

Changes in Irregular Corneal Astigmatism With Age in Eyes With and Without Cataract Surgery

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PURPOSE. To investigate the changes in irregular and regular corneal astigmatism with age in eyes that underwent cataract surgery (surgery group) and in eyes that did not undergo surgery (nonsurgery group).

METHODS. We enrolled 120 eyes in each of four age groups in the surgery and nonsurgery groups: (1) 50 to 59 years of age, (2) 60 to 69 years of age, (3) 70 to 79 years of age, and (4) older than or equal to 80 years of age. Eyes in the surgery group underwent videokeratographic examination, at least 6 months postoperatively. Irregular astigmatism components, corneal asymmetry, and higher-order irregularity components were determined using Fourier analysis. The regular astigmatism vector was decomposed into vertical/horizontal (J_0) and oblique (J_{45}) components using power vector analysis.

RESULTS. Both the mean corneal asymmetry and higher-order irregularity components significantly increased with increasing age in both groups ($P < 0.0001$). Higher-order irregularity was greater in the surgery group than in the nonsurgery group in all age groups ($P \leq 0.0128$). The asymmetry did not differ significantly between groups. Asymmetry and higher-order irregularity were positively correlated with actual age in both the surgery and nonsurgery groups ($P < 0.0001$). The J_0 decreased significantly with age in both groups ($P < 0.0001$), whereas the J_{45} did not vary significantly with age.

CONCLUSIONS. In patients from 50 to 80 years of age who underwent cataract surgery, irregular corneal astigmatism, both the asymmetry and higher-order irregularity components, increased significantly with increasing age, whereas regular astigmatism induces an against-the-rule shift. The higher-order irregularity component persistently increased postoperatively, whereas the asymmetry component did not change significantly.

Keywords: cataract surgery, cornea, corneal topography, irregular astigmatism, regular astigmatism

Regular corneal astigmatism changes to the against-the-rule astigmatism with advancing age.¹⁻⁵ Accordingly, the incidence of eyes with against-the-rule corneal astigmatism increases and that of eyes having the with-the-rule astigmatism decreases with age.⁶ Furthermore, against-the-rule astigmatic changes with age occur to a similar extent in eyes that underwent cataract surgery and eyes that did not undergo cataract surgery, and the changes are not affected by age at the time of surgery.^{6,7}

Irregular corneal astigmatism is defined as astigmatism that cannot be corrected by spherocylindrical lenses. Because irregular corneal astigmatism increases ocular aberrations, visual functions, including corrected visual acuity and contrast sensitivity, are substantially impaired.⁸ Irregular corneal astigmatism is induced by many kinds of corneal pathologies⁹⁻¹¹ as well as ocular surgeries.¹²⁻¹⁴ Changes in irregular corneal astigmatism with aging, however, have not been sufficiently addressed. Goto et al.¹⁵ reported that several videokeratographic indices regarding irregular astigmatism increase with age, but the kinds of changes that occur in irregular astigmatism remain unclear. How ocular surgery affects the changes of irregular astigmatism with age is also unknown.

The purposes of the present study were to investigate the changes in irregular corneal astigmatism with increasing age, and to examine whether the changes in irregular astigmatism with age are affected by cataract surgery. To precisely evaluate the degree and types of irregular corneal astigmatism, we used Fourier harmonic analysis of videokeratography data.¹⁶

METHODS

Study Design

This study was a retrospective cohort study. The study was performed at the Hayashi Eye Hospital, Fukuoka, Japan, from March 2011 through August 2011. The study adhered to the tenets of the Declaration of Helsinki. The institutional review board/ethics committee of the Hayashi Eye Hospital approved the study protocol, and informed consent to participate in the study was obtained from all participants after explaining the nature of the study.

Participants

All patients who had undergone phacoemulsification surgery with implantation of a foldable intraocular lens (IOL) at the

TABLE 1. Patient Characteristics at Baseline in the Surgery and Nonsurgery Groups

Characteristics	Surgery Group	Nonsurgery Group	P Value
50 y of age			
Age	55.53 ± 2.62	55.53 ± 2.50	0.9336
Sex	59/61	62/58	0.7962
Left/right eyes	62/58	60/60	0.8973
MRSE, D	-0.66 ± 0.54	-1.48 ± 2.12	0.0520
Time interval†	32.76 ± 23.78	-	-
60 y of age			
Age	63.91 ± 2.57	63.78 ± 2.59	0.6318
Sex	50/70	46/74	0.6926
Left/right eyes	59/61	60/60	>0.9999
MRSE, D	-0.54 ± 0.57	-0.81 ± 2.27	0.0478*
Time interval†	24.91 ± 19.07	-	-
70 y of age			
Age	73.41 ± 2.18	73.24 ± 1.70	0.3809
Sex	46/74	58/62	0.1519
Left/right eyes	63/57	56/64	0.4386
MRSE, D	-0.42 ± 0.52	0.31 ± 1.41	<0.0001*
Time interval†	29.08 ± 22.31	-	-
80 y of age			
Age	82.05 ± 2.06	82.18 ± 1.63	0.1770
Sex	45/75	49/71	0.6916
Left/right eyes	56/64	62/58	0.5185
MRSE, D	-0.34 ± 0.64	0.85 ± 1.68	<0.0001*
Time interval†	35.51 ± 25.13	-	-

D, diopters; MRSE, manifest spherical equivalent value (D).

* Statistically significant difference between the surgery and nonsurgery groups.

† Elapsed time interval between surgery and examinations.

Hayashi Eye Hospital with a minimum follow-up of 6 months from the time of cataract surgery were sequentially screened for recruitment into the surgery group. The inclusion criteria for the surgery group were: (1) eyes that underwent at least two examinations using an autokeratometer at 6 months postoperatively and later, and the difference between the two examinations was within 0.5 diopters (D) in cylindrical power and within 15° in cylindrical axis; (2) first-operated eye if the patient had undergone bilateral cataract surgery; (3) eyes that

had uneventful surgery with no sutures; (4) eyes without comorbidity of the cornea or chronic eyelid disease; (5) eyes with no history of other surgery or inflammation; and (6) eyes that were not enrolled in other clinical studies. Patient screening was continued until 120 patients were recruited for each of the four age groups: (1) 50 to 59 years of age, (2) 60 to 69 years of age, (3) 70 to 79 years of age, and (4) older than or equal to 80 years of age. For controls, 120 patients that did not undergo ocular surgery were recruited for each of the same age groups during the same time interval (nonsurgery group). Inclusion criteria for the nonsurgery group were (1) eyes that underwent at least two examinations using an autokeratometer, and the difference between the examinations was within 0.5 D in cylindrical power and within 15° in cylindrical axis; (2) unilateral eye of each patient in which cylindrical power was less; (3) eyes with no comorbidity of the cornea or chronic eyelid disease; (4) eyes with no history of other surgery or inflammation; and (5) eyes that were not included in other clinical studies.

