Postblink Changes in the Ocular Modulation Transfer Function Measured by a Double-Pass Method

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Purpose. To examine the temporal changes in the modulation transfer function (MTF) of the eye after a blink.

Methods. The distance MTF of a 5-mm pupil was derived from double-pass retinal images in 20 healthy young subjects at various intervals after a blink (1 second up to 15 seconds). Such measurements include the effects of wavefront aberration, scattered light, and errors in focus and are thus more relevant to real life than are estimates of MTF based on wavefront errors alone.

Results. Optimal MTF by a variety of criteria was found some 6 seconds after a blink.

Conclusions. Inclusion of the effects of stray light and errors of focus does not affect the finding that optimal retinal image quality occurs some time after a blink. It does not appear that a loss in optical quality is the trigger of normal blinking. (*Invest Ophthalmol Vis Sci.* 2005;46:4468–4473) DOI:10.1167/iovs.05-0609

The tear film is the most anterior optical element of the eye. The large refractive index change across the air–tear interface means that any variation in the regularity of this surface caused by local changes in tear-film thickness can significantly alter the optical aberrations of the eye and hence the quality of the retinal image.[1,2] Because the overall thickness of the tear film is usually accepted to be approximately 10 μm[3,4] (although lesser thicknesses have been suggested[5]), substantial variations in optical path in wavelength terms across its surface are, in principle, possible. The basic, normal, dynamic changes in the tear film after its deposition during a blink have been modeled by Wong et al.,[6] who show that they result from a complex interplay between factors such as lid forces, the structure of the film, its viscosity and surface tension,[7] and forces due to the tear menisci at the lids. Experimental studies have given more detailed insights into the local variations across the surface of the film.[8–10] Tear film changes are accelerated in patients with dry eye.[11]

Several experimental studies have confirmed that tear film changes influence ocular aberrations.[12–20] It appears that the wavefront aberrations associated with both the anterior cornea and the whole eye pass through a minimum a few seconds after a blink. This occurs after approximately 6 seconds in normal eyes and 4 seconds in patients with dry eye.[16–20] It is suggested that, after a blink, there is initially a fairly rapid decrease in the aberrations associated with the anterior surface of the tear film, as the tear film stabilizes and becomes smoother. This is followed by a gradual increase, as evaporation and other effects[3,4] cause the tear film to become more irregular and to start to break up.[16–20]

If the wavefront aberration of the eye is known, it is, in principle, possible to calculate such descriptors of retinal image quality as the point-spread function (PSF) and optical transfer function (OTF) by using Fourier methods.[21] A problem, however, is that other factors besides higher-order wavefront aberration can contribute to the time-dependent changes in retinal image quality. In particular, it is well known that local small-scale variations in anterior surface regularity, which are not adequately described by wavefront measurements, cause marked increases in forward light scattering with time, particularly after tear break-up starts to occur. This increased scattering is obvious in, for example, the decrease in clarity of the spot images given by Hartmann-Shack aberrometers[12,13,17] and tend to broaden and depress the retinal PSF and reduce modulation transfer. Any scattering from other sources—for example, the bulk cornea, lens, and retina—produces similar effects, although these do not change over the interblink interval. In general, estimates of retinal image quality based on wavefront aberration alone may be too optimistic[22] and, if anterior corneal scattering increases at a different rate than wavefront aberration, the postblink time at which optimal image quality is obtained may be affected. A further relevant factor under real-life conditions, even in emmetropic or corrected eyes, is the possible presence of lags and leads in accommodation. The associated defocus blur (second-order aberration) on the retina reduces the relative importance of tear-induced changes in higher-order wavefront aberration.

In the present study, the changes in retinal image quality with time after a blink were measured directly under conditions of distance vision with free accommodation, by the well-established double-pass technique,[23,24] to record the retinal point-spread function (PSF). The results are compared with those of studies based on wavefront aberration alone.

