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ORIGINAL ARTICLE

Predicting and Assessing Visual Performance with Multizone Bifocal Contact Lenses

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ABSTRACT: *Purpose.* To investigate how bifocal contact lenses, when combined with the aberrations of the eye, will affect visual performance. Also, to investigate the relationship between the patient's predicted and actual visual benefit with bifocal contact lenses. *Methods.* The monochromatic aberrations of 16 subjects were measured and used to simulate visual quality with three bifocal contact lens designs. Actual and computed visual benefit was compared for an Acuvue bifocal contact lens in 5 of the 16 subjects. *Results.* Subjects were predicted to have either a bifocal response or an increase in depth of focus for all lens designs. Our subjects were predicted to have a decrease in visual benefit for distance viewing and a gain in visual benefit at near compared with not wearing a contact lens. We found a statistically significant association between our subjects' predicted and actual visual benefit with the Acuvue Bifocal contact lens ($r = 0.685$, $p = 0.008$). *Conclusions.* Bifocal contact lens designs, when combined with the aberrations of the eye, will not always provide bifocal vision. Visual quality with a bifocal contact lens can be predicted based on a patient's ocular aberrations. (Optom Vis Sci 2003;80:812–819)

Key Words: bifocal contact lenses, simultaneous vision, monochromatic aberrations, multifocal contact lenses, presbyopia

The United States has approximately 90 million presbyopes, and 45 million more Americans will become presbyopic in the next 10 years.[1] As the population of presbyopic Americans has increased, so has the number of people wearing bifocal contact lenses.[2] The Acuvue Bifocal, a disposable contact lens, first became available in 1999, leading to a 285% increase in new bifocal soft contact lens fits in the first year alone.[3] With this increased interest in bifocal contact lenses, many new questions have come about. Why are some patients satisfied with the vision provided by bifocal contact lenses and others very dissatisfied? In the effort to aid eye care providers in fitting bifocal contact lenses that will provide higher quality bifocal vision for the patient, one must consider the role of ocular aberrations on retinal image quality and how they interact with the contact lens. The ultimate goal would be that one could design, predict, or select the best bifocal contact lens for an individual based on their optical aberrations. First, we need to discuss the basic optical principles behind simultaneous vision bifocal contact lenses and how they interact with the aberrations of the eye.

Simultaneous Vision. Fig. 1 is a series of simple geometrical ray traces that illustrate the impact of a multizone contact lens on near and distant viewing for a perfect eye and an eye with aberrations. The simulated lens has three concentric rings with a center-distance zone. The perfect eye (Fig. 1 A to C) illustrates the intended bifocal response for the lens. When the perfect eye is viewing a distant object, there is a perfect in-focus image of the distant object formed by the distance prescription of the lens along with an out-of-focus image formed by the near prescription of the same distant object on the retina (Fig. 1B). The reverse applies when viewing a near object (Fig. 1C). A human eye has aberrations that do not allow for a perfect image to be focused on the retina (Fig. 1D). When an aberrated eye is viewing a distant object, there is an imperfect image of the distant object and an imperfect out-of-focus image of the same distant object formed on the retina (Fig. 1E). When the eye views a near target, there is an imperfect image of the near object and an imperfect out-of-focus image of the same near object formed on the retina. Neither optical zone of the contact lens provides a sharp image (Fig 1F). Furthermore, effective simultaneous-vision bifocal contact lenses rely on the out-of-focus image to be sufficiently blurred so that the out-of-focus image is reduced to a broad, low-frequency background, serving mainly to reduce image contrast. Fig. 1 shows that the intended effect of the lens is confounded with the aberrations of the human eye. With aberrations present, the retinal images from the near and distant focal zones are less different, and the potential benefits may be lost.

We hypothesize that the variability in the patient's response occur because their ocular aberrations interact with the aberrations