Surgical Procedure

A single surgeon (KH) performed all surgeries using almost the same surgical procedure as described previously.¹⁷ First, a continuous curvilinear capsulorrhexis measuring approximately 5.0 mm in diameter was accomplished using a bent needle through a 0.6-mm side port. After continuous curvilinear capsulorrhexis, a horizontal scleral tunnel, or clear corneal incision was created for phacoemulsification. A straight scleral tunnel incision was made using a diamond knife, a crescent knife, and a 2.4-mm stainless steel keratome (Alcon Laboratories, Ft. Worth, TX, USA), while a single-plane clear corneal incision was made using the 2.4-mm stainless steel keratome (Alcon Laboratories). After hydrodissection, endocapsular phacoemulsification of the nucleus and aspiration of the residual cortex were performed. The clear corneal wound was enlarged to 2.4 or 2.65 mm using a keratome for implantation of single-piece hydrophobic acrylic IOL, while the scleral tunnel wound was enlarged to 3.75 or 4.1 mm for implantation of the multipiece hydrophobic acrylic IOL. The lens capsule was inflated with 1% sodium hyaluronate (Healon; Abbot Medical Optics [AMO], Santa Ana, CA, USA), after which an IOL was placed into the capsular bag using an IOL forceps or injector. After IOL insertion, the viscoelastic material was thoroughly evacuated. No suture was placed and the wound was not hydrated. The single-piece hydrophobic acrylic IOLs implanted through clear corneal incisions included the Acrysof SA60AT and SN60WF (Alcon Laborato-

TABLE 2. Simple Correlation Between Actual Age and the Corneal Asymmetry and Higher-Order Irregularity Components, and Between Age and Distance-Corrected Visual Acuity in the Surgery and Nonsurgery Groups

	Surgery Group		Nonsurgery Group	
	Spearman <i>r</i>	P Value	Spearman <i>r</i>	P Value
Irregular astigmatism components				
First-order asymmetry	0.256	<0.0001*	0.302	<0.0001*
Higher-order irregularity	0.403	<0.0001*	0.428	<0.0001*
Regular astigmatism components				
Vertical/horizontal astigmatism, J ₀	-0.349	<0.0001*	-0.341	<0.0001*
Oblique astigmatism, J ₄₅	-0.036	0.4266	-0.070	0.1175
logMAR visual acuity				
Uncorrected	0.229	<0.0001*	0.228	<0.0001*
Corrected	0.384	<0.0001*	0.798	<0.0001*

* Statistically significant correlation.

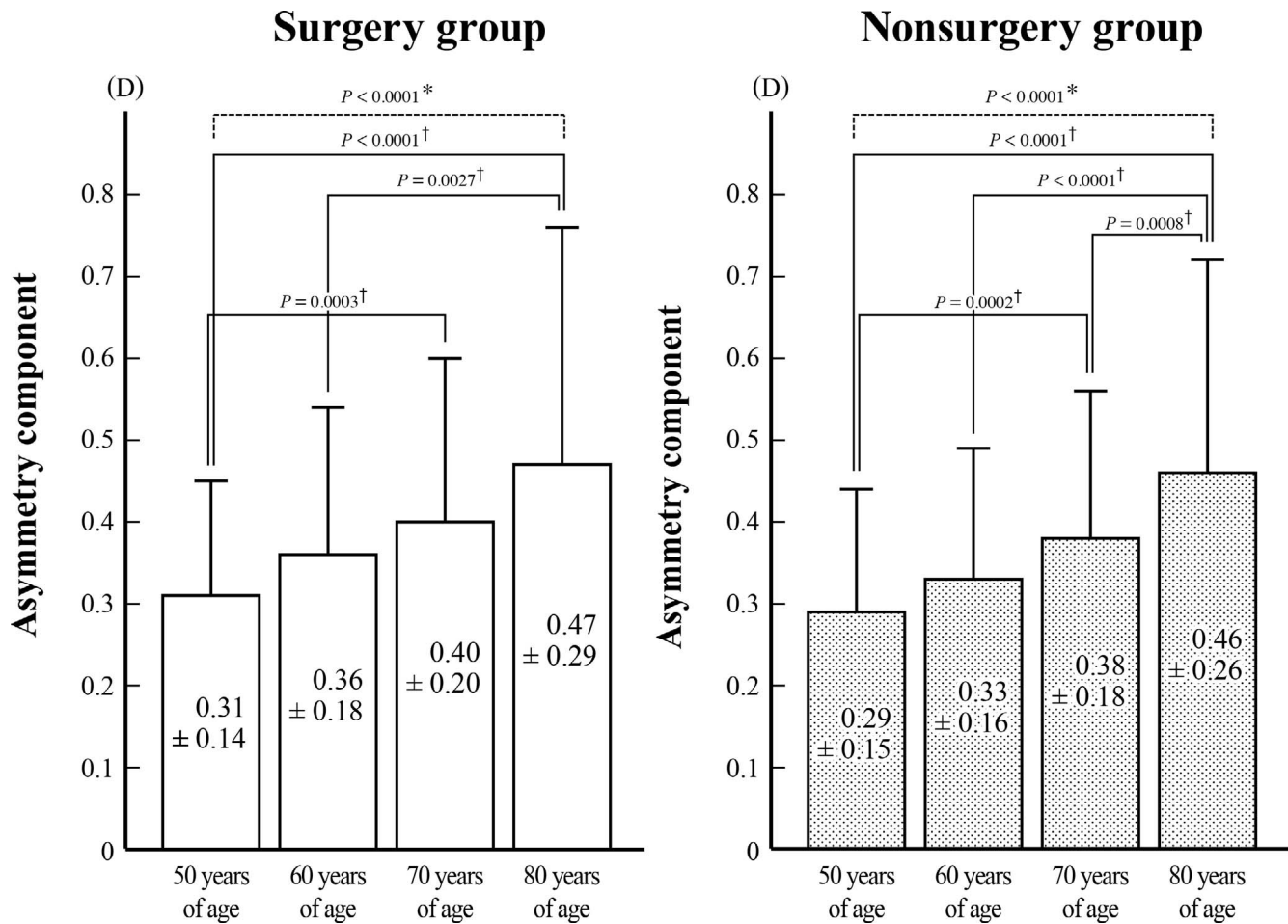


FIGURE 1. Comparison of the mean ± SD corneal asymmetry components among the four age groups in the surgery group and nonsurgery group. The mean asymmetry component increased significantly with age in both the surgery and nonsurgery groups. *P values indicate a significant difference among the four age groups ($P < 0.05$); †P values indicate a significant difference between the two age groups ($P < 0.0125$).

ries), and ZCB00 (AMO), while the multipiece hydrophobic acrylic IOLs implanted through the corneoscleral incisions included the MA60AC and MA60MA (Alcon Laboratories), ZA9003 (AMO), and YA-60BBR (HOYA, Tokyo, Japan).

Outcome Measures

All patients underwent videokeratographic examinations. In the surgery group, these examinations were performed at least 6 months postoperatively. The videokeratographic examination was performed using the Topographic Modeling System-4 (TMS-4; Tomey, Tokyo, Japan), and irregular corneal astigmatism were determined using Fourier series harmonic analysis of the videokeratographic data. Regular corneal astigmatism was also measured using simulated K values of the TMS-4. Refractive spherical and cylindrical power was also examined using an autorefractometer (KR-7100; Topcon, Tokyo, Japan); manifest spherical equivalent value was determined as the spherical power plus half the cylindrical power. Uncorrected and distance-corrected decimal visual acuity was recorded at all postoperative visits. Decimal visual acuity was converted to the logMAR scale for statistical analyses. All examinations were performed by experienced ophthalmic technicians, unaware of the purpose of the study.

A videokeratograph was taken three times, and the highest-quality keratograph of the three images was selected and stored in the TMS-4 computer. The data stored in the TMS-4 computer were used to determine spherical equivalent power, regular astigmatism, and irregular astigmatic components of the cornea by Fourier analysis, as previously described.¹⁶ Briefly, the dioptric powers on a mire ring i , $F_i(\hat{E}-)$ were transformed into trigonometric components as follows:

$$F_i(\hat{E}-) = a_0 + c_1 \cos(\hat{E}- - \hat{E}_{\theta 1}) + c_2 \cos 2(\hat{E}- - \hat{E}_{\theta 2}) + c_3 \cos 3(\hat{E}- - \hat{E}_{\theta 3}) + \dots + c_n \cos n(\hat{E}- - \hat{E}_{\theta n}) \quad (1)$$

where a_0 was the spherical equivalent power of the ring, c_1 the asymmetry component, c_2 the regular astigmatic component, and $c_3 \dots c_n$ the third and higher-order irregularity components. Spherical equivalent power (a_0) and the second order regular astigmatism component (c_2) can be corrected by a spherocylindrical lens, while the first-order asymmetry component (c_1) and third and higher-order irregularity ($c_3 \dots c_n$) components can be regarded as irregular corneal astigmatism. These calculations were performed on rings, 1 through 9 or 1 through 20, which correspond to the central corneal optical zone of 3.0 or 6.0 mm, respectively. The mean value of the 1 to 9 or 1 to 20 rings was determined and considered as the

