Temporal Changes in Optical Quality of Air–Tear Film Interface at Anterior Cornea after Blink

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PURPOSE. To examine temporal changes in the optical quality of the air–tear film interface at the anterior cornea after a blink.

METHODS. Corneal aberrations were determined in fifteen healthy subjects at 1 second time intervals after a blink, up to a total elapsed time of 15 seconds. Corneal aberrations were obtained from corneal elevation maps measured using a Tomey TMS-2N topographer and custom software. All data were decomposed using Zernike polynomials to yield the root mean square (RMS) wavefront deviations, in micrometers, for two pupil diameters (3 and 7 mm).

RESULTS. Total wavefront aberration decreased slightly with time in the first few seconds after a blink for both pupil diameters, reaching a minimum after approximately 6 seconds. Thereafter aberrations increased steadily, exceeding the immediate postblink level after approximately 10 seconds.

CONCLUSIONS. In normal subjects, the contribution of the anterior cornea to the overall ocular aberration remains reasonably stable over the normal interblink interval (approximately 4 seconds) but rises to levels which could perceptibly degrade retinal image quality under circumstances where the interblink interval is increased to exceed 10 seconds, as may occur during the use of visual display screens or when performing difficult tasks. (Invest Ophthalmol Vis Sci. 2004;45:1752–1757) DOI: 10.1167/iovs.03-0839

The front surface of the precorneal tear film is the most anterior optical surface of the eye and hence the most powerful as it is associated with the largest change in refractive index. As a result, any local variation in tear film thickness and regularity will introduce significant additional aberrations into the optical system of the eye. Maintenance of a smooth, intact regularity will introduce significant additional aberrations into the optical system of the eye. Several clinical studies support the hypothesis that the increased aberrations consequent on tear film disruption may reduce retinal image quality.1–3 Other studies using videokeratography clearly illustrate the irregularities in the surface of the tear film which develop with time after a blink.4–12 Timberlake et al.13 were able to show that normal, low contrast, visual acuity was, on average, slightly reduced if blinking was suppressed, although much larger effects were observed with soft contact lens wearers, due to lens dehydration.

In an earlier study,8 an increase was found in total and corneal aberrations 20 seconds postblink compared with immediately after a blink. This was attributed to the increasingly irregular tear film. However, to our knowledge, no time-resolved measurements of optical aberrations of the anterior cornea during the first seconds after a blink have been published to date.

Thus the purpose of the present study was to investigate with good time resolution the pattern of changes of the corneal higher-order aberrations and their impact on the optical quality of the cornea during the first 15 seconds after a blink.

METHODS

Patients

Fifteen subjects, 13 men and 2 women, participated in this study. The study followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all patients after the nature and possible consequences of the study had been explained. All were emmetropes with a visual acuity of 20/20 or better and normal ocular health. Their ages ranged from 24 to 35 years (26 ± 1.7 years). Fluorescein tear breakup times as measured by standard clinical methods14 were normal, ranging from 8 to 15 seconds among subjects.

Corneal Aberrations from Corneal Topography

Topographic data were obtained with a Tomey TMS-2N (Tomey Corporation, Nagoya, Japan) instrument. During the initial setting up, measurements in each eye were repeated until a well-focused and aligned image was obtained. Following the procedure used in an earlier study,9 subjects were instructed to keep their eyelids open during the imaging capture. Topographic images were obtained at 1-second time intervals from 1 to 15 seconds after a blink. Mean pupil diameter during the measurements was 5.2 ± 0.63 mm (photopic conditions, 80 cd/m²). Only the left eye was used for the measurements. To avoid possible longer-term changes to the cornea and/or tear film from successive periods of nonblinking, the experiments on each individual were performed on 3 separate days to yield three sets of measurements. Corneal videokeratographic data were downloaded onto floppy disks in ASCII files, which contained information about corneal elevation, curvature, power, and position of the pupil. The tests were run in a controlled temperature (21 ± 2°C) and humidity (41 ± 3%) at the Instituto Oftalmológico de Alicante (Alicante, Spain).

