1040-5488/03/8009-0637/0 VOL. 80, NO. 9, PP. 637–643
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Simulated Optical Performance of Custom Wavefront Soft Contact Lenses for Keratoconus

JOHN DE BRABANDER, PhD, FAAO, NICOLAS CHATEAU, PhD, GILDAS MARIN, PhD, NORBERTO LOPEZ-GIL, PhD, EEF VAN DER WORP, BSc, FAAO, and ANTONIO BENITO, BSc

Eye Research Institute Maastricht, Department of Ophthalmology Academic Hospital, Maastricht University, The Netherlands (JdB, EvdW), Ocular Sciences, R&D International, Créteil, France (NC, GM), Laboratoria de Optica, Department of Physics, University of Murcia, Spain (NLG, AB)

ABSTRACT: *Purpose.* Outstanding improvements in vision can theoretically be expected using contact lenses that correct monochromatic aberrations of the eye. Imperfections in such correction inherent to contact lenses are lens flexure, translation, rotation, and tear layer effects. The effects of pupil size and accommodation on ocular aberration may cause further difficulties. The purpose of this study was to evaluate whether nonaxisymmetric soft contact lenses could efficiently compensate for higher-order aberrations induced by keratoconus and to what extent rotation and translation of the lens would degrade this perfect correction. *Methods.* Height topography data of nine moderate to severe keratoconus corneas were obtained using the Maastricht Shape Topographer. Three-dimensional ray tracing was applied to each elevation topography to calculate aberrations in the form of a phase error mapping. The effect of a nonaxisymmetric soft contact lens tailored to the corneal aberrations was simulated by adding an opposite phase error mapping that would theoretically compensate all corneal-induced optical aberrations of the keratoconus eyes. Translation (0.25, 0.5, 0.75, and 1.0 mm) and rotation (2.5°, 5.0°, 7.5°, and 10°) mismatches were introduced. The modulation transfer function (MTF) of each eye with each displaced correction and with various pupil sizes (3, 5, and 7 mm) was deduced from the residual phase error mapping. A single performance criterion (mtfA) was calculated as the area under the MTF over a limited spatial frequency range (5 to 15 periods per degree). Finally, the ratio (RmtfA) of corrected mtfA over uncorrected mtfA provided an estimate of the global enhancement in contrast sensitivity with the customized lens. *Results.* The contrast improvement ratios RmtfA with perfectly located lenses were for an average pupil size of 4.5 mm between 6.5 and 200. For small translation errors (0.25 mm), RmtfA ranged between 2 and 7. The largest lens translation tested (1 mm) often resulted in poorer performance than without correction (RmtfA <1). More than threefold improvements were achieved with any of the angular errors experimented. RmtfA values showed significant variations for pupil diameters between 3 and 7 mm. *Conclusions.* Three-dimensional aberration-customized soft contact lenses may drastically improve visual performance in patients with keratoconus. However, such lenses should be well positioned on the cornea. In particular, translation errors should not exceed 0.5 mm. Angular errors appeared to be less critical. It is further questioned whether the visual system is able to adapt to variations in optical performance of the correction *in situ* due to lens positioning and pupil size. (Optom Vis Sci 2003;80:637–643)

Key Words: eye, optical aberrations, keratoconus, soft contact lenses, custom refractive correction

As the first stage of the visual process, the main role of the eye is to focus images on the retina. The optical performance is usually related to the presence of optical aberrations and can be measured by various subjective or objective techniques.[1–4] One way to describe the characteristics of the human eye as an image-forming system is to express its optical transfer function. For most optical systems it is not difficult to obtain a complete description of the optical transfer function, including characteristics on transfer of modulation (MTF) and phase and the ability of the system to image point sources (point-spread function) or lines (line-spread function) at any wavelength and any angle of incidence.[5] Furthermore, in optical systems, the analysis can usually be made from both sides of the system, and test objects, sensors, and apertures can be manipulated as desired.

Measurements on the eye are restricted in many ways. Most important is that the eye can only be assessed from one side, and the *in vivo* sensor is the retina connected to the brain. This means that one has the option of testing subjectively, which incorporates the unknown neural-transfer function, or analyze the light that returns out of the eye after reflection on the retina (so called double-pass techniques), which introduces several uncertain factors in predicting visual performance.[6] Also, the eye is not a stable optical system because both the optical power by accommodation and the aperture by pupil dynamics vary with circumstances or environment. Another major complication in measuring the aberrations of the eye is the fact that it is a physiological system, which expresses in variation of chromatic aberration with age,[7] hydration and condition of the tissues,[8] and disturbance of the tear film.[9]

It is not surprising, therefore, that if normal eyes are considered an optical system, even monochromatic aberrations vary substantially in order and magnitude among individuals.[1, 10] Although most authors found similar trends in the influences of refractive error,[11] accommodation,[12, 13] and pupil size[14, 15] on monochromatic eye aberrations, they typically also indicated that these trends are not valid for all patients if subjectively assessed. These findings make it difficult to relate principles that have proven to work in the technical design of optical systems to a flexible biological system as is represented by the eye-brain complex. A typical example of the complexity of the monochromatic aberration effects on vision is the application of multifocal contact lenses.[16, 17]