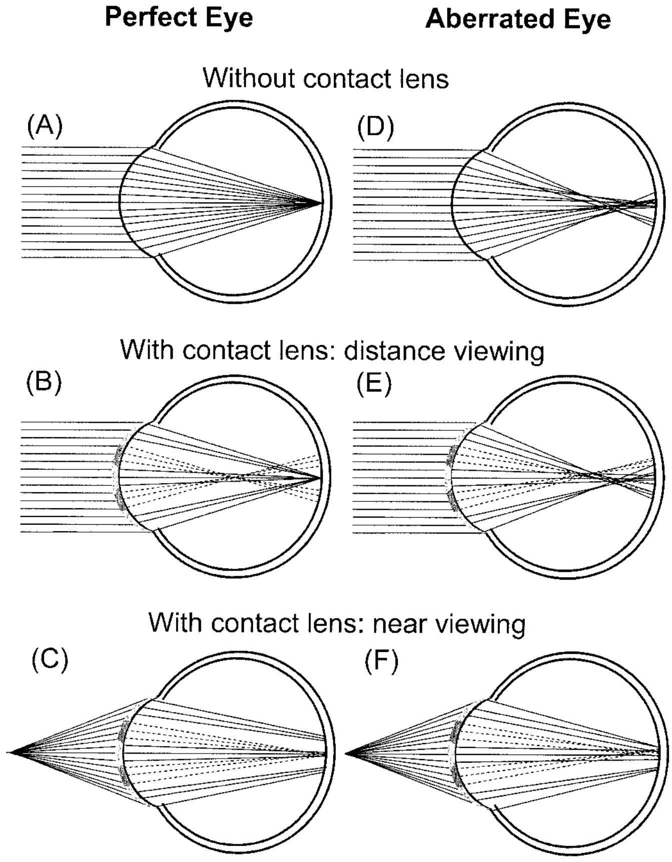

FIGURE 1.

A: Perfect model eye without a bifocal contact lens. B: Perfect model eye wearing a three-ring multizone bifocal contact lens viewing a distant object. C: Perfect model eye wearing a bifocal contact lens viewing a near object. D: Aberrated eye without a bifocal contact lens. E: Aberrated eye wearing a three-ring multizone bifocal contact lens viewing a distant object. F: Aberrated eye wearing a bifocal contact lens viewing a near object. The solid and dashed lines show rays passing through the distance and near zones of the contact lenses, respectively.

that are produced by changes in defocus of a multizone bifocal contact lens. The effect of these lenses on visual quality has been studied previously in the literature.[4–9] Previous models and psychophysical testing have determined that pupil size and lens decentration[5, 7, 9–12] play key roles in predicting a patient's visual quality while wearing bifocal contact lenses. None of the previous studies considered the role of aberrations, but several researchers[5, 8, 9] stated that the lack of consideration of the wave aberrations of the presbyopic eye limited their models. They felt that predicting the performance of bifocal contact lenses could be improved by evaluating optical aberrations of the human eye.

In this study, we used a model that combines the patient's optical aberrations with the optical properties of either of three bifocal contact lens designs and predicted visual performance. We also investigated the relationship between simulated visual quality based on monochromatic aberration measurements and measured visual quality of subjects wearing Acuvue Bifocal soft contact lenses.

METHODS

This research followed the tenets of the World Medical Association Declaration of Helsinki. Informed consent was obtained from the subjects after we explained the nature and possible complications of the study. Our experiments were approved by the University of Houston Committee for the Protection of Human Subjects.

Visual Quality Calculation Procedures

Subjects. Sixteen pre–presbyopic subjects participated in this study. Subject ages ranged from 23 to 34 years. The average age was 26 years. The subjects' spectacle corrections were restricted to ±2.00 D sphere with no more than −0.50 D of astigmatism. All subjects were correctable to 20/20 at distance and near. All subjects were healthy and had no ocular disorders.

Equipment. A Shack-Hartmann wavefront sensor was used to measure the monochromatic aberrations of each eye. The monochromatic aberrations were fitted with a 10th-order Zernike polynomial. This method has been previously described in detail.[13, 14]

Concentric-Ring Bifocal Contact Lenses. Three soft bifocal contact lenses with alternating zones of distance and near prescriptions were modeled in this study. Each contact lens modeled had a +1.50 D add power.

1. Acuvue Bifocal (Vistakon division of Johnson & Johnson Vision Care, Jacksonville, FL) with five concentric rings of alternating-zone, distance and near prescription and a 2-mm center-distance zone.
2. LL Bifocal (Lombart Lens division of Unilens, Largo, FL) with two concentric rings and a 2.25-mm center-distance zone.
3. SimulVue 38 (Unilens) with two concentric rings and a 2.35-mm center-near zone.

The outer radii of the Acuvue Bifocals were measured with a contact lens loupe and are estimates of the lens parameters that are not released by Vistakon. These lenses might have aberrations or design specifics that are unreported by the manufacturers. Nonetheless, our goal was to develop a model for lens performance, but not determine the particular performance of any of the lenses. For that reason, we opt to report the lenses as alternating-zone, center-distance and center-near in this paper.