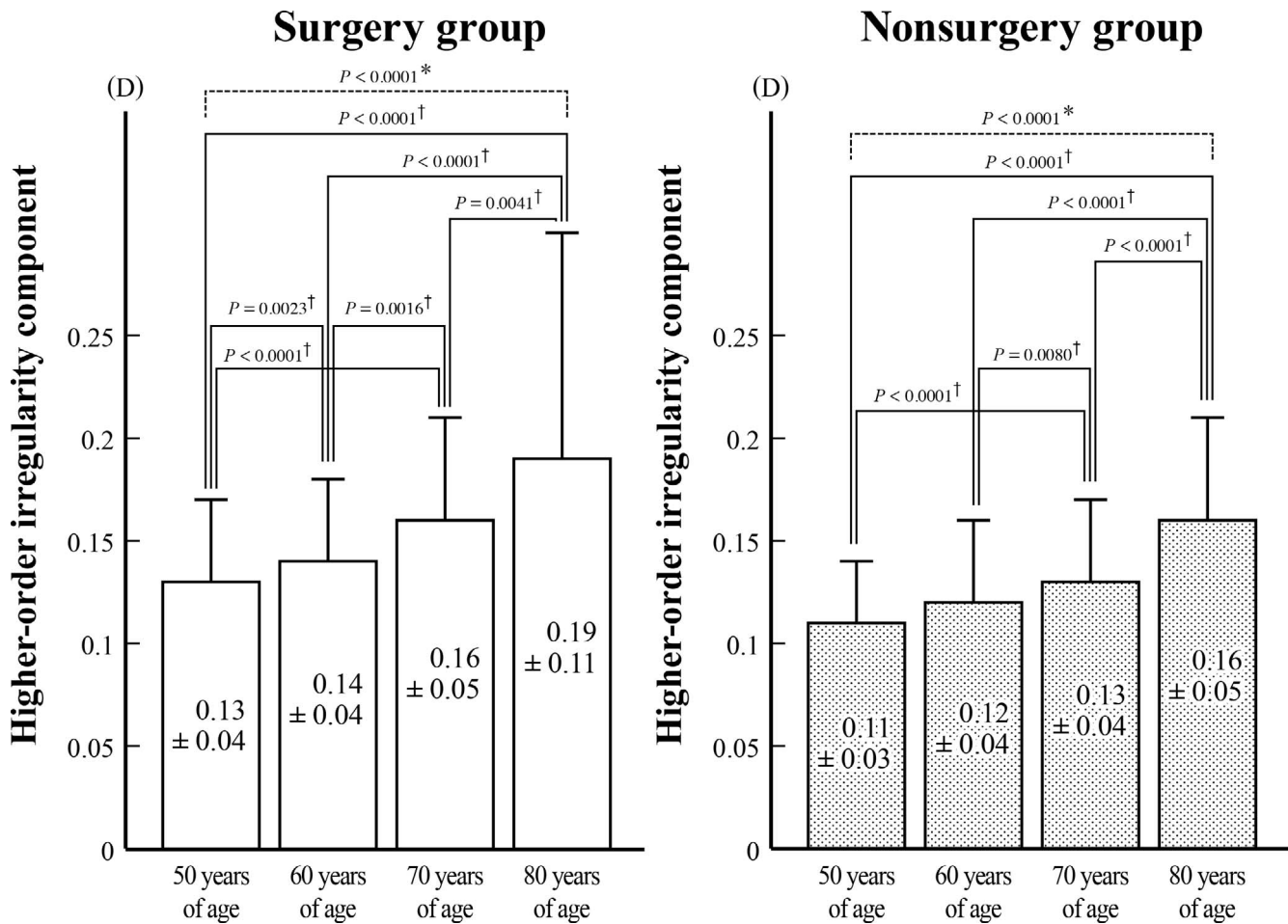


FIGURE 2. Comparison of the mean \pm SD corneal higher-order irregularity components among the four age groups in the surgery group and nonsurgery group. The mean corneal higher-order irregularity component increased significantly with age in both the surgery and nonsurgery groups. **P* values indicate a significant difference among the four age groups ($P < 0.05$); †*P* values indicate a significant difference between the two age groups ($P < 0.0125$).

representative value of each component. Because data from 3.0-mm optical zone are more closely related to the keratometric readings and visual function than data from 6.0-mm optical zone, only the irregular and regular astigmatism components of the central 3.0-mm optical zone are shown in the present study.

The corneal curvature at the steeper meridian and that at 90° from the steeper meridian was measured using the TMS-4, and the vector of regular astigmatism was determined. The astigmatism vector was decomposed into vertical/horizontal (J_0) and oblique (J_{45}) components using the power vector analysis described by Thibos et al.¹⁸ The power vector analysis shows vertical (90°)/horizontal (180°) regular astigmatic component as the J_0 and oblique (45° and 135°) components as the J_{45} . A positive value of the J_0 indicates a with-the-rule astigmatism, while a negative J_0 indicates an against-the-rule astigmatism. Keratometric data from the left and right eyes were analyzed together.

Statistical Analysis

The normality of the data distribution was tested using the Kolmogorov-Smirnov test. Because most of the data were not normally distributed, nonparametric tests were used for

analysis. The irregular astigmatism components, regular astigmatism components, logMAR visual acuity, manifest spherical equivalent value and other continuous variables were compared using the Kruskal-Wallis test among age groups and Mann-Whitney *U* test between the surgery and nonsurgery groups. Categorical variables were compared using the χ^2 goodness of fit test among the age groups, and the χ^2 test or Fisher's exact test between the surgery and nonsurgery groups. When a statistically significant difference was detected among the age groups, the difference between each group pair was compared using the Mann-Whitney *U* test for the continuous variables, and the χ^2 or Fisher exact test for the categorical variables with Bonferroni's adjustment for multiple comparisons. Simple correlations between actual age and the irregular astigmatic components were examined using the Spearman rank correlation analysis. As a subgroup analysis, all analyses were performed separately for the left and right eyes. The continuous variables of the left and right eyes were compared using the Kruskal-Wallis test among the age groups, and the Mann-Whitney *U* test between the surgery and nonsurgery groups. Categorical variables were compared using the χ^2 goodness of fit test among the age groups, and the χ^2 test or Fisher's exact test between the surgery and nonsurgery groups. Any differences with a *P*

