CANADIAN OPTOMETRIC CONTACT LENS SOCIETY
La SOCIETE OPTOMETRIQUE CANADIENNE des LENTILLES CORNEENNES

The CALS Lens: Optical and Perceptual Considerations in Aspheric Topography

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Abstract

When aspheric surfaces are applied to the eye in the form of contact lenses, both optical and perceptual factors must be considered in vivo. Various clinical and theoretical articles are reviewed and limits established for perceptual factors such as tolerance to retinal defocus in the normally aberrated eye. The range of asphericity (k) and eccentricity (e) required to optically correct for presbyopia and astigmatism is predicted for given pupillary radii. The topography of the CALS aspheric front surface is shown to be within the predicted range. Several factors of fitting and lens design are discussed with respect to a previous clinical study of the CALS soft lens.

Abrégé

L'utilisation d'une lentille contact à surfaces asphériques exige la considération de facteurs tant optiques que perceptuels. Ce travail examine certains articles cliniques et théoriques ayant servis à l'établissement de limites pour ces facteurs perceptuels tel la tolérance d'une image retinienne brouillée dans un oeil normal mais ayant les aberrations usuelles. Le degré d'asphéricité et d'excentricité requis pour la correction de la presbytie et l'astigmatisme, est prédit pour des diamètres determinés de la pupille. La topographie de la surface antérieure de la lentille CALS est démontrée comme étant dans les limites prédites. On discute certains aspects des parmètres et de l'ajustement en marge d'une étude antérieure de cette lentille.

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Kaplan[1] proposed an aplanatic hard contact lens with a front paraboloid surface which theoretically corrected for spherical aberration. He theorized that spherical aberration was the major contributor of Seidel's aberrations to the circle of least confusion on the retina. This aplanatic contact lens, Kaplan postulated, improved the visual performance of the eye by creating an optical system where the size of the disc of confusion for distance fixation equals that for near fixation. This new optical system limited the size of the disc of confusion, presbyopia and astigmatism not withstanding. Kaplan[2,3] further stated that the limit of visual resolution was defined more by the separation and neural organization of the retinal receptors and visual pathways than by the quality of the retinal image.

Remole[4] discussed the resolution limit of the receptor mechanism in terms of spatial frequency versus border enhancement and its effect on sensitivity to retinal defocus. The conclusions indicated that the receptor mechanism functioned in the near-focus (minimal defocus) range of ±0.50 D. by interacting with the effects of spherical aberration to decrease sensitivity to retinal defocus. This range was explained if the spatial frequency threshold depended more upon the central maximum intensity than the total diameter or spread of the blur circle. These results described a blur circle tolerance in the human visual system mediated by the receptor mechanism of approximately 1.00 D.

Reduction of blur circle size or changes in the intensity distribution within the blur circle itself alters visual resolution. Wichterle[5] theorized an optical model wherein this intensity distribution at the retinal level was centrally maximized by aspheric contact lenses. Assuming a diffraction limited optical system, he predicted that spin cast back aspheres (which vary from .7 to .9 in eccentricity) in effect extended accommodation or retinal defocus by 0.50 to 1.00 D. without any damage to image sharpness. Further, Wichterle suggested, that production of front aspheres would extend the range of eccentricities and the dioptric effects achievable.

Hard contact lenses which employed aspheric curves were investigated by Goldberg[6] (VFL1 and VFL2 lenses) and Kerns[7] (Neefe's Panofocal lens). These hard lenses have been produced in front, back and biaspheric forms. Most investigators[1,2,5,6,7] have agreed that elliptical, parabolic and hyperbolic eccentricities were of theoretical value in compensating for residual astigmatism, presbyopia and aphakia respectively. Kerns[7] clinically investigated the Panofocal lens and found that this front aspheric (elliptical) hard lens significantly increased visual acuity and efficiency over a spherical hard lens in cases of residual astigmatism of 0.50 to 1.75 D.

Bauer[8] investigated the longitudinal spherical aberration of soft contact lenses by comparing Bausch & Lomb spin-cast (elliptical base curve) to lathe-cut (spherical base curve) polymacon lenses. The spherical aberration of the spin-cast soft lenses was significantly smaller than that of lathe-cut lenses in air but was dependent on back vertex power and also varied with lens series (U_3 and U_4). The maximum spherical aberration tolerable by the visual system was theoretically calculated and clinically investigated to be approximately 0.25 to 0.75 D. at a 2 to 3 mm. pupil radius. These values were chosen because at pupillary radii less than 2.0 mm. diffraction was the major factor controlling resolution and at lower levels of illuminance or radii greater than 3.0 mm., visual acuity decreases and the eye can tolerate rather large aberrations.[8]

