

Natural Pupil Size and Ocular Aberration under Binocular and Monocular Conditions

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Abstract

Purpose: To investigate how activity of natural pupils under binocular and monocular conditions affect wave front aberrations.

Materials and Methods: Eighteen eyes from 18 subjects (mean age 22.3 ± 0.8 years) were included in the study. The undilated pupil diameters under photopic conditions were measured using the FP-10000 (TMI, Japan) infrared pupillometer. Aberrometry measurements were performed using the KR-9000PW (Topcon, Japan) Hartmann-Shack wavefront sensor. Zernike coefficients were recalculated for the diameters of each pupil under binocular and monocular conditions using Schwiegerling's algorithm. Multiple regression analysis was performed to analyze independent predictors of the change of higher-order aberration for 6.0 mm from the binocular to the monocular condition. The independent variables were the change of pupil diameter from binocular to monocular condition; binocular pupil diameter; total higher-order aberration for 6.0 mm, sphere, and cylinder.

Results: Pupil diameter, total, total higher-order, coma-like, and spherical-like aberrations under monocular conditions were significantly greater than the binocular condition (all $P < 0.01$). The multiple regression analysis of variables showed that the change of total higher order aberration from the binocular to the monocular condition was related to the change of pupil diameter, and the amount of higher-order aberrations for 6.0 mm ($P < 0.05$).

Conclusions: The outcomes suggest that increased pupil diameter under monocular conditions produces higher wavefront aberrations than under binocular conditions, resulting in a degradation of retinal image quality. This effect is enhanced in eyes with greater higher order aberrations and pupil diameter.

Keywords: Pupil size; Wavefront aberrations; Binocular condition; Monocular condition; Schwiegerling's algorithm

Introduction

Increasingly the effect of pupil diameter is being incorporated into cataract surgery, refractive surgery [1-4] and the contact lens fittings [5]. This has led to the introduction of infrared pupillometers and the incorporation pupillometry functions into wave front analyzers and corneal topographers [6,7].

Clinically, visual performance is simulated for monocular conditions however, pupil diameter under monocular conditions is greater than under "real life" binocular conditions [8]. This pupil-enlargement effect leads to an increase in the optical aberrations, therefore, the evaluation of visual performance under binocular conditions is important. A number of studies have advocated the importance evaluating post-refractive surgery patients under binocular conditions [9-12]. However, it is unclear how this change in physiologic pupil diameter between binocular and the monocular conditions affects the increase in ocular wavefront aberrations or whether the change depends on pupil size, the magnitude of higher-order aberration, or refractive error.

The current study investigated how the activity of natural pupils under the binocular and monocular conditions affects higher-order wavefront aberrations and whether there is dependency on aberration levels and/or refractive error.

Materials and Methods

Eighteen eyes from 18 subjects (aged 20-24 years; mean 22.3 ± 0.8 years) with no known ocular abnormalities were included in this study. Mean sphere was -5.40 ± 3.26 D (range: 0 to -13.25 D), mean

cylinder was -0.50 ± 0.58 D (range: 0.00 to -2.00 D), mean spherical equivalent refraction was -5.65 ± 3.36 D (range: 0.00 to -13.38 D). The exclusion criteria included distance Best Corrected Visual Acuity (BCVA) (LogMAR) of worse than 0 in either eye, and wearing hard contact lenses or spectacles. Pupil measurements were not performed with spectacles on because they significantly affect pupil magnification or distort infrared light (IR) used in most pupillometers. The tenets of the Declaration of Helsinki were followed and informed consent was obtained from all subjects in the current study.

Pupil measurements

Physiologically dilated horizontal pupil diameters were measured using the FP-10000 (TMI, Saitama, Japan) infrared electronic pupillometer that was connected to a laptop computer with proprietary pupil analysis software (TMI, version 1.08). The sampling rate was 30 Hz. Emmetropic eyes were measured without correction, and myopic eyes were measured with soft contact lenses on. All measurements were performed under photopic conditions with an ambient illuminance

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of 520 lx measured using an illuminance meter (T-10, Minolta Corp, Tokyo, Japan). The FP-10000 can measure pupil diameter in real time under binocular conditions which closely simulate natural viewing conditions (Figure 1). The magnitude of error introduced by variation in the vertex distance between the cornea and FP-10000 using the circular apertures of 3.0 mm and 5.6 mm was calculated. The repeatability of the two measurements by the same examiner was determined in 10 eyes. Evaluation of repeatability were assessed using the method described by Bland and Altman: the mean difference and the 95% limits of agreement (LoA) [13].

