How keratoconus influences optical performance of the eye

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Using a statistical description of keratoconus (KC) topography, schematic eye models of various KC conditions are constructed to study their optical influence on visual performance. The cone shape, protruding height and extent, and distance from the visual zone are independently investigated with the three-dimensional optical eye-modeling and ray-tracing techniques. The subsequent spherical equivalent (SE), cylinder, together with residual high-order ocular aberrations, are examined and related to each separated variable. The results show that myopic nature of SE is greatly dominated by the location of the cone. The cylinder is determined by the cone shape when the cone is inside the visual zone. It is dominated by the cone location when the cone is away from visual axis. The least myopic meridian always falls on the cone direction, and the high-order aberrations strongly relate to the cone dimension. This study investigates KC cone effect on optical quality and provides comprehension of clinical observations.

Keywords: keratoconus, computer modeling, eye model


Introduction

Keratoconus (KC) is the most common corneal dystrophy in the United States and affects one in every 500 to 2000 Americans (Krachmer, Feder, & Belin, 1984). This ocular condition involves progressive corneal thinning that eventually causes an outward bulging of the cornea. In its mild stage KC is often overlooked or misdiagnosed as myopia and astigmatism. Topographic changes are typically the first sign of the disease, and vision does not correlate with the patterns found on topography. In a study of 91 patients presenting for keratorefractive surgery, 5 cases were identified as KC from the topography examination (Nesburn et al., 1995). The age of onset of KC typically occurs during puberty or the 20 s. The National Institutes of Health and National Eye Institute Collaborative Longitudinal Evaluation of Keratoconus (CLEK) Study is a prospective, observational study of 1,209 KC patients; the purpuse was to characterize the
changes in vision, corneal curvature and scarring, and quality of life for keratoconus patients and to understand better the variation of these measures with time (Barr et al., 2006; Kymes, Walline, Zadnik, Gordon, & the CLEK Study Group, 2004; McMahon et al., 2005; Nichols, Steger-May, Edrington, Zadnik, & the CLEK Study Group, 2004; Raasch, Schechtman, Davis, Zadnik, & the CLEK Study Group, 2001). The long duration and the impact of impaired vision on functions of daily life increase the importance of KC as a disease. In fact, Kymes et al. showed that the impact of KC on quality of life indicators extended far beyond what one might expect from the visual acuity alone (Kymes et al., 2004).

Recently, many research studies have employed wavefront aberrations and subsequent Zernike analysis to characterize and correct KC eyes (Barbero, Marcos, Merayo-Lloves, & Moreno-Barriuso, 2002; Carvalho, 2005; Marsack, Pesudovs, Sarver, & Applegate, 2006; Smolek & Klyce, 2005). Although complex factors, including corneal scarring, posterior corneal elevation, and intraocular compensation (Artal, Benito, & Taberneror, 2006; Artal, Guirao, Berrio, & Williams, 2001), contribute to the KC vision impairment, the anterior corneal elevation is believed the dominant factor. However, an understanding of how the KC patient’s individual cone parameters affect the eye’s optical performance is not clear. Therefore, in addition to the observational studies, theoretical models and computations are useful to relate the anatomical changes caused by KC to specific effects on vision performance.

Lately, with the advance of optical computation, creation of eye models using actual clinical data from patients was accomplished with high precision (Navarro, Gonzalez, & Hernandez-Matamoros, 2006; Taberneror, Piers, Nenito, Redondo, & Artal, 2006). We have recently successfully modeled KC eyes using patients’ topographies and manifest refractions, and the ophthalmic measurement simulation using these models was validated with experimental measurements (Chen et al., 2006). These personalized KC eye models not only possess the patients’ optical characteristics but also predict realistic ophthalmic measurements (Tan et al., 2007).