Data Analysis

The videokeratographic data were fitted with Zernike polynomials up to the sixth order to determine aberration coefficients, from which the wavefront aberration function was reconstructed. The calculation of
corneal wavefront aberration was performed using the CT-View 5.0 software (Sarver & Associates, Inc, Merritt Island, FL) for two pupil diameters: 3- and 7-mm. The Zernike coefficients were used to calculate the total monochromatic, anterior corneal aberration, and the aberration contributed by spherical aberration and coma-like aberrations. Corneal wavefront aberrations were calculated relative to the pupil center instead of the vertex normal (videokeratoscope axis) since this is more relevant to visual acuity. The spot diagram corresponding to the corneal aberration was calculated. This showed the results of a geometric ray tracing for an object at infinity for an image plane corresponding to the minimum blur circle. The corneal Point Spread Function (PSF), which is defined as the light distribution in the image of a point source, was also calculated. The shape and width of the PSF depend on the levels of aberrations and the shape of the pupil, and include the effects of diffraction. Both the spot diagram and the PSF reveal how the corneal aberrations, considered alone, affect the final image. The actual retinal image will, of course, additionally depend on the contribution of the posterior cornea and the crystalline lens to the aberrations.

RESULTS

Wave Aberration Patterns, Spot Diagrams, and Point Spread Functions

Figure 1 shows an example of the corneal wavefront aberration contour plots at different times postblink (from 1 to 15 seconds) for an individual eye. Pupil diameter for the aberrations plot is 7 mm and the contour line step is 1 μm. Only higher-order (third to sixth) wave aberrations are shown: piston, prism, defocus, and astigmatism have been compensated by canceling the corresponding first- and second-order Zernike coefficients.

It is evident that the wave corneal wavefront aberration maps show a change in the number of contour lines as a function of the time postblink, reflecting a variation in the aberration. Over the first few seconds, there tends to be a reduction in the number of contour lines, indicating a reduction in the aberration. At around 6 to 8 seconds, the wavefront deviation is relatively flat, but as the postblink time increases further, the wavefront contours start to become increasingly numerous and irregular, reflecting a substantial increase in the aberrations.

Figure 2 shows, for a 7-mm pupil, the spot diagrams associated with the anterior corneal aberrations of Figure 1 at different times postblink (1 to 15 seconds). The spot diagram was obtained by geometric ray tracing, using the local slopes of the wave aberration. Only third- and higher-order aberrations were considered. Positive horizontal coordinates indicate temporal cornea for left eyes. The spot diagrams show that the image quality (directly related to the spread of the spots) changes as a function of the time postblink. In the first two seconds after the blink, the spots are relatively scattered but their concentration improves to give a minimal spread after approximately 6 seconds. Thereafter the spot diagram gradually broadens, as the wavefront aberrations increase.

The corresponding retinal PSFs (not illustrated), which include the effects of diffraction, showed a similar time variation. They confirmed the relatively poor optical quality of the anterior cornea of this eye immediately after a blink and finally at tear film break-up. Best contrast and minimal size of the PSF was obtained at approximately 6 seconds postblink.

Results were reasonably consistent across the three repeated runs on different days for each subject and between individual subjects, although a clear aberration minimum was not obtained on every run. Figure 3 shows the temporal changes in the total amount of higher-order (third to sixth) root-mean-square (RMS) wavefront aberration for a 7-mm pupil diameter, during three runs with the same subject as that illustrated in Figure 1.

Figure 3B shows the mean changes recorded during the three runs with each of the 15 subjects. When the time at which an aberration minimum occurred was plotted against the corresponding tear break-up time (Fig. 4), a reasonable degree of correlation was found (R = 0.63, P = 0.003), with the minimum occurring earlier for those subjects with shorter tear break-up times.