Calculated Visual Quality. The optical properties of the eye while wearing the contact lenses were not measured experimentally. We did not measure the optical properties directly because a Shack-Hartmann wavefront sensor is capable of measuring only smooth continuous changes in a wavefront and is not designed to measure the sharp changes of aberration (or discontinuities) that are present in concentric-ring bifocal contact lens designs. Therefore, it is impossible to directly measure the effect of the contact lens *in situ* with the Shack-Hartmann sensor . The Shack-Hartmann method of wavefront sensing is limited because there is neither sufficient sampling density over the surface being measured nor is the Zernike polynomial of a high enough order to fit the discrete changes in defocus of the bifocal contact lenses. Rather, we opted for a numerical approach where we added the optical properties of the contact lens to the eye using custom-written Matlab software. The numerical approach can properly simulate the bifocal lenses because the discrete phase changes in the lens can be adequately represented provided that large matrix arrays are used. The numerical approach was as follows. First, the aberrations of the eye were written as a phase map in a 400 × 400 complex matrix. The phase profile of each contact lens was written into another complex matrix with the same dimensions and spatial scale. The regions of the lens with the distance correction were written with a constant phase, and the near-add portions of the lens were written as an appropriately curved wavefront. Fig 2 illustrates how the lens and eye wavefronts are added, although in the actual model, the wavefronts are represented as complex phase and not as simple height. To simulate objects at different distances, an additional defocused wavefront, mimicking that of the wavefront from a real (or virtual) object, was added. The Fourier transform of the complex phase map of the eye + lens + object vergence yields the point-spread function (PSF) for that particular viewing distance. In mathematical form (Equation 1), the pupil function, P(x,y) is:

$$P(x, y) = A(x, y)\exp\{-2\pi i[W_{eye}(x, y) + W_{lens}(x, y) + W_{object}(x, y)]\} \quad (1)$$

where $A(x,y)$ defines the area of the pupil (which is 5 mm in our case) and W_{eye}, W_{lens}, and W_{object} represent the wavefronts of the eye, lens, and object, respectively. Lopez-Gil et al.[15] showed that the total wave aberration of the eye wearing a soft contact lens is simply the sum of the two separate wave aberrations. Their technique involved applying contact lenses with known wave aberration profiles and measuring wave aberrations of the contact lenses on and off the eye.

Point-Spread Function and Strehl Ratio Calculation. A series of PSF's were computed for a nonaccommodating eye viewing objects at different distances for each subject with and without a contact lens. Fig. 3 includes a series of PSF's and 20/20 letters blurred by the corresponding PSF for a perfect model eye without a contact lens and with an alternating-zone contact. The Strehl ratio was calculated from each computed PSF.

The Strehl ratio, which is a measure of the sharpness of the retinal image, is defined as the ratio of the peak intensity of a human eye's point-spread function, to the peak intensity of the point-spread function for a perfect eye, both having the same pupil size. The Strehl ratio has been shown to correlate with visual acuity.[16] A higher Strehl ratio corresponds to a higher quality retinal image.

The Strehl ratio was computed as a function of object vergences ranging from +0.50 D (distance) to −3.00 D (near) for a nonaccommodating eye with and without each bifocal contact lens design.

Modulation Transfer Function Calculation. To provide a more direct comparison to contrast sensitivity function (CSF) and simulated visual quality (see next section), the modulation transfer function (MTF) was computed using Matlab for vergences ranging from distance through the near add power. Calculating the MTF allows for a closer comparison to be made between simulated visual quality and actual visual quality because of the similarity in the CSF and MTF scales.[17] To reduce the data further, we opted to compute the area under the CSF (AUCSF)[18] or area under the MTF (AUMTF) to facilitate comparisons between objective and subjective measures.

Visual Quality Measurement

Contact Lens. The Acuvue Bifocal contact lens was the lens design used for all comparisons between simulated and actual visual quality measurements. All subjects were fitted in an Acuvue Bifocal contact lens with 0.00 DS, add +1.50 DS, 8.5 BC, and 14.2 OAD parameters.

Subjects. Five of the 16 subjects were randomly selected for visual quality measurements. To simulate presbyopia, one drop of cyclopentolate hydrochloride 1.0% was instilled into the subject's eye. Pupil size was monitored, and cycloplegia was reported subjectively.