To investigate how each independent KC cone factor influences a patient’s optical quality of vision, we constructed geometrically simplified KC eye models. The cornea is assumed to be the only affected ocular element in KC eyes, and the constructed KC eye model uses a statistical description of the KC’s anterior corneal surface and an otherwise healthy adult eye of average properties; this is described in the following section. Subsequently, three-dimensional ray tracing on KC eye models was performed to determine the resulting optical imaging quality. The investigation and analysis are presented in five parts. First, computations were used to indicate the general effect on refraction of the size, shape, and corneal location of KC cones. Using the measured statistical distribution of cone dimension and shape, various cones were placed on the center of the cornea, at the average cone location, and at a more peripheral location. For the purpose of relating these KC features with a commonly used measure of ocular optical quality, computations were performed to determine the spherical equivalent and cylinder refraction for each cone. The overall trend in behavior becomes clear once these cones are characterized by one of four degrees of severity (mild, moderate, advanced, and severe) that corresponds approximately to the cone volume. Second, the effect of cone location was investigated. For this, three right-circular cone sizes (small, medium, and large) were used, and the cone peak distance from visual center was the variable. Third, the astigmatism orientation is discussed in light of the cone location. Next, we inspected the effect of the cone size. The most typical KC cone shape was used and the size was changed across a large range. Finally, the effect of cone shape was examined with the average fixed cone size. The optical investigation was performed for consequent refractive error and high-order ocular aberration.

**Construction of KC eye model**

An accurate KC model requires knowledge of the typical values and distribution ranges of the sizes, shapes, and positions of the conical structures. With the advent of the photokeratoscope the height map of the cornea surface can be measured. The KC cornea height is the elevation above a reference spherical surface or the healthy cornea surface. To reveal the cone’s morphology the normal corneal surface should be determined and subtracted from the height map. This can be done by decomposing the analytical corneal surface into Zernike polynomials \(\{Z_n^m\}\) and then eliminating the low-order polynomials that represent the defocus (near- and farsightedness) and cylindrical power (astigmatism).

This method was used by Schwiegerling et al. to examine the resulting cone from the topographical map (Schwiegerling, Greivenkamp, & Miller, 1995). The height maps from 56 KC eyes were decomposed into Zernike polynomials. Then the parabolic \(C_1^1Z_2^1\) and the cylindrical \((C_1^2Z_2^2 + C_2^3Z_2^3)\) components were eliminated to yield a residual height map (Schwiegerling, 1997; Schwiegerling et al., 1995). Corneas with normal refractive errors appear to have relatively flat residual maps. In contrast, a KC cornea’s residual map reveals more significant high-order Zernike terms, which represent the irregular surface of the KC cone. After the cones’ surfaces were obtained, they were fitted to two-dimensional Gaussian surfaces to define the sizes and positions of the assumed right elliptical cones. This allows an accurate optical KC cornea model to be constructed based
on the 5 cone parameters, \((x_o, y_o, \sigma_x, \sigma_y, h_o)\), from the Gaussian expression (Equation 1):

\[
f(x, y) = h_o \exp \left\{ \frac{(x - x_o)^2}{2\sigma_x^2} + \frac{(y - y_o)^2}{2\sigma_y^2} \right\},
\]

where \(h_o\) is the peak height of the cone, \((x_o, y_o)\) is the cone’s center location with respect to the visual axis, and \((\sigma_x, \sigma_y)\) are the corresponding dimensions where the height drops to \(e^{-1/2}\) of the cone’s peak height. The full width at half maximum of a Gaussian function is equal to \(2.35\sigma\). The 56 clinically diagnosed KC corneas’ residual height maps were processed and each parameter’s statistical distribution was reported (Schwiegerling, 1997).

In addition to the Schwiegerling 1995 and 1997 studies using the elliptical Gaussian fitting of KC topographies, a recent simulation study (Tang, Shekhar, Miranda, & Huang, 2005) of a 4-parameter round Gaussian elevation also successfully illustrates the most typical axial, tangential, and curvature topographical appearances of keratoconus and pellucid marginal degeneration (PMD) measurements. The statistics of 19 KC cones in Tang’s study agree with Schwiegerling’s report. The 5-parameter elliptical Gaussian elevation is a simple assumption on KC cone structure. Although many KC cones have more complex shapes, Gaussian surface fits well to a very good portion of KC cases. The more particular and complex cones that are not well modeled in this study include significant asymmetric cones and cones with multiple peaks. These complex shapes can be mathematically modeled by adopting more shape parameters. Here we use the least number of parameters to enable the study on the comprehension of the optical influences of (a) cone location that requires at least 2 variables, \((x_o, y_o)\), (b) cone shape that needs no less than 2 variables, \((\sigma_x, \sigma_y)\), and (c) cone dimension that requires at least one additional variable, \((h_o)\).