Ocular wavefront aberration measurements and computation to natural pupil sizes

Aberrometry measurements were performed with the KR-9000PW (Topcon, Tokyo, Japan) Hartmann-Shack wavefront sensor. Wavefront aberrations were analyzed at a 6.0 mm pupil diameter for total (S2 ~ S6), total higher-order (S3 ~ S6), coma-like (S3+S5), and spherical-like (S4+S6) aberrations. The magnitude of the Zernike polynomial coefficients were represented as the root mean square (RMS) [14]. Zernike coefficients were recalculated for each pupil diameter for binocular and the monocular conditions, using Schwiegerling's algorithm for recalculating expansion coefficients for an arbitrary pupil size for a 6.0 mm pupil diameter [15].

Procedure

Ten minutes were allowed for adaptation to the room illuminance prior to the measurements. A crisscross fixation target of 1 degree in the central visual field was placed at a distance of 5.0 m. Under binocular conditions pupil diameters of the right eye were continuously measured for 10 seconds and averaged. Subsequently the left eye was occluded with a black patch, and after two minutes, the pupil diameter of the right eye was again continuously measured for 10 seconds and averaged. The effects of blinking were disregarded.

Data Analysis

Wilcoxon's signed rank sum test and multiple regression analyses using StatView version 5.0 software (SAS, Cary, USA) were performed. Multiple regression was performed to analyze the impact of binocular to monocular conditions on the change in higher-order aberrations. The independent variables were the change in pupil diameter from binocular to monocular conditions, binocular pupil diameter, total higher-order aberrations for a 6.0 mm pupil, and refractive error (sphere and cylinder). A $P < 0.05$ was considered statistically significant.

Results

The relative error introduced by variation in the vertex distance between the cornea and the FP-10000 pupillometer was 0 to 5% (Figure 2). Under photopic conditions, the mean difference between repeated measurements was 0.07 mm and the 95% LoA were -0.51 to +0.65 mm for binocular measurements, and the mean difference was -0.16 mm and -0.70 to 0.39 mm (95% LoA) for monocular measurements.

Mean RMS was $0.46 \pm 0.19 \mu\text{m}$ for total higher order aberrations, $0.36 \pm 0.13 \mu\text{m}$ for coma-like aberrations and $0.25 \pm 0.17 \mu\text{m}$ for spherical-like aberrations. Mean pupil diameter under significantly increased under monocular conditions compared to the binocular conditions ($P < 0.001$, Table 1). Additionally total wavefront aberrations, total higher-order, coma-like, spherical-like aberrations all increased significantly (all $P < 0.001$, Table 1).

Multiple regression analysis of variables ($P = 0.0005$, adjusted $R^2 = 0.731$; Table 2) showed that the change of total higher-order aberrations from the binocular to the monocular condition: Equation 1: monocular RMS - binocular RMS was related to the change of pupil diameter ($P < 0.0001$), and the magnitude of total higher-order aberrations ($P = 0.038$) for a 6.0 mm pupil diameter (Table 2). There was no correlation to the diameter the binocular pupil ($P = 0.356$), sphere ($P = 0.572$) or cylinder, ($P = 0.367$) (Table 2).

Two eyes were selected as sample eyes to demonstrate the data acquired for 330 seconds with the pupillometer. One eye had relatively

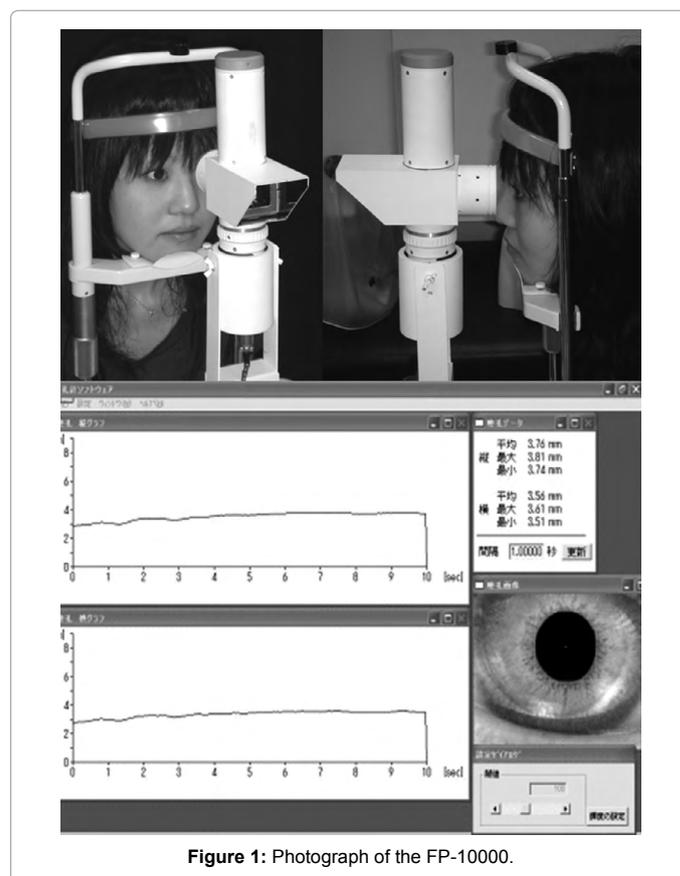


Figure 1: Photograph of the FP-10000.

