Corneal Asphericity and Retinal Image Quality: 
A Case Study and Simulations

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ABSTRACT

Purpose
The optical quality of retinal images is dependent on the refracting elements of the eye including the nominally aspheric cornea and crystalline lens. This paper presents a retrospective theoretical analysis of the impact of corneal asphericity on the quality of retinal images. Clinical data are from the VISX, Incorporated CustomVue™ IDE.

Method
Topography, contrast sensitivity, and visual acuity data were collected from 278 myopic eyes before and after wavefront-guided laser surgery. The measured corneal surface of each eye was fitted to a conic, and a Q-value was computed for a 5.5 mm pupil. A model eye was employed to simulate various amounts of optical asphericity.

Results
Preoperatively, most corneas exhibited negative conic shape constants. Postoperatively, corneas were about equally divided between positive and negative conics. There was no statistically significant correlation between the shape of the cornea and the subjects’ perceptions of image quality including contrast sensitivity (CSF) and visual acuity (VA). Simulations showed that the corneal Q-value could vary from more to less prolate depending upon the shape of the internal surface.

Conclusion
Following wavefront-guided LASIK, CSF is usually good and is not dependent upon the corneal conic shape. Better visual outcomes are more likely with a customized shape than a standard best conic shape.
INTRODUCTION

Most of the refractive interfaces of a human eye are aspheric. Geometry and changes in the refractive index determine the optical aberrations contributed by each aspheric surface. The quality of retinal images depends on the combined optical effects of all these elements. The individual aberrations of an optical element of a human eye are partially compensated by other elements. By this compensatory effect, overall aberration of the eye becomes smaller and results in better image quality. Artal et al.\textsuperscript{1,2} published a study showing that higher order aberrations, in particular spherical aberration, of the cornea and crystalline lens are usually of opposite signs, which explains the compensatory effect.

Because the most substantial change in the refractive index occurs at the cornea, the geometry of that structure greatly impacts retinal image quality. The corneal surface is often modeled as conic or bi-conic.\textsuperscript{3} A conic surface is characterized by the radius of curvature at the apex and a conic constant. A prolate (tip-of-the-egg) surface has a positive conic constant. An oblate (flat-side-of-the-egg) surface has a negative conic constant. Modeling the cornea as a conic is a simplification. A general aspheric shape would be more accurate. An even closer representation of the cornea can be achieved with a numerical surface map.

Refractive surgery changes the optical power of the eye by modifying the corneal surface. The cornea is made steeper for hyperopic corrections and flatter for myopic corrections, altering the curvature of the corneal surface, and thus its asphericity.

The conventional LASIK procedure is designed to correct only the low order optical aberrations of defocus and astigmatism. However following conventional LASIK procedures, many eyes have experienced increases in spherical aberration. This unexpected and undesirable phenomenon has provoked a great deal of interest and investigation. Because most natural corneas are
prolate, it has been suggested that the post-surgical increase in spherical aberration arises from changing the prolate shape, and that good quality vision can best be achieved with a theoretically optimal conic shape. This thesis is at odds with the thesis that the best vision can be created by customized wavefront-guided treatments, which correct defocus and higher order aberrations of the whole eye on an individual basis.

The purpose of this study was to quantify the relevance of the corneal conic constant to quality of vision. The study was approached from two different perspectives: 1) an analysis of data from pre- and post- LASIK eyes, all of which had received wavefront-guided treatments; and 2) through optical simulations.

The correlation between the objectively measured corneal conic constant and subjectively measured image quality in pre- and post-surgical eyes was analyzed based on data from a multi-center clinical study of wavefront-guided LASIK surgeries for the correction of myopia. Corneal surfaces were measured by topography, and the quality of retinal images was assessed with contrast sensitivity and visual acuity measurements. The optical simulations were conducted in an attempt to identify a theoretically preferred conic corneal shape that would provide good images for the range of optical aberrations naturally present in the internal optics of the human eye.

METHODS

A retrospective analysis was done of data from a multi-center study in which wavefront-guided LASIK surgeries were performed using the STAR S4™ Excimer Laser System (VISX, Incorporated, Santa Clara, CA). Wavefront measurements were performed using the WaveScan Wavefront® system (VISX, Incorporated, Santa Clara, CA), which is based on the Shack-Hartmann wavefront sensor.
Study Patients

One hundred forty-two females and 136 males participated in the study. Two hundred seventy-eight eyes with myopic astigmatism underwent wavefront-guided LASIK procedures.