To corroborate the KC statistics of Schwiegerling’s 56 eyes, 15 additional KC topography maps from the Wang Vision Institute at Nashville, TN, were examined. These 15 KC cases include 2 cases with steepest corneal curvature less than 45 diopter, 9 cases between 45 and 52 diopter, and 4 greater than 52 diopter. The statistical distributions of the 5 cone parameters from measurement and reported data were then adopted to model various KC cone dimensions and locations.

Four degrees of KC cones (mild, moderate, advanced, and severe) are created based on the statistical distribution of measured cone volumes (shown in the left column of Table 1). The volume enclosed by the two-dimensional Gaussian surface is given by

\[
V = 2\pi h_o \sigma_x \sigma_y.
\]

The shape-correlated eccentricity \(e\) of the cross-sectional ellipse of semi-major and minor axis \(a\) and \(b\), respectively, is

\[
e = \sqrt{1 - \frac{b^2}{a^2}}.
\]

The eccentricity always lies between \(0 \leq e < 1\). An eccentricity \(e = 0\) corresponds to a circular cone, and as \(e\) increases the cone becomes more elliptical. The synthetic

<table>
<thead>
<tr>
<th>KC cones</th>
<th>#</th>
<th>(h_o) (mm)</th>
<th>(\sigma_x) (mm)</th>
<th>(\sigma_y) (mm)</th>
<th>Volume, (V) (mm³)</th>
<th>(V^{1/3}) (mm)</th>
<th>Eccentricity (e)</th>
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<tr>
<td>Mild (&lt; 0.02) mm³</td>
<td>1</td>
<td>0.0051</td>
<td>0.4183</td>
<td>0.4729</td>
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<td>0.1848</td>
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<tr>
<td></td>
<td>2</td>
<td>0.0087</td>
<td>0.4348</td>
<td>0.5718</td>
<td>0.0136</td>
<td>0.2389</td>
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<tr>
<td></td>
<td>3</td>
<td>0.0090</td>
<td>0.5170</td>
<td>0.4960</td>
<td>0.0146</td>
<td>0.2442</td>
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<tr>
<td>Moderate (0.02–0.1) mm³</td>
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<td>0.6944</td>
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<td>0.3185</td>
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<td></td>
<td>5</td>
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<td>0.8581</td>
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<tr>
<td></td>
<td>6</td>
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<td>0.6417</td>
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<td>7</td>
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<td>0.8000</td>
<td>0.0804</td>
<td>0.4316</td>
<td>0.000</td>
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<td>Advanced (0.1–0.4) mm³</td>
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<td>1.1821</td>
<td>0.8553</td>
<td>0.1561</td>
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<td>0.0400</td>
<td>1.2000</td>
<td>1.2000</td>
<td>0.3619</td>
<td>0.7126</td>
<td>0.000</td>
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<tr>
<td>Severe (&gt; 0.4) mm³</td>
<td>12</td>
<td>0.0410</td>
<td>1.7380</td>
<td>1.0590</td>
<td>0.4746</td>
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Table 1. Elliptical Gaussian cone parameters of 14 synthetic keratoconus (KC) eyes. As defined in Equation 1, \(h_o\) is the peak height of the cone, \((x_o, y_o)\) is the cone’s apex location, and \((\sigma_x, \sigma_y)\) are the horizontal and vertical dimensions. The volume \(V\) and eccentricity \(e\) are defined in Equations 2 and 3. The volume-classification of 4 keratoconus degrees is indicated in blue in the leftmost column. Cones #7 and #11 are round Gaussian cones.
anterior KC corneal surface is generated by superimposing the Gaussian surface onto a normal corneal surface of the emmetropic eye model (Escudero-Sanz & Navarro, 1999). Although the posterior corneal surface is also affected in KC patients, the posterior irregularity was omitted in the modeling. The optical influence of irregular posterior surface was estimated 10–20% of the anterior influence due to the smaller refractive index difference.