Despite the above, it is clear that the corneal shape[18] (actually the tear film on it) represents by its interface with air the main refractive surface of the eye and, therefore, is largely responsible for optical aberrations.[19, 20] The extreme deformation of corneal shape as is present in keratoconus degrades the retinal image to a degree that makes normal visual functioning impossible. Optical correction of the keratoconus eye with spectacle lenses is difficult because this mode is limited to correction of only the lower-order optical aberrations of defocus and regular astigmatism. Therefore, rigid corneal and scleral contact lenses are widely used to correct the keratoconus eye.[21, 22] The principle behind these aids is that the irregular corneal surface is replaced by the regular anterior surface of the contact lens. The tear layer between cornea and posterior lens surface reduces the aberrations because its refractive index is closer to that of the cornea and the corrective contact lens. However, usually the front surface of the corrective rigid contact lens is spherical. It has been demonstrated in normal eyes that such a surface would induce spherical aberration rather than correct it.[19, 23–26] Furthermore, the movement of a rigid corneal contact lens on the irregular-shaped cornea in advanced cases of keratoconus produces asymmetric refractive surfaces and, consequently, coma-like aberrations.[27–30]

The use of regular soft contact lenses on keratoconus eyes, even if these include correction for astigmatism (toric lenses), is not very successful because the flexibility of the lens makes it deform to match the irregular cornea.[31] Even if this were not the case, regular toric lenses only compensate the lower-order aberrations.

Attempts have been made to combine the advantages of soft and rigid contact lenses in one lens[32] or with a system known as "piggyback,"[22, 33, 34] in which a rigid lens rides on a soft lens *in situ*. Although these modes can be successful in terms of comfort and visual correction of lower-order aberrations, the problem of correcting the severe higher-order aberrations in cases like keratoconus remains.

Outstanding improvements of vision can theoretically be expected using contact lenses with custom three-dimensional shapes that correct all optical aberrations of the eye. However, this is only possible assuming that the perfect correction is present under all circumstances. Rigid contact lenses bear the inherent problem of substantial movement and rotation, whereas normal soft contact lenses would be imperfect due to lens flexure. However, it has been indicated that soft lens flexure only plays a minor role in inducing optical aberrations given a perfect match to the cornea.[35] In this case, the aberrations of the lens perfectly add to those of the eye, and the resulting wavefront is almost only affected by the errors in the lens position. Furthermore, it has been found that although systematic correction of spherical aberration of soft contact lenses is of no use, it seems possible to correct spherical aberration individually.[36] It should be mentioned here that the effects of pupil size and accommodation on ocular aberration may introduce some extra difficulties.

Because severe optical aberrations are present in keratoconus, it is of interest to study to what extent visual function could be improved using custom wavefront nonaxisymmetric soft contact lenses. Studying the theoretical effects of translation and rotation of these aberration-customized soft contact lenses would give some insight in the practical feasibility of such corrective systems.

The purpose of this study was to theoretically evaluate whether nonaxisymmetric soft contact lenses could efficiently compensate severe optical aberrations induced with keratoconus and to what extent rotation and translation of the lens can degrade this perfect correction.

METHODS

Our methodology involved six successive steps (examples of the methodology in each step are given in Figs. 1 to 3).

Step 1: The corneas of nine patients with keratoconus were measured using the Maastricht Shape Topographer, a system based on Fourier profilometry.[36] The outcome of the measurement are x, y, and z values of the height topography that can be presented as a color-coded height map or as a cross-section profile (Fig. 1, top left).

Step 2: With the assumption that monochromatic aberrations were entirely due to the anterior shape of the cornea[19, 20] three-dimensional ray tracing was applied to each height topography map to calculate the aberrations in the form of a phase error mapping (Fig. 1, bottom left). Because the spherical defocus error cannot be predicted from corneal data alone (it also involves other optical components of the eye and eye length) the phase error maps were normalized for the spherical component of the measured corneal height data by ignoring the so-called "defocus" Zernike term.