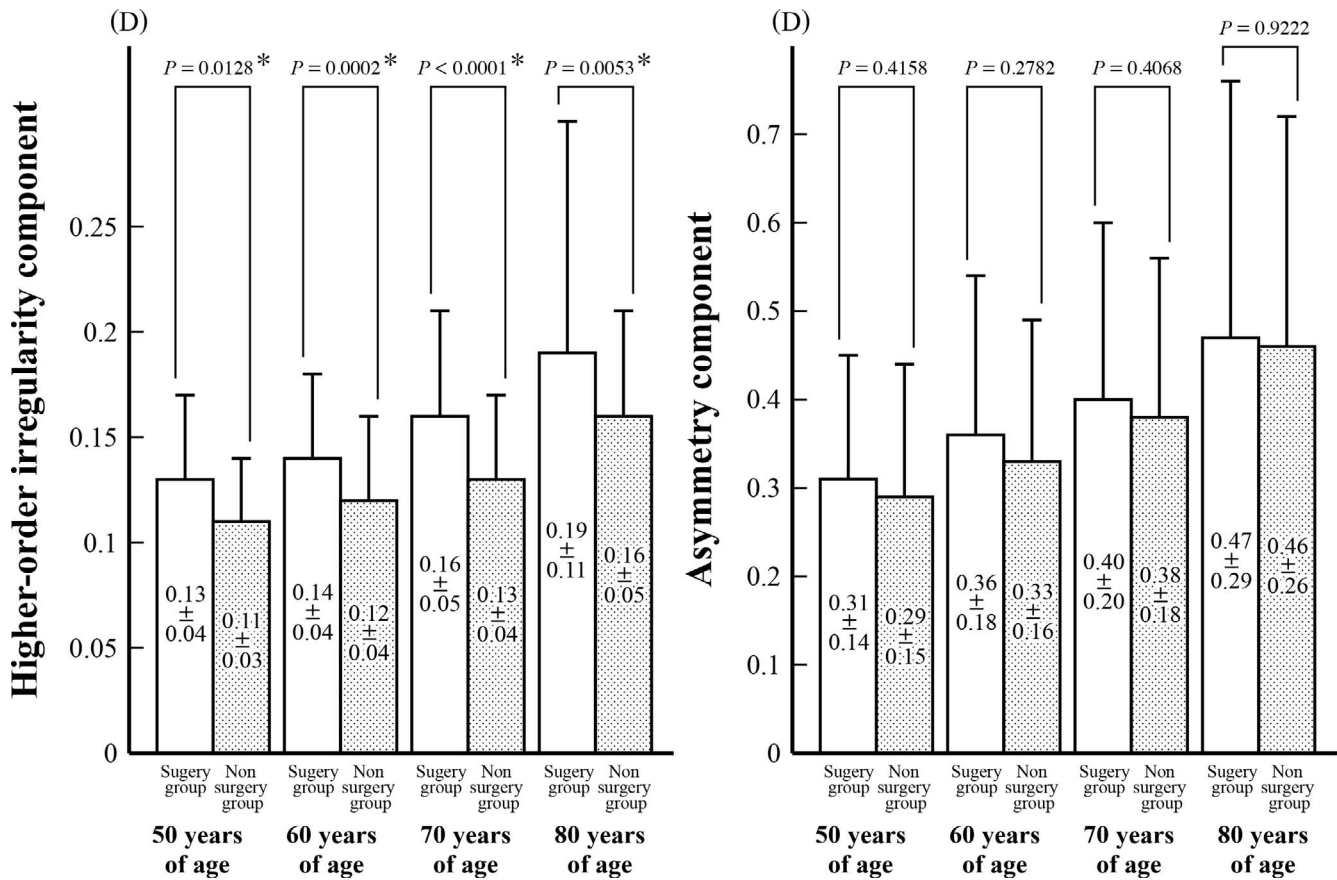


FIGURE 3. Comparison of the mean ± SD corneal higher-order irregularity components between the surgery group and nonsurgery group. The mean corneal higher-order irregularity component was greater in the surgery group than in the nonsurgery group in all age groups. *P values indicate a significance difference between the surgery and nonsurgery groups ($P < 0.05$).

value of less than 0.05 were considered to be statistically significant.

RESULTS

The mean age of the patients at the time of baseline (\pm SD) was 69.9 ± 10.5 years (415 men and 545 women). The mean time interval between surgery and examination was 30.6 ± 23.0 months (range, 6–114 months). Patient characteristics of the surgery and nonsurgery groups in the four age groups are shown in Table 1. The two groups did not differ significantly in age, sex, or the ratio of left to right eyes in all age groups. The manifest spherical equivalent value was significantly different between groups in the 60 years of age, 70 years of age, and 80 years of age groups ($P \leq 0.0478$).

For the 3.0-mm optical zone, both the mean corneal asymmetry (Fig. 1) and higher-order irregularity components (Fig. 2) increased significantly with age in both the surgery and nonsurgery groups ($P < 0.0001$). In the surgery group, the asymmetry component differed significantly between the 80 years of age group and the 50 and 60 years of age groups, and between the 50 and 70 years of age group ($P \leq 0.0027$). In the nonsurgery group, the asymmetry component differed significantly between the 80 years of age group and the 50, 60, and 70 years of age groups, and between the 50 and 70 years of age group ($P \leq 0.0008$). The higher-order irregularity component differed significantly between any two age groups in the

surgery and nonsurgery groups ($P \leq 0.0041$), except for between the 50 years of age group and the 60 years of age nonsurgery groups ($P = 0.0492$). In all age groups, the higher-order irregularity component was greater in the surgery group than in the nonsurgery group in all age groups ($P \leq 0.0128$), while the asymmetry component did not differ significantly between the surgery and nonsurgery groups (Fig. 3). The results of the statistical comparisons regarding irregular astigmatism were similar between the 3.0- and 6.0-mm optical zones (Supplementary Figs. S1–S3).

Regarding regular corneal astigmatism, the mean J_0 decreased significantly with age in both the surgery and nonsurgery groups ($P < 0.0001$; Fig. 4), but the mean J_{45} did not differ significantly among age groups in both groups ($P = 5033$ in the surgery group, and $P = 0.2737$ in the nonsurgery group). In the surgery group, mean J_0 differed significantly between any two age groups ($P \leq 0.0089$), except for between the 70 and the 80 years of age groups ($P = 0.0368$). In the nonsurgery group, mean J_0 differed significantly between any two age groups ($P \leq 0.0030$), except for between the 50 and the 60 years of age groups ($P = 0.2224$). Mean J_0 was significantly greater in the surgery group than in the nonsurgery group in the 50 ($P < 0.0001$), 60 ($P = 0.0235$), and 80 years of age group ($P = 0.0045$), while mean J_{45} did not differ significantly between the surgery and nonsurgery groups for any age.

The actual age of each patient was significantly positively correlated with the asymmetry component and higher-order