<table>
<thead>
<tr>
<th>Cohort Description</th>
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<tr>
<td>(n = 278 eyes)</td>
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<tr>
<td>Average (±SD) age</td>
</tr>
<tr>
<td>Baseline manifest refraction</td>
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<td></td>
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<tr>
<td>BCVA</td>
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All procedures conformed to the Declaration of Helsinki for research involving human subjects. Ethics committee approval was obtained, and all participants in the study signed an informed consent form.

Measurements

Eleven surgeons participated in the study. Subjects were recruited from five different surgical centers across the United States. The subjects who wore contact lenses were asked to discontinue contact lens use three weeks before surgery.

Comprehensive evaluations of vision and ocular health were done before surgery and at each post-surgical follow-up visit. Corneal topographies were taken at each visit using a Zeiss®-Humphrey Topography unit (Zeiss Meditech, Dublin, California). Visual acuity data and subjective manifest refractions were collected using the ETDRS chart (Vector Vision, Dayton, Ohio). Contrast sensitivity data were collected using the contrast sensitivity chart from Vector Vision. Retro-illumination of both charts was 85 cd/m². Spatial frequencies of 3,
6, 12, and 18 cpd were tested with 15 steps (0.12-0.15 logCS per step) at each frequency. Contrast sensitivity under mesopic conditions was tested at 3 cd/m² with patients wearing a neutral density filter. The glare source was generated by attaching two 50-watt halogen flood lights to each side of the chart to simulate oncoming headlights.

**Topography Analysis**

Corneal topography data were analyzed using MATLAB® (The MathWorks Inc, Natick, MA) software. Pupil size was 5.5 mm for all the eyes. The conic shape constant (Q) value was derived by fitting the data from each eye to a conic surface using a least square approach.

**Optical Simulation**

A model eye (Figure 1) with clinically relevant parameters was used in optical simulations performed in ZEMAX®-EE software (ZEMAX Development Corporation, San Diego, CA). ZEMAX performed ray tracing through the model eye using three wavelengths, 0.45, 0.55, and 0.65 microns. Images, MTF and other relevant optical matrixes were calculated by weighting the monochromatic response of each of the three wavelengths by 0.1, 0.65, and 0.25, respectively. The weighting factors were set according to the human color response. The modeled surfaces were radially symmetrical conics or aspheric surfaces with even-power radial terms. Because modeling the lens with a graded index profile does not result in significantly different optical performance, and its index profile is not accurately known, the refractive index was assumed to be constant across the lens. The crystalline lens and posterior cornea were modeled as conic surfaces. In simulations, their conic shape constants were changed, and
the conic shape of the anterior corneal surface was optimized for each set of parameters.

Figure 1: The model eye used in simulations

RESULTS

Analysis of preoperative topography showed that most eyes had a negative conic constant (prolate shape). Very few eyes had a conic constant between 0 and +0.25 (oblate shape). Post-operative topography data showed that 6 months after the surgery the eyes were almost equally divided between positive and negative conic constants.

Contrast Sensitivity and Q-Value

Figure 2 shows a plot of Q-value vs. contrast sensitivity measured 6 months after surgery at a spatial frequency of 12 cpd. These data reveal an almost equal spread of negative and positive Q-values. The correlation coefficients between contrast sensitivity and Q-values were calculated for eyes pre-surgery and 6 months post surgery. Contrast sensitivity data included in this analysis was collected under three different illumination conditions (photopic, mesopic and mesopic with glare) and at four (3, 6, 12, and 18cpd) different spatial frequencies. As shown in Table 1, all of these correlation coefficients are insignificant. These data imply that in both pre-operative and post-operative eyes there is no correlation between contrast sensitivity and Q-value.
Table 1: Correlation coefficient between Q-factor and contrast sensitivities

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<th>mesopic-glare</th>
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<th>mesopic</th>
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Figure 2: Six-month post-op data do not show any correlation between contrast sensitivity and Q-factor. As shown in Table 1, all the correlation coefficients are statistically insignificant.

Visual Acuity and Q-Value

Best corrected visual acuity (BCVA) and Q-values of the eyes before surgery is plotted in Figure 3A. Uncorrected visual acuity (UCVA) and BCVA at 6 months after surgery are plotted in Figures 3B and 3C, respectively. Distribution of pre-operative eyes and post-operative eyes between negative and positive Q-values is very similar for different visual acuity levels. The ratio of prolate to oblate eyes is very different before and after surgery. However, before and after surgery the ratio of prolate to oblate eyes in each different acuity category is similar to the respective ratio of total eyes. These data imply that BCVA is not dependent on Q-values either before or after surgery.

