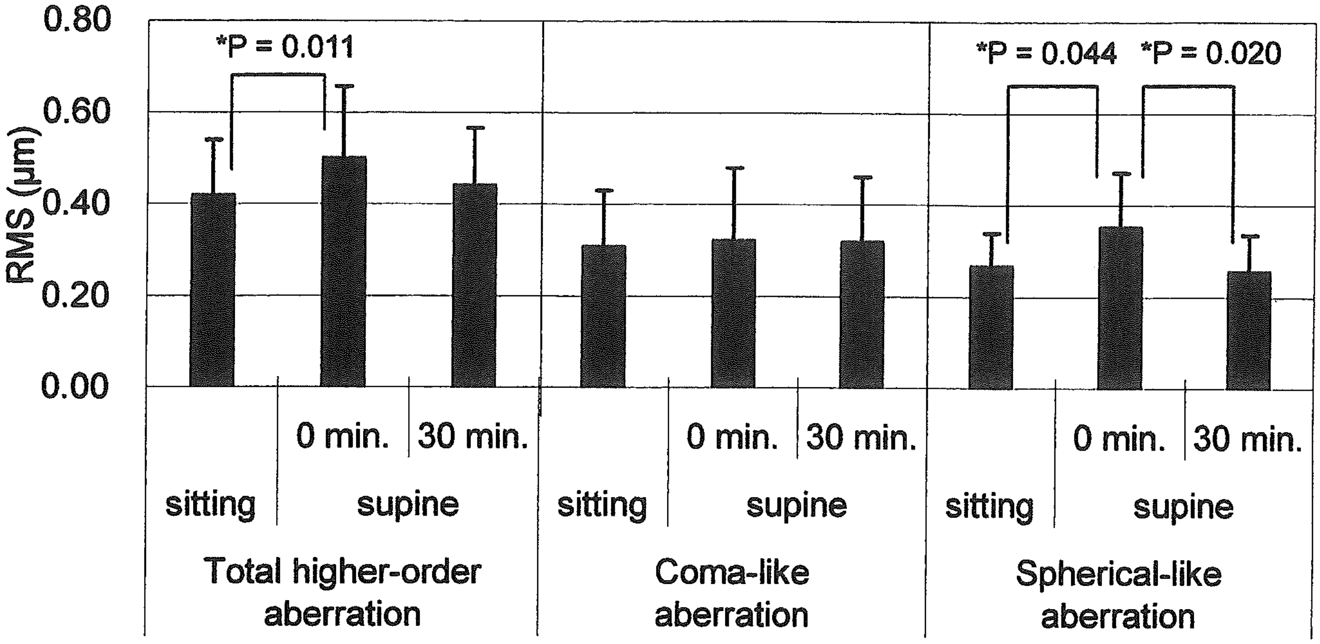

FIGURE. Comparison of corneal aberration for a 6-mm pupil diameter in sitting and supine positions (immediately and after 30 minutes). Data are expressed as mean ± standard deviation. Statistical significance: $*P < .05$; Scheffé test.

TABLE. Comparison of Corneal Curvature, Vertical Axis, Pupil Diameter, and Off-set

			Sitting	Supine 0 min.	Supine 30 min.	*P* Value
Corneal curvature (D)	3.0 mm	Steepest	43.51 ± 1.56	43.78 ± 1.74	43.74 ± 1.68	.120
		Flattest	42.12 ± 1.47	42.44 ± 1.68	42.34 ± 1.61	.148
	5.0 mm	Steepest	43.41 ± 1.57	43.79 ± 1.78	43.68 ± 1.58	.135
		Flattest	42.14 ± 1.48	42.49 ± 1.71	42.33 ± 1.58	.157
	7.0 mm	Steepest	43.27 ± 1.60	43.77 ± 1.84	43.59 ± 1.54	.124
		Flattest	41.99 ± 1.47	42.40 ± 1.71	42.22 ± 1.55	.117
Vertical axis (degrees)			93.50 ± 7.82	94.95 ± 7.80	94.29 ± 6.25	.773
Pupil diameter (mm)			3.96 ± 0.60	4.08 ± 0.54	3.82 ± 0.46	.161
Off-set (mm)			0.20 ± 0.10	0.18 ± 0.09	0.20 ± 0.08	.718

Data are expressed as mean ± standard deviation.
Statistical significance: $P > .05$; repeated measure analysis of variance (ANOVA).

Nine eyes from nine volunteers (three men, six women; aged 20 to 28 years; mean 21.9 ± 2.8 years) with no known abnormalities were included in the study. All of them were noncontact lens wearers. Informed consent was obtained from all volunteers. The tenets of the Declaration of Helsinki were followed in this study.

Corneal aberration and curvature (axial power) measurements were carried out with a Placido-ring videokeratoscope Keratron (Optikon 2000, Rome, Italy) improved to measure patients in the supine position; this topography instrument was fixed in a vertical position. Corneal wavefront aberrations were analyzed at a 6-mm pupil diameter for total higher-order, coma-like (S3 + S5), and spherical-like (S4 + S6) aberrations. Measurements were taken three times on each volunteer's left eye, and were averaged. The first measurement was taken with the subject in the sitting position and the others in the supine position, immediately after assuming the supine position and then 30 minutes later, having remained supine. The data were analyzed by repeated measure analysis of variance (ANOVA) and the Scheffé test.

The total higher-order aberration for 6-mm pupil diameter significantly increased from 0.419 ± 0.120 µm in the sitting position to 0.500 ± 0.157 µm in the supine position (Scheffé test, $P = .011$) (Figure). The spherical-like aberrations found immediately after the supine position, also showed a significant increase compared with the sitting position (Scheffé test, $P = .044$), and significantly decreased within the 30 minutes thereafter (Scheffé test, $P = .020$) (Figure). In the coma-like aberration (Figure), corneal curvature, vertical axis, pupil diameter, and off-set (Table), no significant differences were found through the experimental procedure.

Although the cyclotorsion may be associated with change in the aberration pattern,[3] we found no significant change in the vertical axis. Another factor may well have to do with the intraocular pressure. It is known that the intraocular pressure in the supine position is greater than that in the sitting position.[4] For this reason, and to avoid corneal deformation that might be caused by the measuring instrument, we did not measure intraocular pressure in this study. In vitro, Hjortdal and Jensen reported that, with the increase in the intraocular pressure, the corneal strain increased, the central corneal thickness decreased and, over time, the impact of the intraocular pressure on the corneal strain changed.[5] However, even if such changes occurred, they would only slightly affect normal eyes. Actually, there was not a considerable difference in the corneal curvature between the sitting and the supine position. This was in agreement with the result from a previous study wherein measurements were made using a handheld keratometer.[4] However, as even a slight distortion of the corneal structure can be caused by an increase in the intraocular pressure and/or the force of gravity, which of these has the greater influence is open to question. Arising from the change in posture, the aberration pattern might change during customized refractive surgery. In particular, if the cornea were to become thinner, this would result in preventing the desired improvements in visual performance.

Such factors as the effects of tear film in the supine position, or a slight tilt of the instrument, may also lead to an increase in corneal aberrations. Despite these limitations, our results suggest that the biomechanical behavior of the cornea during an operation should be considered.

REFERENCES

1. Aizawa D, Shimizu K, Komatsu M, et al. Clinical outcomes of wavefront-guided laser in situ keratomileusis: 6-month follow-up. J Cataract Refract Surg 2003;29:1507–1513.
2. Bille JF, Harner CFH, Loesel FH. Aberration-free refractive surgery: new frontiers in vision. Berlin: Springer-Verlag, 2003: 1–203.
3. Chernyak DA. Cyclotorsional eye motion occurring between wavefront measurement and refractive surgery. J Cataract Refract Surg 2004;30:633–638.
4. Lam AK, Douthwaite WA. The effect of an artificially elevated intraocular pressure on the central corneal curvature. Ophthalmol Physiol Opt 1997;17:18–24.
5. Hjortdal JØ, Jensen PK. In vitro measurement of corneal strain, thickness, and curvature using digital image processing. Acta Ophthalmol Scand 1995;73:5–11.

Reoperation for Persistent Myopic Foveoschisis After Primary Vitrectomy

Kaori Sayanagi, MD, Yasushi Ikuno, MD, and Yasuo Tano, MD

PURPOSE: **We performed vitrectomy on two eyes for persistent myopic foveoschisis (MF) after primary surgery that did not include internal limiting membrane (ILM) peeling.**

DESIGN: **Interventional case reports.**

METHODS: **Two highly myopic eyes of two patients with persistent MF after primary vitrectomy and gas tamponade but without ILM peeling were treated with pars plana vitrectomy, residual vitreous cortex removal, ILM peeling, and long-term gas tamponade.**

RESULTS: **Total foveal reattachment was achieved and best-corrected visual acuity (BCVA) improved in both eyes.**

CONCLUSIONS: **Reoperation including complete vitreous cortex removal and ILM peeling could be beneficial for patients with persistent MF after primary surgery, indicating that vitreous cortex removal and ILM peeling are critical in treating MF. (Am J Ophthalmol 2006;141: 414–417. © 2006 by Elsevier Inc. All rights reserved.)**

MYOPIC FOVEOSCHISIS (MF) TYPICALLY OCCURS IN highly myopic eyes, and optical coherence tomography (OCT) is useful for diagnosis.[1] MF is believed to occur before macular hole formation in some cases,[2] and vitrectomy and internal limiting membrane (ILM) peeling followed by gas tamponade are useful treatments.[3] However, incomplete ILM peeling may lead to persistent MF. We performed vitrectomy on two eyes (two patients) with persistent MF after primary vitrectomy. These observations imply that resolution of persistent MF and consequent visual improvement can be achieved by repeat vitrectomy with removal of residual vitreous cortex and ILM peeling.

• CASE 1: A 58-year-old woman with high myopia reported decreased vision in her right eye. She had undergone cataract surgery 7 years previously. She had visited another eye clinic and was diagnosed with posterior retinal detachment. She underwent vitrectomy and gas tamponade, and remained in a prone position for 2 weeks. Triamcinolone acetonide (TA) was not used intraopera-

Accepted for publication Sep 9, 2005.

From the Department of Ophthalmology, Osaka University Medical School, Room E7, 2-2 Yamadaoka, Suita 565-0871, Osaka, Japan.

Inquiries to Kaori Sayanagi, MD, Department of Ophthalmology E7, Osaka University Medical School, 2-2 Yamadaoka, Suita 565-0871, Japan; fax: +81-6-6879-3458; e-mail: sayapon@aol.com

J CATARACT REFRACT SURG - VOL 31, DECEMBER 2005

Modulation transfer function and pupil size in multifocal and monofocal intraocular lenses in vitro

Takushi Kawamorita, CO, Hiroshi Uozato, PhD

PURPOSE: To investigate the relationship between pupil size and the modulation transfer function (MTF) of a multifocal intraocular lens (IOL) in vitro and to predict the visual effects in vivo.

SETTING: Department of Ophthalmology and Visual Science, Kitasato University Graduate School of Medical Sciences, Kitasato, Japan.