### Optical performance evaluation

Refractive error is usually the first sign of the presence of KC and its consequent vision impairment. For a modeled or simulated KC eye, the clinical equivalent refractive errors can be established by computer-based optical optimization using the ray-tracing optical program. Some of the CLEK studies have suggested using the vector representation of power to describe KC instead of the conventional sphere, cylinder, and axis because the three parameters are not independent (Raasch et al., 2001). We chose to use sphere, cylinder, and axis because these are measured in the clinic using a standard eye examination. The sphere, cylinder, and axis can be easily transformed into the vector power representation.

In addition to the refractive errors, a metric that describes the visual quality under the best sphero-cylindrical correction would be beneficial. The clinical best-corrected visual acuity is difficult to attempt theoretically because of the non-optical factors involved on human cognition process. However, a variety of other optical metrics in terms of wavefront aberration and image quality such as point spread function (PSF) and optical transfer function (OTF) are possible (Hong, Thibos, Woods, & Applegate, 2003; Thibos, Hong, Bradley, & Applegate, 2004). Among these, the root-mean-square (RMS) wavefront aberration is a convenient index to use. Applegate found that although for low levels of aberration, the RMS wavefront aberration may not be a good predictor of visual acuity, over a large range of aberrations the RMS wavefront aberration characterizes the visual performance reasonably well (Applegate et al., 2000; Applegate, Marsack, Ramos, & Sarver, 2003). Since KC has large amounts of high-order aberrations, the RMS wavefront error is used in this study.

Determination of the subsequent refractive error is achieved using optimization in ZEMAX. A Gaussian thin lens with three variables, spherical equivalent, cylindrical power, and astigmatic axis, is placed in front of the optical model eye. These three values are set to be the iteration variables in the ray-tracing program to achieve optimized optical performance. It is noted that the wavefront aberration maps of KC patients are very irregular and that the high-order Zernike coefficients, including the \( m \neq 0 \) terms, are pronounced. Because of this, the simplified Zernike derivation methods (Atchison, 2004; Dorsch, Haimearl, & Esser, 1998) that use only the \( p^2 \)- Zernike terms do not provide adequate results for KC cases. We find that the optimization method provides stable, converged results that are significantly different from the Zernike-derived prediction. The iteration is carefully examined over the 180-deg meridians to prevent convergence of local minimum.

Once the sphero-cylindrical prescription is determined, the residual RMS wavefront aberration provides the measure of the high-order ocular aberration that causes the higher level of difficulty for the KC patient. The remaining 2nd-order Zernike terms are included since the optimization procedure has been performed and the 2nd-order terms, if existing, still contribute to the error. The sum of the second-to-eighth order residual aberrations \( RMS_{W^{2-8}} \) is related to best-corrected visual acuity and is used, in addition to the refractive error, to evaluate the optical quality of KC vision.

Because both refraction and visual acuity are pupil-size dependent, a fixed pupil diameter is required before a comparison or analysis can be performed. Due to the compromise between the diffraction and aberration limits, a pupil size that provides practically optimal visual acuity should be used. In general, the maximum visual acuity occurs in 2-to-3-mm diameter pupils, but larger pupils (3–5 mm) reduced acuity only marginally (Atchison, Smith, & Efron, 1979; Smith & Atchison, 1997). Although pupils of 3.5-mm, 5-mm, and 7-mm diameter were investigated, results from 3.5-mm pupil diameter are the most relevant for patients performing visual tasks in the daytime or room light, and the majority of the results shown in the figures will relate to this pupil size. The effects of larger pupil size on the optical performance of vision will be addressed following discussion of each KC cone parameter.