The total amounts of the higher-order (third to sixth) RMS wavefront aberration of the anterior cornea, averaged across all subjects, are plotted in Figure 5 as a function of the time after the blink, for 3- and 7-mm pupil diameters. From both graphs we can observe an initial improvement (lower values) and subsequent worsening (higher values) of the corneal wavefront aberrations in the first 15 seconds after a complete blink. The trend line for 3-mm pupil reached its minimum level, on average, at 6.2 ± 0.6 seconds after a blink and that for the 7-mm pupil at 6.1 ± 0.5 seconds.

For the temporal dynamic analysis, the mean and SD of the wavefront aberrations were calculated for each time after the blink. The RMS values shown in Figure 5 were fitted with a second-order polynomial equation using the least-squares fitting method (SigmaPlot, Version 8.0; SPSS Inc., Version 11.0.1, Chicago, IL). Statistical analysis was performed using the SPSS software package (SPSS Inc.). For evaluation of statistical significance, the analysis of variance ANOVA one-way test was

![Figure 1. Corneal wavefront aberration contour plots at different times postblink (eye #6). Contour line step, 1 μm; pupil diameter 7 mm.](image-url)

![Figure 2. Spot diagrams (1.18 x 1.18 mm) calculated at different times postblink (eye #6). Pupil diameter 7 mm.](image-url)
Immediately after the blink (9 to 13 seconds range did not differ from that obtained immediately after the blink). For a 7-mm pupil diameter, RMS values obtained in the first 5 seconds postblink were significantly higher than those immediately after the blink (P < 0.01). From 11 to 15 seconds postblink, RMS values were significantly higher than those immediately after the blink (P < 0.01). For a 3-mm pupil diameter, RMS values obtained at 9 and 10 seconds were comparable to that obtained immediately after the blink (P > 0.01). From 11 to 15 seconds postblink, RMS values were significantly higher than those immediately after the blink (P < 0.01). For a 7-mm pupil diameter, RMS values obtained in the 9 to 13 seconds range did not differ from that obtained immediately after the blink (P > 0.01). At 14 and 15 seconds postblink RMS values were significantly higher than those immediately after the blink (P < 0.01). For both pupil diameters there was a statistically significant reduction in the corneal wavefront aberration between immediately after the blink and the 5 to 8 seconds range, the minimum value occurring at 6 seconds. After 8 seconds, significance at different times postblink differed, depending on the pupil diameter. In both 3- and 7-mm pupils, corneal wavefront aberration values increased significantly at 15 seconds postblink compared to immediately after the blink. Thus the corneal wavefront aberration pattern revealed that after a blink, there is a reduction in corneal aberrations, a minimum value being reached at around 6 seconds. Aberrations then start to increase, first reaching the initial value (immediately after the blink) and then attaining still higher values at 15 seconds postblink. An alternative approach is to consider whether the data are better fitted by a second-order polynomial than by a linear trend. The squares of the Pearson product moment coefficients for linear fits to the 3- and 7-mm pupil data are R² = 0.48 and 0.39, respectively, whereas those for corresponding quadratic fits are R² = 0.88 and 0.87, so that the second-order fits are significantly better.

Spherical Aberration

Figure 5 shows mean values of the RMS spherical aberration (Z₂,0 and Z₅,0), for 3- and 7-mm pupil diameters, as a function of time postblink. Solid lines represent the best second-order polynomial trend equation. For both pupil diameters, there is an increase in spherical aberration after a blink. Over the 15-second observing period, the mean RMS spherical-aberration across all subjects increased from 0.012 µm to 0.044 µm for the 3-mm pupil, and from 0.185 µm to 0.532 µm, for the 7-mm pupil.

Coma-like Aberration

Figure 6 also illustrates mean values of the RMS coma-like aberration (Z₄,0 and Z₅,0), for 3- and 7-mm pupil diameters, as a function of time postblink. Dashed curves represent the best second-order polynomial fit equations to the RMS coma-like values. There is a reduction immediately after the blink, minimum values being reached at 5 to 7 seconds postblink, followed by a progressive increase up to the measured maximum value at 15 seconds postblink. This behavior differs from that observed for spherical aberration, which showed a progressively increasing trend postblink, with no minimum.

