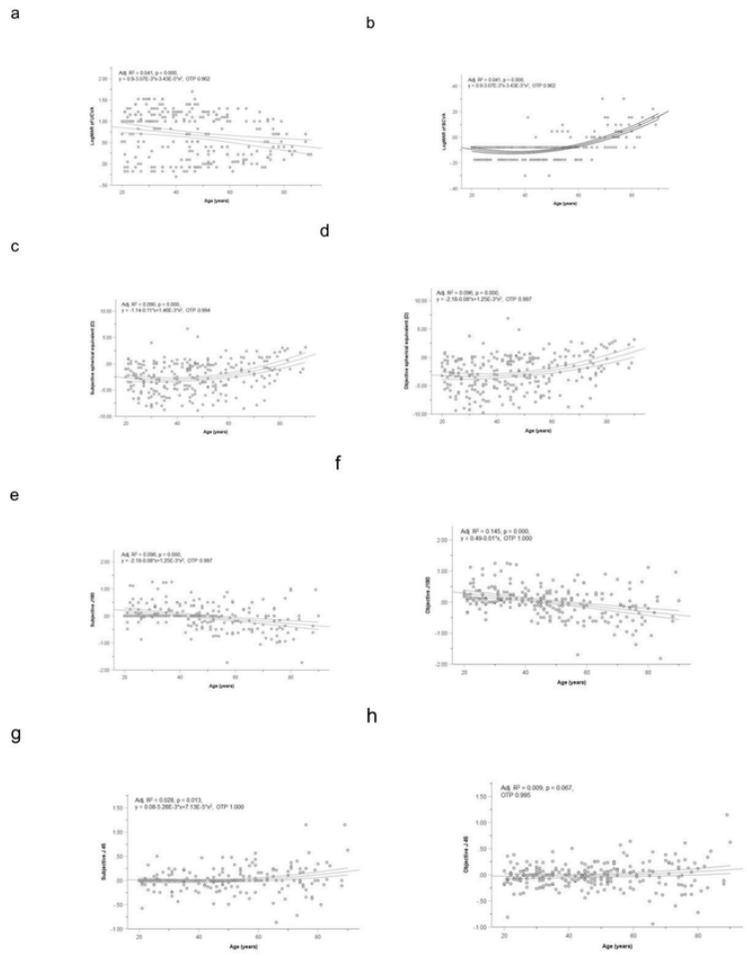


Figure 1

Age-Associated changes in visual acuity and refraction for each study parameter (only significant correlations have been extracted from Table 3). (a) Log minimum angle of resolution (logMAR) of the uncorrected distance visual acuity (UDVA); (b) logMAR of the corrected distance visual acuity (CDVA); (c) Subjective spherical equivalent; (d) Objective spherical equivalent; (e) Subjective J180; (f) Objective J180; (g) Subjective J45; (h) Objective J45. The three lines represent regression curves and 95% confidence intervals. D, diopter; Adj. R2, adjusted R2; OTP, observation test power