### Optical performance of KC eyes

To obtain a general comprehension of how KC cones affect the optical quality of vision, parameters of three cones in each of the four degree-of-severity categories are randomly generated within the statistical distribution ranges. Additionally, two circular cones are added for comparison and calibration. Table 1 gives the characteristic variables describing the 14 KC cones. The cones are numbered according to the peak height. These four KC degrees are defined with the ranges of volume as indicated in blue in the first column in Table 1. This classification does not have a direct correspondence with dioptric degrees. These 14 chosen cones are illustrated in false-colored images in the upper Figure 1. The maximum cone height in the severe degree case is 54 μm. The cross in each image indicates \( \sigma_x \) and \( \sigma_y \). Cones #7 and #11 represent the circular cones.

The lower part of Figure 1 shows three KC cone locations. Reference circles of 5 mm and 10 mm are
illustrated and centered on the visual axis (indicated in red). The KC cones tend to occur inferior to the visual axis \((y_o = -0.9 \pm 0.5 \text{ mm})\) in the temporal quadrant \((x_o = 0.4 \pm 0.7 \text{ mm})\) as indicated in green. A far location at \((x_o = 1.1 \text{ mm}, y_o = -1.4 \text{ mm})\), is also indicated (in blue). The KC cones on the three marked locations are investigated as will be discussed later.

The refractive errors of the 14 synthetic KC eyes are illustrated in Figure 2. The calculation is performed for three cone locations: centered at the visual axis, the average cone location, and the selected far location, as indicated in Figure 1. As the results show, refractive error becomes larger with increasing KC cone volume. When the 14 KC cones reside on the center of the visual zone (yellow symbols), significant nearsightedness (negative spherical equivalence, SE) is observed with relatively smaller cylinders except for the severe cones. For advanced and severe KC cones (numbers 8–14), the SE powers reach \(-6\) to \(-9\) diopters. For the 14 cones that are located at the average location (green symbols), the SE values are greatly reduced. When the cones are farther away from the axis (blue symbols), the SEs become near zero and slightly positive, thereby indicating far-sightedness.

The cylinder values are relatively large. All 42 KC cases exhibit certain degrees of astigmatism except for the 2 circular cones (#7 and #11) when they reside on axis. When on-axis, the shape of KC cone is the dominant factor for the cylindrical power. When away from the axis, cylindrical power is less sensitive to cone shape and is more influenced by the location of cone. The high-order aberrations of the 42 cones are not presented in this figure. However, the result seems to indicate that, although the on-axis cones have most significant refractive errors, high-order aberration for these cases is less than for those found at the average location. When the cones are located at the average location, the high-order aberrations are the largest as compared to the same cones at the center and the far locations.

For larger pupil sizes at 5 and 7 mm, both spherical and cylindrical refractive errors reduce in magnitude while the RMS high-order aberrations increase, thereby...
indicating an increased difficulty with conventional refractive correction.

**Influence of KC cone location**

Among various KC characteristics, the cone location may be the most influential for vision distortion, and an evaluation was made of the location effect on spherical equivalent and cylindrical powers and the residual root-mean-square of wavefront aberration. To investigate the effect of cone location without influence of cone shape, three circular cones, one mild, one moderate, and one severe, are evaluated at locations between the visual center and 3.5-mm temporal for pupil diameters of 3.5, 5, and 7 mm. The results are shown in Figure 3. KC cones produce nearsightedness when located at the center of the visual zone for all pupil diameters shown (upper plot). As the cone location moves off-center, the magnitude of myopia reduces. The SE powers approach zero when the cones are de-centered at distances approximately equal to or larger than the $2\sigma$ distance for the 3.5- and 5-mm pupil diameters. At the very far locations, KC cones result in mild hyperopic conditions for this same pupil-size range. This occurs because the KC cone curvature (the second derivative of elevation) determines the supplementary power on the cornea surface. The contribution from outside the $2\sigma$ zone of a cone is hyperopic instead of myopic. This effect is clearly seen for the 3.5- and 5-mm pupil diameters, and the trend is noted for the 7-mm pupil case of Figure 3. Also, as Figure 3 shows, the cylinder power increases and then decreases with the cone distance for all pupil sizes studied. For all but the largest pupil diameters, the locations of maximum cylinder error correspond to approximately the zero-SE locations.