Campbell[9] commenting on Bauer's study, pointed out that once the contact lens is placed on the eye it is the characteristics of the front surface (and not the base curve) which determine the spherical aberration of the eye - lens optical system. This is obvious because of the significantly larger differential in refractive indices at the air - lens interface compared to the lens-tear interface.[9] There were two additional limitations of a back aspheric contact lens. Firstly since the aberration characteristics of spin cast lenses were dependent on back vertex power and varied with series (U_3 and U_4),[8] this then imposed limitations in providing the best fit and/or vertex power for the eye. Secondly, according to Wichterle,[5] the amount of eccentricity achievable with spin cast back aspheres, even in air, was limited and could only be increased by the addition of a front aspheric surface.

Consideration of the optical limitations of the eye - contact lens system by diffraction and spherical aberration and the perceptual characteristics exhibited by the receptor mechanism led to the development of the CALS soft lens (a front asphere with a spherical base curve). The topography of the CALS front surface was developed empirically in accordance with production techniques. The clinical effectivity of the CALS lens has been demonstrated in a recent study.[10] This effect may be understood if, as suggested by Remole[4], there is a 1.00 D. (±0.50) range of desensitivity of retinal defocus (blur circle tolerance) in the aberrated visual system. Bauer[8] accounted for 0.25 to 0.75 D. of this range as tolerance to spherical aberration. Wichterle[5] and Bauer[8] concluded that back aspheric contact lenses exhibited reduced spherical aberration in air. Furthermore, Wichterle[5] suggested that the eccentricity of a contact lens can be modified to correct for optical aberrations beyond the amount achievable with spin cast back aspheres by increasing the eccentricity of the front surface to result in eccentricity values of e >.9. If the CALS soft lens corrects the eye for its optical defects, both ammetropic and aberrated, then the 1.00 D. range of blur circle tolerance may be utilized and extended by variations in eccentricity to correct for presbyopia and astigmatism. The author's explanation of CALS clinical effects[10] (unlike the Wichterle model[5]) assumes some residual accomodation on the part of the eye to aid centration (with respect to the retinal plane) of the zone of clear vision thus created.

It is the purpose of this article to describe CALS lens topography in terms of its asphericity (k) and its eccentricity (e) and to show these values to be within the theoretical range suggested by the various authors reviewed to be effective in correcting the eye-lens optical system for diffraction and spherical aberration. Emphasis is given in the discussion to aperture radii of 1.5 to 3.5 mm. which expands the range suggested by Bauer[8] to include an area in the diffraction limited pupillary zone. The topography of the entire optic zone is presented as is a discussion of various factors of fitting and lens design and their effect on eccentricity.

Methods and Calculations

The front suface of a CALS lens is lathe-cut and is defined by an equation which describes an aspheric locus of points in polar coordinates[11].

$$\rho = r_0 + kr_0 \left(\frac{1 - \cos\theta}{1 + \cos\theta}\right) \quad (1)$$

which can be written

$$\rho = r_0 + \Delta r_0 \quad (2)$$

$$\text{where } \Delta r_0 = kr_0 \left(\frac{1 - \cos\theta}{1 + \cos\theta}\right)$$

r_0 = central radius of a spherical surface when θ = zero

k = an asphericity constant

θ = the angular sub tence of ρ with the x-axis

ρ = the distance between the focus and a point on the curve (see figure 1)

Bennett[12,13] discusses a formula which may be used to calculate the eccentricity of a conic section.

$$p = \frac{2r_0 x - y^2}{x^2} \quad (3)$$

x = sagittal depth of a conic section

r_0 = central radius

$p = 1 - (e)^2$, in which e = eccentricity

y = aperture radius

(see figure 1)

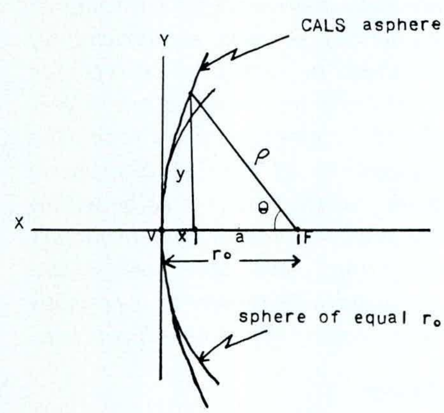

Fig. 1.

A CALS aspheric surface showing its sagittal depth (x).

