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Three-Dimensional Analysis of Corneal Image Forming Properties: A Monocular Diplopia Example

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Abstract

The method presented displays cross-sectional slices of image planes produced by ray tracing an entire cornea. The diplopia example shows quantitative agreement with psychophysical measurements.

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Introduction:

Corneal topography methods of representing the image-forming properties of the cornea include, but are not limited to, refractive error, wavefront error and irregularity mapping. Additional information about potential image quality is provided through topographic indices of surface regularity, irregularity, asymmetry, shape factor or predicted acuity.[2,6] Generally, corneal maps provide a graphic display of the surface which can be used in conjunction with the various indices to draw conclusions about the potential vision of a particular cornea. Another way to determine the potential image quality is to ray trace incoming parallel light and analyze the resultant coherence of rays at the retinal plane. Ray tracing is a powerful tool for the determination of the point spread function and aberrations of the cornea.[3,5,7,8] The purpose of this study was to develop a method to visualize what transpires when light passes through corneas with various refractive and shape abnormalities and improve the analysis of the quality of focus at the retina.

Methods:

Data files of subjects with monocular diplopia, photorefractive keratotomy, radial keratotomy, and keratoconus were extracted from the EyeSys 2000 and Humphrey MasterVue Topographers. The data were reanalyzed using the Berkeley Topography Algorithm providing a surface output of the cornea in terms of x, y and z coordinates and the surface normals.[4] Using Matlab, a ray tracing program was developed which refracts and follows incoming parallel light through the cornea and at any given distance provides a cross-sectional slice of the ray bundle as it approaches or passes through the retinal plane.

The program allows for input of corrective cylinder and pupil size. Spherical correction and crystalline lens power were not included for the purposes of this study, therefore the "retinal plane" values in the examples exceed normal axial length. The output of our process is a "movie-like" visualization of the spatial location of refracted rays in sequential planes. The plane corresponding to the retinal plane is captured and analyzed in terms of coherence of focus. Additional mapping capabilities include a combination of the planar slices into a 3-dimensional representation of the refracted light bundle.

Results:

A representative case of monocular diplopia is used here for illustration of our results. The figures are selected from the series of cross-sectional slices of the refracted rays and each represent an area of 0.8 by 0.8 mm square centered and perpendicular to the corneal axis. The distance from the cornea to each plane is given by the f value displayed. The first two figures depict the incoming rays prior to the introduction of a correcting cylinder. Clearly there are two developing foci. At a distance of 26.5 mm from the cornea, the top image is in focus vertically (Fig 1). At f = 27mm, the bottom image has better vertical focus and the top image is beginning to be blurred vertically (Fig 2).

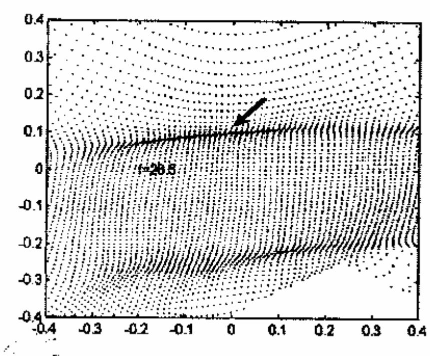

Fig 1 Cross-sectional slice showing the beginning of the interval of Sturm for the main image formed by the cornea

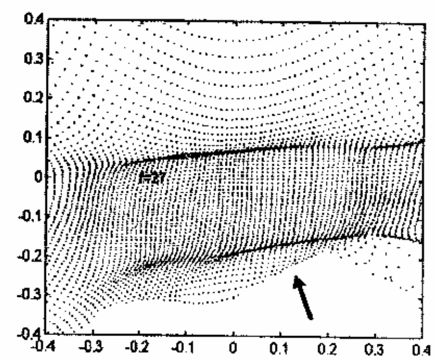

Fig 2 One-half millimeter downstream toward the retina, the beginning of the interval of Sturm corresponding to the ghost image rays

When the correcting Jackson cross cylinder specified by keratometry for each eye is applied, one obtains Figure 3 for the monocular diplopia eye and Figure 4 for the subject's normal eye.