METHODS: A refractive multifocal IOL (Array SA-40N, Allergan) and a monofocal IOL (PhacoFlex SI-40NB, AMO) were evaluated using the OPAL Vector system and a model eye with a variable effective aperture. With effective pupil diameters of 2.1, 3.0, 3.4, 3.9, 4.6, 5.1, and 5.5 mm, the in-focus and defocus MTFs were measured in the multifocal and monofocal IOLs.

RESULTS: With increases in effective pupil diameter, the far MTF progressively decreased at all spatial frequencies. In contrast, the near MTF began to increase at effective pupil diameter 2.1 mm, showed a peak at 3.4 mm, and decreased at diameters greater than 3.4 mm. The ratio of near MTF to far MTF showed an increase with larger effective pupil diameters and at lower spatial frequencies.

CONCLUSIONS: With a zonal progressive multifocal IOL, the pupil size effected a trade-off between the far and near MTFs: The near MTF increased at the expense of the far MTF at large pupil sizes (effective pupil diameter >3.4 mm). To enhance near vision with a multifocal IOL, the desirable effective pupil diameter should be 3.4 mm or larger.

J Cataract Refract Surg 2005; 31:2379–2385 © 2005 ASCRS and ESCRS

Multifocal intraocular lenses (IOLs) are designed to increase depth of field and to enhance near vision for cataract patients. The effectiveness of multifocal IOLs in enhancing quality of vision has been shown in many clinical studies.[1,2] The refractive design of the Array SA-40N IOL (Allergan), a typical multifocal IOL, has a beneficial effect on near vision.[3] However, many problems, including loss of corrected visual acuity at near distance and contrast sensitivity, glare, halos, and dependence on pupil size have been reported.[4–6] Pupil size affects the relative power distributions of the light generated by the zonal-progressive design of the Array IOL, whose concentric zones of progressive aspheric surfaces provide repeatable distributions of the power.[7] Furthermore, controls of optical aberration,[8] diffraction,[9] retinal illuminance,[10] pupil centration,[11] and the Stiles-Crawford effect[12] are affected by pupil size. Therefore, pupil size is expected to have an effect on the modulation transfer function (MTF), which is defined as the amplitude of the image contrast divided by the amplitude of the object contrast and is a function of spatial frequency.[13]

The aim of this study was to investigate the relationship between pupil size and near and far MTFs in a multifocal IOL in vitro. The results were used to predict the visual performance of patients with a multifocal IOL.

MATERIALS AND METHODS

The IOLs studied were the multifocal Array IOL and the monofocal PhacoFlex SI-40NB IOL (AMO). Both IOLs were 20.0 diopters (D) and 13.0 mm in length with an optic of 6.0 mm. The multifocal Array, structurally identical to the monofocal PhacoFlex according to the manufacturer's data (Table 1), is designed with 5 concentric annular refractive zones and aspheric surfaces. The additional power in the near zones, zones 2 and 4, is +3.50 D, which is approximately equivalent to +2.80 D in the spectacle plane.

The line-spread function of the multifocal and monofocal IOLs were recorded with the OPAL Vector system (Image Science Ltd.) and a model eye (Menicon Co.) composed of a wet cell

0886-3350/05/$-see front matter
doi:10.1016/j.jcrs.2005.10.024

Table 1. Optical performance in multifocal and monofocal IOLs.

Parameter	Model SI-40NB	Model SA-40N
Refractive index	1.460	1.460
Curvature radius (mm)		
Anterior surface	10.26	10.26
Posterior surface	15.54	15.54
Central thickness (mm)	0.94	0.99
Resolution in air (c/mm)	>242	>244

(Figure 1). The MTF was calculated from the line-spread function by using fast Fourier transform techniques. The model eye consisted of a model cornea (Achromat, SSK4 and SF8), a variable effective aperture (from 2.1 to 5.5 mm), and BK7 windows. In the OPAL Vector system, the light source was confined to 546.1 nm (monochromatic e-line). The detector type used the Reticon K series silicon linear photodiode array 12.8 mm long with 512 pixels. The position of best focus was determined by measuring the variation of MTF with focus at a spatial frequency of 50 c/mm, which is approximately equivalent to 15 cycles per degree. The MTF values were formed with an average of 16 array scans.

The MTF measurements conformed to the requirements of the International Organization for Standardization, except for the effective aperture. The effective aperture sizes were sorted on the basis of (1) the optical zones in the Array IOL (2.1, 3.4, 3.9, and 4.6 mm), and (2) the 1.0 near to far area ratio, 3.0 and 5.1 mm. The effective aperture sizes were 2.1, 3.0, 3.4, 3.9, 4.6, 5.1, and 5.5 mm (Figure 2). However, in calculating the near to far area ratio, the transition zones, consisting of the aspheric surface and the intermediate zone, were disregarded.

RESULTS

The change in MTF with defocus is shown in Figure 3. The graph shows the 3-dimensional through focus response. The clinographic projections show the highest, that is, the best-focus, MTF. With the increases in effective pupil diameter, the far MTF in the vicinity of distance focus, defocus 0 D, progressively decreased at all spatial frequencies. In contrast, the near MTF in the vicinity of near focus, defocus −2.8 D, increased at effective pupil diameter 2.1 mm, showed a peak at 3.4 mm, and decreased at values greater than 3.4 mm. There was scarcely any rise in the intermediate MTF in the vicinity of intermediate focus, defocus −2.0 D, at any effective pupil diameter or spatial frequency.

The in-focus MTF of the multifocal and monofocal IOLs at various effective pupil diameters and 3 spatial frequencies, 100, 60, and 20 c/mm, are given in Figure 4, *A*, *B*, and *C*, respectively. The far MTF in the multifocal IOL was totally lower than that in the monofocal IOL. As the spatial frequency decreased, this difference increased. Also, although the near multifocal IOL MTF was lower than the far multifocal MTF and the monofocal MTF, the MTF of the defocus −2.8 D in the monofocal IOL showed even lower levels, approximating 0 and never more than 2% to 3%.

Figure 5 shows the far in-focus MTF normalized at effective pupil diameter 2.1 mm. With the multifocal IOL, MTF with effective pupil diameters between 2.1 mm and 3.0 mm showed the lowest rate of decline and the pace of decrease greater than 3.0 mm was approximately congruent with that in the monofocal IOL. Additionally, the attrition rate of the normalized far in-focus MTF increased slightly with increasing spatial frequencies.

Figure 6 presents the ratio of near MTF to far MTF, comparing the multifocal with the monofocal IOL. With the multifocal IOL, the ratio increased with the larger effective pupil diameters and with the decreased spatial frequencies. At high or intermediate spatial frequencies, a similar increase in the near to far MTF ratio appeared where the effective pupil diameter was greater than 3.0 mm. With the monofocal IOL, no increase in the ratio was found.

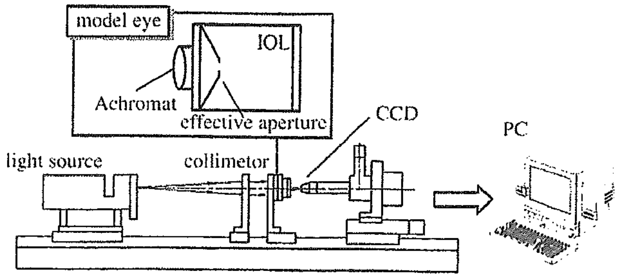

Figure 1. Structure of OPAL Vector system and a model eye with variable effective aperture.

DISCUSSION

The MTF measurements in vitro have been shown to be the internationally accepted standard method for evaluating

Accepted for publication April 26, 2005.

From the Department of Ophthalmology and Visual Science (Kawamorita, Uozato), Kitasato University Graduate School of Medical Sciences, and the Department of Orthoptics and Visual Science (Uozato), Kitasato University School of Allied Health Sciences, Sagamihara, Japan.

Supported in part by a Grant-in-Aid for Aging and Health Research from the Ministry of Health, Labour and Welfare (H16-Choju-012 [Uozato]), a Grant-in-Aid for Exploratory Research from the Ministry of Education, Culture, Sports, Science and Technology (No.15659416 [Uozato]), and a Project Research Grant from the Kitasato University Graduate School (Uozato).

Jack Yohay critically read the manuscript.

No author has a financial or proprietary interest in any materials or methods mentioned.

Reprint requests to Hiroshi Uozato, PhD, Department of Ophthalmology and Visual Science, Kitasato University Graduate School of Medical Sciences, 1-15-1 Kitasato, Sagamihara, 228-8555, Japan. E-mail: uozatoh@ahs.kitasato-u.ac.jp.

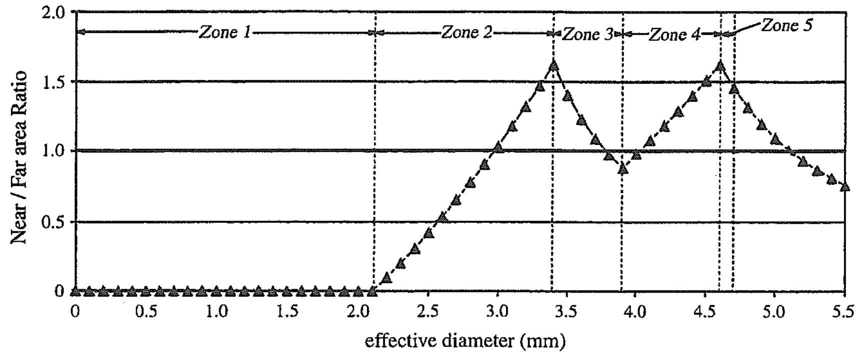

Figure 2. Near to far area ratio. The heavy line shows near to far area ratio 1.0.

the performance of IOL image quality, and it has been reported that the contrast sensitivity in vivo can be predicted from MTF values in vitro.[14] We analyzed the MTFs of multifocal and monofocal IOLs and investigated the relationship to the pupil size.

Effect of Distance Focus

The effect of defocus in any MTF depends on the effective pupil diameter and spatial frequencies, as shown in Figures 3 and 4. Based on these results, the far contrast sensitivity and visual acuity at any pupil size and spatial frequency in eyes with multifocal IOLs would be low compared with the values in eyes with monofocal IOLs. In fact, some studies have shown that distance contrast sensitivity and low contrast visual acuity with multifocal IOLs are lower than those in monofocal IOLs.[3,15] Montés-Micó et al.[16] found that distance contrast sensitivity shows deficits at higher spatial frequencies under dim mesopic conditions. However, in best corrected high contrast visual acuity, it has been reported that there is no difference.[1,3] This could be attributed to the resolution of multifocal and monofocal IOLs, which was almost the same as that shown in Table 1, or caused by aspects of the neural system.[17,18]

As illustrated in Figure 5, loss or sudden change in visual performance within the effective pupil diameter of 2.1 mm to 3.0 mm could occur, but none has been reported. Also, our finding (Figure 6) that the near to far MTF ratio at effective pupil diameters greater than 2.1 mm in multifocal IOLs increases suggests that near focus parts of lenses, particularly zone 2, have a significant impact on the far MTF.

Effect of Near Focus

From our results, it would be expected that near visual performance with a multifocal IOL is higher than that with a monofocal IOL. In clinical studies, Steinert et al.[19] report that the multifocal IOL improved uncorrected and distance-corrected near visual acuity and reduced dependency on spectacles. Montés-Micó and Alió[18] report that near contrast sensitivity improved over time but was always lower than at distance and in the monofocal near-corrected patients. The lower near contrast sensitivity was nevertheless acceptable at providing near visual function. Therefore, our results in vitro concur with their report of those in vivo.