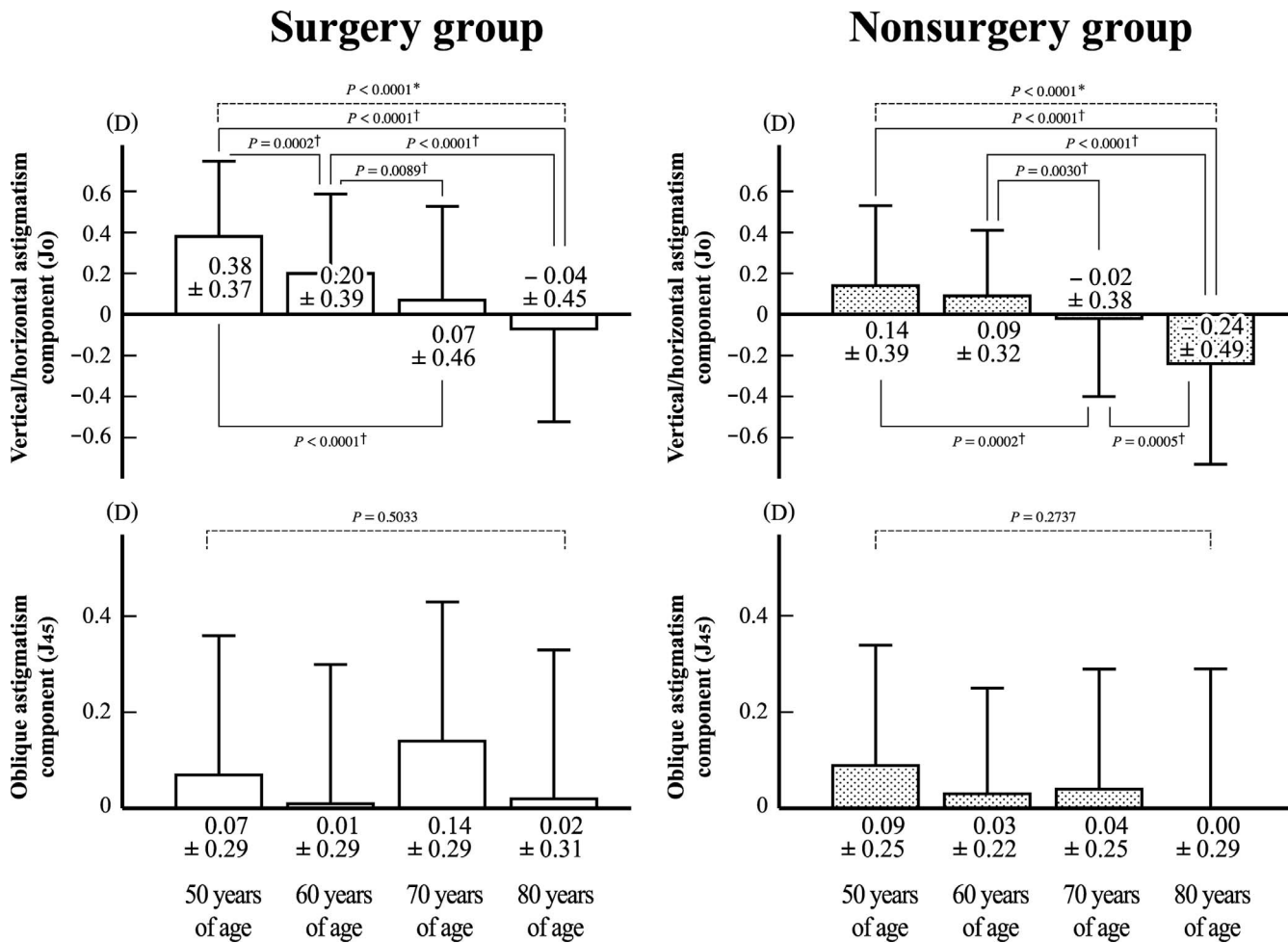


FIGURE 4. Comparison of mean \pm SD J_0 and J_{45} values among the four age groups. Mean J_0 decreased significantly with age in both the surgery and nonsurgery groups, whereas mean J_{45} did not differ significantly among age groups in the surgery and nonsurgery groups. * P values indicate a significant difference among the four age groups ($P < 0.05$); † P values indicate a significant difference between the two indicated age groups ($P < 0.0125$).

irregularity component in the surgery and nonsurgery groups ($P < 0.0001$, Table 2). Figure 5 shows a scatterplot depicting the significant correlation between older age and the increased higher-order irregularity component in both the surgery and nonsurgery groups ($P < 0.0001$). Actual age was significantly negatively correlated with J_0 ($P < 0.0001$), while there was no significant correlation between age and J_{45} (Table 2).

Mean uncorrected and distance-corrected visual acuity worsened with age in the surgery and nonsurgery groups ($P < 0.0001$; Fig. 6). Mean uncorrected or corrected visual acuity was significantly better in the surgery group than in the nonsurgery group in all age groups ($P < 0.0001$). Uncorrected or corrected visual acuity was significantly correlated with the actual age of each patient; worse uncorrected and corrected visual acuity correlated significantly with increasing age in both the surgery and nonsurgery groups ($P < 0.0001$, Table 2).

In subgroup analyses of the left and right eyes, the statistical results regarding the mean asymmetry component (Fig. 7) and higher-order irregularity component (Fig. 8), regular astigmatism components (J_0 and J_{45} ; Supplementary Fig. S4), and visual acuity (Supplementary Fig. S5) were essentially equivalent to those of bilateral eyes, except for the difference in the higher-order irregularity component at 50 and 80 years of age between the surgery and nonsurgery groups in the right eyes

(Fig. 9), and the difference in the J_0 at 70 and 80 years of age between groups in the left eyes, although the measurement values differed slightly.

DISCUSSION

The findings of the present study revealed that irregular corneal astigmatism components, both corneal asymmetry and higher-order irregularity components, increased significantly with increasing age in the 50, 60, 70, and 80 years of age groups in eyes that underwent cataract surgery and in eyes that did not undergo surgery. In addition, actual age at the time of cataract surgery was significantly positively correlated with the asymmetry component or higher-order irregularity component in eyes with and without surgery. The correlation coefficient was greater between age and the higher-order irregularity component than between age and the asymmetry component. These findings suggest that irregular corneal astigmatism, particularly higher-order corneal irregularity, worsens from middle to older age whether or not patients who undergo cataract surgery.

The corneal higher-order irregularity component was significantly greater in eyes that underwent cataract surgery

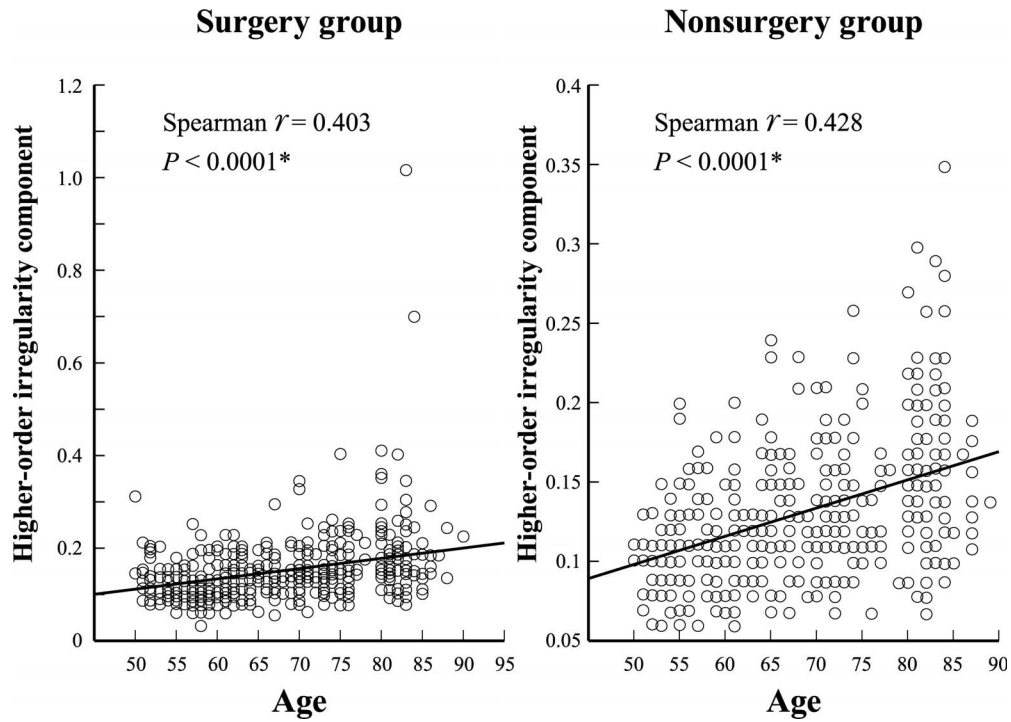


FIGURE 5. Scatterplots of the correlation between age and higher-order irregularity component in the surgery and nonsurgery groups. Older age was significantly correlated with an increase in the higher-order irregularity component in the surgery and nonsurgery groups.