Step 3: The effect of a nonaxisymmetric soft contact lens tailored to the corneal aberrations was simulated by adding an opposite phase error mapping. This would account for a perfect static correction of the optical aberrations of the keratoconus eyes. In this case, the total eye + contact lens phase error would be constant (not shown). To simulate the real situation on the eye, a rotational 2.5°, 5.0°, 7.5°, and 10° clockwise and counterclockwise or a translation of 0.25, 0.50, 0.75, and 1.0 mm in x and y direction mis-

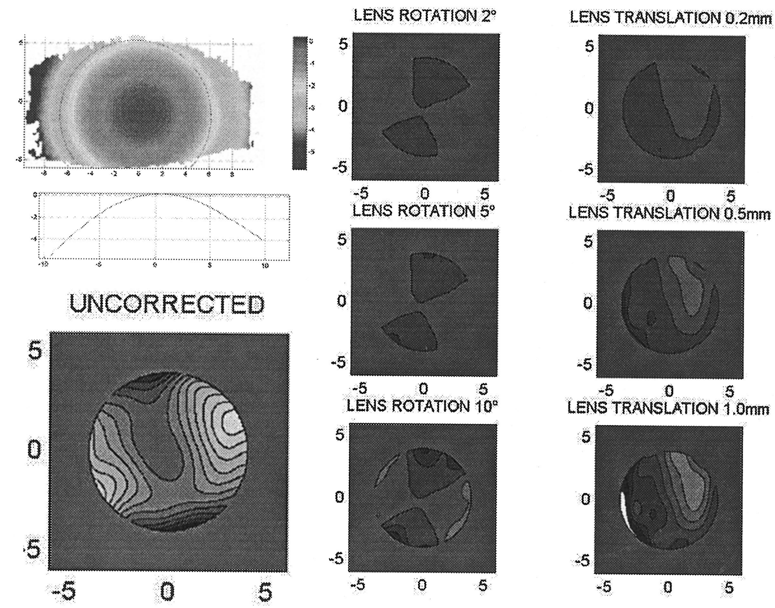

FIGURE 1.
Example of steps 1 to 3 used to compute wavefronts from corneal topography with effects of rotation and translation. From the corneal height topography (top left, height map and cross section), the uncorrected phase error map (bottom left) is obtained. The influences on a perfect correction of the phase error map are shown for various degrees of rotation (middle column) and translation (right column).

match of the surfaces was introduced. These errors were intended to account for the usual imprecision in positioning of a soft lens on the cornea due to movement and rotation with blinking. These factors are of physiological importance to ensure the circulation of tears between the cornea and the contact lens. Examples of the resulting phase error maps with the introduced rotations or translations are shown in Fig. 1, middle column and right column, respectively.

Step 4: The modulation transfer function (MTF) of each eye with each displaced correction was deduced from the residual phase error mapping. The MTF's were calculated for a wavelength of 550 nm incorporating the Stiles-Crawford effect.[37] This effect compensates for the different effects of energy transformation related to the angle of incidence of the optical rays approaching the retina. The same MTF calculations were repeated for pupil diameters of 3, 5, and 7 mm. Fig. 2 shows an example of the resulting data (one eye) in which the MTF's for uncorrected, perfectly corrected, and rotations (top) or translations (bottom) are displayed in one graph per assumed pupil diameter.

Step 5: A single performance criterion was calculated as the area under the MTF (mtfA) over a limited spatial frequency range (5 to15 periods per degree). These values were chosen to compare contrast sensitivity performance with and without correction of optical aberrations in low and high spatial frequencies relative to the sensitivity of the eye.

Step 6: Finally, the ratio of corrected mtfA over uncorrected mtfA (RmtfA) was computed using the integrals of MTF's between 5 and 15 periods per degree. This procedure is known as the "normalized area evaluation of image quality"[5] or "relative modulation transfer"[39] and helps to estimate the global enhancement in contrast sensitivity with the customized lens. Similar to Fig. 2, the results of computation of the RmtfA on one eye in the various situations are presented in Fig. 3.

RESULTS

The final results of the calculated RmtfA for all nine cases and an average pupil diameter of 4.5 mm are given in Table 1 for rotations and Table 2 for translations. The cases are listed in relation to the severity of the keratoconus according to the classification of Amsler[40] from moderate (case 1) to severe (case 9). For comparison, the second column in each table presents the RmtfA assuming a perfectly centered lens (perfect position). The contrast improvement ratios RmtfA with perfectly located lenses and for pupil sizes

TABLE 1.
RmtfA results for rotation.[a,b]

Case	Perfect Position	Rotation (degrees)			
		2.5	5.0	7.5	10.0
1	10.08	8.38	5.87	4.07	2.96
2	13.05	10.03	6.50	4.55	3.68
3	56.02	23.04	12.37	9.12	6.94
4	65.80	25.55	9.40	6.44	5.30
5	73.87	22.38	7.03	4.50	3.57
6	29.63	20.83	11.41	6.80	5.00
7	20.07	12.87	6.58	4.32	3.30
8	91.06	21.57	8.24	4.52	3.19
9	194.65	31.20	14.26	8.89	6.25

[a] Numbers in the table account for an average pupil diameter of 4.5 mm and are relative to RmtfA 1.0 in the uncorrected situation. Perfect position means zero rotation (perfect positioning of the lens). The RmtfA values are for each case given for 2.5, 5.0, 7.5, and 10 degrees of rotation and are pooled for (not significantly different) rotations clockwise and counterclockwise.

[b] RmtfA, ratio of corrected over uncorrected area under the modulation transfer function.