The results shown in Figures 4 and 6 suggest that the desirable effective pupil diameter to acquire good near visual performance is a minimum of 3.0 mm, optimally 3.4 mm and larger. Because our experiment reports the actual pupil in a human eye, these data need to be converted to entrance pupil, the apparent size of the pupil, to evaluate pupil size with the multifocal Array IOL in the clinical field. The magnitude of the entrance pupil depends on corneal power, anterior chamber depth, and optical aberration, which are magnified about 13% according to Gaussian optics.[20] Therefore, the desirable pupil size would be a minimum of 3.4 mm, optimally 3.8 mm and larger. However, Hayashi et al.[6] found that a pupil diameter smaller than 4.5 mm cannot provide useful near visual acuity. Ravalico and coauthors[17] concluded that there are no differences in the relationship between visual acuity and pupil size. These differences may be ascribed to factors such as tilt or decentration of IOL[6] and corneal astigmatism,[21] which tend to decrease the MTF and reduce the sensitivity to pupil size. Also, Koch et al.[22] showed that preoperative pupil size does not predict postoperative size, and pupil size depends on age and illumination,[23] so it may be difficult for a surgeon to decide on an appropriate patient from preoperative pupil size.

Effect of Intermediate Focus

Although approximately 13% of available light in a multifocal IOL is allocated to intermediate focus, the MTFs showed low intermediate focus values at all effective pupil diameters (Figure 3). Therefore, low MTFs at intermediate focus are also supposed to lead to loss in visual performance. However, because the results were obtained in monochromatic light, they cannot be generalized to real

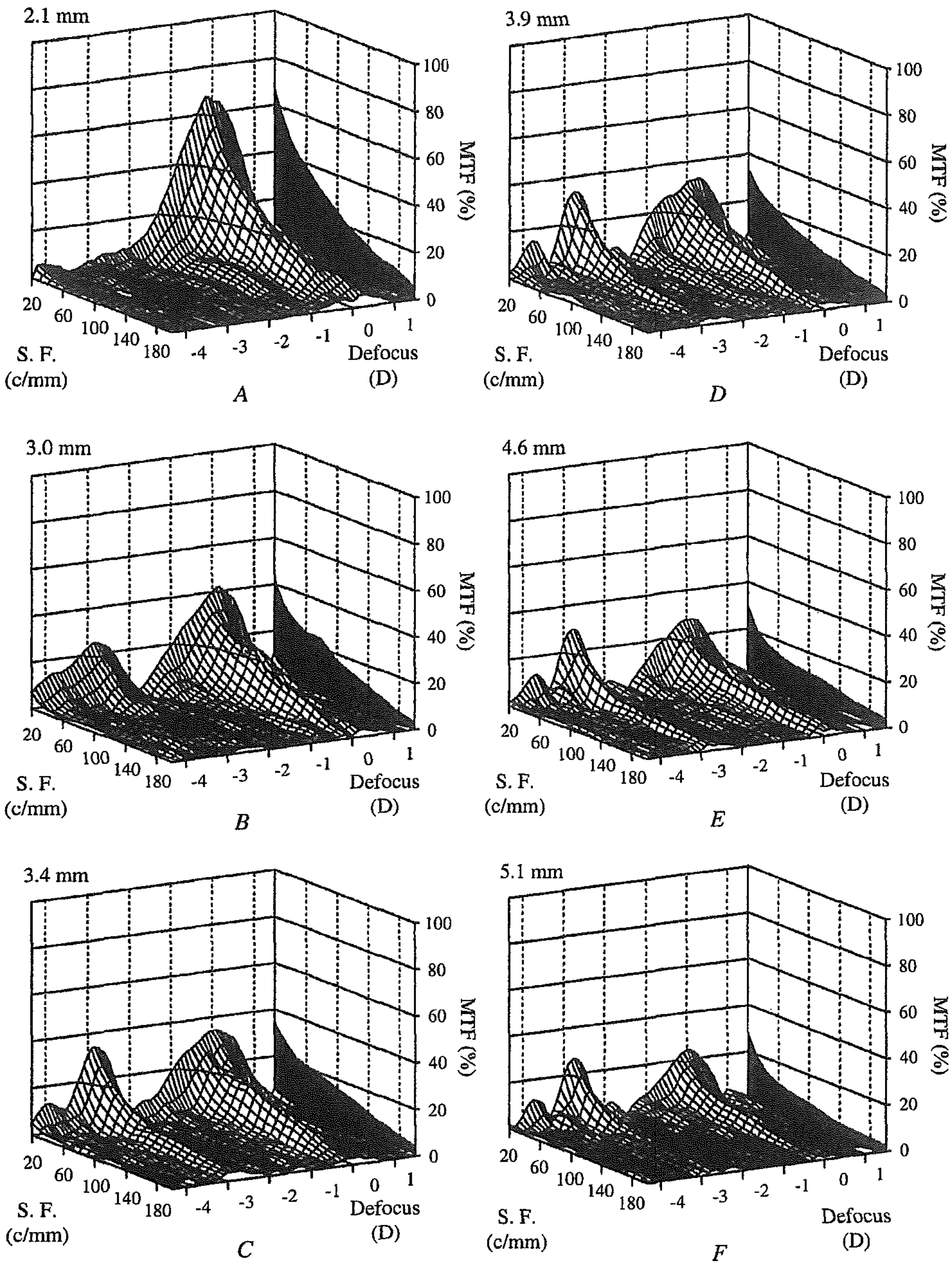

Figure 3. For various effective pupil diameters and spatial frequencies (S.F.), measured defocus MTF for the multifocal IOL.

life. In everyday white light, the longitudinal chromatic aberration will lead to an increase in the MTF at intermediate focus, which will help to improve visual performance at intermediate distances. In a clinical report, Weghaupt and coauthors[24] found that visual acuity was limited at intermediate distance. In contrast, Vaquero-Ruano et al.[25] report that Array IOLs provide excellent intermediate vision. Further studies in vitro and in vivo are needed to clarify the visual effect at intermediate distances.

Optical Performance of Multifocal IOL Array

The decrease in the MTF for multifocal IOLs is presumably caused by the inhibitory effect of in-focus and out-of-focus images produced by the far and near focus parts of lenses. Charman and coauthors[26] show there is a close correspondence between practical measurement of contrast sensitivity and the theoretical predictions of MTFs and a 50% contrast degradation of the distance

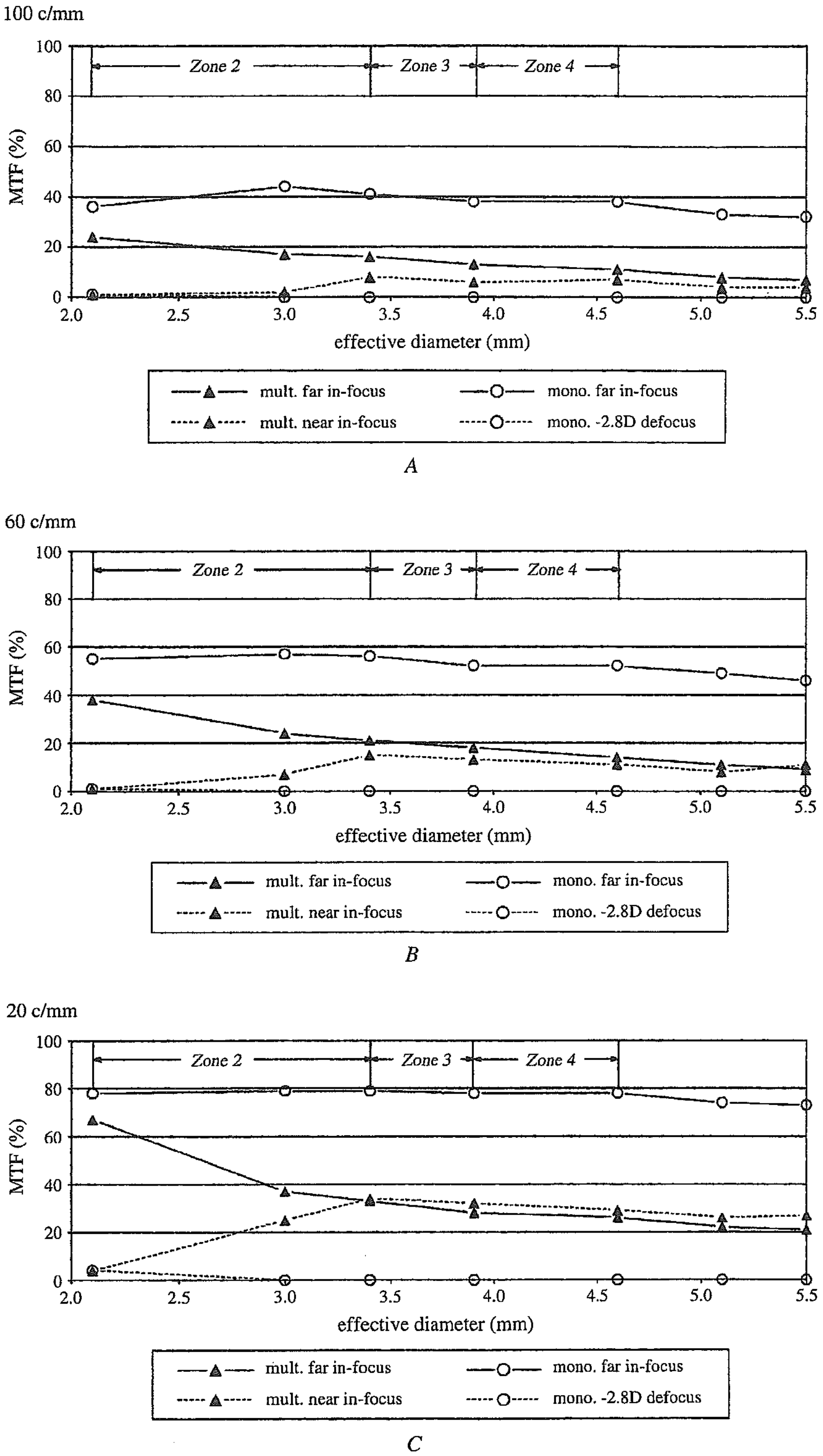

Figure 4. The in-focus multifocal (Mult.) and monofocal (Mono.) MTF at 100, 60, and 20 c/mm for various effective pupil diameters.