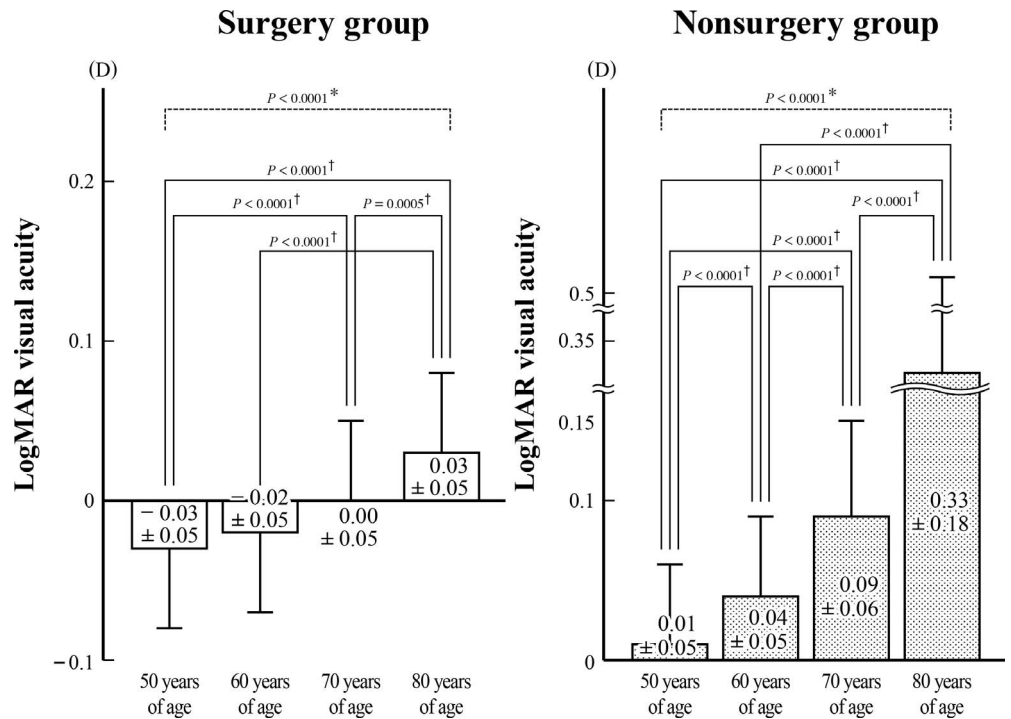


FIGURE 6. Comparison of the mean \pm SD distance-corrected logMAR visual acuity among the four age groups in the surgery group and nonsurgery group. The mean corrected logMAR visual acuity worsened significantly with age in both the surgery and nonsurgery groups. **P* values indicate a significant difference among the four age groups ($P < 0.05$); †*P* values indicate a significant difference between the two age groups ($P < 0.0125$).

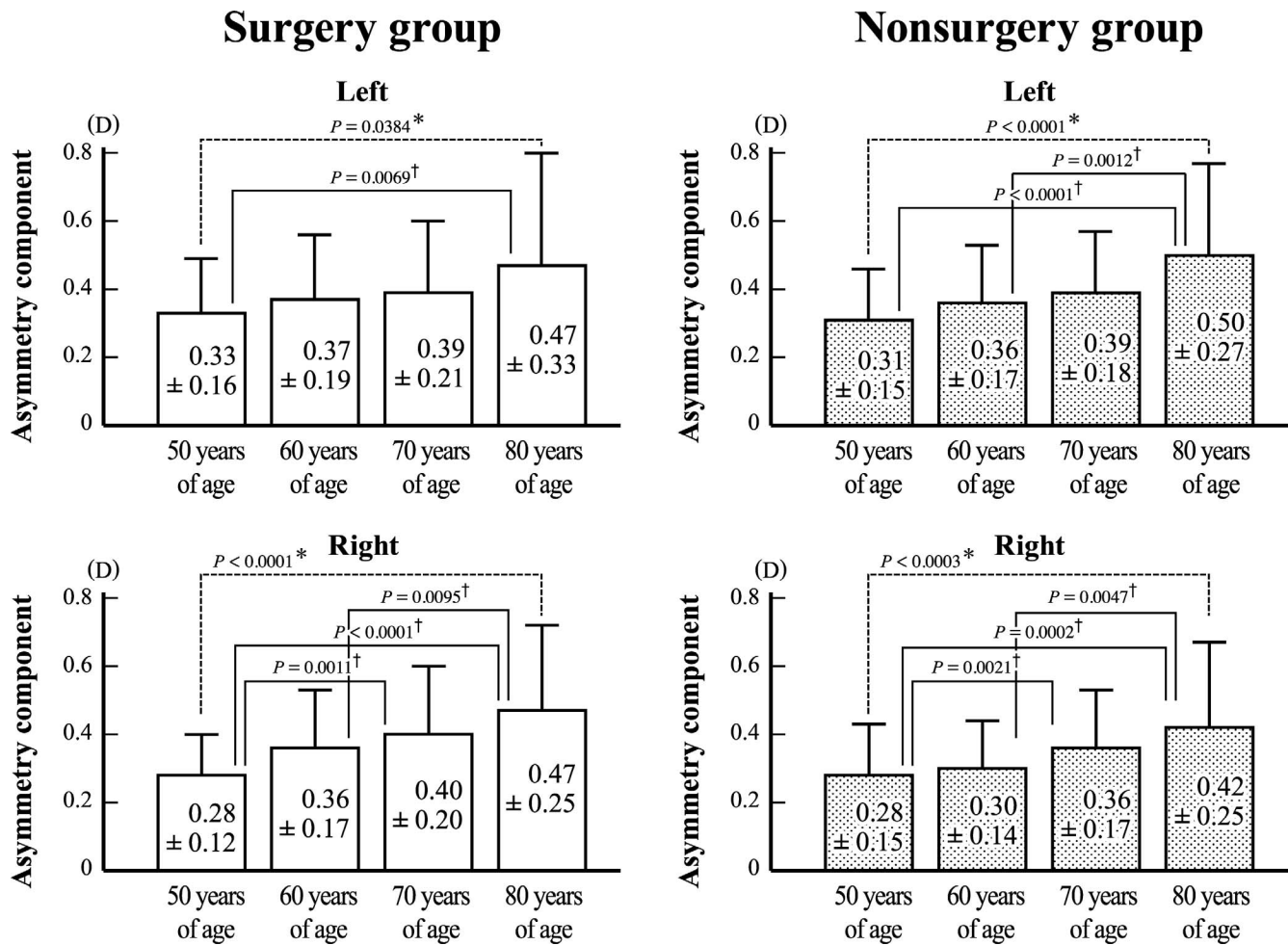


FIGURE 7. Comparison of the mean \pm SD corneal asymmetry components among the four age groups in the surgery group and nonsurgery group of the left and right eyes. The mean asymmetry component increased significantly with age in both the surgery and nonsurgery groups of the left and right eyes. **P* values indicate a significant difference among the four age groups ($P < 0.05$); †*P* values indicate a significant difference between the two age groups ($P < 0.0125$).

than in eyes that did not undergo surgery in all age groups. The corneal asymmetry component, however, did not differ significantly between eyes with and without cataract surgery. Because the mean time interval between surgery and examination was approximately 30 months in the surgery group, cataract surgery may persistently increase the higher-order irregularity of the cornea. Previous studies demonstrated that videokeratographic indices representing irregular astigmatism increase after many kinds of ocular surgery, including cataract surgery or glaucoma surgery, but the corneal asymmetry gradually returns to the preoperative level for some months.^{12,13} These findings suggest that surgically-induced higher-order irregularity is likely to persist for a long time after cataract surgery.

We calculated the statistical power of the asymmetry and higher-order irregularity components between the surgery and nonsurgery groups. When we assumed a corneal asymmetry component of 0.10 D to be a clinically meaningful magnitude of difference between the surgery and nonsurgery groups based on the Mann-Whitney *U* test, the statistical power was more than 86%. When we assumed a higher-order irregularity component of 0.10 D to be a clinically meaningful difference between the surgery and nonsurgery groups based on the

Mann-Whitney *U* test, the statistical power was 100%. Thus, the statistical power of our comparisons was sufficient to detect a clinically meaningful difference between groups.

Based on power vector analysis, the vertical/horizontal astigmatic component decreased significantly with age, whereas the oblique astigmatic component did not differ significantly among the age groups in eyes that underwent surgery and in eyes that did not undergo surgery. Additionally, the vertical/horizontal component was negatively associated with older age in both the surgery and nonsurgery groups, indicating an against-the-rule astigmatic change with age in eyes with and without cataract surgery. Our previous studies revealed that the against-the-rule change occurs with age in eyes that underwent cataract surgery to a similar extent as eyes that did not undergo surgery.^{6,7} Thus, the findings of the present study are consistent with those of previous studies.