The subjects underwent a routine contact lens fitting and were examined to ensure a suitable contact lens fit. A slit lamp biomicroscope with a graticule was used to document lens centration, coverage, and movement. An over-refraction was then performed to determine the best spherical equivalent trial lens necessary to correct each subject's distance refractive error.

Contrast Sensitivity Function Measurement. Spatial CSFs were measured for all five subjects with and without an Acuvue Bifocal contact lens. Contrast thresholds were determined using the method of adjustment from nonseeing to seeing for spatial frequencies at 1, 2, 4, 6, 8, 12, 16, 20, and 24 cpd, with a mean luminance of 110 cd/m^2, field size of 3.3°, and a testing distance of 5.56 m. Horizontal sine-wave grating targets were generated using a VSG 2/3 board housed in a pc computer and monochrome monitor (Image Systems) with a frame rate of 239 Hz. The monochrome monitor had a peak luminance at 565 nm and a bandwidth of 90 nm. The monitor bandwidth, combined with the chromatic tuning of the spectral luminosity function of the eye,[19] minimized contrast losses that would normally occur because of the chromatic aberration in the eye. The subject's CSF was an average of four random-order trials for each spatial frequency.

CSF testing was performed for the right eye while viewing through a 5-mm artificial pupil mounted in the trial frame's lens well that was most adjacent to the patient. Each subject centered the artificial pupil with respect to the natural pupil of the viewing eye by ensuring that the display monitor always remained in the center of their field of view, which was limited to about 35° by the artificial pupil. Centration was aided by a large alignment cross that was marked at the furthest extent of the patient's field of view before the CSF testing. This alignment cross was placed so that it surrounded the display monitor. Subjects were instructed that proper alignment was achieved when equal extents of this cross were visible above, below, and to the right and left of the display monitor and that cross markings were always visible at the edge of the patient's field of view. A chin rest ensured that the subject's head position remained stable and thereby helped to maintain appropriate eye alignment during CSF testing. Each subject viewed the grating targets with and without the contact lens through the combination of trial lenses that provided the best spherical equivalent refractive correction. Random object vergences were induced with trial lens powers of the following amounts: 0.0, −0.75, −1.50, and −2.25 D.

RESULTS

Visual Quality Calculation

Model Eye. To better explain the results obtained from this experiment, it is best to first show the predicted outcome of a perfect model eye that is free of aberrations when wearing a concentric-ring bifocal contact lens. Fig. 4 shows a comparison of a perfect eye's predicted Strehl ratio as a function of defocus with

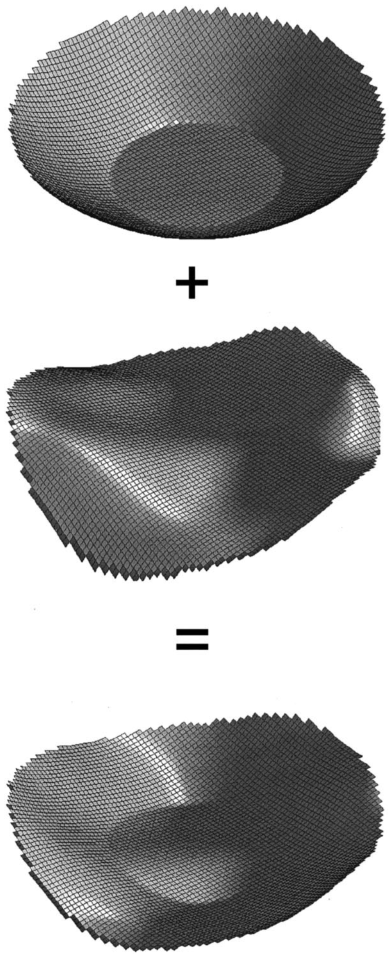

FIGURE 2.

Numerical method to add contact lens and eye aberrations. The upper wavefront shows the aberrations of a center-distance contact lens. The wavefront is flat in the central zone and has positive curvature at the margins. The second wavefront is a wave aberration plot from one of the subjects. The third wavefront is the sum of both the lens and the eye's aberrations. The central zone is no longer flat, but has assumed the shape of the subject's wave aberration.