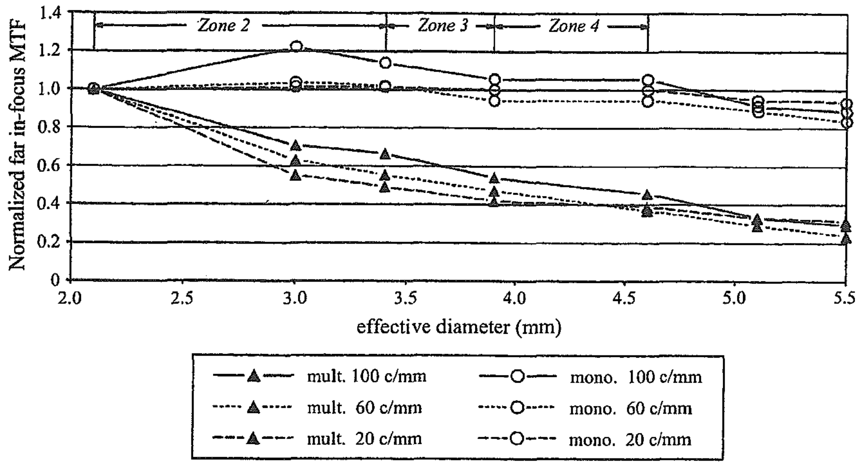

Figure 5. The far MTF normalized to the MTF at an effective pupil diameter of 2.1 mm for various spatial frequencies and effective pupil diameters. (Mult. = multifocal IOL; Mono. = monofocal IOL).

retinal image across all spatial frequencies above 3 cycles per degree, although the IOLs estimated were bifocal. Also, Holladay et al.[27] show that the multifocal IOLs had a 2-fold to 3-fold increase in depth of field with at least a 50% lower contrast in the retinal image compared with monofocal IOLs. Considering these reports and our results, the pupil size in a multifocal IOL would affect the trade-offs between (1) the depth of field and the in-focus, defocus MTF and (2) the far and near MTFs. Also, as shown in Figures 4 and 6, the distinction between zones 1 and 2 in the multifocal Array IOL depends mainly on the distribution of the trade-offs. Therefore, we have not been able to find any significance of the multiple blending zones in the multifocal Array IOL. Further in vitro and in vivo studies integrating zonal geometry are needed to determine the optimum design of the multifocal IOL.

In our laboratory measurements, each IOL was centered with respect to an effective aperture, and the phase transfer function was effectively 0. However, phase shifts greatly affect visual performance, particularly with multifocal IOLs, in terms of increased optical aberration,[28] which is caused by tilt and decentration of the IOL[6] or corneal astigmatism.[21] Also, not considered were such factors as the neural system, that is, brain adaptation,[16,17] or eye dominance.[29,30] Despite these limitations, we believe that our results are of use in predicting visual performance with multifocal IOLs, taking into consideration pupil size, far or near vision, and corrected versus uncorrected prior visual performance. In light of pupil size, further studies are needed to help identify patients for whom IOLs are indicated for whom the depth of field and near vision is enhanced.

REFERENCES

1. Javitt JC, Steinert RF. Cataract extraction with multifocal intraocular lens implantation; a multinational trial evaluating clinical, functional, and quality-of-life outcomes. Ophthalmology 2000; 107:2040–2048

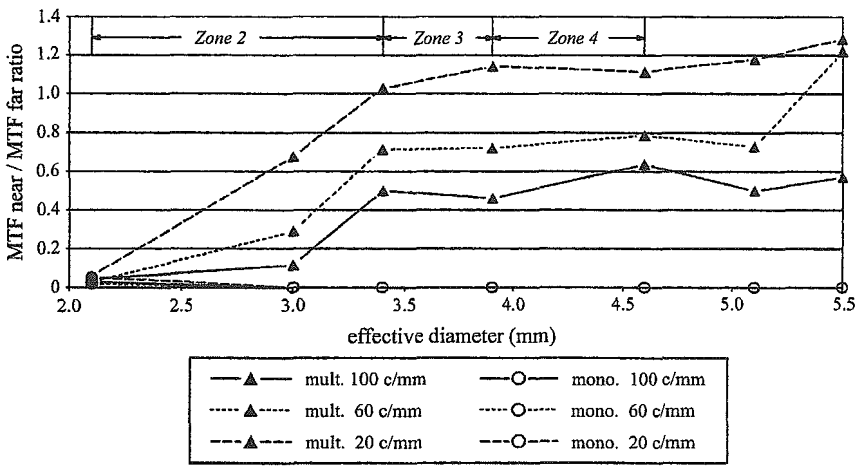

Figure 6. The ratio of near MTF to far MTF in the multifocal IOL (Multi.) compared with the monofocal IOL (Mono.).

2. Shoji N, Shimizu K. Clinical evaluation of a 5.5 mm three-zone refractive multifocal intraocular lens. J Cataract Refract Surg 1996; 22:1097–1101
3. Steinert RF, Post CT Jr, Brint SF, et al. A prospective, randomized, double-masked comparison of a zonal-progressive multifocal intraocular lens and a monofocal intraocular lens. Ophthalmology 1992; 99:853–860; discussion by JT Holladay, 860–861
4. Leyland M, Zinicola E. Multifocal versus monofocal intraocular lenses in cataract surgery; a systematic review. Ophthalmology 2003; 110: 1789–1798
5. Dick HB, Krummenauer F, Schwenn O, et al. Objective and subjective evaluation of photic phenomena after monofocal and multifocal intraocular lens implantation. Ophthalmology 1999; 106:1878–1886
6. Hayashi K, Hayashi H, Nakao F, Hayashi F. Correlation between pupillary size and intraocular lens decentration and visual acuity of a zonal-progressive multifocal lens and a monofocal lens. Ophthalmology 2001; 108:2011–2017
7. Ravalico G, Parentin F, Sirotti P, Baccara F. Analysis of light energy distribution by multifocal intraocular lenses through an experimental optical model. J Cataract Refract Surg 1998; 24:647–652
8. Howland HC. High order wave aberration of eyes. Ophthalmic Physiol Opt 2002; 22:434–439
9. Smith G, Atchison DA. The Eye and Visual Optical Instruments. Cambridge, UK, Cambridge University Press, 1997; 527–553
10. Wilson MA, Campbell MCW, Simonet P. Change of pupil centration with change of illumination and pupil size; the Jules F. Neumueller Award in Optics. Optom Vis Sci 1992; 69:129–136
11. Uozato H, Guyton DL. Centering corneal surgical procedures. Am J Ophthalmol 1987; 103:264–275; correction, 852
12. Atchison DA, Scott DH, Strang NC, Artal P. Influence of Stiles-Crawford apodization on visual acuity. J Opt Soc Am A Opt Image Sci Vis 2002; 19:1073–1083
13. Schwiegerling J. Theoretical limits to visual performance. Surv Ophthalmol 2000; 45:139–146
14. Lang AJ, Lakshminarayanan V, Portney V. Phenomenological model for interpreting the clinical significance of the *in vitro* optical transfer function. J Opt Soc Am A 1993; 10:1600–1610
15. Post CT Jr. Comparison of depth of focus and low-contrast acuities for monofocal versus multifocal intraocular lens patients at 1 year. Ophthalmology 1992; 99:1658–1663; discussion by DD Koch, 1663–1664
16. Montés-Micó R, España E, Bueno I, et al. Visual performance with multifocal intraocular lenses; mesopic contrast sensitivity under distance and near conditions. Ophthalmology 2004; 111:85–96
17. Ravalico G, Baccara F, Bellavitis A. Refractive bifocal intraocular lens and pupillary diameter. J Cataract Refract Surg 1992; 18: 594–597
18. Montés-Micó R, Alió JL. Distance and near contrast sensitivity function after multifocal intraocular lens implantation. J Cataract Refract Surg 2003; 29:703–711
19. Steinert RF, Aker BL, Trentacost DJ, et al. A prospective comparative study of the AMO ARRAY zonal-progressive multifocal silicone intraocular lens and a monofocal intraocular lens. Ophthalmology 1999; 106:1243–1255
20. Atchison DA, Smith G. Optics of the Human Eye. Oxford, Butterworth-Heinemann, 2000; 137–159
21. Ravalico G, Parentin F, Baccara F. Effect of astigmatism on multifocal intraocular lenses. J Cataract Refract Surg 1999; 25:804–807
22. Koch DD, Samuelson SW, Villarreal VR, et al. Changes in pupil size induced by phacoemulsification and posterior chamber lens implantation: consequences for multifocal lenses. J Cataract Refract Surg 1996; 22:579–584
23. Koch DD, Samuelson SW, Haft EA, Merin LM. Pupillary size and responsiveness: implications for selection of a bifocal intraocular lens. Ophthalmology 1991; 98:1030–1035
24. Weghaupt H, Pieh S, Skorpik C. Visual properties of the foldable Array multifocal intraocular lens. J Cataract Refract Surg 1996; 22:1313–1317
25. Vaquero-Ruano M, Encinas JL, Millan I, et al. AMO Array multifocal versus monofocal intraocular lenses: long-term follow-up. J Cataract Refract Surg 1998; 24:118–123
26. Charman WN, Murray IJ, Nacer M, O'Donoghue EP. Theoretical and practical performance of a concentric bifocal intraocular implant lens. Vision Res 1998; 38:2841–2853
27. Holladay JT, van Dijk H, Lang A, et al. Optical performance of multifocal intraocular lenses. J Cataract Refract Surg 1990; 16:413–422; erratum, 781
28. Applegate RA. Glenn Fry Award Lecture 2002: wavefront sensing, ideal corrections, and visual performance. Optom Vis Sci 2004; 81: 167–177
29. Shoji N, Shimizu K. Binocular function of the patient with the refractive multifocal intraocular lens. J Cataract Refract Surg 2002; 28: 1012–1017
30. Handa T, Mukuno K, Uozato H, et al. Ocular dominance and patient satisfaction after monovision induced by intraocular lens implantation. J Cataract Refract Surg 2004; 30:769–774

Posterior corneal surface changes after hyperopic laser in situ keratomileusis

Tesuo Ueda, MD, Yoshiaki Nawa, MD, Kozo Masuda, CO, Hidetoshi Ishibashi, MD, Yoshiaki Hara, MD, Hiroshi Uozato, PhD

PURPOSE: To evaluate posterior corneal surface topographic changes after hyperopic laser in situ keratomileusis (H-LASIK) using Orbscan I (Orbtek, Inc.).

SETTING: Department of Ophthalmology, Nara Medical University, Nara, Japan.

METHODS: In 25 eyes of 15 patients who had H-LASIK, the posterior corneal surface was measured with slit-scanning corneal topography (Orbscan I) preoperatively and 1 year postoperatively. The center as a fit zone and calculated posterior corneal surface changes were taken at 4 points: nasal, temporal, superior, and inferior sides in the 5.0 mm diameter. The posterior corneal topographic changes were analyzed using an analysis of variance. The postoperative:preoperative magnification ratio of the posterior corneal surface was calculated in a theoretical eye model.

RESULTS: When a "+" reading was defined as the forward displacement and "−" was defined as the backward displacement, the mean posterior corneal topographic changes were −2.8 μm ± 27.9 (SD) at the nasal side, −4.5 ± 27.8 μm at the temporal side, −3.9 ± 20.1 μm at the superior side, and −2.3 ± 20.1 μm at the inferior side. The posterior corneal surface between any 2 examined points showed no significant difference after H-LASIK. In addition, the hypothetical change in the posterior cornea was −8.3 μm after +3.0 diopter H-LASIK, which was approximately closer to the study results. In each side, the amount of the attempted correction was significantly correlated with the posterior corneal topographic change.

CONCLUSIONS: Clinical measurement of the posterior corneal displacement after H-LASIK with Orbscan revealed a backward shift. This change corresponded to the hypothetical artifactual changes with Orbscan; that is, changes in the magnification ratio.