The influence of cone location on RMS high-order aberration (HOA) is shown in the bottom row of Figure 3 for the three pupil sizes. It is seen that the medium-sized cone exhibits the largest HOA for the 3.5-mm pupil, but for the pupils of 5- and 7-mm, the largest cone size

![Figure 3](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933045/)

Figure 3. Cone location effects. The X-axis is the distance from the visual zone center to the apex of cone. From top to bottom plots are the spherical equivalent power, cylindrical power, and residual root-mean-square of wavefront aberration. Wavelength = 555 nm. Vertical lines indicate dimensions ($2\sigma$ distances) of the three cones. Left, middle, and right columns are results of 3.5-, 5-, and 7-mm pupil, respectively.
produces the largest HOA. The Gaussian-cone shape has a full-width half-maximum of 2.35\(\sigma\), and twice that size is a good measure of the extent of the cone base on the cornea. The HOA results indicate that the maximum aberration exists when the cone is, of course, off-center and the curvature of the cone overlaps most of the visual zone. It is seen that the HOA is on the order of 0.1–0.6 to 0.3–1.5 and 0.3–2.0 \(\mu\text{m}\) for 3.5–5–, and 7-mm pupil, respectively. This level of KC aberration is significant compared to that for normal healthy adults (\(n = 2,560\)) of 0.10 \(\pm 0.044\) \(\mu\text{m}\) at 4-mm pupil and 0.19 \(\pm 0.08\) \(\mu\text{m}\) at 5-mm pupil, and 0.50 \(\mu\text{m}\) at 7-mm pupil (Salmon & van de Pol, 2006).

**Astigmatism orientation in KC eyes**

Considering a de-centered KC cone, it is anticipated that one astigmatic meridian will be aligned with the cone direction and will exhibit a power of \(S_{\parallel}\). The computation results prove the situation. The power difference (\(S_{\parallel} - S_{\perp}\)) between the major and minor meridians represents the cylindrical error. Intuitively, one might expect that both meridians would contribute positive power (myopic) and that the power along the cone direction is greater than along the perpendicular direction, that is, \(|S_{\parallel}| > |S_{\perp}|\). Figure 4 illustrates \(S_{\parallel}\), \(S_{\perp}\), and \(SE = (S_{\parallel} + S_{\perp})/2\) of the three circular cones. The three KC cones exhibit similar behavior. When located at the visual center, \(S_{\parallel} = S_{\perp}\). For the cones located peripherally, the myopic \(S_{\parallel}\) reduces to zero and becomes hyperopic. As the cones are moved farther from the center, \(S_{\parallel}\) exhibits a maximum of hyperopic condition and then reduces again and approaches zero according to the corneal curvature contribution. On the other hand, \(S_{\perp}\) is a monotonic myopic function of cone distance. Note that the myopic power along the cone direction is always less than the power in the perpendicular meridian for all circumstances. This theoretical prediction is in sound agreement with our clinical observation in all 15 KC cases.

**Influence of KC cone size**

Figure 5 shows the result of the investigation of cone dimension. KC cones with the most typical shape of \(h_{\parallel}\): \(\sigma_{\parallel} : \sigma_{\perp} = 0.1 : 4.29 : 3.26\) (Schwiegerling, 1997) over the range of volume from 0 to 8.78 mm\(^3\) are studied. Three vertical lines in the center plots define the mild, moderate, advanced, and severe KC dimensions as volume values given in Table 1. The vertical lines correspond to the dimension (Volume\(^{1/3}\)) = 0.27, 0.46, and 0.74 mm.