Figure 3A: Best corrected visual acuity at pre-op vs. Q; Figure 3B: Uncorrected visual acuity at 6 months post-op vs. Q and Figure 3C: Best corrected visual acuity at 6 months post-op vs. Q. Visual acuity does not correlate with Q-values in pre-op or 6-month post-op data.
Simulation Results

Figure 4 shows that corneal Q-factor varies significantly depending on the spherical aberration of the internal optics, suggesting that the optimal corneal shape is determined by the total aberrations of the internal optics, and therefore there is no single or narrow range of preferred conic shapes that would provide good images for all eyes. An additional check was made by introducing asymmetric aberrations into the internal optics of the model eye. When coma was introduced to the model eye by tipping the crystalline lens, the resulting image could not be corrected by optimizing the conic shape of the cornea (Figure 5).

Figure 4: Corneal Q-value vs. asphericity of the internal optics of the model eye. In the simulation the internal optics were changed, and the corneal Q-value was computed to optimize the retinal image. Depending upon the asphericity, (or effective Q of the internal optics) the cornea had to be more or less of the prolate type to achieve good retinal images.

Figure 5: A – This example of the PSF of the model eye with coma illustrates the fact that coma-like aberrations cannot be corrected by the conic shape or a radially symmetrical aspheric corneal surface. Coma was introduced by tipping the crystalline lens and then optimizing the conic shape parameter of the cornea. The effect of coma is still present in the PSF. B – PSF without the tip in the lens.

Furthermore, if other higher order aberrations were assigned to the internal optics, the optimal corneal shape would have to be one that compensated all the higher order aberrations of the internal optics. The resulting corneal surface would be more complicated than a conic surface or a radially symmetric aspheric surface
DISCUSSION

Data from a clinical study of 278 eyes revealed no statistically significant correlation between the conic constant of the cornea and contrast sensitivity or visual acuity. Most of the eyes had negative Q-values or prolate shape before the surgery. Post operatively, eyes were equally distributed between positive and negative values. Before and after the surgery the contrast sensitivity distribution of eyes that had positive Q-values was similar to that of the eyes with negative Q-values, i.e., no relationship was observed between contrast sensitivity and Q-values. Similarly, the visual acuity distribution of eyes of pre-op and post-op was similar for eyes with positive and negative Q-values.

Simulations showed that the conic shape of the cornea cannot correct asymmetric aberrations. Variation of internal optics naturally present in the population is too great for conic shaped corneas with a narrow range of conic constants to provide optimal vision for all eyes. In general, good retinal images are achieved when defocus is corrected and the higher order aberrations are optimally corrected with a customized corneal shape.

The ablation algorithms for this generation of wavefront-guided surgeries are mathematically more advanced than in the early days of refractive surgery. However, to harness the benefits of customization, a high degree of accuracy and precision in ablating the desired shape on the cornea is needed. Accuracy is compromised by system errors; e.g., registration errors, eye movements, and disparity between the assumed shape and the shape created by the laser. By taking these errors into account, more accurate ablations can be made, and the true potential of customization can be realized. The target shape of the ablation remains an open question. Should all monochromatic higher order aberrations be completely removed, or will some preferred amount of higher order aberrations
provide better visual satisfaction? The question of the optimal target correction is a complex one—ocular aberrations may change over the short term as well as over the long term; they change as the pupil changes size with lighting and accommodation; and they change with age. What is the best balance? All of these unanswered questions are currently under investigation.

**References**

Figures

Figure 1

Figure 1: The model eye used in simulations
Figure 2: Six-month post-op data do not show any correlation between contrast sensitivity and Q-factor. As shown in Table 1, all the correlation coefficients are statistically insignificant.
Figure 3

A

Best Corrected Visual Acuity and Corneal Shape pre-op

B

Uncorrected Visual Acuity and Corneal Shape 6M post-op

C

Best Corrected Visual Acuity and Corneal Shape 6M post-op

Figure 3A: Best corrected visual acuity at pre-op vs. Q; Figure 3B: Uncorrected visual acuity at 6months post-op vs. Q and Figure 3C: Best corrected visual acuity at 6 months post-op vs. Q. Visual acuity does not correlate with Q-values in pre-op or 6-month post-op data.
Figure 4

Figure 4: Corneal Q-value vs. asphericity of the internal optics of the model eye. In the simulation the internal optics were changed, and the corneal Q-value was computed to optimize the retinal image. Depending upon the asphericity, (or effective Q of the internal optics) the cornea had to be more or less of the prolate type to achieve good retinal images.
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