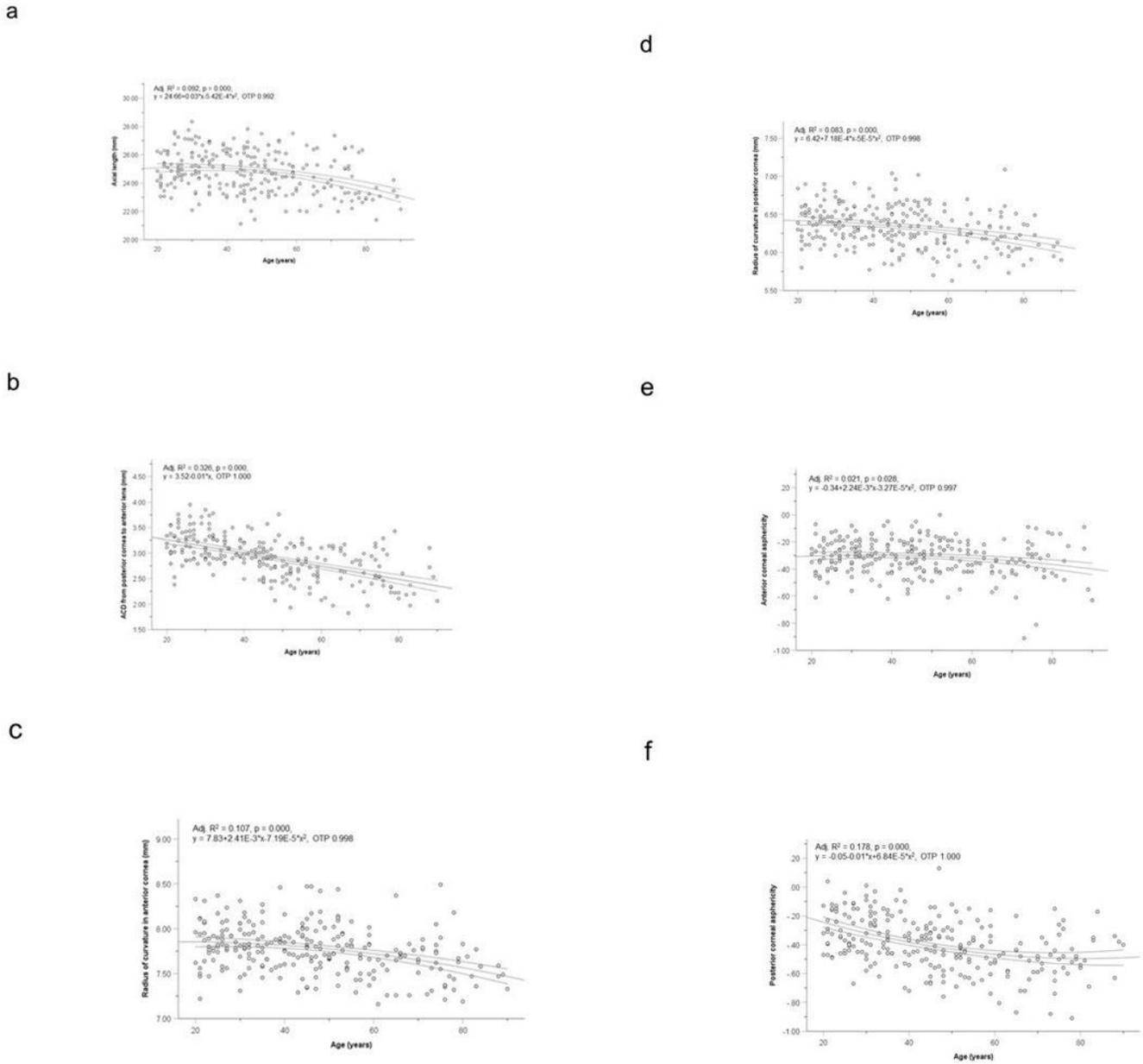
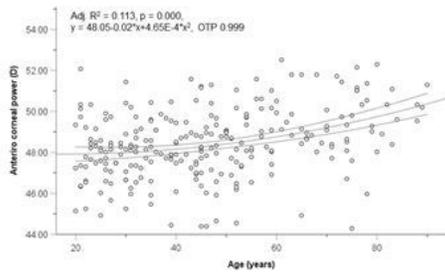


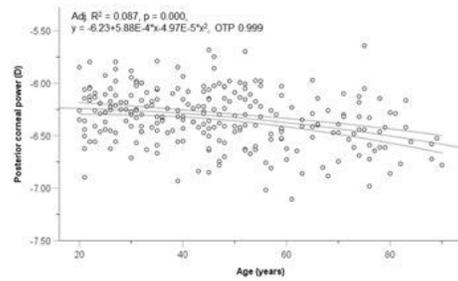
Figure 2

Ocular biometry. Age-associated changes for each study parameter (only significant correlations have been extracted from Table 3). (a) Axial length; (b) Anterior chamber depth (ACD) from the posterior cornea to the anterior lens; (c) Radius of curvature of the anterior cornea; (d) Radius of curvature of the posterior cornea; (e) Anterior corneal asphericity; (f) Posterior corneal asphericity. The three lines represent regression curves and 95% confidence intervals. Adj. R2, adjusted R2; OTP, observation test power

a



b



c

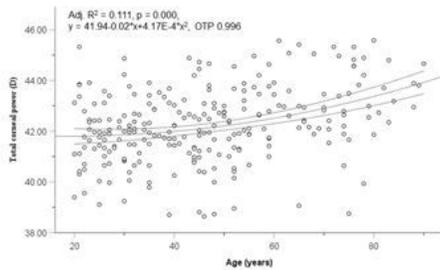


Figure 3

Age-associated changes in the corneal power. (a) Anterior corneal power; (b) Posterior corneal power; (c) Total corneal power. The three lines represent regression curves and 95% confidence intervals. D, diopter; Adj. R², adjusted R²; OTP, observation test power