Influence of Corneal Shape on Limbal Light Focusing

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Purpose. Light incident at the temporal cornea is focused by the peripheral anterior eye to the nasal limbus, the usual site of pterygium formation. Parameters that may contribute to observed individual variations in the degree of limbal light focusing were assessed.

Methods. Computer-assisted optical ray tracing techniques were applied to a human anterior segment model. The angle of incident light ($\theta$, 95° to 108° posterior to the sagittal plane), corneal central radius of curvature ($r_c$, 7.2 to 8.4 mm), and shape factor ($p$) were varied, and the effect on distal limbal intensity ($I$) was calculated.

Results. The magnitude of intensity peaks ($I_{\text{peak}}$) is dependent on $\theta$ and $r_c$. Steeper corneas have higher intensity peaks ($I_{\text{peak}} \approx 21.5X$ at $r_c = 7.2$ mm, $p = 0.75$), and flatter corneas have lower intensity peaks ($I_{\text{peak}} \approx 8X$ at $r_c = 8.4$ mm, $p = 0.75$) (cf $I_{\text{peak}} \approx 14X$ for a standard cornea, $r_c = 7.8$ mm, $p = 0.75$). Anteroposterior location of intensity peaks is dependent on $\theta$ and $r_c$. Steeper corneas have intensity peaks situated more anteriorly, whereas flatter corneas have more posteriorly placed peaks. Distal light distribution profiles demonstrate that intensity peaks are not always centrally located. At lower angles of incidence ($\theta = 100^\circ, r_c = 7.8$ mm, $p = 0.75$), peak intensity is located approximately 1 mm above and below the horizontal plane. The overall distribution (envelope) of light at the distal limbus is apparently independent of corneal shape.

Conclusions. Differences in corneal topography can account for the clinical observation of individual variation in the degree of limbal light focusing. Whether individuals with corneas capable of developing intense limbal foci may be more predisposed to developing pterygium requires further study. Invest Ophthalmol Vis Sci. 1994;35:2592-2598.

We have previously hypothesized that peripheral light focusing by the anterior eye may play a role in the pathogenesis of certain sun-related eye diseases (ophthalmohelioses).1-5 The human eye is exposed laterally, simultaneously allowing a large temporal visual field as well as a large collection zone for peripheral light rays. This light may be focused at the limbus (Fig. 1), crystalline lens equator and eyelid margin depending on the angle of incidence. These foci coincide with the usual sites of pterygium, cortical cataract and eyelid malignancy.

In the initial observations of limbal light focusing,1 it was demonstrated that this phenomenon was more easily observed in subjects with high keratometry readings than in those with significantly lower keratometry readings. In this communication, we explore the factors that influence limbal light focusing in a model of the human anterior eye.

METHODS

The phenomenon of limbal peripheral light focusing of the anterior segment is presented in diagrammatic form (Fig. 2). These properties have been described previously.2,3

The optical properties of the anterior segment were simulated using geometric optics principles. Ocular structures modeled include the anterior and posterior corneal surfaces and limbus. As the periphery of the typical anterior cornea approximates an ellipse,6-8 an ellipsoid of revolution was used to model the anterior corneal surface. The generating ellipse for the ellipsoid of revolution was defined by its central radius of curvature ($r_c$) and peripheral shape factor ($p$). The shape factor is a geometric coefficient describing the...
rate of flattening of the peripheral cornea.\textsuperscript{9} The posterior corneal surface was modeled simply as a sphere, coaxial and concentric with the anterior corneal surface.

Five model corneas were constructed in the following three categories:

**'Standard' Cornea**

A baseline "standard" using values quoted from literature\textsuperscript{6,8,10-15} on the normal Caucasian ocular parameters.

**Corneas of Varying Radius**

Two corneas, one with larger and the other with smaller than standard radii, were modeled.

**Corneas of Varying Shape Factor**

Two corneas with respectively higher and lower shape factors than the standard cornea were modeled.

Key parameters assigned to each corneal model include radius and shape factor of anterior and posterior corneal surfaces (Table 1). In all models, central and peripheral corneal thicknesses were kept constant. The sagittal height of the anterior corneas were allowed to vary according to the radius and shape factor chosen. However, corneolimbal diameter, central and peripheral (at limbus) corneal thicknesses were kept constant for all corneas by adjusting the \( r_{o} \) of the posterior cornea. The effect of the precorneal tear film was assumed to be negligible and was not modeled.