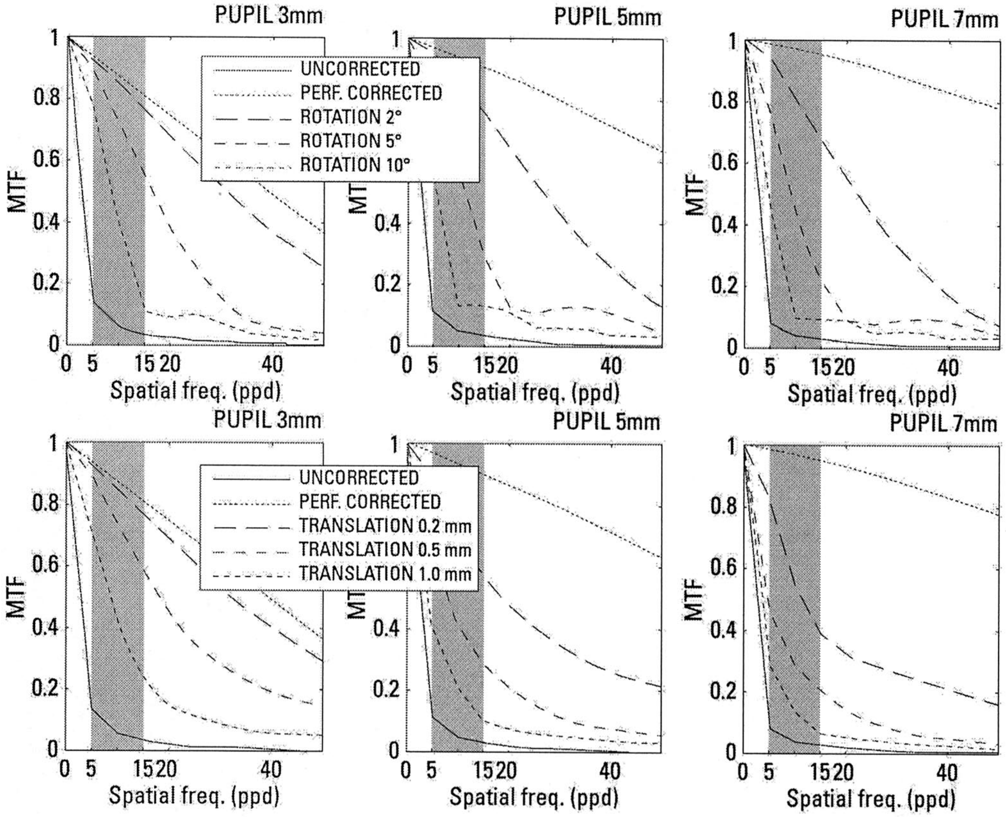

FIGURE 2.

Example of step 4 and 5 incorporating the computation of modulation transfer functions (MTF's) with induced rotation (top) and translation (bottom) for pupil sizes of 3 mm (left column), 5 mm (middle column), and 7 mm (right column). In each graph, the MTF is drawn for the situation without correction, with perfect correction, and with various amounts of rotation or translation. The shaded area between 5 and 15 periods per degree (ppd) was used to analyze the results relative to the sensitivity of the eye.

from 7.0 to 3.0 mm ranged between 6.5 and 195 with a median of 39.6.

The RmtfA for introduced rotations clockwise and counterclockwise and from 2.5 to 10.0° gradually declined in RmtfA with almost no difference between clockwise and counterclockwise rotations (maximum difference, 0.16). Even the worse case of 10° clockwise rotation and the largest pupil diameter (7.0 mm) still theoretically enhanced contrast sensitivity at a ratio of 2.8. The computed minimum and maximum RmtfA values for pupil sizes from 7.0 to 3.0 mm with the four conditions of rotation (2.5°, 5.0°, 7.5°, and 10.0°) ranged from 6.2 to 38.0, 5.3 to 15.9, 4.0 to 11.1, and 2.8 to 9.0, respectively.

The same analysis made for translations showed that (although there was more variation than with rotations) the differences between displacements in +, −, x, and y directions were small (maximum difference, 1.41). As with rotations, the RmtfA declined gradually with the increase in the amount of translation. Contrary to the effects of rotations, for translations above 0.5 mm and the extreme condition of a 7.0-mm pupil, the minimal RmtfA was <1, meaning theoretically that contrast sensitivity with such a lens in place would be worse than uncorrected. The computed minimum and maximum RmtfA values for pupil sizes from 7.0 to 3.0 mm with the four conditions of translation (0.25, 0.50, 0.75, and 1.00 mm) ranged from 2.0 to 6.5, 1.2 to 3.6, 0.81 to 2.5, and 0.4 to 2.0, respectively.

DISCUSSION

In this study of the theoretical enhancements that customized nonaxisymmetrical soft contact lenses could offer in visual functioning of severely aberrated eyes as in keratoconus, we found little variation in (RmtfA) results between the directions of rotation (clockwise and counterclockwise) or translation (+, −, x, and y direction) of such lenses simulated on the eye.