J Cataract Refract Surg 2005; 31:2084–2087 © 2005 ASCRS and ESCRS

Myopic laser in situ keratomileusis (M-LASIK) and hyperopic LASIK (H-LASIK) have been efficiently, safely, and predictably performed worldwide. However, we found several reports of keratectasia after M-LASIK,[1–3] myopic photorefractive keratectomy (PRK)[4] and posterior corneal surface changes[1,5–7] after M-LASIK. Some reports suggest that a residual corneal bed less than 250 μm or a total corneal thickness less than 400 μm could cause keratectasia.[1–4] On the other hand, to our knowledge, there are no reports of posterior corneal surface changes after H-LASIK.

With the advent of slit-scanning topography,[8] Orbscan (Orbtek Inc.), we have been able to evaluate the shape of the posterior cornea. However, the data obtained by Orbscan are limited in the accuracy of measurement. In a discussion of a study by Wang and coauthors,[1] Maloney pointed out that the accuracy of Orbscan was approximately 20 μm. Moreover, some studies report that data displayed on Orbscan may occasionally be inaccurate.[9,10] Cairns and coauthors[11] report a corneal model for slit-scanning elevation topography, but the measurement principle has not been actually described by the manufacturer.

We previously reported that the posterior corneal surface changes after M-LASIK[12] and the corneal endothelial cell changes after H-LASIK[13] may be related to the

Accepted for publication April 25, 2005.

Department of Ophthalmology (Ueda, Nawa, Masuda, Ishibashi, Hara), Nara Medical University, Nara, and Department of Orthoptics and Visual Science (Uozaro), Kitasato University School of Allied Health Sciences, Sagamihara, Japan.

No author has a financial or proprietary interest in any materials or methods mentioned.

Reprint requests to Tetsuo Ueda, MD, Department of Ophthalmology, Nara Medical University, 840, Kashihara-shi, Nara, 634-8522, Japan. E-mail: tueda@naramed-u.ac.jp.

Published by Elsevier Inc.

0886-3350/05/$-see front matter
doi:10.1016/j.jcrs.2005.04.034

postoperative:preoperative magnification ratio. In this study, we report the clinical outcomes of the posterior corneal surface change after H-LASIK using Orbscan and evaluate our results as compared with the data hypothetically calculated by the postoperative:preoperative magnification ratio.

PATIENTS AND METHODS

Twenty-five eyes of 15 patients who had H-LASIK without significant decentration (>0.5 mm) participated in this study. This study was performed as part of the Nidek EC-5000 H-LASIK clinical trial at the Department of Ophthalmology, Nara Medical University, between December 2000 and March 2002. The postoperative follow-up period was at least 1 year. Patients with keratoconus, active inflammatory disease, ocular surface disease, and previous ocular surgery were excluded. In all patients, the MK-2000 microkeratome (Nidek) was set to create a flap measuring 9.5 mm in diameter and 160 µm in thickness. New blades in the microkeratome were used in each eye. The ablation zone was 5.5 mm and the transition zone, 8.0 mm. Neither corneal thickness nor flap thickness was routinely measured intraoperatively. There were no major intraoperative or postoperative complications.

In all patients, the corneal topography was measured with the Orbscan I (Orbtek Inc.) preoperatively and 1 year postoperatively. A difference map of the posterior corneal surface was used to assess the posterior corneal surface change after H-LASIK. The center of the cornea was predetermined as a fit zone because the ablation profile of the hyperopic correction theoretically keeps almost 0.2 mm of the central area untouched (personal communication, Nidek, September 29, 2004). The mean elevation of the posterior corneal surface was determined by the reading at 4 points on a line of 5.0 mm diameter (nasal, temporal, superior, and inferior sides). Also, a "+" reading was defined as the forward displacement and a "−" reading was defined as the backward displacement. The posterior corneal surface changes were analyzed using an analysis of variance (ANOVA). If the *P* value was less than 0.05, it was considered significant.

In addition, the postoperative:preoperative magnification ratio was calculated under the following assumptions: preoperative corneal refractive power, 43.0 diopters (D); postoperative corneal refractive power, $43 + X$ (X = amount of refractive correction); refractive power of the cornea, 1.376; preoperative paracentral corneal thickness, 550 µm. If the posterior radius of curvature of the cornea was 6.8 mm, the relationship between the amount of correction and posterior corneal topographic change is shown in Figure 1. The Appendix shows the equation to calculate how much overestimation or underestimation occurred after LASIK.

RESULTS

The mean age of the patients was 57.3 years (range 30 to 78 years). The mean of the attempted refractive correction (spherical component) was 3.50 D ± 1.29 (SD) (range +2.0 to +6.0 D) with a mean ablation depth of 38.29 ± 14.74 µm. The mean posterior corneal topographic change was −2.8 ± 27.9 µm at the nasal side, −4.5 ± 27.8 µm at the temporal side, −3.9 ± 20.1 µm at the superior side, and −2.3 ± 20.1 µm at the inferior side. The posterior corneal surface topographic change in any 2 examined points showed no significant difference after H-LASIK ($P = .38$, ANOVA). After this population was grouped (1.0 D step), the result was similar to that before grouping (Table 1).

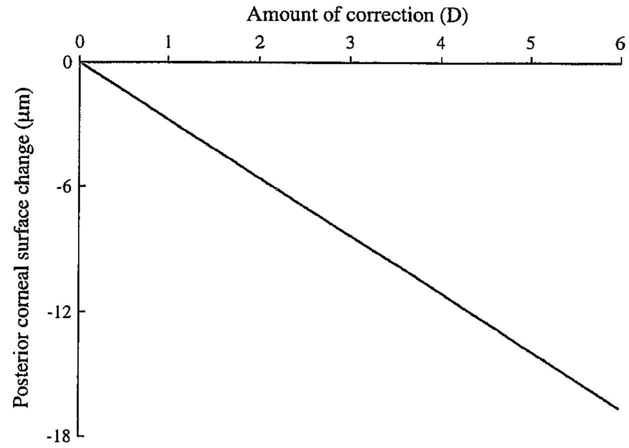

Figure 1. The relationship between the amount of correction and apparent posterior corneal surface change; +3.0 D H-LASIK hypothetically induced 8.3 µm of the backward shift in the posterior corneal surface.

In the theoretical eye model, the posterior corneal surface topographic change showed by −8.3 µm on the difference map after +3.0 D H-LASIK (Figure 1). The hypothetical shift of the posterior cornea was close to the value of the difference map obtained by Orbscan.

Figure 2 shows the relationship between the amount of the attempted correction and the posterior corneal topographic change. In each side, there was a significant correlation between both.

DISCUSSION

In our study, there were no significant posterior corneal surface changes in any 2 examined points. This may be attributed to the choice of a population with better centration or alignment and the excimer laser ablation profile in H-LASIK. Moreover, the value of the posterior corneal surface change was approximately −3 µm at each examined point. Taking the accuracy of Orbscan (approximately ±20 µm) into consideration,[1] this would be smaller and thus could be included within measurement errors. In addition, a small change may be attributed to a relatively lower amount of correction up to 6.0 D as compared with myopic corrections. On the other hand, the high standard deviation may mask possible differences between points. The high standard deviation may be related to the inclusion of many different refractive corrections into one single category. Therefore, we recalculated data after grouping, but standard deviation was not more compact and we found

Table 1. The posterior corneal topographic change at each side.

Attempted Correction (D)	Mean Posterior Corneal Topographic Change (μm) ± SD				*P* Value*
	Nasal	Temporal	Superior	Inferior	
+2 to +6 (n = 25)	−2.8 ± 27.9	−4.5 ± 27.8	−3.9 ± 20.1	−2.3 ± 20.1	.38
After grouping					
+2 to +3 (n = 10)	2.9 ± 18.5	3.1 ± 18.6	2.9 ± 19.5	2.2 ± 13.1	.39
+3 to +5 (n = 8)	−1.9 ± 12.0	−8.1 ± 23.2	−1.8 ± 11.7	1.0 ± 26.3	.69
+4 to +5 (n = 4)	−3.5 ± 25.9	2.5 ± 19.9	−18.5 ± 23.0	−4.0 ± 16.5	.41
+5 to +6 (n = 3)	−23.7 ± 21.1	−29.7 ± 17.7	−13.0 ± 17.0	−24.0 ± 21.0	.76

*ANOVA

a similar result. This may be due to the small sample size and the accuracy of Orbscan. Further studies should be conducted to validate this issue.

Based on the same assumption as M-LASIK, the posterior corneal surface may be considered to change forward in the area on which excimer laser ablation is performed.[1–3] Our results showed inversely the backward change. On the other hand, we calculated the postoperative:preoperative magnification ratio[12,13] and compared our results with the hypothetical posterior corneal surface change. A +3.0 D H-LASIK procedure theoretically induced 8.3 μm of the backward change in the posterior corneal surface. Considering the accuracy of Orbscan to be ±20 μm,[1] our result almost corresponded to the theoretical change. That is, the posterior corneal surface change may be mostly an artifact, although we agree that ectasia of the posterior cornea occasionally exists. In addition, the difference map obtained by Orbscan may be insufficient for evaluating the posterior corneal surface change after keratorefractive surgery because the measurement of the posterior cornea could be affected by various factors, such as the anterior cornea.[11]

In each side, moreover, correlation of the attempted correction with posterior corneal topographic change was

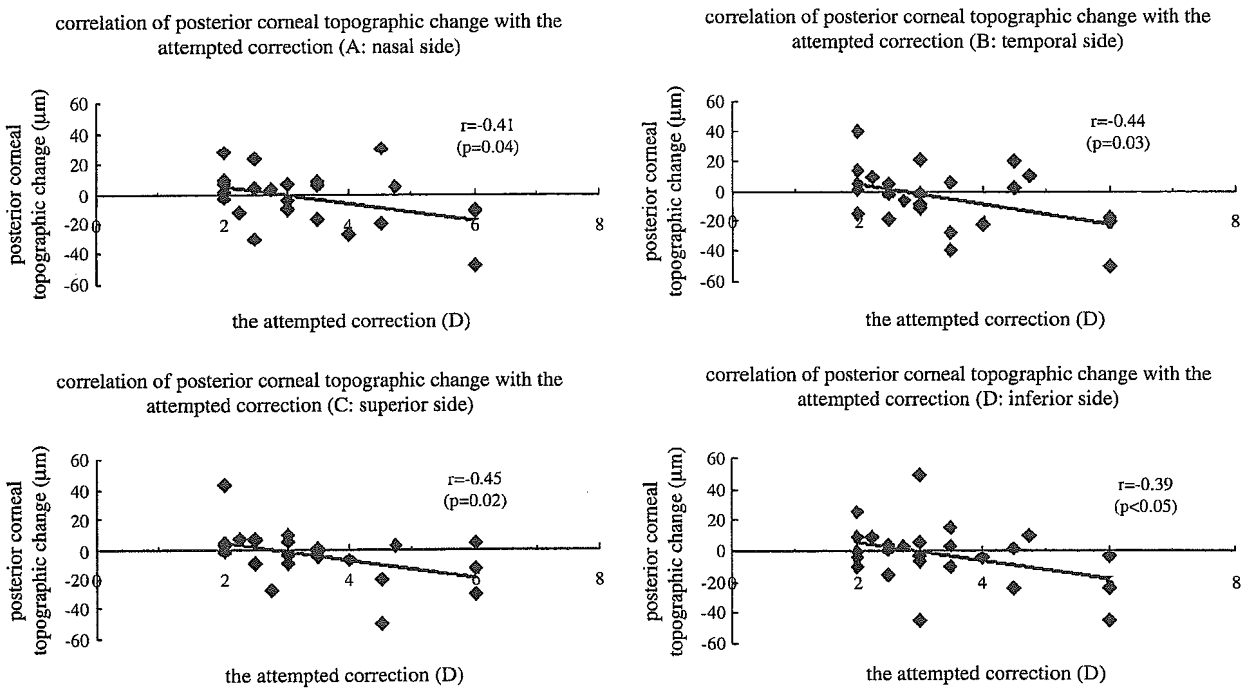

Figure 2. The relationship between the amount of the attempted correction and the posterior corneal topographic change at the nasal (*A*), temporal (*B*), superior (*C*), and inferior (*D*) sides. In each side, there was a significant correlation between the 2.

significant; the larger the attempted correction, the larger the backward shift of the posterior cornea. This relation between the 2 could support our hypothesis.