In subgroup analyses of the left and right eyes, the statistical results of the irregular and regular astigmatism components, and visual acuity were essentially equivalent to those of both eyes, except for the difference in the higher-order irregularity component between the surgery and nonsurgery groups at 50 and 80 years of age in the right eyes, and in the J_0 between the groups at 70 and 80 years of age in the left eyes. These findings

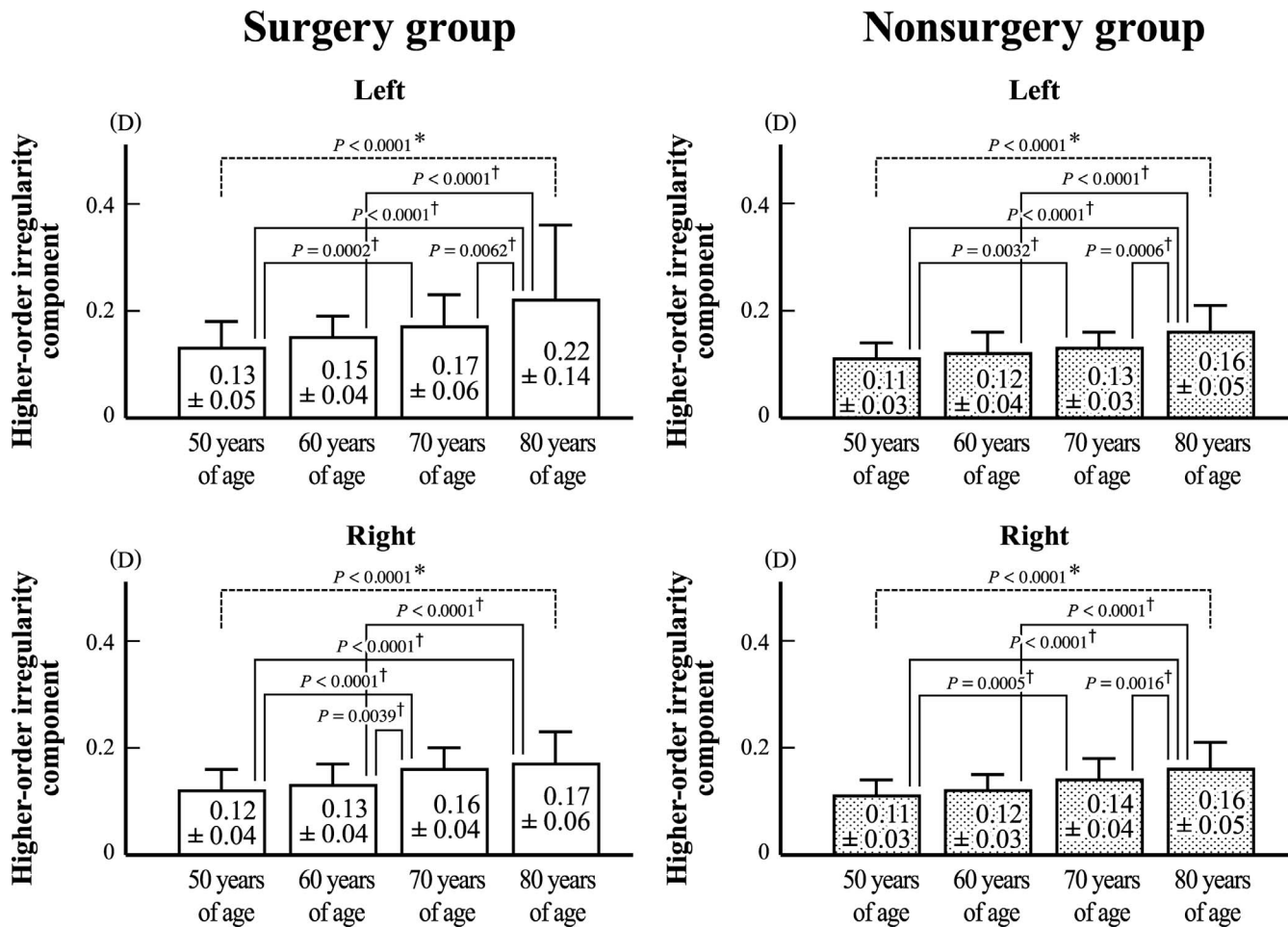


FIGURE 8. Comparison of the mean SD corneal higher-order irregularity components among the four age groups in the surgery group and nonsurgery group of the left and right eyes. The mean corneal higher-order irregularity component increased significantly with age in both the surgery and nonsurgery groups of the left and right eyes. **P* values indicate a significant difference among the four age groups ($P < 0.05$); †*P* values indicate a significant difference between the two age groups ($P < 0.0125$).

suggest that changes in the irregular and regular astigmatism with age after cataract surgery were similar between the left and right eyes, and the effect of the horizontal scleral incisions on the irregular astigmatism of the left and right eyes also was not markedly different.

A few studies examined the aging changes in irregular corneal astigmatism. Goto et al.¹⁵ reported that several videokeratographic indices representing irregular astigmatism increased with age. Some studies using a corneal wavefront aberrometer revealed that some corneal higher-order aberrations, specifically the corneal coma, increase with age, which suggests an asymmetrical change of the cornea.^{19–23} Although Guirao et al.²¹ compared the corneal higher-order aberrations between subjects of younger, middle, and older age, they did not focus on patients who had undergone cataract surgery. The present study confirmed with a large number of subjects that higher-order irregularity as well as asymmetry of the cornea increased linearly in patients from middle to older age who had undergone cataract surgery. Furthermore, a certain degree of higher-order irregularity was persistently induced by cataract surgery. Visual function, including corrected visual acuity or contrast sensitivity, is impaired with age.⁸ Accordingly, the increase in irregular corneal astigmatism with age may partly affect the deterioration of visual function with age.

A limitation of the present study is that a Placido disk-based videokeratography system was used for calculating irregular corneal astigmatism. This device measures only the corneal power of the anterior surface, and does not measure the corneal power of the posterior surface. Because the ratio of the posterior/anterior corneal power is virtually maintained in nonpathologic corneas; however, this device can appropriately evaluate irregular corneal astigmatism in nonpathologic eyes and eyes that underwent cataract surgery. Indeed, the anterior corneal power determined using the Placido disk-based system is proportional to the total corneal power obtained using a scanning slit-based system or Scheimpflug photography in nonpathologic corneas.^{24,25}

In conclusion, irregular corneal astigmatism, both the corneal asymmetry and higher-order irregularity components, increased significantly from middle to older age in eyes that underwent cataract surgery as well as in eyes that did not undergo surgery. In addition, these components were positively associated with the age of each patient. Furthermore, corneal higher-order irregularity persistently increased after cataract surgery, whereas corneal asymmetry did not increase significantly. Thus, accompanying an against-the-rule change of the regular corneal astigmatism, irregular corneal astigmatism, particularly the surface irregularity of the cornea, worsened