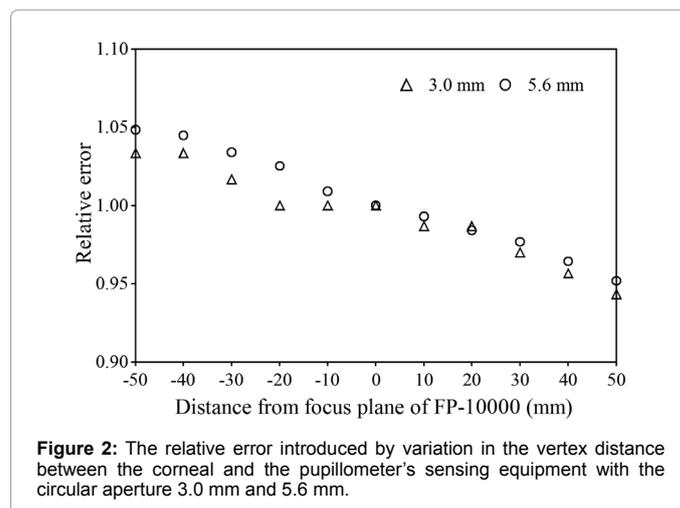


Figure 2: The relative error introduced by variation in the vertex distance between the corneal and the pupillometer's sensing equipment with the circular aperture 3.0 mm and 5.6 mm.

Measurement	Binocular Condition	Monocular Condition	P Value
PD (mm)	3.973 ± 0.698	5.059 ± 0.933	< 0.001
Computed wavefront aberration (um)			
Total aberration	2.962 ± 3.916	3.294 ± 6.476	< 0.001
Total higher order aberration	0.164 ± 0.114	0.322 ± 0.247	< 0.001
Coma-like aberration	0.125 ± 0.051	0.252 ± 0.181	< 0.001
Spherical-like aberration	0.092 ± 0.115	0.178 ± 0.193	< 0.001

Data are expressed as mean ± standard deviation
PD=pupil diameter

Table 1: Mean Pupil Diameters and Wave front Aberrations under the Binocular and the Monocular Conditions.

Explanatory variables	Regression coefficients (SE)	Standardized coefficients	P Value	95% CI
Intercept	-0.368 (0.148)	-0.368	0.029	-0.692 to -0.045
Mocular PD - Binocular PD (mm)	0.242 (0.042)	0.764	< 0.0001	0.151 to 0.333
Binocular PD (mm)	0.033 (0.034)	0.129	0.356	-0.042 to 0.128
Total higher order aberration for 6.0mm (um)	0.315 (0.135)	0.311	0.038	0.020 to 0.611
Sphere (D)	0.005 (0.008)	0.084	0.572	-0.012 to 0.022
Cylinder (D)	-0.040 (0.043)	-0.131	0.367	-0.1345 to 0.053

P=0.0005, Adjusted R²=0.731

SE=Standard Error; CI=Confidence Interval; PD=Pupil Diameter

Dependent variable is the change of the total higher order aberration from the binocular to the monocular condition

Table 2: Results of Multiple Regressions.

low values and/or changes in ocular aberration (Subject 1) (defocus value 3.60 μm) and pupil diameter, and the other eye, had higher values (Subject 2) (defocus value 14.73 μm) (Figures 3A and 3B, respectively). Once the fellow eye was occluded, the pupil diameter in the right eye increased within 30 seconds and remained maximally dilated for 3 minutes or longer (Figure 3A and 3B). The pupil diameter in subject 2 gradually decreased after approximately 3 minutes (Figure 3B). In subject 2 there were concomitant changes in higher order aberrations that follow the changes in pupil diameter (Figure 3B). For Subject 2, the increases and decreases in lower-order aberrations followed the changes in pupil diameter (Figure 4).

