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MEASUREMENT OF THE DYNAMIC ABERRATIONS INTRODUCED BY THE TEAR FILM IN THE HUMAN EYE USING A CURVATURE SENSOR FOR THE OPTIMIZATION OF RETINAL IMAGING WITH ADAPTIVE OPTICS

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Abstract. The dynamic topography of the tear film in the human eye is measured using a curvature sensor. The time series of topographies obtained are used to determine the contribution of the tear film to the overall aberrations of the human eye, giving us a better understanding of ocular aberrations. An overview of the optical arrangement is presented together with the evolution with time of the wavefront transmitted through the tear film, the change in RMS wavefront error produced and the variation of individual Zernike components. The impact on ophthalmic adaptive optics is discussed.

1 Introduction

The static low order aberrations of the human eye have been studied and corrected for centuries, however it has been only recently that the dynamic aberrations of the eye have been measured. In the quest for ever higher resolution when imaging the retina or performing vision experiments, it was necessary to correct also for these changing aberrations. For this reason, the technique which was used by astronomers to correct for the varying aberrations of the turbulent atmosphere when imaging with ground based telescopes, namely adaptive optics, looked just as promising in ophthalmology. The transfer of technology from astronomy to ophthalmology soon gave a number of adaptive optics systems to image the retina or to investigate vision, such as those described by Liang *et al.* (1997), Glanc *et al.* (2004) and Diaz-Santana *et al.* (2003).

However, to take the analogy between astronomy and ophthalmology further, whereas the atmospheric aberrations are well known and statistical models exist to simulate them, very little is known about the ocular aberrations. As ophthalmic

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adaptive optics systems strive to achieve better correction, a better knowledge of the aberrations they are aiming to correct will be highly beneficial.

Hofer *et al.* (2001) have suggested several causes for the dynamic aberrations of the eye. These include the involuntary ocular movements and micro-fluctuations of the crystalline lens, both mechanisms which are essential in the visual process, the pulsation of the retina and the change in structure of the tear film. This work concentrates solely on the latter of these issues.

The tear film in the human eye is a layer approximately 10μm thick made up mostly of water. Its biological purposes include the protection of the cornea from external particles, the transfer of oxygen, nutrients, antibacterial proteins and waste products to and from the avascular cornea and lubrication between the eye lids and the corneal surface. Optically, the tear film offers the first optical surface of the eye which, because of its large curvature and high refractive index step, is the most powerful surface in the eye's optics. Furthermore, the liquid nature of the tear film means that due to the effects of eye movements, pressure exerted by the eye lids and evaporation, this surface is not static, and hence the aberrations it introduces to transmitted wavefronts are also dynamic.

In this work, the aberrations introduced by the tear film are obtained from the measurement of the dynamic tear film topography using an optical system based on the principle of curvature sensing.

2 Measuring the tear film dynamic aberrations

The optical system used is illustrated schematically in Fig. 1 (Koechlin 2003; Gruppetta *et al.* 2005). Incoherent illumination illuminates the cornea such that the light incident on the cornea has the same curvature as the average corneal curvature. The intensity of the reflected light is measured using 2 CCD cameras, each conjugate to a defocused corneal plane, one having positive and the other negative defocus. The difference of these intensity signals is then used to reconstruct the wavefront following the method described by Roddier & Roddier (1991). This measured wavefront represents the tear film topography. The optical setup and reconstruction method used is described in detail in Gruppetta *et al.* (2005).

Data was collected for 14 subjects; they were asked to place their heads on an appropriate head and chin rest and to place their eyes on the optical axis of the system using translation stages and following a specific procedure. Once this was done, a series of intensity measurements from both CCD cameras were recorded at 22Hz, and the corresponding tear film topographies could be calculated.