$a = (\cos\theta)\,\rho \qquad y = (\sin\theta)\,\rho \qquad x = r_0 - a$

$\rho = r_0 + kr_0 \left(\frac{1 - \cos\theta}{1 + \cos\theta}\right)$

The value of ρ can be calculated from equation (1) given θ, k and r_0. Since from figure 1, a = (cos θ) ρ and y = (sin θ) ρ, then given ρ both a and y may be derived. Since FV = r_0 and x = r_0 - a, then x can be derived given r_0 and a. Therefore the eccentricity of the CALS asphere can be calculated using equation (3). This mathematical approach describes an aspheric curve as a series of conic sections of equivalent sagittal depth. This method is analogous to the commonly used calculations in optical design which describe a conic section as a series of circles of

Table 1

Values of ρ, k, e, y (aperture radius) and the hydrated radius of the front curve of the CALS lens (r_0 when $\theta = 0$).

r_0 (mm.)	θ degrees	k	ρ (mm.)	y (mm.)	Δr_0 (mm.)*
8.57	35	0.015	8.5828	4.92	0.0128
8.37	35	0.015	8.3825	4.81	0.0125
8.17	35	0.015	8.1822	4.69	0.0122
9.90	35	0.015	9.9148	5.69	0.0148
9.63	35	0.015	9.6444	5.53	0.0144
9.36	35	0.015	9.3740	5.38	0.0140
8.37	35	0.030	8.3950	4.82	0.0250
8.37	35	0.045	8.4074	4.82	0.0374
8.37	35	0.060	8.4199	4.83	0.0499
8.37	35	0.075	8.4324	4.84	0.0624
8.37	25	0.015	8.3762	3.54	0.0062
8.37	20	0.015	8.3739	2.86	0.0039
8.37	15	0.015	8.3722	2.17	0.0022
8.37	10	0.015	8.3710	1.45	0.0010

* $\rho = r_0 + \Delta r_0$ (2) therefore $\Delta r_0 = \rho - r_0$

equivalent sagittal depth and radius.[12,13,14] (see appendix)

Results

Table 1 shows variations in ρ, aperture radius (y), and Δr_0 for constant and varying values of r_0, k and θ. Table 2 demonstrates the effect on eccentricity (e) of variations in θ, k, r_0, base curve and central power (F_0). It can be seen that ρ varies directly with θ, k and r_0. Eccentricity is unaffected by variations in central power, base curve and central radius, but is increased by increasing k or decreasing θ.

Discussion

It must be remembered when discussing numerical values of eccentricity, that with a soft lens which conforms to the corneal curvature the corneal eccentricity is a participant in the resultant or summation eccentricity of the CALS lens on the eye and that the eccentricity of the CALS front surface varies inversely with aperture size.

Table 2 indicates a change in eccentricity (e) with θ. This points out that the CALS front surface is not a conic section, but that its eccentricity increases toward the centre of the lens, as described by equation (1). It is seen from Tables 1 and 2 that Δr_0 with decreasing values of θ reaches the order of magnitude of microns (θ = 10 degrees, y = 1.45mm., r_0 = 8.37mm., Δr_0 = .001mm. = 1 micron, e = 1.0). Thus, the CALS front surface is an aspheric curve resembling (within fractions of microns) the conic sections. Figure 2b demonstrates that the conic sections (circle, ellipse, parabola and hyperbola) are similar in asphericity near the x-axis.

The cornea has been described[6,14] as an aspheric curve resembling an ellipse of between .5 and .6 eccentricity. Holden and Zantos[15] discuss a pattern of three point contact to describe the conformity of soft lenses fitted flatter than the corneal curve: (1) a central area 8 - 9mm. wide; (2) vaulting over the limbus; and (3) contact at the periphery of the lens with the conjunctiva covering the sclera (Figure 2a). The degree of non-conformity of soft lenses fitted in this way was proven to be very small in area (1). Increased lens thickness and decreased water content had the effect of increasing non-conformity.

Only in the case of total non-conformity of the CALS to the corneal curvature could the resultant eccentricities be equal to the values

Table 2

Values of eccentricity (e) calculated for various values of θ, k, r_0, F_0 and B.C.R. F_0 is the hydrated central power. B.C.R. is the hydrated back curve radius. The first six lenses represent the CALS fitting set.