When we compare the changes in corneal height against a best-fit sphere, we have to set a fit zone. In M-LASIK, a 3.0 mm wide peripheral annular fit-zone from 7.0 to 10.0 mm in diameter is often used for surface alignment in the difference map. In H-LASIK, the surgeon attempts to obtain the largest corneal flap diameter possible so that the stromal bed area is wide enough to accommodate the ablation. Excimer laser H-LASIK is mostly focused on peripheral corneal ablation as opposed to the predominantly central ablation in M-LASIK. Therefore, the assumptions in M-LASIK cannot be applied to H-LASIK. In other words, we must define the fit zone in the assessment of the difference map generated from preoperative and postoperative elevation maps. Therefore, we took the center as the fit zone under the assumption that the corneal center was theoretically almost unaffected by the surgical procedure, as Maloney pointed out regarding the choice of a specific point (eg, its center) in a discussion on a study by Wang and coauthors.[1]

In conclusion, the clinically measured posterior corneal surface moved backward after H-LASIK. This was consistent with our hypothetical eye model, considering the postoperative:preoperative magnification ratio. If the posterior cornea shifts backward, patients with a shallow anterior chamber should have the following risk; a much shallower anterior chamber depth, or the increase of the risk in glaucoma followed by a much shallower anterior chamber depth. New devices such as Pentacam using the Scheimpflug method (Oculus) may be helpful in demonstrating these changes, including anterior chamber measurement with high-resolution imaging. We will have to validate this hypothesis using other devices and reevaluate and discuss this problem.

APPENDIX

Calculation of Apparent Change in Posterior Corneal Surface Based on the Postoperative: Preoperative Magnification Ratio[13]

In calculating the shift of the posterior corneal surface based on the postoperative/preoperative magnification ratio (R),[13] the following was assumed: The preoperative refractive power of the anterior corneal surface is 43.0 D, the preoperative paracentral thickness of the cornea is 550 μm, the refractive index of the cornea is 1.376, the preoperative and postoperative radius of curvature of the posterior surface is 6.8 mm, the amount of hyperopic correction is X, which varies from 0 to +6 D.

In addition, if we assume that the hypothetical change is directly translated into the shift of the posterior corneal surface in the calculation of the difference map, the apparent posterior corneal surface change (Y) is expressed as follows:

$$Y = 6800 \times (1 - R)$$

where

$$R = 1.35235/[1.37600 - 0.00055 \times (43 + X)]$$

REFERENCES

1. Wang Z, Chen J, Yang B. Posterior corneal surface topographic changes after laser in situ keratomileusis are related to residual corneal bed thickness. Ophthalmology 1999; 106:406–409; discussion by RK Maloney, 409–410
2. Seiler T. Iatrogenic keratectasia: academic anxiety or serious risk? [editorial] J Cataract Refract Surg 1999; 25:307–1308
3. Binder PS. Ectasia after laser in situ keratomileusis. J Cataract Refract Surg 2003; 29:2419–2429
4. Naroo SA, Charman WN. Changes in posterior corneal curvature after photorefractive keratectomy. J Caratact Refract Surg 2000; 26:872–878
5. Hernández-Quintela E, Samapunphong S, Khan BF, et al. Posterior corneal surface changes after refractive surgery. Ophthalmology 2001; 108:1415–1422
6. Seitz B, Torres F, Langenbucher A, Behrens A, Suárez E. Posterior corneal curvature changes after myopic laser in situ keratomileusis. Ophthalmology 2001; 108:666–673
7. Baek TM, Lee KH, Kagaya F, et al. Factors affecting the forward shift of posterior corneal surface after laser in situ keratomileusis. Ophthalmology 2001; 108:317–320
8. Liu Z, Huang AJ, Pflugfelder SC. Evaluation of corneal thickness and topography in normal eyes using the Orbscan corneal topography system. Br J Ophthalmol 1999; 83:774–778
9. Cairns G, McGhee CNJ, Collins MJ, et al. Accuracy of Orbscan II slit-scanning elevation topography. J Caratact Refract Surg 2002; 28:2181–2187
10. Ormonde S, McGhee CN. Changes in the posterior corneal surface after LASIK. J Caratact Refract Surg 2004; 30:533–534
11. Cairns G, Collins A, McGhee CNJ. A corneal model for slit-scanning elevation topography. Ophthalmic Physiol Opt 2003; 23:193–204
12. Nawa Y, Masuda K, Ueda T, et al. Evaluation of apparent ectasia of the posterior surface of the cornea after keratorefractive surgery. J Catatact Refract Surg 2005; 31:571–573
13. Nawa Y, Ueda T, Masuda K, et al. Evaluation of the corneal endothelium after hyperopic laser in situ keratomileusis. J Catatact Refract Surg 2003; 29:1543–1545

④

眼光学の基礎 その10

超解像とアポダイゼーション

北里大学大学院医療系研究科　魚里　博

1．はじめに

白内障手術も視覚の質（quality of vision 以下QOV）への要求が高まるとともに，屈折矯正の精度は格段に高まり，眼内レンズ（以下 IOL）挿入術も一種の屈折矯正手術に位置づけされるようになってきている。また，屈折だけではなく術後調節機能の喪失を補う老視矯正の取り組みも盛んになりつつある。本稿では，白内障術後のQOVを更に高めるために，今後ますます必要になるであろう眼光学の波動光学的取り扱いについて，とくに，アポダイゼーション，超解像と偽解像について解説する。

2．網膜像の評価

従来の屈折や視力検査では，詳細な網膜像の評価は困難であったが，最近では，波面収差解析や点像強度分布（point spread function 以下 PSF）や光学的な変調伝達関数（modulation transfer function 以下 MTF）や空間周波数特性などの臨床評価が可能になってきている。眼球光学系の形状や波面収差解析が進み，網膜像のシミュレーションも臨床的に可能になってきた。また視覚系全体のコントラスト弁別閾は臨床的にはコントラスト感度測定により行える。眼球光学系の結像特性は，波面収差や点像強度分布から網膜像の評価が可能になり臨床的な応用が期待されている。

3．フィルタリングによる像改良

光学系はその開口の大きさによって決まる遮断周波数（cut-off frequency，カットオフ周波数ともいう）をもっている。正方形開口での無収差光学系の遮断周波数は，レーレー（Rayleigh）の定義した分解能の逆数に等しく，円形開口ではレーレーの分解能は遮断周波数の逆数の1.22倍となっている。

透過率や位相の変化を与えるフィルターを光学系の瞳面において，点像の形を所望するものに変えて，よい像にすることをフィルタリングによる像改良という。透過率を変えるには，光の振幅のみを変える振幅フィルター，位相のみを変える位相フィルター，振幅と位相を同時に変える複素フィルターがある。

可干渉性の高い（coherentな）光で照明されている物体の結像とインコヒーレント（incoherent）の場合では結像特性は異なるが，ここでは後者の場合を考えよう。インコヒーレントな光学系では，フーリエ（Fourier）スペクトルがあらわれる面がないので，物体からのスペクトルをフィルタリングするには，瞳面での特殊な開口関数（フィルターや絞り）を挿入する方法が用いられる。インコヒーレント光学系のoptical transfer function（以下 OTF）は瞳関数の自己相関であるから，開口関数を変えることで各種のフィルタリングが可能となる。以下には，フィルタリングによる像改良の体表的なものを示す。

4．超解像とアポダイゼーション

像の改良には，像の中心部の広がりを狭くしてレーレーの解像力を向上させるものや，点像の中心部の広がりは少し大きくなるが周辺部の強度を弱くする目的のものがある。前者を超解像（super resolution），後者をアポダイゼーション（apodaization）という。一般に，光学系における開口部の振幅透過率を操作する

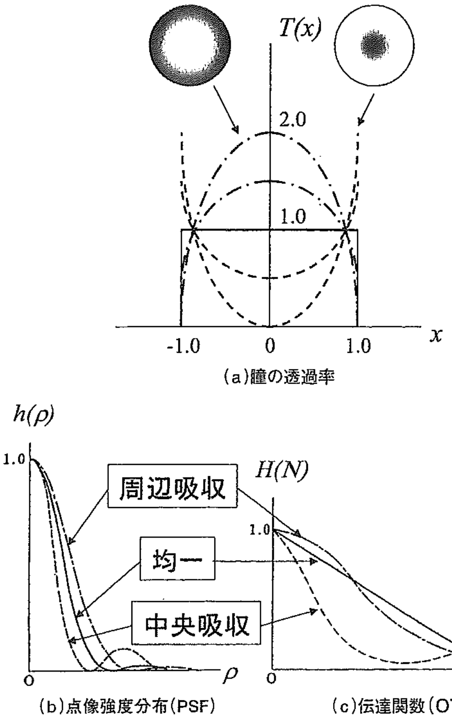

図1　アポダイゼーションフィルターとPSF，OTF

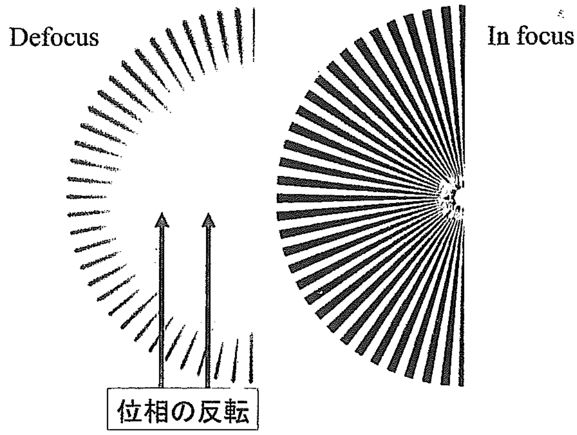

図2　Siemen's Starによる偽解像の例

ことを広くアポダイゼーションと呼ぶこともある。この用語の語源はギリシャ語で，aはない，podosは脚の意味で，すそを切ることから名付けられたものである。本来は，プリズム分光器や天体望遠鏡での分解能・解像力を高めるためにこの原理が用いられる。天体観測では，明るい星の近くの弱い光の星を観察したり，分光器の明るい線の側の弱い側線を分離観察するのに必要となる。