Methods

Subjects

Twenty patients, 15 men and 5 women, participated in this study. Their ages ranged from 22 to 32 years (mean, 26.6 ± 3.1). All were emmetropes with a visual acuity of 20/20 or better and normal ocular health. Fluorescein tear break-up times (TBUTs) as measured by standard clinical methods[25] were normal, ranging from 8 to 15 seconds among subjects. Mean TBUT was 10.4 ± 1.9 seconds and mean interblink interval was 5.7 ± 0.5 seconds. The study followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all

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patients after the nature and possible consequences of the study had been explained.

MTF Measurement

The ocular MTF (the modulus of the OTF) was evaluated with a commercial system (Optical Quality Analysis System [OQAS]; Visiometrics, Terrassa, Spain). The instrument is based on the double-pass technique, which was developed to perform an objective optical quality measurement of the eye.[23,24] The image of a monochromatic point source (780 nm) is first formed on the retina. The reflected light passes back through the eye, and the double-pass PSF in air is recorded by a low-noise digital camera. In the OQAS instrument, the entrance and exit pupils used to form the initial and final PSFs differ. The entrance pupil is small enough (1.5 mm) for the initial PSF to be diffraction limited, because ocular aberrations are negligible for small pupils.[26] In contrast, a larger diameter (5 mm in the present study) is used for the exit pupil, so that the ocular aberrations affect the second stage of the formation of the double-pass PSF. Thus, when the modulus of the two-dimensional Fourier transform of the PSF is derived to yield the double-pass MTF, this function can be corrected for the known, monochromatic MTF of the first, diffraction-limited stage of image formation, to give the MTF due only to the second stage of the imaging processes, which gives the single-pass MTF of the eye for a pupil diameter equal to that of the exit pupil of the instrument. The advantage of this method is that it yields information on the asymmetric as well as the symmetric aberrations of the eye.[27,28] Its disadvantage is that measurements cannot be made at higher spatial frequencies than the cut-off imposed by the 1.5-mm entrance pupil (34 cyc/deg). It is also necessary to assume an absence of scattering from lens sutures, the retina or other structures.[29] For the purposes of the present study, the mean one-dimensional MTF was calculated as the average over all orientations of the two-dimensional MTF for the 5-mm pupil exit pupil used. It should be noted that averaging the MTF over all orientations leads to a loss in information on the presence of asymmetric aberrations like coma and astigmatism and tends to reduce intersubject differences associated with asymmetric aberrations. It was felt that this was justified in view of the greater ease in comparing effects at different times (described later).

Experimental Procedure

The subject's head was stabilized on a three-dimensional translating stage. The subject was instructed to blink three or four times and fixate on a distant image (a high-contrast Snellen E against a red background) created by the double-pass system while keeping the eyes wide open as long as possible. Subjects used natural pupils and were not under cycloplegia. However, an artificial pupil in the apparatus restricted the effective measurement pupil to 5 mm, the diameter of the natural pupil always being larger than this. During the period of nonblinking, 15 images were captured with the apparatus. The first was taken immediately after the blink (nominally $t = 0$) and the others at 1-second time intervals from 1 to 15 seconds after a blink. Only the left eye was used for the measurements, the other eye being occluded. To avoid possible longer-term changes in the cornea and/or tear film from successive periods of nonblinking, the experiments on each individual were performed on five separate days to yield five sets of measurements. The tests were run in a room with controlled temperature (23 ± 1°C) and humidity (40% ± 2%).

RESULTS

Figure 1 shows the changes in mean MTF of a 5-mm pupil (all subjects, all trials, and all orientations) as a function of time after a blink. The SD in modulation transfer at any time or spatial frequency was typically approximately 10% of the mean. Whereas there was little change in modulation transfer at lower spatial frequencies (e.g., 5 cyc/deg) with time, modulation transfer at higher spatial frequencies varied substantially, with optimal levels being reached approximately 6 seconds after a blink.

This behavior is illustrated more clearly in Figure 2, which plots the value of mean modulation transfer at a series of spatial frequencies as a function of time after a blink. Note that a high-contrast 30-cyc/deg grating is only likely to be visible over a limited period of ~6 seconds after a blink.