For the on-axis case (red line), as the KC cone size grows, the degree of myopia increases until it reaches the maximum where the size is between the moderate and advanced, and then the myopia reduces as the volume continues to grow where the curvature inside the visual zone reduces. Similarly, the cylinder increases and then reduces as the cone develops. For the distantly located cone (blue line), increasing the cone dimension results in hyperopia because the cone curvatures near the center visual zone are negative at the outset. When the cone dimension develops into the visual zone, the spherical equivalence becomes myopic. The cylinder is a result of not only the shape but also the location of the cone. As the bottom plot in Figure 5 shows, the high-order aberrations seem to have a strong correlation with the cone dimension. For all 3 locations, moderate-sized cones have the worst high-order aberration. This is also shown in the bottom plot in Figure 3. From the calculation of 5- and 7-mm pupils, it appears, again, that the worst refractive error as well as high-order aberration occurs when the cone dimension is relatively close to the effective pupil diameter.
Influence of KC cone shape

The investigational result of cone-shape effect is shown in Figure 6. A moderate-to-advanced cone volume of 0.12 mm³ and a constant cone height of 24 μm (medium size) were used for all calculated cases while the ratio \( \sigma_x/\sigma_y \) of cones varied from 2.5/1 to 1/2.5. As we observed before, the on-axis cones (red line) have the worst myopic conditions and the greatest shape influence on their cylinder. However, their high-order aberrations are considerably smaller. For the distantly located cones (blue line), the dioptric contribution to the visual central area is negative and farsightedness results from the cone in this specified size range, regardless of its shape. Due to the far distance from visual center, cone shape does not significantly affect cylindrical powers and the high-order aberrations. For the cones at the average location (green line), the spherical equivalent power has a strong coupling effect between the shape and location. The shape slightly affects the cylindrical power. Within the worst cone volume range and at a bad location, the high-order aberration is dramatic. Moderate-to-advanced-sized cones located at about average locations with irregular shape have the worst high-order aberrations.

At the increased pupil size of 7 mm, the midsize KC cone is relatively small inside the visual zone. Therefore, the influence of cone shape reduces significantly. It may
be more appropriate to state that the optical quality of a KC eye is so poor at large pupil sizes that the shape of cone plays only a trivial role.

Summary

The optical performance for different KC conditions is theoretically investigated. A general, healthy, adult eye model is used with modification to only the anterior corneal surface. The KC cone dimension (volume), location, and shape are independently considered. The results show that a KC eye’s optical performance is changed by the effective cone curvature in the pupillary visual zone. The clinician would expect the keratometry readings to correlate with the optical performance. The more irregular the keratometry measurements (or inability to measure them) would indicate more severe disease. The refractive (spherical equivalent) depends largely on the cone location. The clinician would expect that those patients with central cones would be more nearsighted and those with more peripheral cones less so. SE tends to be slightly hyperopic for an outlying cone. The cone shape plays a less significant role.

The cylindrical error, on the other hand, is affected by both the cone location and the shape. When near the visual center, the cone shape plays the major role on the amplitude of astigmatism. If far away from visual center, the cone location dominates. The meridian pointing to the cone apex corresponds to the less powerful meridian. The power in the perpendicular meridian is always myopic, although the SE could be hyperopic for an outlying cone. For an inferior KC cone at a 4-to-8-o’clock position, the resulting astigmatism is against the rule.

The high-order aberrations strongly relate to the cone dimension. The greatest, most visually significant high-order aberrations occur when the cone dimension or cone location is comparable to the pupil size. The combination of these cone sizes, location, and an irregular shape results in the worst scenario of high-order aberrations.

In our study, we note that the first-order aberration, the tilt, is considerable in all of the KC eyes. The tilt results in only the shift of image location and does not affect the imaging quality. It is therefore not taken into account for the optical performance evaluation. However, it may explain why keratoconus does affect daily living tasks significantly, and may also affect cognition and comprehension of visual tasks. While the disease progresses, the rapid changes of tilt may require significant efforts for KC patients to compensate.

The extension of this work and future research on early keratoconus modeling can include posterior corneal surface effects and the development of methods of detection of KC in early stages for effective new treatment options.

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