From the data in Tables 1 and 2, it is clear that translation affects the RmtfA more than rotation does. For the 4.5-mm pupil, 0.75 mm is a critical translation value to maintain RmtfA >1. With a larger pupil diameter (7.0 mm), translation should not exceed 0.5 mm to still benefit from the optical correction that the customized soft lens would give, including the most severe keratoconus of this study. This is just around the border of what has been established as a clinically efficient movement of soft contact lenses to avoid compromising tear circulation.[41]

In the dynamic situation of a soft contact lens on the eye, a combination of rotation and translation errors can be present. However, with the finding that directional differences in rotational and translation effects are low, it can be assumed that such a combination would not drastically change our results.

When compared to the much larger movements that are present with the application of rigid contact lenses, our results indicate that from a standpoint of correcting optical aberrations, customized

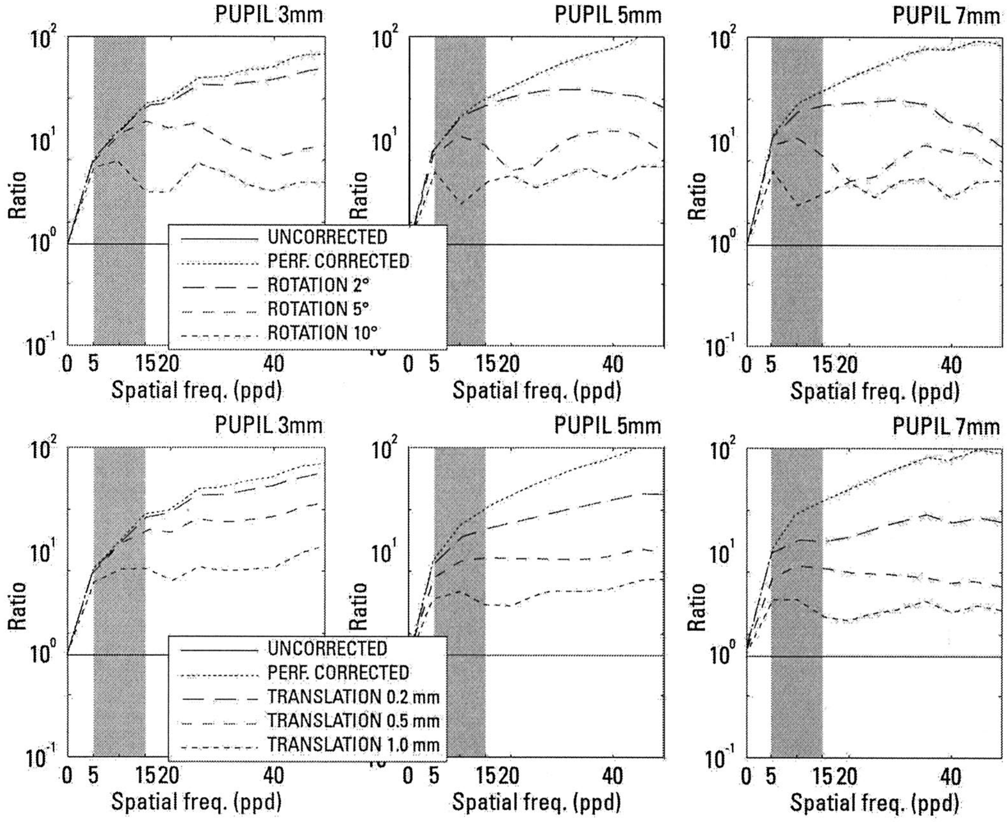

FIGURE 3.

Example of step 6 showing the computed contrast improvement ratios for rotation effects (top) and translation effects (bottom) for pupil sizes of 3 mm (left column), 5 mm (middle column), and 7 mm (right column). In each graph, the contrast improvement ratio for a spatial frequency range of 0 to 50 periods per degree (ppd) are given for the situation without correction, with perfect correction, and with various amounts of rotation or translation. The shaded area between 5 and 15 ppd was used to analyze the results relative to the sensitivity of the eye.

nonaxisymmetric soft contact lenses would be superior to rigid lenses. However, the question remains of how, in reality, the minor movement of nonaxisymmetric soft lenses with possible changes of their anterior shapes would balance the more pronounced movement but the more solid anterior surfaces of rigid lenses in optical performance.