光学系の瞳面に振幅透過率が一様でないフィルターを付加すると，PSFや伝達関数（OTF，MTF）を変えることができる（**図1**）。一般的な円形開口の場合には，中心から周辺部に向かって振幅透過率を増大させるものと，逆に減少させる方法がある。中心より周辺部が明るいフィルターの場合には，点像の第1暗輪の半径がエアリーディスク（airy disk）の半径よりも小さくなり，レーレーの分解能が向上しているかのようにみえるが，第1明輪の強度が大きくなる。OTFは高域でよくなるが，低～中域で低下する。

逆に中心より周辺部が暗いフィルターを用いると，点像の第1暗輪の半径はエアリーディスクよりも大きくなるが，第1明輪の強度は小さくなり，低域でのOTFはよくなる。回折による周辺部への光の広がり（明輪）を抑えることで，回折像の裾が有害な影響を及ぼすような天体観測や分光測定の場合に有用である。しかしながら，アポダイゼーションの効果は透明な位相フィルターでは実現できないので，必ず光の吸収による損失が伴い，それに加えて回折像の広がりがフィルターを付加しないときよりも大きくなる。これらがアポダイゼーションの本質的な欠点である。

眼の場合には，白内障による混濁で水晶体の透過率分布が加齢とともに変化するが，混濁部位や程度により，一種のフィルタリングでアポダイゼーションや超解像に似た現象が起こっている可能性もある。人工水晶体であるIOLも瞳面に近い位置に挿入されることから，レンズの形状デザインによる非球面や多焦点レンズだけでなく，振幅透過率を考慮してレンズの結像特性を改善したり，アポダイゼーションを応用する新しいレンズも期待される。

5．超解像と偽解像

結像系への種々の特殊な処理，もしくは像への種々の後処理によって非常に高い解像力をもたせる技術を超解像（super resolution）という。前述のアポダイゼーションの応用，空間周波数フィルタリングやモアレ縞を利用した超解像などがある。

また，伝達関数（OTF，MTF）で，コントラストが最初にゼロになった点での空間周波数（カットオフ周波数）よりも高い周波数で像の細部がみえ，あたかも解像（超解像）しているかのようにみえる現象を偽解像（spurious resolution）と呼んでいる（**図2**）。この

現象で，位相の反転によって例えば白黒像では白黒が反転してみえ，高度に収差補正されたレンズをピンボケの状態で用いると，この現象がよく発生する。最近の wavefront-guided laser in situ keratomileusis（LASIK）などによる屈折矯正手術で，極めて高い術後視力が得られる場合があり，super visionと呼ばれるが，視力検査でもこのような偽解像が発生している可能性も考えられる。

6. あとがき

像改良により光学特性やとくに視覚特性を改善し，視機能の向上を図る試みは今後更に増加していくものと思われる。そのためにも，従来の幾何光学だけではなく，今後，波動光学の取り扱いが眼光学の分野にもますます必要となる。

（別刷請求先）魚里　博　〒288-8555　相模原市北里1-15-1　北里大学大学院医療系研究科

⑤

原　著

両眼視と単眼視下における瞳孔径が昼間視と薄暮視下の視機能に与える影響

川守田拓志*，魚里　博*,**

*北里大学大学院医療系研究科眼科学，**北里大学医療衛生学部視覚機能療法学専攻

Effect of Pupil Size on Photopic and Mesopic Vision under Binocular and Monocular Viewing Conditions

Takushi Kawamorita* and Hiroshi Uozato*,**

*Department of Ophthalmology and Visual Science, Kitasato University Graduate School of Medical Sciences

**Department of Orthoptics and Visual Science, Kitasato University School of Allied Health Sciences

背景輝度や視標のコントラストが変化するとき，瞳孔径や収差の変化が両眼視と単眼視でのコントラスト視力に及ぼす影響を検討した。対象は，健常被験者13名22眼である。本実験は，瞳孔径を計測するために2台の小型カメラを取り付けて改良したCAT-2000と収差計OPD-Scanを用い，また，ある解析径で得られたZernike係数を任意の解析径のZernike係数に再展開し，推定するSchwiegerlingのアルゴリズムを用いて自然瞳孔径に対応した高次収差の総和を再計算した。結果，今回用いたすべての視標コントラスト下と背景輝度において，単眼視下瞳孔径と高次収差の総和は，両眼視下のそれらに比べ有意に高値を示した。また，昼間視かつ低コントラスト視標下における単眼と両眼logMAR値の差は，薄暮視下に比べて大きかった。単眼視下で起こる瞳孔径の拡大は，背景輝度や視標のコントラストにかかわらず起こり，また高次収差を増加させる。その結果，視機能に影響を与える可能性が示唆された。　　(視覚の科学　26: 71−75, 2005)

キーワード：瞳孔径，高次収差，コントラスト視力，昼間視，薄暮視

We investigated the effect of pupil size on photopic and mesopic vision under binocular and monocular conditions in 22 eyes of 13 subjects. Pupil diameter was continuously recorded during contrast visual acuity measurement (logMAR scale) with modified CAT-2000. Aberrometry measurements were performed with OPD-Scan. Zernike coefficients were calculated for natural pupil diameters under binocular and monocular conditions, using Schwiegerling's algorithm to recalculate the expansion coefficient. In photopic and mesopic vision, mean pupil diameter and total higher-order aberration increased significantly under monocular condition, as compared to binocular condition. Monocular visual acuity was significantly worse than binocular visual acuity. The differences between monocular logMAR and binocular logMAR in photopic vision were greater than in mesopic condition, especially with visual targets of low contrast. These results suggest that increase in pupil diameter from binocular to monocular condition give rise to increase in higher-order aberration with every contrast of visual target and background luminance, impacting subjective visual performance.　　(Jpn J Vis Sci 26: 71-75, 2005)

Key Words: Pupil size, Higher-order aberration, Contrast visual acuity, Photopic vision, Mesopic vision

別刷請求先：228-8555　相模原市北里1-15-1　北里大学大学院医療系研究科眼科学　魚里　博
(2005年11月4日受理)
Reprint requests to: Hiroshi Uozato, PhD　Dept of Ophthalmol & Visual Science, Kitasato Univ Graduate School of Medical Sciences
1-15-1 Kitasato, Sagamihara 228-8555, Japan
(Received and accepted November 4, 2005)

1. 緒　　言

近年，眼科領域において，視機能が瞳孔径に大きく依存する光学的屈折矯正法あるいは治療法が増加し，瞳孔径と収差，視機能との関係が注目されている[1-4]。そして以前我々は，視機能検査下の自然瞳孔径（入射瞳）と高次収差は，両眼視下より単眼視下で大きく，単眼視下視機能検査において過小評価を導く可能性について報告した[5]。しかしながら，この瞳孔径の差に関して報告は少なく[6-8]，背景輝度（昼間視と薄暮視）や視標コントラストの依存性については，ほとんど知られていない。そこで今回，コントラスト視力計に瞳孔計測用の小型カメラとモニターを取り付けた改良型 CAT-2000 を用い，背景輝度と視標コントラストを変化させたときの視力と視力検査下の瞳孔径，また，その瞳孔径による高次収差量を再計算し，比較検討した。

2. 方　　法

対象は，眼科的疾患のない正常被験者13名22眼（平均年齢22.6±1.9歳）で，自覚的平均等価球面値は−5.61±3.37D である。また，片眼矯正視力1.0未満，Titmus stereo test（Stereo Optical）の circle 視標にて8/9以下，弱視，斜視，斜位10⊿以上，ハードコンタクトレンズ装用者は除外した。被験者には，十分なインフォームドコンセントを行った。

コントラスト視力（logMAR 値）と瞳孔径の計測は，左右眼瞳孔計測用2台の小型カメラ 15-BC20CML（Security System）と7インチ液晶モニター TW-7ML1（Panasonic）を取り付けて改良した CAT-2000（Menicon）を用いた（図1）。このカメラは，瞳孔径に影響を与えないよう赤外線透過フィルター IR-76（HOYA）が取り付けられ，可視光はカットされている。そして，このカメラで得られた瞳孔径の画像データは，FP-10000（TMI）の瞳孔径解析プログラムにて平均瞳孔水平径として算出された。瞳孔径の校正に関して，CAT-2000 のワーキングディスタンスの位置に実測値 3.0 mm の円形開口を置き，取得した画像データを FP-10000 にて解析した後，実測値と比較，そこから回帰式を算出し，補正式として用いた。

眼球全体の高次収差の計測は OPD-Scan ARK-10000（Nidek）を用い，解析径は 6.0 mm，Zernike 多項式にて算出される3次～6次までの Zernike 係数を評価した。また，コントラスト視力検査時の自然瞳孔径に対応した高次収差量を算出するため，Schwiegerling のアルゴリズムを用い，OPD-Scan による解析径 6.0 mm の Zernike 係数を，CAT-2000 で計測された瞳孔径に対応した Zernike 係数に再展開し，更に高次収差の総和を算出した[9]。Schwiegerling のアルゴリズムは，ある解析径の Zernike 係数（original expansion coefficients）を任意の瞳孔径における Zernike 係数（new expansion coefficients）へ再展開し，推定する方法である[9]。

環境設定について，CAT-2000 の視標コントラストは，100，25，10，5，2.5%の5段階，平均背景輝度は，昼間視 100 cd/m²，薄暮視 5 cd/m²である。また測定は完全暗所にて前順応を10分行い，その後，遠見視オートモードと閾値決定3/5モードにて検査を行った。そのとき，被験者の屈折状態は眼鏡およびソフトコンタクトレンズにて矯正された。また測定順序について，コントラスト視力と瞳孔径の計測は両眼視，単眼視の順で実行され，左右眼の測定順序はランダムで行った。統計解析は，Wilcoxon の符号付順位検定を用いた。有意水準は5%未満とした。

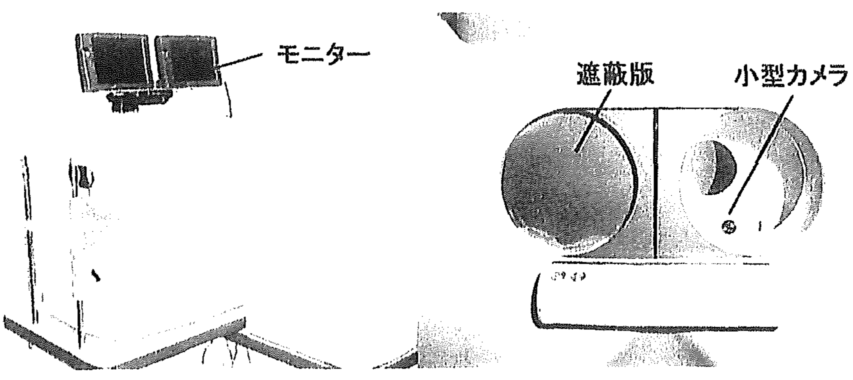

図1　瞳孔径計測用小型カメラとモニターを取り付けた改良型 CAT-2000（Menicon）

3. 結　　果

OPD-Scanによる解析径6.0mmの平均高次収差の総和，コマ様収差，球面様収差は各々0.44±0.18μm，0.36±0.14μm，0.24±0.15μmであった。