Discussion

The outcomes from the current study revealed that; (1) as has been reported previously [8], pupil and ocular wavefront aberrations are larger under monocular viewing conditions than binocular viewing conditions; (2) eyes with larger wavefront aberrations and/or pupil diameters are more significantly affected by this change; and (3) the change of the total higher-order aberrations from the binocular to the monocular condition does not depend on refractive error. Secondly we confirmed that under photopic conditions, the FP-10000 had good repeatability and introduced very low error due to variation in the vertex distance between the cornea and the pupillometer.

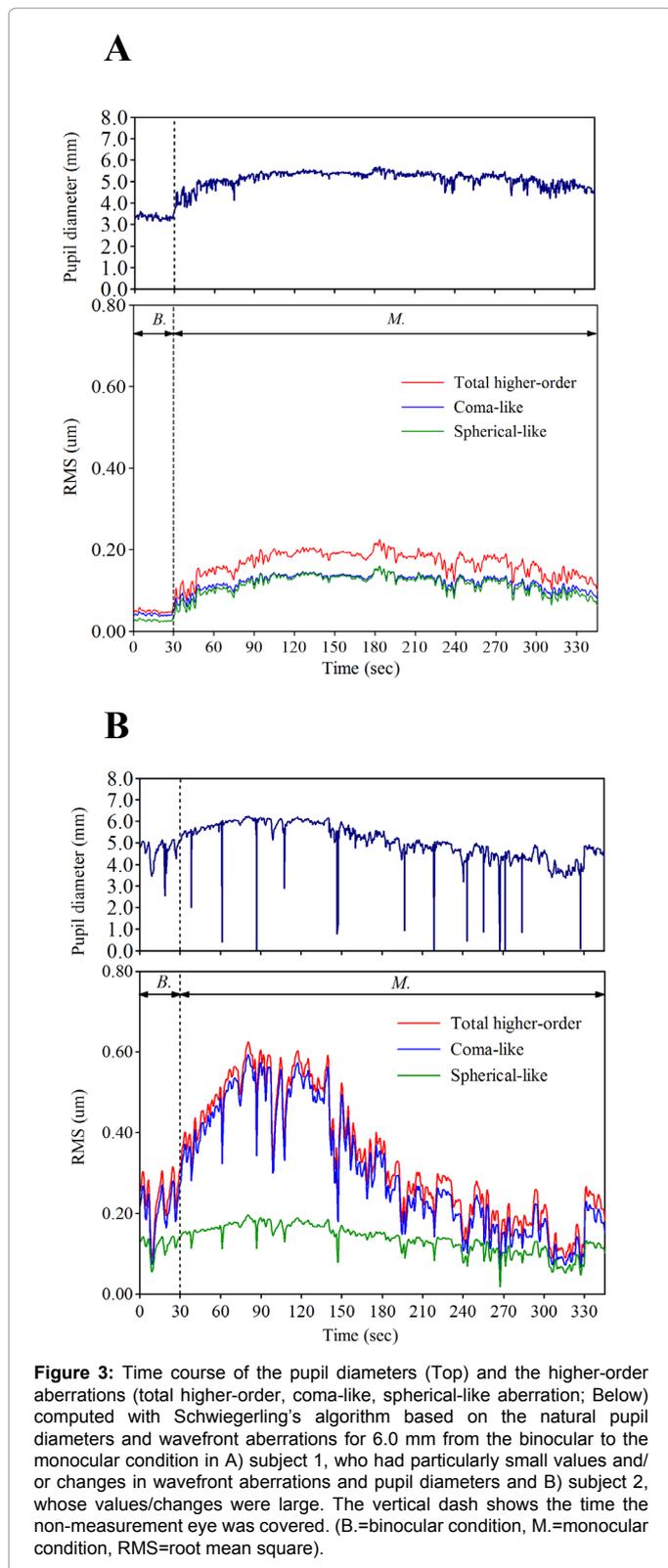
An increase in the pupil diameter will generally cause an increase in optical aberrations [14] causing distortions in the point- and line spread functions [16]. A reduction in modulation transfer function (MTF) and decrease in the Strehl ratio all of which indicate diminished retinal image quality [17,18]. Clinically, the change in the pupil diameter would affect measures of subjective visual performance such as visual acuity, contrast sensitivity and on the like. Our results suggest that the larger the wavefront aberrations, the greater the effects would be. Therefore, eyes that have undergone corneal surgery [19], cataract surgery [20], or eyes with corneal pathology (eg. dry eye) [21] and keratoconus [22] that have higher than normal optical aberrations and are depend on pupil diameters, would be affected by pupil enlargement.