DISCUSSION

Before discussing the variations in MTF with time in more detail, it is reasonable to ask how the present optimal mean MTFs for a 5-mm pupil, which are found approximately 6 seconds after a blink, compare with those in the literature, particularly those based on wavefront aberration alone. Figure 3 makes this comparison. The MTF by the method of Artal[30] is based on the double-pass technique in monochromatic light and hence includes the effects of intraocular scattered light, while those of Walsh and Charman[31] and Liang and Williams[32] are derived from wavefront data alone and hence would be expected to be a little higher, due to the absence of the contrast-degrading effects of scattered light. All these earlier data were obtained with carefully corrected eyes under cycloplegia, so that errors of focus were minimized. Although the times after a blink at which these earlier data were obtained were not specified, it seems reasonable to assume that they represent near-optimal optical performance.

It can be seen that our optimal double-pass MTF was lower than all the others. It was also slightly more irregular. We attribute these effects mainly to a combination of errors of focus associated with accommodative lead for many of our subjects when viewing the distant target of our OQAS double-pass instrument under natural viewing conditions and the longitudinal chromatic aberration between the wavelengths of the red visible accommodation target and the infrared wavelength (780 nm) at which the PSFs were measured. The signs of these defocus effects are opposite one another. Although accommodative leads (excesses in ocular power) for a target at infinity vary between subjects, at photopic levels, they typically amount to approximately 0.50 D.[33] In contrast, the reduction in apparent ocular power associated with the ocular longitudinal chromatic aberration and the fact that infrared is reflected from deeper retinal–choroidal layers than the receptors probably also amounts to approximately 0.5 D for a wavelength of approximately 780 nm,[34] so that there is an approximate balance between the two defocus effects. The normal fluctuations in accommodation, over a range of approximately 0.5 D,[35] will be superimposed on the mean defocus and cause variations in individual sampled MTFs, even in the absence of changes in higher-order aberration. Last, there may be some residual uncorrected second-order spherical and cylindrical wavefront errors in our "emmetropic" subjects, whereas second-order aberrations have been removed from the wavefront aberration-based MTFs in Figure 3. Higher-order aberrations are essentially the same in visible and the infrared[34] when expressed in micrometers, but the same wavefront errors will have less impact in the infrared because the wavelength is longer. In contrast, image-degrading light-scattering within the retina and choroid may be higher at the longer wavelength, so that overall the MTF measured in the near infrared would not be expected to differ greatly from that which would be measured if visible light were to be used. An error of focus of approximately 0.25 D or less would be sufficient to explain the discrepancy between our optimal MTF and that in the earlier work.[36] Finally, we note that that the use of the small (1.5 mm)