昼間視における単眼視下瞳孔径は，今回用いたすべての視標コントラスト下において，両眼視下の瞳孔径と比べ約1.5mm有意に高値を示し（Wilcoxonの符号付順位検定，p<0.01）（図2），高次収差の総和もこの瞳孔変化に対応し，単眼視下で有意に高値を示した（Wilcoxonの符号付順位検定，p<0.01）（図3）。またコントラスト視力は，単眼視下に比べ両眼視下で有意に高く（Wilcoxonの符号付順位検定，p<0.05），視標コントラストの低下とともに両者の差が増加した（図4）。

薄暮視における単眼視下瞳孔径は，昼間視と同様にあらゆる視標コントラスト下において約1.5mm高値を示した（Wilcoxonの符号付順位検定，p<0.01）（図5）。薄暮視における単眼視下高次収差の総和は，両眼視下と比べ有意に高値を示し（Wilcoxonの符号付順位検定，p<0.01）（図6），また，昼間視より大きな増加を示した（Wilcoxonの符号付順位検定，

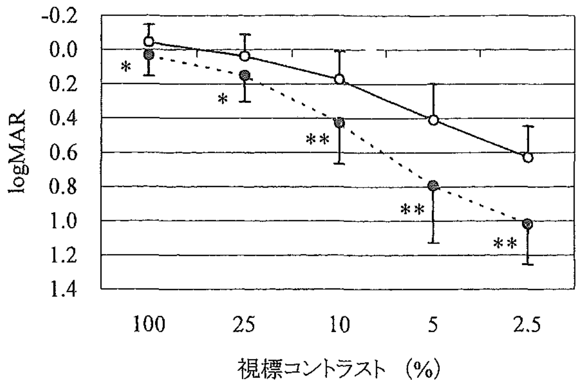

図4　昼間視における視標コントラストとlogMAR値：両眼視と単眼視の比較
**: p<0.01, *: p<0.05
—○—：両眼視，……●……：単眼視

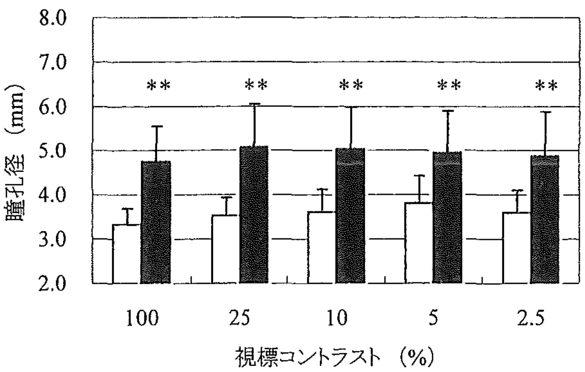

図2　昼間視における視標コントラストと瞳孔径：両眼視と単眼視の比較
**: p<0.01，□：両眼視，■：単眼視

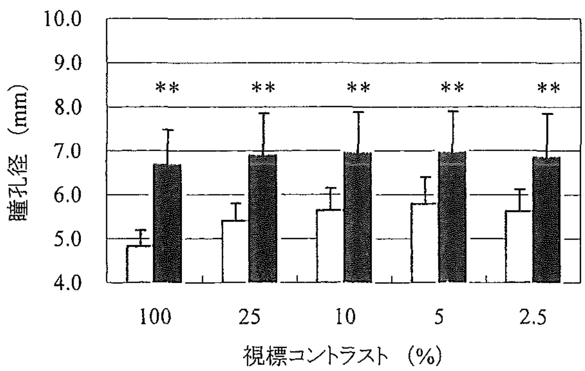

図5　薄暮視における視標コントラストと瞳孔径：両眼視と単眼視の比較
**: p<0.01，□：両眼視，■：単眼視

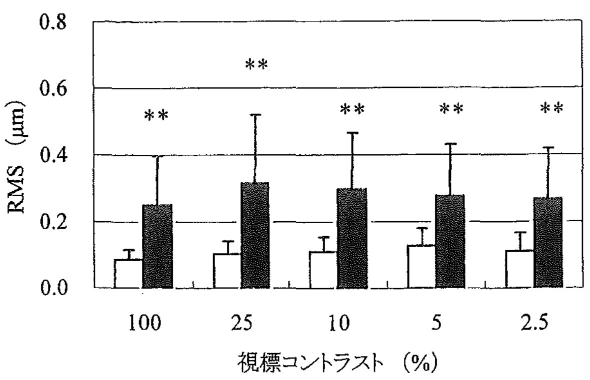

図3　昼間視における視標コントラストと高次収差の総和：両眼視と単眼視の比較
RMS：root mean square，**: p<0.01
□：両眼視，■：単眼視

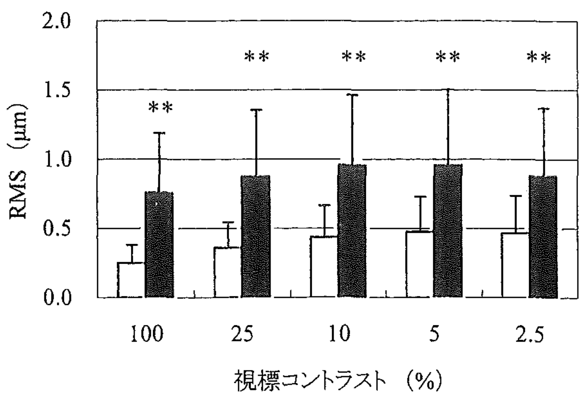

図6　薄暮視における視標コントラストと高次収差の総和：両眼視と単眼視の比較
RMS：root mean square，**: p<0.01
□：両眼視，■：単眼視

p<0.01)（図７）。薄暮視におけるコントラスト視力に関して，単眼視下より両眼視下で有意に良好であったが（Wilcoxonの符号付順位検定，p<0.05）（図８），昼間視と比べると単眼視下logMAR値と両眼視下logMAR値の差は，小さな結果を示した（Wilcoxonの符号付順位検定，p<0.05）（図９）。

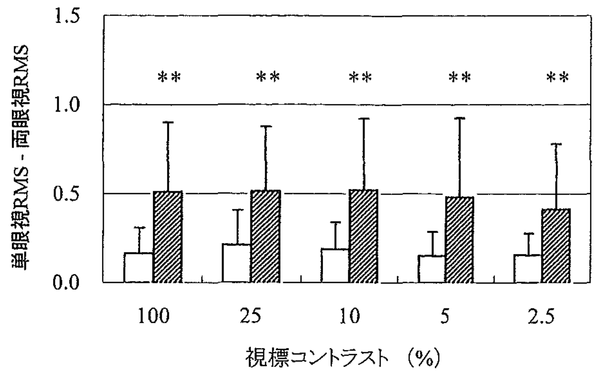

図７　単眼視と両眼視下高次収差の総和の差：昼間視と薄暮視の比較
RMS：root mean square，**: p<0.01
□：昼間視，▨：薄暮視

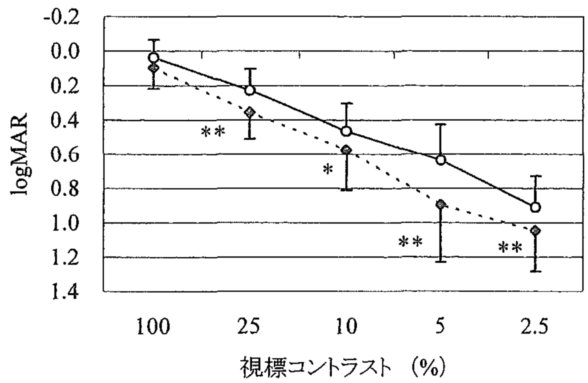

図８　薄暮視における視標コントラストとlogMAR値：両眼視と単眼視の比較
**: p<0.01, *: p<0.05
—○—：両眼視，‥‥◆‥‥：単眼視

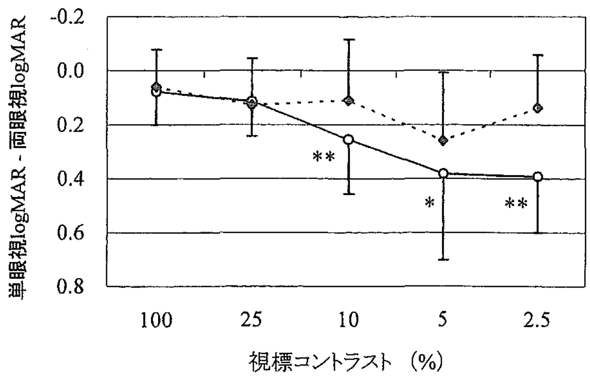

図９　単眼視と両眼視下logMAR値の差：昼間視と薄暮視の比較
**: p<0.01, *: p<0.05
—○—：昼間視，‥‥◆‥‥：薄暮視

4. 考　　按

本検討により，視機能検査時の瞳孔径と高次収差は背景輝度（昼間視と薄暮視），視標のコントラストにかかわらず，両眼視下に比べ単眼視下で有意に高値を示した。両眼視下と単眼視下の瞳孔径に関する過去の報告[6-8]では，視機能検査下のリアルタイム計測や収差測定は行われていないが，単眼視下の瞳孔径は両眼視下と比べ高値を示しており，本研究結果や以前報告した我々の結果[5]と一致している。また瞳孔径は，CampbellとGubisch[10]によって結像特性（線像強度分布）の観点から最適径（入射瞳）が約2.4 mmと報告されており，一般的にはそれ以上拡大すると収差が増加し，視機能は低下する[11]。したがって今回の結果より，比較的広い範囲の背景輝度において，両眼視下に比べ単眼視下で瞳孔径が高値を示し，このことが収差の増加と網膜結像特性の低下を導き，その結果，視機能に影響を与えることを示唆している。

また，昼間視と薄暮視の比較に関して，単眼視下の高次収差の増加は薄暮視で大きかったにもかかわらず（図７），コントラスト視力への影響は昼間視（とくに低コントラスト視標下）で大きいという矛盾する結果となった（図９）。これは，第一種Stiles-Crawford効果[12]や網膜照度[13]が関与しているか，杆体系（薄暮視）が錐体系（昼間視）に比べ収差の影響を受けにくく，単眼視下の視機能の低下が起きにくい可能性，あるいは昼間視時，とくに低コントラスト視標下において両眼加算が起こりやすい，などが考えられる。ただし，今回用いたSchwiegerlingのアルゴリズムは，数学的に算出された推定値である。したがって，OPD-Scanによって得られた解析径6.0 mmのZernike係数から6.0 mm径以上へのZernike係数に再展開する場合，眼球光学系の周辺領域が考慮されていないため，誤差を含んでいる可能性が示唆され，あくまで推定値として結果を解釈する必要がある。

両眼視と単眼視下の瞳孔径の差が生じる原因については完全に解明されていないが，両眼の照度加算（binocular luminance summation）や，片眼の網膜照度の変化，融像除去や眼位などが関与していると考えられている[14,15]。そして，この現象に関する臨床上