F_0 (D)	B.C.R. (mm)	r_0 (mm)	θ degrees	k	e
+3.00	9.35	8.57	35	0.015	0.30
+3.00	9.10	8.37	35	0.015	0.30
+3.00	8.86	8.17	35	0.015	0.30
–3.00	9.35	9.90	35	0.015	0.30
–3.00	9.10	9.63	35	0.015	0.30
–3.00	8.86	9.36	35	0.015	0.30
+3.00	9.10	8.37	35	0.030	0.43
+3.00	9.10	8.37	35	0.045	0.53
+3.00	9.10	8.37	35	0.060	0.62
+3.00	9.10	8.37	35	0.075	0.70
+3.00	9.10	8.37	25	0.015	0.41
+3.00	9.10	8.37	25	0.030	0.59
+3.00	9.10	8.37	25	0.045	0.73
+3.00	9.10	8.37	25	0.060	0.84
+3.00	9.10	8.37	25	0.075	0.95
+3.00	9.10	8.37	20	0.015	0.51
+3.00	9.10	8.37	15	0.015	0.67
+3.00	9.10	8.37	10	0.015	1.00

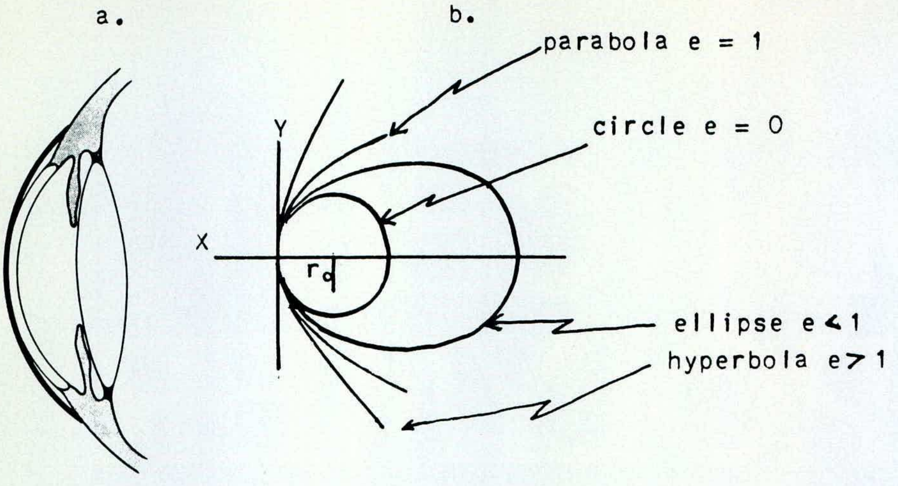

Fig. 2.

a.: Schematic representation of the 3-point contact fitting from Holden [15].

b.: Relationship of conic sections and their similarity near the x-axis having all the same r_0.

calculated in Table 2. In the case of total conformity the resultant eccentricities would be a sum of the corneal and the CALS eccentricities. The final product of this summation remains unknown and theoretically complicated by variability in corneal topography and changes in CALS eccentricity with aperture size. Given, from tables 1 and 2, k = .015, aperture radii less than y = 2.86 mm., e = .51, and assuming a high degree of conformity to corneal curvature (e = .5 to .6), the CALS aspheric front curve in vivo can be reasonably expected to exceed e = .9. At aperture radii less than 1.45 mm., e = 1.0, (again assuming minimal increments in eccentricity due to summation with the host cornea) the eccentricity of the CALS front surface in vivo would be hyperbolic. Interpolation of the Wichterle model[5] predicts that a hyperbolic contact lens (e = 1.2) would in effect extend accommodation or desensitivity to retinal defocus by 1.75 to 2.00 D.

Garner[16] discussed a model for calculation of the sagittal depth of the anterior eye, taking into consideration corneal and scleral asphericity as well as corneal diameter. These calculations indicated that soft lenses fitted on a semi-scleral basis tended to decrease in sagittal depth when applied to the eye and that increasing base curve radius (B.C.R.) decreases the differential between anterior eye and contact lens sagittal depth. It is this differential in sagittal depth which determines the amount and direction of soft lens flexure on the eye. The procedure of increasing B.C.R. until optimal visual acuity is achieved (an established CALS clinical routine[10]) decreases the magnitude of flexure. It is the author's opinion that increasing B.C.R. tends to increase the conformity of the CALS lens to the corneal curvature.

Having discussed variation in B.C.R. the second variable most often considered clinically, is diameter. The major effect of variations in diameter of the CALS lens would be in centration of the lens with respect to the visual system. There is considerable difficulty in assessing the effect on flexure of diameter alone. There are many factors which will act in concert to affect flexure and non-conformity such as diameter, lens thickness and power, water content, peripheral curve design (radius and width), and even lens coating due to tear instability.