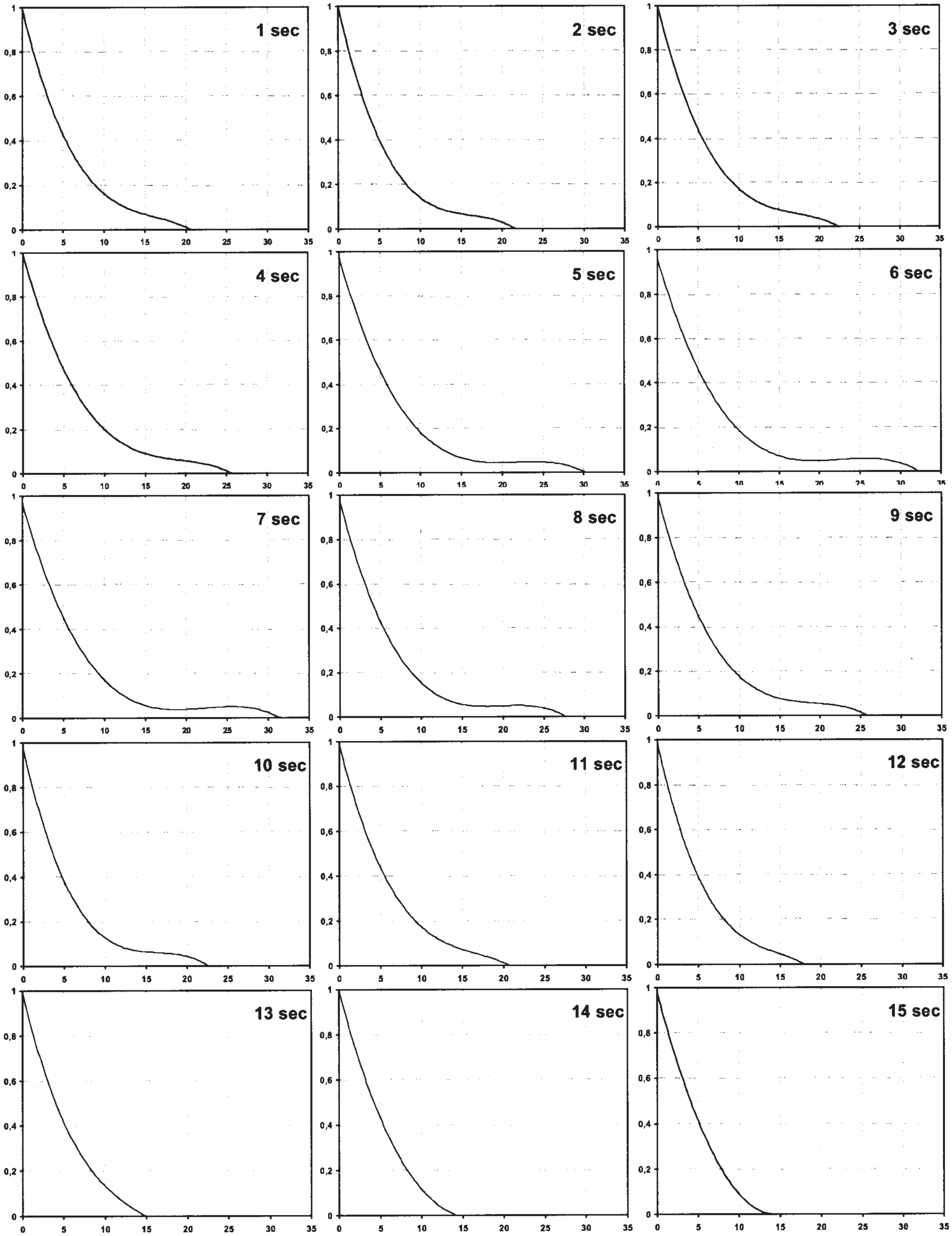

FIGURE 1. Calculated MTFs at each second post-blink for all subjects evaluated. Radial projection, averaged over all orientations, of the two-dimensional MTF (*y*-axis) versus spatial frequency (*x*-axis in cycles per degree).

entrance pupil in our equipment and a wavelength of 780-nm limits spatial frequencies reaching the retina to a maximum of approximately 35 cyc/deg, so that we cannot make measurements at spatial frequencies higher than this; however, this effect does not explain our comparatively low readings at spatial frequencies of approximately 10 cyc/deg.

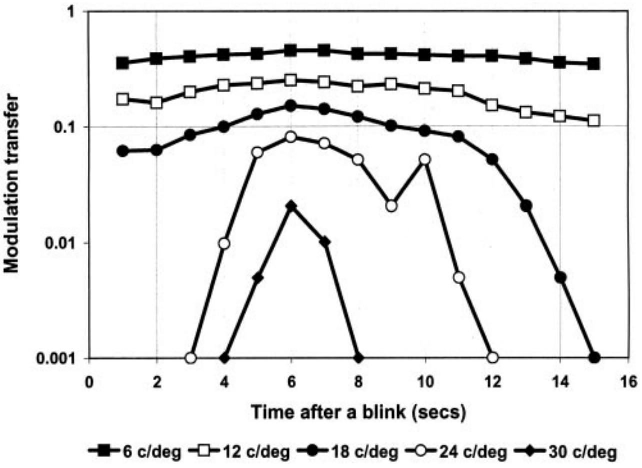

FIGURE 2. Mean MTF at fixed spatial frequency as a function of time after a blink (5 mm pupil).