A total of 1000 light rays were generated to be incident on the anterior segment optical system for selected angles posterior to the coronal plane (Fig. 2). These angles were 5°, 10°, 12°, 14°, 16°, and 18°. This series of six angles of incidence were repeated in the five models. The cross-sectional distribution of the incident rays was a square grid, each ray being separated vertically and horizontally by 0.1 mm from neighboring rays. Sampling of image light rays occurred at the distal limbus 6.0 mm from the geometric axis of the anterior cornea, lying just scleral to the limbus.
TABLE 1. Parameters of Five Corneas Modeled

<table>
<thead>
<tr>
<th>Model</th>
<th>Anterior Cornea</th>
<th>Posterior Cornea</th>
<th>Corneal Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r_o$ (mm)</td>
<td>$r_o$ (mm)</td>
<td>$t_c$ (mm)</td>
</tr>
<tr>
<td>Standard</td>
<td>7.8</td>
<td>7.10</td>
<td>0.6</td>
</tr>
<tr>
<td>Flat radius</td>
<td>8.2</td>
<td>7.35</td>
<td>0.6</td>
</tr>
<tr>
<td>Steep radius</td>
<td>7.4</td>
<td>6.85</td>
<td>0.6</td>
</tr>
<tr>
<td>High shape factor</td>
<td>7.8</td>
<td>6.94</td>
<td>0.6</td>
</tr>
<tr>
<td>Low shape factor</td>
<td>7.8</td>
<td>7.25</td>
<td>0.6</td>
</tr>
</tbody>
</table>

RESULTS

The distribution of imaging rays at the distal limbus for the five corneal models is plotted (Figs. 3a to 7a). Points on these plots define the position at which image rays pass through the distal limbus. In these plots, the horizontal axis (distance along limbus) denotes distance away from the midpoint of the focus as measured perpendicularly to the direction of the light rays. The vertical axis (limbal depth) denotes anteroposterior position within the limbus. According to this coordinate system, the distance along the limbus when light is directed horizontally (as in Fig. 1) would be measured vertically along the sagittal plane at the nasal

FIGURE 3. Scatter plot (a) and peak intensity profile (b) of limbal light distribution for the standard corneal model.

FIGURE 4. Scatter plot (a) and peak intensity profile (b) of limbal light distribution for the corneal model with a larger (8.2-mm) radius of curvature.
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STEEP RADIUS

Distance Along Limbus (mm)

Steep Rod Us

FIGURE 5. Scatter plot (a) and peak intensity profile (b) of limbal light distribution for the corneal model with a smaller (7.4-mm) radius of curvature.

By assigning incident light rays an arbitrary intensity of 1 (unitless), image ray intensity (I) at the distal limbus relative to incident light ray intensity was calculated. In all models and at all angles of incidence tested, there was a high relative image intensity of at least one order of magnitude greater than incident intensity.

The three-dimensional peak intensity profiles (Figs. 3b to 7b) corresponding to the plots of image ray distribution (Figs. 3a to 7a) for the corneas modeled are also shown. A comparison of the effect of corneal shape can be readily seen. It should be noted that data averaging techniques have not been used. This is reflected in the irregularity of the intensity plots.

'Standard Cornea'

The anterior focus lies in the anterior third of the limbus and the intensity peak (magnitude of intensity peak, \( I_{\text{peak}} = 21.5 \times \)) at 14° lies at the junction of the middle and posterior thirds (total number of rays = 3568).

Corneas of Varying Radius

Corneas with steeper radii focus light more anteriorly, whereas those with flatter radii focus light as far anteriorly as the mid stroma. The overall envelope for corneas with steeper radii is more rounded, whereas it is less rounded for those with flatter radii. The intensity peaks are the same (\( I_{\text{peak}} = 19.0 \times \)) but lie at different levels (total number of rays = 3885 for steep radius versus 3006 for flat radius).