The CALS lens has been shown to be successful using a standardized fitting criterion and clinical routine[10] in 85% of cases with k = .015 in presbyopia and/or astigmatism up to 2.00 D. Two cases of altered k values were shown in the appendix of a previous article[10]. Asphericity constants of up to k = .0675 were used to fit up to 4.00 D. of spectacle cylinder successfully. The third case in the appendix deals with more than 20.00 D. of myopia with 2.00 D. of astigmatism successfully fitted using k = .015. This demonstrates that the effect of lens power on flexure seems to clinically require little change in k values. The conclusions reached in the previous article clearly indicate that variations in B.C.R. with standard k = .015 will be effective in the vast majority of cases. The pattern of variation of k (the asphericity constant) given constant B.C.R. values is beyond the scope of this article and is the subject of research in progress.

Conclusions

Values of eccentricity are derived for the CALS front surface which is an asphere of variable eccentricity. Eccentricity increases with increasing values of the asphericity constant k and decreasing aperture radius. At aperture radii from 1.45 to 2.86 mm. the calculated values of eccentricity are within the range theoretically predicted to be effective in controlling the optical aberrations of the eye. It is the author's opinion that increasing B.C.R. increases the conformity to corneal curvature of the CALS lens on the eye. Factors such as diameter, lens power and thickness, water content, peripheral curve design and even lens coating in the eye affect flexure and non-conformity and thus the resultant summation of the lens with corneal eccentricity. These theoretical complexities must be considered within the clinical context. The CALS lens was found to be clinically successful in 85% of cases using standard k values and a relatively non-complex fitting criterion and clinical routine[10].

Appendix

A conic section can be defined geometrically as the locus of a point which moves such that its distance from a given fixed point, the focus, bears a constant ratio to its perpendicular distance from a fixed straight line, the directrix[12]. This ratio is the eccentricity (e). In describing an optical surface a more relevant approach is to describe eccentricity in terms of sagittal depth and sagittal radius of curvature. The centre of curvature in any sagittal section is the intersection of the normal to the curve (at the point concerned) with the axis[13]. In Figure 3, AG is the sagittal radius at a point A on the curve and at a point B, BH is the sagittal radius. The distances AF and BF are equal to the entity ρ in the polar equation (1) for the CALS asphere. It can be seen from Figure 3 that ρ equals the radius of curvature only when $\theta = 0$ (r_0 = vertex radius). At all other points on an asphere the sagittal radius exceeds ρ and lengthens as the chosen point moves along the asphere from the vertex. By comparing figures 1, 2b and 3 it can be seen that increasing the asphericity constant, k, (equation 1) increases the magnitude of ρ and this has the effect of increasing eccentricity from elliptical ($e < 1$) to parabolic ($e = 1$), to hyperbolic ($e > 1$). Bennett[13] developed a formula to calculate the sagittal radius of curvature.

$$r_s = \sqrt{r_0^2 + (1 - p)\, y^2} \quad (4)$$

r_0 = central radius
$p = 1 - (e^2)$
y = aperture radius

Thus given r_0, e and y (which can be derived from equations 1 and 3) the sagittal radii of curvature of the CALS asphere can be calculated. As previously stated, this calculation compares the CALS asphere to a series of conic sections of equivalent sagittal depths and radii.

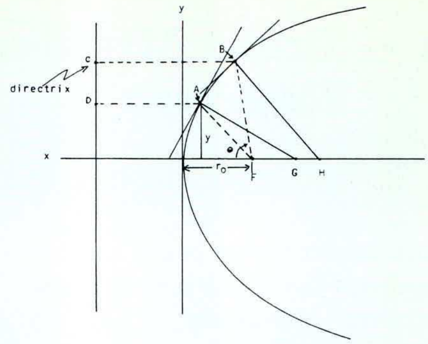

Fig. 3.

A sagittal section of an aspheric surface showing the sagittal radii of curvature at two points on the curve (AG and BH) where $e = \frac{AF}{AD} = \frac{BF}{BC}$ and $\rho_A = AF$, $\rho_B = BF$.

In summary: The eccentricity constant (e) of an aspheric curve is the ratio of ρ to the perpendicular distance from a point on the curve to the directrix. The asphericity constant (k) determines the rate of elongation of ρ resulting in the varying eccentricity of the CALS asphere. These factors in turn determine the rate of elongation of the sagittal radii derived from equation (4). Ultimately, it is this elongation of the radius of curvature which alters the vergence of light passing through the aspheric contact lens to correct the aberration characteristics of the eye-lens system. The eccentricity and asphericity constants are primarily mathematical entities which indirectly determine and describe the rate of change of the radius of curvature of an asphere. For the conic sections this is an accelerating change (with increasing aperture size) but for the CALS aspheric curve there is a relatively constant elongation of the radius of curvature due to the variation in eccentricity.

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