If we now consider the postblink changes in MTF recorded in the present experiment, Figure 2 suggests strongly that, if high spatial frequencies are important, optical performance is optimal after approximately 6 seconds. It is, however, of interest to use other performance criteria to see whether they lead to the same conclusion. A large number of MTF-based, single-figure performance metrics have been suggested in the literature.[37] We have chosen to use the following: the cut-off frequency at which the mean MTF falls to zero; the visual high-contrast cut-off frequency at which the MTF intersects the neural contrast threshold curve; the area under the MTF; the area between the MTF and the neural contrast threshold; the volume under the two-dimensional MTF (which relates to the Strehl ratio[2]); and the volume between the two-dimensional MTF and the corresponding two-dimensional neural threshold (which relates to the visual Strehl ratio[37]). Objective refraction based on finding the correction that maximizes the volume under the MTF has been shown to correlate well with subjective refraction.[38] The results of the six image metrics as a function of time after a blink are shown in Figure 4. The neural contrast threshold used, which is plotted in Figure 3, is that appropriate to the luminance level that typically leads to a 5-mm natural pupil and gives a retinal illuminance of 130 trolands.[39,40]

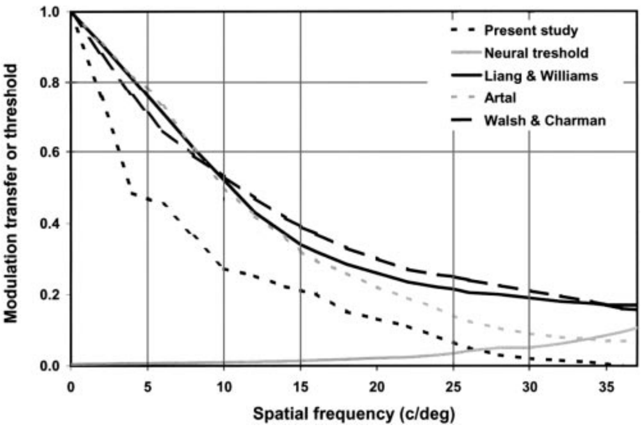

FIGURE 3. Comparison of MTFs with 5-mm pupils and the neural contrast threshold appropriate to this natural pupil size (found for a retinal illuminance of approximately 130 trolands, *gray curve*). The present data are the optimal MTF found approximately 6 seconds after a blink (780 nm). Other curves are from Artal[30] (double-pass method under cycloplegia with optimal correction at 633 nm); Walsh and Charman[3] (based on wavefront aberration data alone, 555 nm); and Liang and Williams[32] (based on wavefront aberration data alone, 633 nm).