Taking into consideration the criterion of Maréchal,[42] optics in normal young eyes even with 7 D of myopia, accommodation up to 3 D,[11] or in the presence of front-surface aspheric soft contact lenses[43] operate nearly diffraction limited at a pupil size of around 3 mm. In our calculations, assuming perfectly situated nonaxisymmetric aberration customized soft contact lenses, a nearly diffraction-limited correction could theoretically be obtained for pupil sizes up to 7 mm. This likely means that the retina becomes the limiting element of the entire optical system of the eye under the corrective circumstances we have computed. Due to the increased Strehl ratio,[5] which means a more efficient distribution of light energy in the image, contrast vision may even further be improved with such lenses *in situ*. On the other hand, our calculations were solely based on corneal topographic data and pupil size assuming a perfect centration of the pupil in relation to the topography. It has been shown that even a small pupil diameter of 1.5 mm can be critical in the optical system concerning pupil centration.[3] This could degrade the final image quality in real application of the nonaxisymmetric soft contact lenses as subject to our theoretical calculations.

In our computations of optical aberrations of the keratoconus eyes from the corneal topography, we could not include the effect of decentration of the pupil relative to the topography. These decentration effects could contribute to the aberrations that are present in the keratoconus eye. The question remains whether the results of rotation and translation errors would be significantly different if we could incorporate these effects into the original optical aberration data and compensate using the opposite phase error mapping.

We have found from our theoretical calculations that a perfect correction using nonaxisymmetric soft contact lenses in keratoconus eyes can be achieved. However, the computed improvements in image quality vary substantially among cases and, in particular, if we include the critical value of physiologically demanded translation respecting tear film exchange. Assuming the *in situ* application of axisymmetric soft contact lenses designed to theoretically compensate all ocular aberration of the eye, the interesting question is whether the neural-transfer function of the eye-brain complex in keratoconus eyes would be able to compensate (average) the variation in optical performance related to the temporary variation due to lens movement and pupil size or would be confused by it. There seems to be some similarity with the phenomena as encountered with the application of varifocal soft contact lenses,[17] in which a combination between the Stiles Crawford effect, the Strehl ratio, pupil size, behavior of the lens, and the individual neural-

TABLE 2.
RmtfA results for translation.[ab]

Case	Perfect Position	Translation (mm)			
		0.25	0.50	0.75	1.00
1	10.08	3.66	1.74	1.15	0.89
2	13.05	3.35	1.59	1.20	0.96
3	56.02	5.31	2.59	1.75	1.38
4	65.80	6.52	3.48	2.49	1.97
5	73.87	4.47	2.48	1.72	1.41
6	29.63	3.54	1.70	1.12	0.85
7	20.07	2.78	1.37	1.00	0.78
8	91.06	3.50	1.76	1.22	0.97
9	194.65	4.22	2.10	1.62	1.32

[a] Numbers in the table account for an average pupil diameter of 4.5 mm and are relative to RmtfA 1.0 in the uncorrected situation. Perfect position means zero translation in x and y direction (perfect centering lens). The RmtfA values are for each case given for translations of 0.25, 0.50, 0.75, and 1.00 mm and are pooled for (not significantly different) +, −, x, and y directions.

[b] RmtfA, ratio of corrected over uncorrected area under the modulation transfer function.

transfer function seems to play an important role in the visual satisfaction that is finally reported by the individual patient.

The Amsler[40] classification on which the cases in our study were ranked in severity (ranked 1 to 9 in Tables 1 and 2) shows weak relation with our data on RmtfA in the perfect position (with the exception of cases 1, 2, 8, and 9). This means that central radius of curvature of the cornea and the distortion of keratometric mirrors are not adequate predictors of optical aberrations in keratoconus. This is in accordance with clinical practice and with studies of the visual outcome with contact lenses to correct keratoconus, which vary substantially among subjects in relation to corneal parameters.[44–50]

Recently, Guirao et al.[51] computed the residual aberrations that appear as a result of translation or rotation on an otherwise ideal correction in 10 normal eyes for which actual wave aberrations were obtained using a Shack-Hartmann sensor. In their study, they only report on one keratoconus case as an example. This is due to the present limitations of the systems to measure severely aberrated eyes with the normally used Shack-Hartmann technique. For this reason, we have computed the aberrations from corneal topographic data rather than made attempts to really measure it on the eyes. Despite this limitation of our study, the results of the two studies are comparable. This indicates that incorporating whole-eye aberration measurements would not have much influence on our results predicting the effects of rotation and translation using custom wavefront contact lenses for keratoconus. In practice, this would mean that in eyes that suffer from severe higher-order optical aberrations due to corneal problems (e.g., keratoconus, corneal transplants, and failures of refractive surgery), one could use corneal topography as a basis to design custom wavefront soft contact lenses. This conclusion is in accordance with the finding that regardless of the cause, corneas with increased wavefront variance showed a quantifiable decrease in visual performance that was pupil size dependent.[52] In normal eyes, the situation might be different because in these eyes, the contribution of corneal shape to the whole-eye aberrations can be lower. In eyes with high ametropia, it has been shown that systematic correction of spherical aberration of the contact lenses does not automatically lead to higher contrast sensitivity function.[36] In these cases, the measurement of individual whole-eye spherical aberration seems to be essential. However, in relation to induced rotation and translation errors of corrective lenses in high ametropia, we agree with Guirao et al.[51] that an individual selection of the aberrations to correct could be more beneficial than a systematic attempt to correct all aberrations.