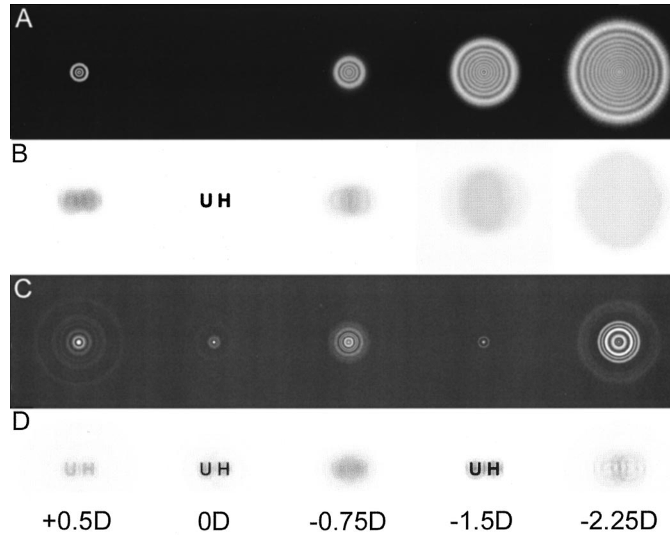

FIGURE 3.

A: Calculated point-spread function as a function of defocus for a model eye without a contact lens. B: 20/20 letters (5 min of arc per side) blurred by the corresponding point-spread function in (A) for each defocus value. The UH letters are legible only at 0.00 D defocus (distant viewing) without the bifocal contact lens. C: Calculated point-spread function as a function of defocus for a model eye wearing an Acuvue Bifocal contact lens. D: 20/20 letters blurred by the corresponding point-spread function in (C) for each defocus value. The UH letters are legible for both distant viewing (0.00 D) and near viewing (−1.50 D) but with less contrast and a noticeable halo around the UH letters compared with 0.00 D in (B).

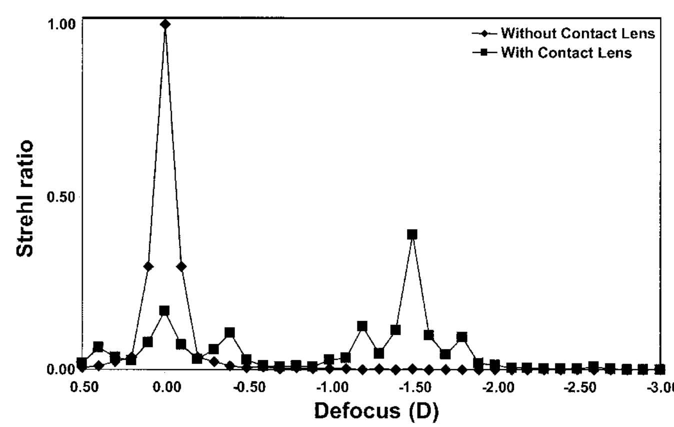

FIGURE 4.

Computed Strehl ratio as a function of defocus for a perfect model eye with and without an alternating-zone contact lens (5-mm pupil). The model eye without a contact lens had one main peak with a Strehl ratio value of 1.0 at 0.00 D representing clear vision for distant viewing only. The model eye with a contact lens had two main peaks for distant and near viewing conditions representing bifocal vision. The smaller peaks surrounding the two main peaks at 0.00 D and −1.50 D are due to diffraction of the point-spread function.

and without an alternating-zone contact lens. Without a bifocal contact lens, there is one large peak in Strehl ratio intensity at distance. This corresponds to a Strehl ratio of 1.0. When a perfect eye is wearing an alternating-zone contact lens, there are two main peaks in Strehl ratio at distance (0.00 D) and near (−1.50 D). The smaller peaks beside the main peaks in Strehl ratio are due to diffraction effects in the PSF as defocus changes. The predicted benefit gained in vision quality at near by wearing the bifocal contact lens comes at the cost of losing quality of vision at distance.

Predicted Visual Quality. A minimum criterion was set to determine whether a subject had either an increase in depth of focus or a bifocal response. To be considered a bifocal response, each peak in Strehl ratio at distance, 0.00 D, and near, −1.50 D, had to be at least 20% higher than the minimum in Strehl ratio between the two peaks at −0.75 D. Any subject who did not match the minimum criteria for a bifocal response was considered to have an increase in depth of focus. An increase in depth of focus was defined as an increase in Strehl ratio over an extended range of defocus.

Six subjects were predicted to have a bifocal response for all three lens designs. Four subjects were predicted to have an increase in depth of focus for all lens designs. Six subjects were predicted to have a mixed response of either depth of focus or bifocality for the three lens designs (Table 1).