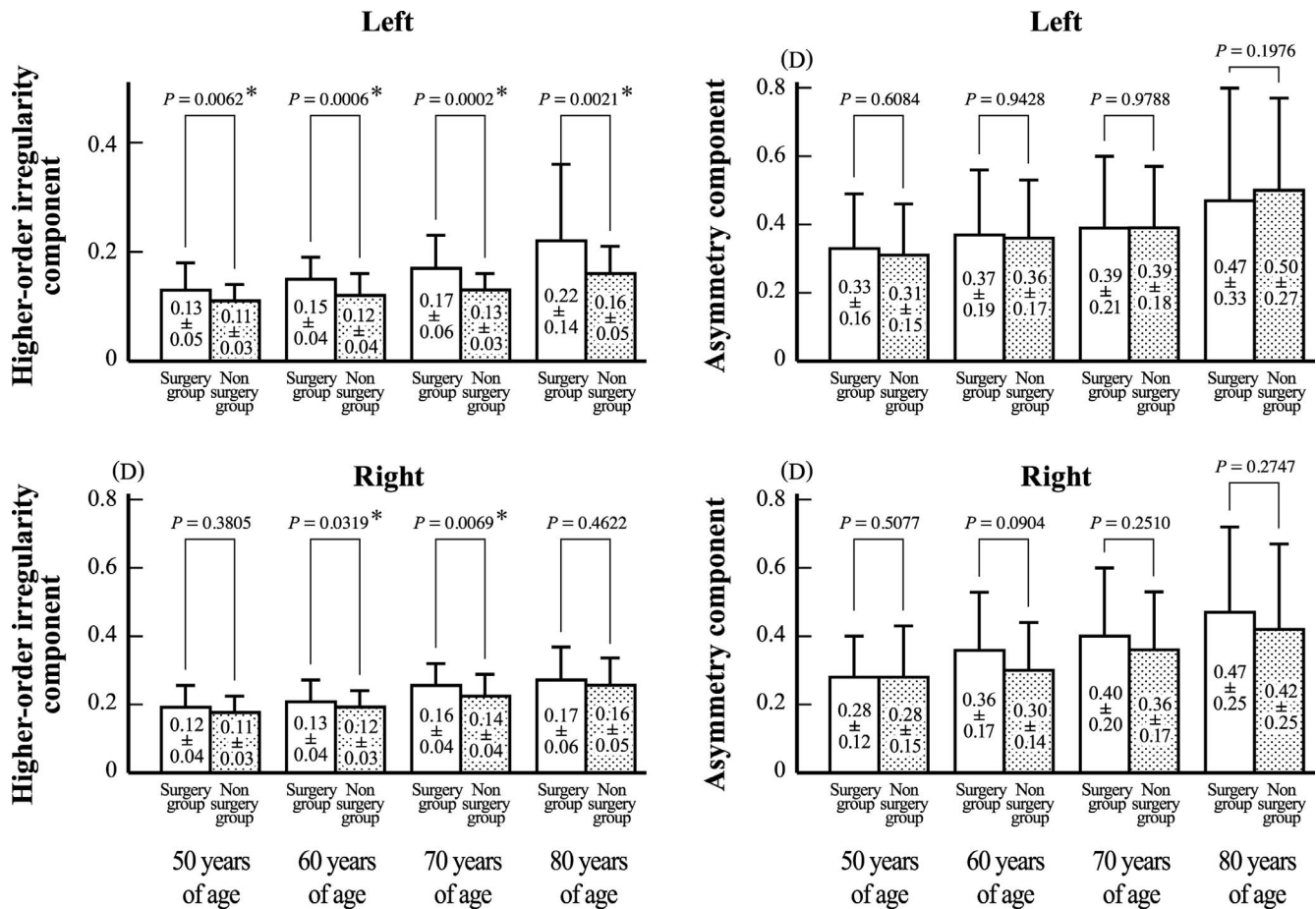


FIGURE 9. Comparison of the mean SD corneal higher-order irregularity components between the surgery group and nonsurgery group. The mean corneal higher-order irregularity component was greater in the surgery group than in the nonsurgery group in the left eyes of all age groups. The higher-order irregularity component was greater in the surgery group than in the nonsurgery group at 60 and 70 years of age of the right eyes. *P values indicate a significance difference between the surgery and nonsurgery groups ($P < 0.05$).

with advancing age. Such changes in corneal astigmatism may impair visual function of older patients. Aging changes in total irregular astigmatism of the cornea, including the anterior and posterior surface were not evaluated in the present study. Further studies are necessary to examine irregular astigmatism of the total cornea, including the posterior surface.

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References

- Hayashi K, Nakao F, Hayashi F. Topographic analysis of the changes in corneal shape due to aging. *Cornea*. 1995;14:527-532.
- Gudmundsdottir E, Jonasson F, Jonsson V, Stefánsson E, Sasaki H, Sasaki K. "With the rule" astigmatism is not the rule in the elderly. Reykjavik Eye Study: a population based study of refraction and visual acuity in citizens of Reykjavik 50 years and older. Iceland-Japan Co-Working Study Groups. *Acta Ophthalmol Scand*. 2000;78:642-646.
- Asano K, Nomura H, Iwano M, et al. Relationship between astigmatism and aging in middle-aged and elderly Japanese. *Jpn J Ophthalmol*. 2005;49:127-133.

- Ho JD, Liou SW, Tsai RJ, Tsai CY. Effects of aging on anterior and posterior corneal astigmatism. *Cornea*. 2010;29:632-637.
- Ueno Y, Hiraoka T, Beheregaray S, Miyazaki M, Ito M, Oshika T. Age-related changes in anterior, posterior, and total corneal astigmatism. *J Refract Surg*. 2014;30:192-197.
- Hayashi K, Hirata A, Manabe S, Hayashi H. Long-term change in corneal astigmatism after sutureless cataract surgery. *Am J Ophthalmol*. 2011;151:858-865.
- Hayashi K, Ogawa S, Manabe S, Hirata A. Influence of patient age at surgery on long-term corneal astigmatic change subsequent to cataract surgery. *Am J Ophthalmol*. 2015;160:171-8.e1.
- McLellan JS, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. *Invest Ophthalmol Vis Sci*. 2001;42:1390-1395.
- Oshika T, Tanabe T, Tomidokoro A, Amano S. Progression of keratoconus assessed by Fourier analysis of videokeratography data. *Ophthalmology*. 2002;109:339-342.
- De Paiva CS, Lindsey JL, Pflugfelder SC. Assessing the severity of keratitis sicca with videokeratographic indices. *Ophthalmology*. 2003;110:1102-1109.
- Tomidokoro A, Oshika T, Amano S, Eguchi K, Eguchi S. Quantitative analysis of regular and irregular astigmatism induced by pterygium. *Cornea*. 1999;18:412-415.

12. Hayashi K, Hayashi H, Oshika T, Hayashi F. Fourier analysis of irregular astigmatism after implantation of 3 types of intraocular lenses. *J Cataract Refract Surg*. 2000;26:1510-1516.
13. Hayashi K, Hayashi H, Oshika T, Hayashi F. Fourier analysis of irregular astigmatism after trabeculectomy. *Ophthalmic Surg Lasers*. 2000;31:94-99.
14. Smolek MK, Oshika T, Klyce SD, Maeda N, Haight DH, McDonald MB. Topographic assessment of irregular astigmatism after photorefractive keratectomy. *J Cataract Refract Surg*. 1998;24:1079-1086.
15. Goto T, Klyce SD, Zheng X, Maeda N, Kuroda T, Ide C. Gender- and age-related differences in corneal topography. *Cornea*. 2001;20:270-276.
16. Oshika T, Tomidokoro A, Maruo K, Tokunaga T, Miyata K. Quantitative evaluation of irregular astigmatism by Fourier series harmonic analysis of videokeratography data. *Invest Ophthalmol Vis Sci*. 1998;39:705-709.
17. Hayashi K, Tsuru T, Yoshida M, Hirata A. Intraocular pressure and wound status in eyes immediately after scleral tunnel incision and clear corneal incision cataract surgery. *Am J Ophthalmol*. 2014;158:232-241.
18. Thibos LN, Horner D. Power vector analysis of the optical outcome of refractive surgery. *J Cataract Refract Surg*. 2001;27:80-85.
19. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. *Invest Ophthalmol Vis Sci*. 1999;40:1351-1355.
20. Amano S, Amano Y, Yamagami S, et al. Age-related changes in corneal and ocular higher-order wavefront aberrations. *Am J Ophthalmol*. 2004;137:988-992.
21. Guirao A, Redondo M, Artal P. Optical aberrations of the human cornea as a function of age. *J Opt Soc Am*. 2000;17:1697-1702.
22. Nemeth G, Hassan Z, Szalai E, Berta A, Modis L Jr. Analysis of age-dependence of the anterior and posterior cornea with Scheimpflug imaging. *J Refract Surg*. 2013;29:326-331.
23. Wei S, Song H, Tang X. Correlation of anterior corneal higher-order aberrations with age: a comprehensive investigation. *Cornea*. 2014;33:490-496.
24. González Pérez J, Cerviño A, Giraldez MJ, Parafita M, Yebra-Pimentel E. Accuracy and precision of EyeSys and Orbscan systems on calibrated spherical test surfaces. *Eye Contact Lens*. 2004;30:74-78.
25. Read SA, Collins MJ, Iskander DR, Davis BA. Corneal topography with Scheimpflug imaging and videokeratography: comparative study of normal eyes. *J Cataract Refract Surg*. 2009;35:1072-1081.