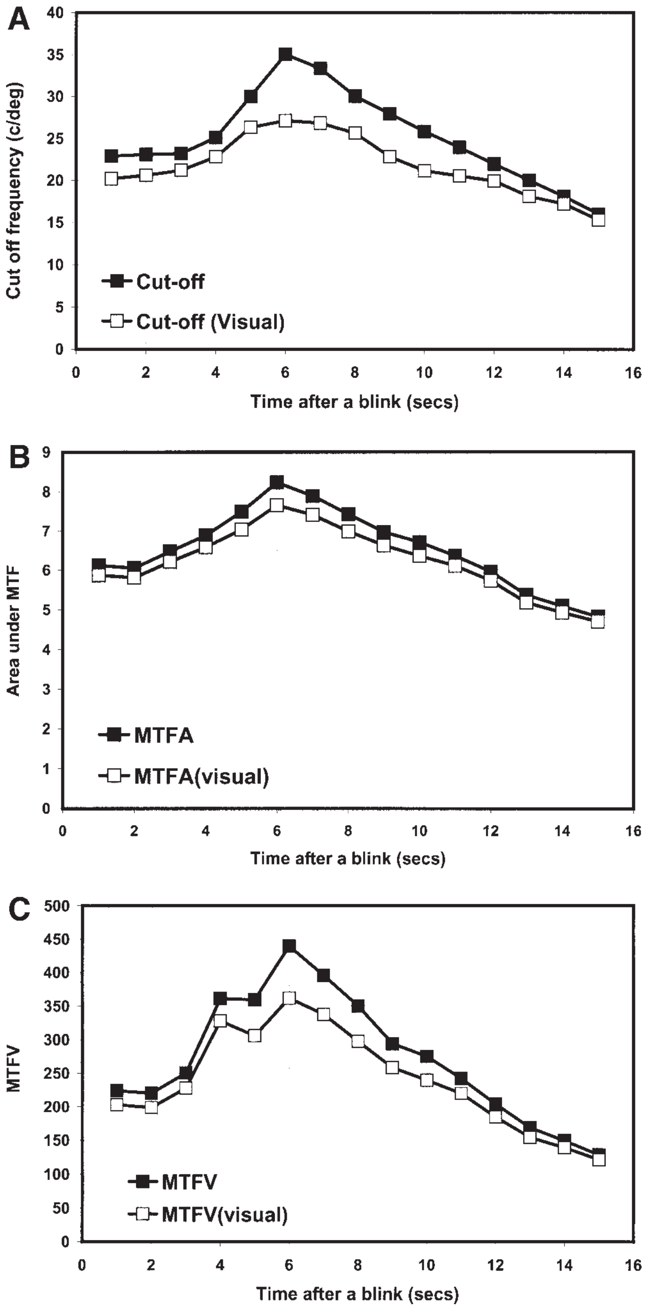

FIGURE 4. MTF metrics: cutoffs for MTF alone and MTF with neural contrast threshold (**A**), area under MTF and between MTF and neural threshold (**B**), and volume under MTF and between MTF and neural threshold (**C**).

It can be seen that all the performance measures peaked at approximately 5 to 6 seconds. The inclusion of neural as opposed to purely optical effects may tend to move the peak performance to slightly shorter times, presumably because it reduces the importance of modulation transfer at high spatial frequencies. In general, though, it appears that assessing optical performance by direct measurement of the retinal MTF leads to the same conclusion as was reached on the basis of wavefront measurements[16,17]—that optical performance in normal subjects is best some 6 seconds or so after a blink.

This result is perhaps not surprising, in that marked increases in light scattering from the eye's anterior surface would be expected to arise only after the tear film has started to break up, which occurred at an average of approximately 10 seconds in our subjects. Before this time, dynamic changes in both the wavefront aberration and the single-pass MTF are caused mainly by aberration changes associated with the local alterations in the thickness of the still-unbroken tear layer although, as noted earlier, the MTF is additionally degraded by time-invariant intraocular scattering and by focus errors. Note too that we cannot exclude the possibility that lid pressure during blinking has some effect on corneal contour and that the contour changes during the interval between blinks to produce local changes in optical path that are independent of tear film changes. Buehren et al.[41] have interpreted their videokeratoscope data in terms of effects of this kind, and their results suggest that the upper and lower areas of a 5-mm pupil may be affected.

The results of this study therefore support those of earlier work based purely on wavefront aberration measurements. Optimal optical performance in normal subjects occurs some 5 to 6 seconds after a blink. If indeed optical quality continues to improve over this timescale, it may be wondered why blink intervals are usually comparable to or shorter than this (normal blink intervals were around 6 seconds in our subjects). Our results provide no evidence that, in normal subjects, blinking is delayed until tear film break-up starts within the corneal area corresponding to that of the pupil. The discomfort caused by spot-wise drying of the precorneal tear film has been suggested to be an initiating factor for blinking in some normal persons and patients with dry eye.[42] The present results imply that most blinking is not triggered by any detectable deterioration in the retinal image (as is, of course, also evidenced by the fact that blink rates are similar in darkness), and it may be that the local dry spots involved in the initiation of some blinks are usually located in the peripheral cornea,[42] where they have no impact on axial image quality. Another possible factor in blink initiation is that blinking may also be an unconscious part of the mechanism to correct for slow drifts in fixation, accommodation and convergence. The basic blink rate appears to be a characteristic of the individual, although it can, of course, be affected by a variety of external stimuli, such as stress or task difficulty.[43–45]

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