Corneas of Varying Shape Factor

Corneas with high shape factors focus more anteriorly, beyond the anterior margin of the limbus, whereas those with lower shape factors focus light just into the posterior third of the limbus. The overall en-
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**DISCUSSION**

Our initial reports of peripheral light focusing by the anterior human eye presumed that these phenomena had not previously been described. In fact, von Helmholtz used peripheral light focusing onto the iris to demonstrate anterior movement of the iris (and anterior lens) during accommodation. He did not describe limbal focusing but his ray diagram to explain iris surface focusing anticipates focusing beyond the distal limbus (type III phenomenon). Graves used peripheral light as a means of illuminating the cornea and presumed that light crossed via total internal reflection in the cornea, so called "sclerotic scatter." We have demonstrated that the contribution to limbal focusing by this phenomenon is minimal. Mackevicius proposed a photothermal mechanism in pterygium pathogenesis caused by limbal sunlight focusing at the nasal limbus. Coroneo was unable to demonstrate a focal increase in temperature at the nasal limbus after 5 minutes of insolation. Rizzuti used peripheral illumination of the anterior eye to show foci at the limbus and beyond in keratoconic corneas. He specifically states that in "normal" eyes the distal limbus is illuminated diffusely; ie, a focus was not observed. This may well be related to the light source used or to the range of "normal subjects" observed. Taylor and Hanks observed limbal light focusing in Hereford cows' eyes in sunlight and suggested that this played a role in the development of bovine ocular squamous cell carcinoma. The transcameral pathway was not identified and an explanation for the focusing was not provided. Interestingly, the focusing phenomena are most easily seen in bovine eyes and we used these to model the phenomena, being at the time unaware of Taylor and Hanks' report.

Our initial report demonstrated that limbal light focusing was more readily seen in subjects with relatively high keratometry readings. We believe that this

**TABLE 2. Summary of Peak Intensity Versus Angle of Incidence**

<table>
<thead>
<tr>
<th>Corneal Model</th>
<th>Angle of Incidence (°)</th>
<th>Peak Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>14</td>
<td>21.5</td>
</tr>
<tr>
<td>Flat Radius</td>
<td>14</td>
<td>19.0</td>
</tr>
<tr>
<td>Steep Radius</td>
<td>12</td>
<td>19.0</td>
</tr>
<tr>
<td>High P Value</td>
<td>10</td>
<td>21.0</td>
</tr>
<tr>
<td>Low P Value</td>
<td>14</td>
<td>15.0</td>
</tr>
</tbody>
</table>
was the first realization that scattered ultraviolet (UV) light could be focused at the distal limbus and that this phenomenon may be at the root of pterygium pathogenesis. The dependence of limbal light focusing on corneal shape also provided the first hypothesis to explain individual susceptibility to pterygium development. Further support for this hypothesis is provided by our ability to predict pterygium shape using the concepts of limbal stem cell maintenance of the limbal barrier and a population balance model of corneal epithelial maintenance.

In the current study we have sought to further define the phenomenon of peripheral light focusing at the distal limbus. We have confirmed and quantified the focusing of light by the cornea at the distal limbus for varying corneal shapes, and have demonstrated a theoretical explanation for the clinical findings noted above. Variation in peripheral corneal curvature as modeled by corneal shape factor is here demonstrated to have a marked effect on the peak intensity and its location in the limbus. This is illustrated by Figure 8, which shows the relative peak intensity versus limbal depth for the five corneal models. Simple keratometry readings may not fully characterize the focusing properties of the peripheral cornea. We are currently investigating the possibility that individuals with corneas capable of developing intense limbal foci may be predisposed to developing pterygium.

In this study, the standard refractive indices for visible light were used. Because of dispersion, the refractive index of the cornea to UV would be slightly different. However, no reliable value for refractive index for cornea to UV is available in the literature. Furthermore, we have directly demonstrated this phenomenon using light at 308 nm. This is not unexpected as the cornea transmits significant amounts of these energetic and biologically active wavelengths (60% of radiation at 320 nm and 80% at 400 nm). In epidemiologic studies, there is a clear association between high personal exposure to broad band UV radiation (290 to 400 nm) as well as to visible light and increase risk of developing pterygium.

The evidence that UV- and short-wavelength visible light is important in the etiology of pterygium has strengthened. It has been predicted that increased UV insolation will result in increased pterygium prevalence especially as it now appears that ozone layer thinning may be progressive.

It has been observed that pterygium develops a decade earlier than (and hence may be an early predictor of) the dermatohelioses. This may well be attributable to the eye being the only organ possessing optical surfaces with significant focusing properties. Limbal light focusing of UV- and short-wavelength visible light may alter limbal integrity by several mechanisms. The corneal epithelial stem cells may be
particularly vulnerable to such focusing and these cells are locally altered in pterygia. 

Our findings may provide the basis for identification of individuals at risk of developing anterior ophthalmohelioses (sun-related eye disease) so that appropriate preventative measures can be recommended.

**Key Words**

ophthalmohelioses, pterygium, ultraviolet radiation, corneal topography, peripheral light focusing

**References**