In summary, three-dimensional custom wavefront nonaxisymmetric soft contact lenses may significantly improve visual performance in patients with keratoconus. However, such contact lenses should be positioned on the cornea within more severe tolerances than conventional contact lenses. More than threefold improvements were achieved with any of the angular errors considered, meaning that angular errors appeared to be less critical. Translation errors were more critical and should ideally not exceed 0.5 mm. Based on results of the present study, it can be predicted that patients suffering from severe keratoconus would probably benefit from correction with customized nonrotational symmetric soft contact lenses if the translation of the lenses can be limited to 0.5 mm and the retinal-brain system is able to adapt to the variations in presented optical images to the retina.[38]

ACKNOWLEDGMENTS

This study was part of the BRITE-EURAM project BE96-4608, Contact Lenses with Aspheric Asymmetric Surfaces (CLAAS) and supported by a grant from the European Commission. Preliminary results were presented as a poster at the 2001 Association for Research in Vision and Ophthalmology meeting.

Received October 24, 2002; revision received April 28, 2003.

REFERENCES

1. Howland B, Howland HC. Subjective measurement of high-order aberrations of the eye. Science 1976;193:580–2.
2. Charman WN. Wavefront aberration of the eye: a review. Optom Vis Sci 1991;68:574–83.
3. Artal P, Iglesias I, Lopez-Gil N, Green DG. Double-pass measurements of the retinal-image quality with unequal entrance and exit pupil sizes and the reversibility of the eye's optical system. J Opt Soc Am (A) 1995;12:2358–66.
4. Moreno-Barriuso E, Marcos S, Navarro R, Burns SA. Comparing laser ray tracing, the spatially resolved refractometer, and the Hartmann-Shack sensor to measure the ocular wave aberration. Optom Vis Sci 2001;78:152–6.
5. Smith WJ. Modern Optical Engineering: the Design of Optical Systems. New York: McGraw-Hill, 1966.
6. Losada MA, Navarro R, Santamaria J. Relative contributions of optical and neural limitations to human contrast sensitivity at different luminance levels. Vision Res 1993;33:2321–36.
7. Millodot M. The influence of age on the chromatic aberration of the eye. Albrecht Von Graefes Arch Klin Exp Ophthalmol 1976;198: 235–43.
8. Cohen SR, Polse KA, Brand RJ, Mandell RB. Humidity effects on corneal hydration. Invest Ophthalmol Vis Sci 1990;31:1282–7.
9. Guillon M, Styles E, Guillon JP, Maissa C. Preocular tear film characteristics of nonwearers and soft contact lens wearers. Optom Vis Sci 1997;74:273–9.
10. Brink van den G. Measurements of the geometrical aberrations of the eye. Vision Res 1962;2:233–44.