Reduction in visual performance after photorefractive keratectomy

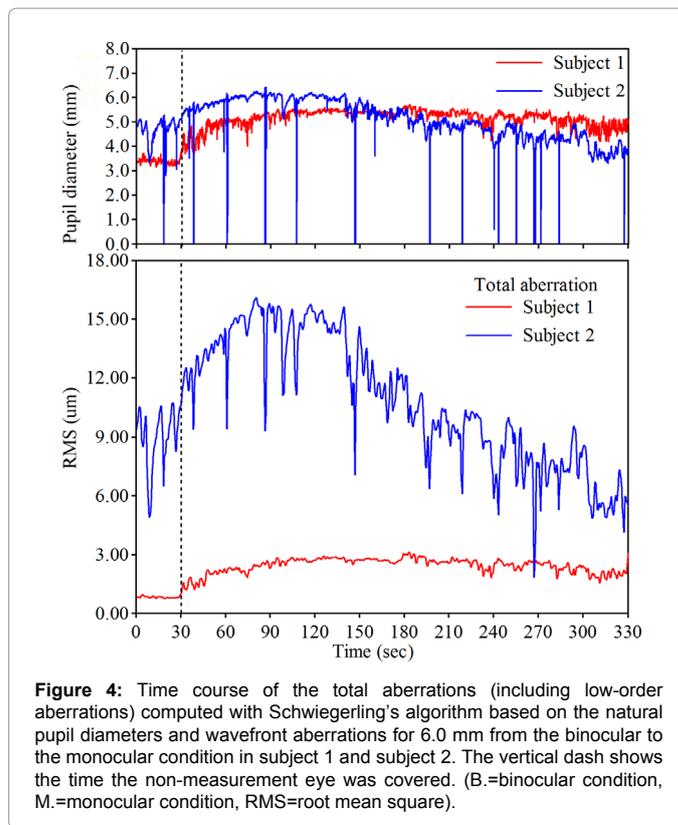
and laser in situ keratomileusis (LASIK) have been previously reported [23,24]. However, the visual performance under monocular conditions in the laboratory would be an underestimate, a worse evaluation, as compared with that in real life. Additionally, this pupil-enlargement phenomenon might have a significant effect on uncorrected visual performance, especially in myopic eyes as shown in Figure 4 and previous studies [25]. Cuesta et al. [10] and Anera et al [9] reported that interocular differences in ocular aberrations and corneal asphericity affect binocular visual function and should be considered in refractive surgery. Therefore the pupil-enlargement phenomenon described in the current study also affects interocular difference, having important implications for refractive surgery.

As the wavefront aberrations increase under monocular viewing conditions, the larger pupil diameter would theoretically increase the retinal illuminance. This indicates that other factors may mitigate the effects of increased aberrations. Analyzing post-LASIK (with presumably higher wavefront aberrations) and non-LASIK groups, Boxer Wachler [8], found no differences in the improvement in contrast sensitivity and visual acuity from the binocular to monocular testing conditions. However, the optical aberrations were not reported in Boxer-Wachler's study and measurements of visual performance were tested under dim-lighting conditions unlike our study. Oshika et al. [26] reported that increased spherical aberration in pre and post-LASIK eyes with larger photopic pupils, predominately affected contrast sensitivity. These conflicting results indicate that further studies are required to determine the effect of pupil enlargement on subjective visual performance, such as low contrast visual acuity and mesopic contrast sensitivity. Further studies are also required to clarify the effect of hippus and accommodative miosis [27], and whether the pupil size changes with time as shown in Subject 2 (Figures 3B and 4), which may lead to inconsistent results during assessment of visual performance.

A limitation of the current study was that the pupillometer will slightly reduce the illuminance of the eye being tested. The values we obtained under photopic conditions were larger than those reported previously [28]. Likely, the pupil enlargement effect might have to



be considered as a function of the state of retinal adaptation in the occluded eye even under photopic conditions as retinal adaptation affects pupil size [29,30]. We did not incorporate the effects of retinal adaptation in the current study. We did not account for the change in



pupil center due changes in pupil size and the effect on the magnitude or pattern of higher order aberrations. Walsh reported that even for a 3 mm pupil diameter, shifts in the pupil center of 0.2 mm can change the MTF up to 50% at high spatial frequencies. The change in MTF would be greater, eyes with larger shifts in pupil centration from binocular to monocular conditions [31]. Further limitations of the current study include investigation of monochromatic aberrations, and small sample size, especially the lack of hyperopic eyes.

In conclusion, increased pupil diameter under monocular conditions increases higher optical aberrations, resulting in worse retinal image quality. In eyes with higher optical aberrations and pupil diameter this effect is likely enhanced. The outcomes from the current study show the importance of measuring pupil diameter under both binocular and monocular conditions, especially in eyes with larger optical aberrations. Practically, pupil diameter should be measured under binocular conditions.

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