**DISCUSSION**

The present study supports the work of earlier authors in demonstrating that tear film dynamics can have an important impact on the higher-order aberrations of the anterior cornea and hence on those of the whole eye. The most striking finding is that, for normal subjects, the total aberrations pass through a minimum at approximately 6 seconds after the blink. This agrees well with several earlier studies on the time taken for the tear film to stabilize and with the high-speed videokerographic measurements of Németh et al. who found that the tear film reached its most regular state some 5 to 10 seconds after a blink.

Analysis of the wave aberration in terms of its individual Zernike components suggests that the observed behavior cannot be accounted for by changes in the rotationally-symmetric spherical aberration terms (Z₄,0 and Z₅,0), which tend to in-

**FIGURE 3.** Temporal changes in the higher-order (third to sixth) RMS wavefront aberration for a 7-mm pupil diameter; (A) three runs with same subject, (B) mean of three runs for each of 15 subjects used; P < 0.05 was regarded as statistically significant. Appropriate post-hoc Bonferroni correction for multiple comparisons was used.

ANOVA one-way tests revealed statistically significant differences in corneal wavefront aberrations versus time for both pupil diameters (3- and 7-mm, P < 0.0001). A Bonferroni test of multiple comparisons showed that values immediately after a blink differed from those obtained at 5 to 8 seconds interval postblink for both pupil diameters (P < 0.01). For a 3-mm pupil diameter, RMS values obtained at 9 and 10 seconds were comparable to that obtained immediately after the blink (P > 0.01). From 11 to 15 seconds postblink, RMS values were significantly higher than those immediately after the blink (P < 0.01). For a 7-mm pupil diameter, RMS values obtained in the 9 to 13 seconds range did not differ from that obtained immediately after the blink (P > 0.01). At 14 and 15 seconds postblink RMS values were significantly higher than those immediately after the blink (P < 0.01). For both pupil diameters there was a statistically significant reduction in the corneal wavefront aberration between immediately after the blink and the 5 to 8 seconds range, the minimum value occurring at 6 seconds. After 8 seconds, significance at different times postblink differed, depending on the pupil diameter. In both 3- and 7-mm pupils, corneal wavefront aberration values increased significantly at 15 seconds postblink compared to immediately after the blink. Thus the corneal wavefront aberration pattern revealed that after a blink, there is a reduction in corneal aberrations, a minimum value being reached at around 6 seconds. Aberrations then start to increase, first reaching the initial value (immediately after the blink) and then attaining still higher values at 15 seconds postblink. An alternative approach is to consider whether the data are better fitted by a second-order polynomial than by a linear trend. The squares of the Pearson product moment coefficients for linear fits to the 3- and 7-mm pupil data are R² = 0.48 and 0.39, respectively, whereas those for corresponding quadratic fits are R² = 0.88 and 0.87, so that the second-order fits are significantly better.

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**FIGURE 4.** Postblink time at which minimum total aberration occurred for a 7-mm pupil, as a function of the tear break-up time for each subject.
crease monotonically with postblink time. This is presumably because the greater rate of evaporation at the center of the palpebral aperture\textsuperscript{15} causes the tear film to thin more rapidly at the center than peripherally. The resultant progressive change in the shape of the air-tear film surface, from a prolate toward an oblate shape, is reflected in a change of spherical aberration toward more negative values (mean $Z_{ab} = -0.11 \mu m$ immediately after the blink and $-0.31 \mu m$ 15 seconds postblink).