Films were obtained showing the progression of the aberrated wavefronts due to the tear film. Figure 2 shows the evolution of the root-mean-square (RMS) wavefront error for typical series acquired following a blink. In Fig. 2(b), the dashed line represents break up of the tear film when dry patches start to form and grow. The RMS wavefront error increases steadily once tear film break up occurs and this will inevitably happen if an eye is refrained from blinking, as in many ophthalmic instruments. In Fig. 2(c) we can compare the evolution of the tear film aberrations for the same subject with and without soft contact lenses

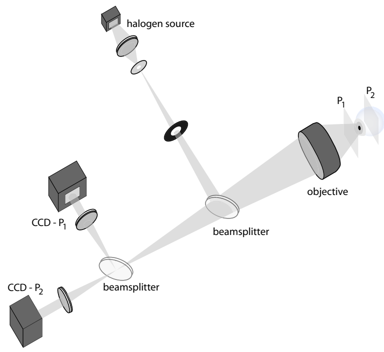

Fig. 1. Schematic diagram of the optical setup

worn. The overall aberrations as well as the amount of variation is larger when the contact lens is worn.

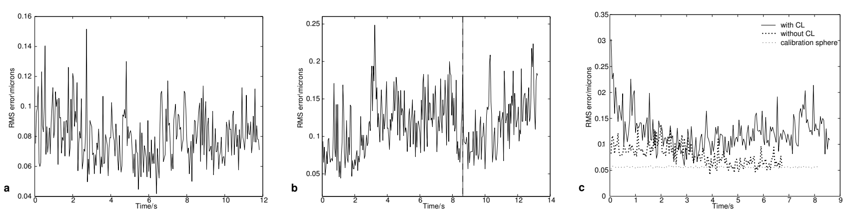

Fig. 2. Typical RMS wavefront error evolution. (a) Subject 2. (b) Subject 11; the dashed line indicates break up in the tear film. (c) Subject 6 with (solid line) and without (thick dotted) contact lens. The RMS wavefront error for a static calibration surface is also shown (light dotted).

The aberrated wavefronts due to the tear film were decomposed into their constituent Zernike terms in order to analyse whether certain orders and terms contribute more strongly than others. The histogram in Fig 3 shows the average Zernike coefficient over all frames in each series and all series collected. It can be noticed that the fourth order Zernike terms contribute significantly more than other orders. Furthermore, the positive azimuth orders which represent aberrations with vertical symmetry have a more significant contribution than the negative azimuth orders. This can be seen for example with term $Z^2{}_4$ which is 84% larger than $Z^{-2}{}_4$, and $Z^4{}_4$ which is 48% larger than $Z^{-4}{}_4$. This asymmetry is explicable due to the continuous pressure exerted in the vertical direction by the upper and lower eye lids.

Finally, the power spectra of the RMS wavefront error evolution were also computed. Figure 4 shows a typical example showing that the most significant contributions come from the low frequencies, typically below 2Hz, and that the contribution of higher frequencies decreases progressively.

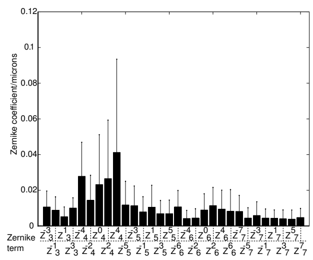

Fig. 3. Values of individual Zernike coefficients averaged over all the data.

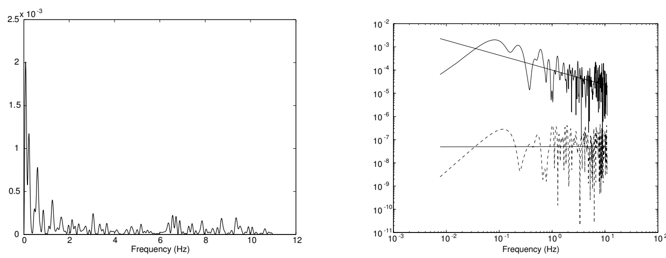

Fig. 4. Typical power spectrum plotted on linear axis (left) and logarithmic axis (right). Also shown is the power spectrum obtained for a static calibration surface (dashed).

3 Conclusion

The study of the dynamic tear film aberrations is essential in obtaining a better knowledge of the overall ocular aberrations. Such knowledge is paramount in designing future generations of adaptive optics systems since they will serve as a guide in choosing the appropriate wavefront sensors and corrective devices which perform best for the aberrations present in the eye. Measuring the tear film aberrations and aberrations generated by other layers within the eye might also lead to multi-conjugate adaptive optics for the eye.

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