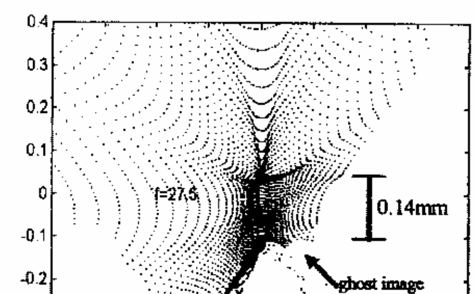

Fig 3 The retinal image plane of the monocular diplopic right eye. Correcting cylinder in place

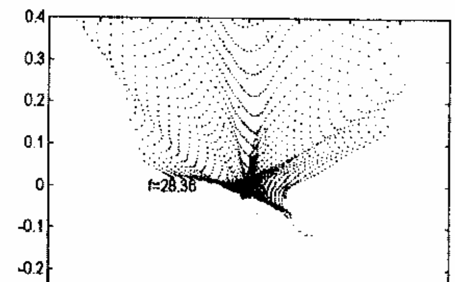

Fig 4 The retinal image plane of the normal left eye. Correcting cylinder in place

More rays contribute to the upper part of the graph since the initial corneal topography map included more data points for the lower cornea (upper points are often lost due to shadowing by eyelashes or the upper lid). To interpret the output in terms of retinal location, the linear distance between any features of the raytracing output can be read directly off the graph. For example, at f = 27.5 in figure 3, the distance of the center of mass of the main focus to the center of mass of the second focus is about 0.14 mm (140μm). The subject is known to have a diplopic image subjectively 0.8^{Δ} above the main focus of her right eye. This translates to 137μm on the retina. The ray tracing results (scale in mm) agree with the subject's localization of the second image.

Another feature of the program is the ability to modify pupil size in order to evaluate the quality of the retinal image under various lighting conditions. This is especially useful for evaluating post-refractive surgery corneas.[1] For all previous figures a large pupil size (7 mm diameter) was chosen such that all corneal points available from the map contribute to the image. Reduction in pupil size to 4 mm diameter attenuates the spurious rays and allows further interpretation of the image quality (Fig 5).

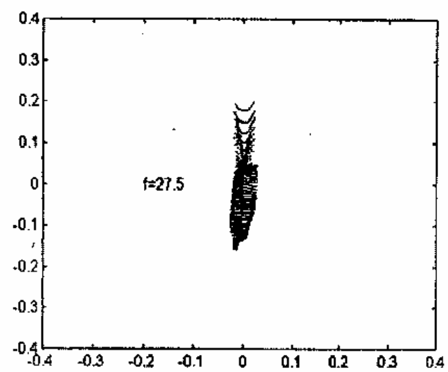

Fig 5 Effect of reduced pupil size on spurious image rays. Further reduction would eliminate the ghost image.

Discussion:

The agreement between the output of our method and the psychophysical localization of a diplopic image by the subject is evidence of the power of this approach to displaying corneal image forming properties. The qualitative nature of the display shows graphically the corneal rays contributing to the retinal image versus those not contributing to the retinal image. Spurious rays lead to decreased visual performance in terms of low contrast acuity and glare disability, especially in low light, large pupil conditions. The improvement in image quality with reduction in pupil size is evident in the comparison of figures 3 and 5. We feel, therefore, that this form of retinal image quality mapping has clinical potential as a tool for the prediction of visual performance. Incorporating spherical correction and lens power values in the future will improve the absolute positioning of the retinal plane, but the spherical correction is not anticipated to change the qualitative and quantitative values of multiple foci. The aberrations of images formed by the cornea may be affected (positively or negatively), however, by the inclusion of the spherical aberration effect of the lens. The effect of this factor on the predictions of our program remains to be investigated. Further work is also required to match the predicted image quality with the actual visual performance of a large variety patients on a multiplicity of tasks.

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