It seems more reasonable to attribute the temporal minimum in the overall aberration to the changes in coma-like aberrations illustrated in Figure 6, together with analogous changes in some of the other aberrations which lack rotational symmetry. Such changes presumably result from such factors as the directional characteristics of lid movement, the effects of gravity on the tear movement, the uneven local rates of evaporation associated with the shape of the palpebral aperture, and, perhaps, dynamic change in the contour of the underlying cornea after lid pressure.\textsuperscript{11}

How serious are the effects of these levels of aberration and is it likely that they will cause perceptible effects on vision? With a 3-mm pupil, total monochromatic higher-order RMS aberration is generally $\lesssim 0.06 \mu m$, or about a tenth of a wavelength. This is close to the Marechal criterion for near diffraction-limited performance (wavefront aberration < fourteenth of a wavelength). Thus, since images are normally also degraded by longitudinal chromatic aberration, it seems unlikely that any perceptible changes in the visual image will normally be noticed when the pupil is small. This agrees with the results of Ridder and Tomlinson,\textsuperscript{16} who found no systematic change in photopic contrast sensitivity over a time interval
0.1 to 3.2 seconds postblink (blink-induced suppression occurs for the immediate 0.1 second postblink). Tutt et al.\(^5\) whose measurements had much poorer time resolution, found no consistent change in contrast sensitivity in the first 10 seconds after a blink, although a noticeable drop occurred after 15 seconds.

The typical interblink interval in normal patients is around 4 to 5 seconds.\(^{17}\) It may, however, be extended to 10 to 20 seconds when “gazing” during difficult tasks,\(^{18}\) higher-speed driving,\(^{19}\) or working with visual displays,\(^{20,21}\) when the increased levels of aberration observed during the present study may well become relevant.

The time course of the aberrational changes observed is likely to be accelerated in dry-eye patients or those with other ocular surface diseases. In a comparison of the overall higher-order ocular aberrations in the eyes of a group of dry-eye patients (mean and SD of tear break-up time 3.8 ± 1.1 seconds) and a group of normals (9.7 ± 3.2 seconds), Montés-Micó et al.\(^{22,23}\) found that third and fourth order aberrations 5 to 10 seconds after a blink were some 2.5× greater for the dry-eye patients. It would clearly be of interest to attempt to correlate wavefront aberration measurements of the present type with the results of other methods for studying the dynamics of the normal and dry-eye tear film, for example, interferometry.\(^{24,25}\)

Tear film-induced changes in the aberration contributed by the anterior cornea have obvious relevance to discussions on the extent to which corneal aberrations are balanced by the aberrations of the rest of the eye to yield reduced values of

![Figure 6. Root-mean-square wavefront error (RMS) for spherical (Z<sub>0</sub>, and Z<sub>0</sub>; □) and coma-like aberration (Z<sub>i</sub> and Z<sub>i</sub>; ○) for a 3- (above) and 7-mm (below) pupil diameters as a function of time (seconds) postblink. Lines represent the best polynomial trend equation (quadratic) for spherical (solid) and coma-like aberrations (dashed). Error bars have been omitted for clarity. Typical values of the SD are approximately 0.006 and 0.03 for 3- and 7-mm pupil diameters, respectively.](https://joj.arvojournals.org/03/27/2019)
overall aberration. Clearly, exact balancing cannot be achieved if the corneal contribution is variable. While a good degree of compensation of corneal aberration by lenticular aberration has been claimed by some authors, it is difficult to see how any controlled compensatory growth mechanism, analogous to that thought to be involved in emmetropization, could function if one of its inputs was characterized by short-term variability.

Finally the present results suggest, like the data of Buehren et al., that the topography of the air-tear film surface can change significantly over the time interval during which videokeratoscope images are typically acquired (up to around 12 seconds). This suggests that, for the most consistent results, efforts should normally be made to complete videokeratography within the time span of the normal interblink interval (approximately 4 to 5 seconds, see also Nemeth et al.12).

The aberration introduced by the air-tear film interface changes with time. It appears to be minimal approximately 6 seconds after a blink. Under normal photopic conditions, when the pupil diameter is modest, and the interblink interval is short (approximately 4 seconds), it appears unlikely that the changes in aberration will produce detectable effects on vision. The increasing amounts of aberration observed after 10 seconds and with larger pupils may, however, lead to perceptible degradation in vision in circumstances, which lead to an increase in interblink interval or for patients with naturally large pupils.

References