11. Collins MJ, Wildsoet CF, Atchison DA. Monochromatic aberrations and myopia. Vision Res 1995;35:1157–63.
12. Ivanoff E. About the spherical aberration of the eye. J Opt Soc Am 1963;46:901–4.
13. Schober H, Munker H, Zolleis F. Variations of aberration with accommodation. Opt Acta 1968;15:47–57.
14. Walsh G, Charman WN. Measurement of the axial wavefront aberration of the human eye. Ophthalmic Physiol Opt 1985;5:23–31.
15. Artal P, Navarro R. Monochromatic modulation transfer function of the human eye for different pupil diameters: an analytical expression. J Opt Soc Am (A) 1994;11:246–9.
16. Atchison DA, Thibos LN. Diffractive properties of the Diffrax bifocal contact lens. Ophthalmic Physiol Opt 1993;13:186–8.
17. de Brabander J, Chateau N, Molenaar H, Bouchard F. Presbyopia and contact lenses: a literature review and a clinical study. Contactologia 2000;22:99–108.
18. Mandell RB. Everett Kinsey lecture: the enigma of the corneal contour. CLAO J 1992;18:267–73.
19. Campbell CE. The effect of spherical aberration of contact lens to the wearer. Am J Optom Physiol Opt 1981;58:212–7.
20. Seiler T, Reckmann W, Maloney RK. Effective spherical aberration of the cornea as a quantitative descriptor in corneal topography. J Cataract Refract Surg 1993;19(Suppl 1):55–65.
21. Kok JH, Wagemans MA, Rosenbrand RM, von Mil C. Computer assistance in keratoconus lens design. CLAO J 1990;16:262–5.
22. Kok JH, van Mil C. Piggyback lenses in keratoconus. Cornea 1993; 12:60–4.
23. Westheimer G. Aberrations of contact lenses. Am J Optom Arch Am Acad Optom 1961:445–8.
24. Cox I. Theoretical calculation of the longitudinal spherical aberration of rigid and soft contact lenses. Optom Vis Sci 1990;67:277–82.
25. Hammer RM, Holden BA. Spherical aberration of aspheric contact lenses on eye. Optom Vis Sci 1994;71:522–8.
26. Atchison DA. Aberrations associated with rigid contact lenses. J Opt Soc Am (A) 1995;12:2267–73.
27. Oxenberg LD, Carney LG. Visual performance with aspheric rigid contact lenses. Optom Vis Sci 1989;66:818–21.
28. Carney LG. Is the quality of vision with contact lenses adequate? Not only adequate but often superior. Cornea 1990;9(Suppl 1):S16–9; discussion S23–4.
29. Forst G. Comparison of the movement of contact lenses with spherical and aspherical back surfaces. Contact Lens J 1990;18:129–32.
30. Campbell MC, Harrison EM, Simonet P. Psychophysical measurement of the blur on the retina due to optical aberrations of the eye. Vision Res 1990;30:1587–602.
31. Holden BA, Zantos SG. On the conformity of soft lenses to the shape of the cornea. Am J Optom Physiol Opt 1981;58:139–43.
32. Maguen E, Caroline P, Rosner IR, Macy JI, Nesburn AB. The use of the SoftPerm lens for the correction of irregular astigmatism. CLAO J 1992;18:173–6.
33. Massin M, Denis-Morere A, Ninine G. Keratoconus and contact lenses. Klin Monatsbl Augenheilkd 1976;168:24–32.
34. Soni PS, Gerstman DR, Horner DG, Heath GG. The management of keratoconus using the corneal modeling system and a piggyback system of contact lenses. J Am Optom Assoc 1991;62:593–7.
35. Lopez-Gil N, Castejon-Mochon JF, Benito A, Marin JM, Lo-a-Foe G, Marin G, Fermigier B, Renard D, Joyeux D, Chateau N, Artal P. Aberration generation by contact lenses with aspheric and asymmetric surfaces. J Refract Surg 2002;18:S603–9.
36. de Brabander J, Chateau N, Bouchard F, Guidollet S. Contrast sensitivity with soft contact lenses compensated for spherical aberration in high ametropia. Optom Vis Sci 1998;75:37–43.
37. Jongsma FH, de Brabander J, Hendrikse F, Stultiens BA. Development of a wide field height eye topographer: validation on models of the anterior eye surface. Optom Vis Sci 1998;75:69–77.
38. Stiles WS, Crawford BH. The luminous efficiency of rays entering the eye pupil at different points. Proc Roy Soc Lond (Biol) 1933;112: 428–50.
39. Charman WN, Voisin L. Optical aspects of tolerances to uncorrected ocular astigmatism. Optom Vis Sci 1993;70:111–7.
40. Amsler M. Early diagnosis and microsymptoms. Ophthalmologica 1965;149:438–46.
41. Terry RL, Schnider CM, Holden BA, Cornish R, Grant T, Sweeney D, La Hood D, Back A. CCLRU standards for success of daily and extended wear contact lenses. Optom Vis Sci 1993;70:234–43.
42. Born M, Wolf E. Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light, 5th ed. Oxford: Pergamon Press, 1975.
43. Cox I, Holden BA. Soft contact lens-induced longitudinal spherical aberration and its effect on contrast sensitivity. Optom Vis Sci 1990; 67:679–83.
44. Carney LG. Contact lens correction of visual loss in keratoconus. Acta Ophthalmol (Copenh) 1982;60:795–802.
45. Zadnik K, Mutti DO. Contact lens fitting relation and visual acuity in keratoconus. Am J Optom Physiol Opt 1987;64:698–702.
46. Carney LG, Lembach RG. Management of keratoconus: comparative visual assessments. CLAO J 1991;17:52–8.
47. Wilson SE, Klyce SD. Advances in the analysis of corneal topography. Surv Ophthalmol 1991;35:269–77.
48. Wicker D, Sanislo S, Green DG. Effect of contact lens correction of sine wave contrast sensitivity in keratoconus patients after penetrating keratoplasty. Optom Vis Sci 1992;69:342–6.
49. Edrington TB, Zadnik K, Barr JT. Keratoconus. Optom Clin 1995; 4:65–73.
50. Szczotka LB, Thomas J. Comparison of axial and instantaneous videokeratographic data in keratoconus and utility in contact lens curvature prediction. CLAO J 1998;24:22–8.
51. Guirao A, Williams DR, Cox IG. Effect of rotation and translation on the expected benefit of an ideal method to correct the eye's higher-order aberrations. J Opt Soc Am (A) 2001;18:1003–15.
52. Applegate RA, Hilmantel G, Howland HC, Tu EY, Starck T, Zayac EJ. Corneal first surface optical aberrations and visual performance. J Refract Surg 2000;16:507–14.

John de Brabander
Eye Research Institute Maastricht
AZM, Dept. of Ophthalmology
PO Box 5800
6202 AZ Maastricht
The Netherlands
e-mail: john.de.brabander@planet.nl