Monochromatic Aberrations and Calculated Responses. The root-mean-square (RMS) of a wave aberration is a measurement of the magnitude of each subject's aberrations departure from a plane wavefront. Higher RMS values indicate that the overall amount of an individual's aberrations increases. Table 1 lists the predicted responses for all subjects compared with each subject's RMS wave aberrations without the defocus component or the contact lens in place. The defocus component of the patient's aberrations was assumed to be corrected by the bifocal contact lens. There was no trend between the subjects' RMS values and predicted responses based on the lens designs. Fig. 5 shows plots of the predicted Strehl ratio as a function of defocus for all three lens designs based on each subject's aberrations. In all cases, near vision was improved at the expense of a drop in Strehl ratio for distant viewing. The relative optical performance between distance and near vision depended on the particular contact lens design.

Visual Quality Measurement

Contrast Sensitivity and MTF. Fig. 6A shows that all five subjects had a decrease in AUCSF[18] as defocus increased when not wearing the bifocal contact lens. AUCSF was calculated from 1 to 24 cpd. This was the expected response because all subjects were cyclopleged and corrected for distance. While wearing the Acuvue Bifocal contact lens (Fig. 6B), responses were flatter relative to Fig. 6A. Four subjects demonstrated a decrease in contrast sensitivity at distance and an increase in average contrast sensitivity at near viewing.

Bifocal Benefit. To quantify the effect of the bifocal contact lens, we developed a relative measure of bifocal benefit. Bifocal benefit is based on the differences in the CSF or MTF for each subject with and without the Acuvue Bifocal contact lens (Equations 2 and 3).

$$BB_{calculated} = \frac{AUMTF_{\text{with contact lens}}}{AUMTF_{\text{without contact lens}}} \qquad (2)$$

$$BB_{actual} = \frac{AUCSF_{\text{with contact lens}}}{AUCSF_{\text{without contact lens}}} \qquad (3)$$

A bifocal benefit <1 represents a decrement in visual quality with the contact lens, and a bifocal benefit >1 represents an improvement in visual quality with the contact lens. The calculated bifocal benefit was determined for all five subjects based on the subjects' MTF values with and without the contact lens. Actual bifocal benefit was determined based on the subjects' contrast sensitivity with and without the contact lens. Bifocal benefit was determined for a range of vergence values from distance through the near add power.

Fig. 7A shows the predicted bifocal benefit of each subject. The darker line represents the average bifocal benefit for all five subjects. A bifocal benefit <1 is indicated by the shaded region in Fig. 7. All subjects were predicted to have a bifocal benefit <1 for distance viewing and a bifocal benefit >1 at near. Fig. 7B shows the actual bifocal benefit obtained for all five subjects. The subjects have similar results for their actual and predicted bifocal benefits. Both bifocal benefit values are >1 at near.

To compare the actual vs. predicted results, we plotted the correlation between the calculated bifocal benefit vs. the actual bifocal benefit (Fig. 8). We found a statistically significant association between our subjects' predicted bifocal benefit and actual bifocal benefit ($r = 0.685$, $p = 0.008$). The association between calculated and actual bifocal benefit allows for 47% of the subject's actual bifocal benefit to be predicted solely based on their calculated bifocal benefit ($r^2 = 0.469$).

DISCUSSION

Our contact lens simulations show that a bifocal contact lens does not guarantee bifocal vision. Some patients will obtain bifocal

TABLE 1.
The table shows the RMS of the wave aberration (defocus removed) for each subject along with the predicted responses, based on our computer model, for all three contact lens designs, alternating, center-distance, and center-near zone[a]

Subject	RMS	Alternating Zone	Center Distance	Center Near
PHB	0.156141	B[b]	B	B
TRM	0.335324	B	B	B
COW	0.326046	B	DOF	B
ANB	0.172100	B	B	B
AUR	0.309982	B	B	B
BRD	0.331908	DOF	DOF	DOF
ALT	0.333013	DOF	DOF	DOF
DAH	0.462427	DOF	DOF	B
AAR	0.220039	DOF	B	B
EEW	0.357913	DOF	DOF	B
GRG	0.292142	DOF	DOF	B
ANT	0.323547	DOF	DOF	B
BRK	0.378581	B	B	B
LIW	0.397418	B	B	B
MIR	0.330198	DOF	DOF	DOF
RET	0.312918	DOF	DOF	DOF

[a] RMS, root-mean-square.
[b] B indicates that there was a bifocal response and DOF indicates that there was no bifocal response but only in increase in the depth of field. The criteria for bifocal and depth-of-field responses are described in the text. There was no relationship between the subjects' RMS values and the predicted responses based on the three lens designs.

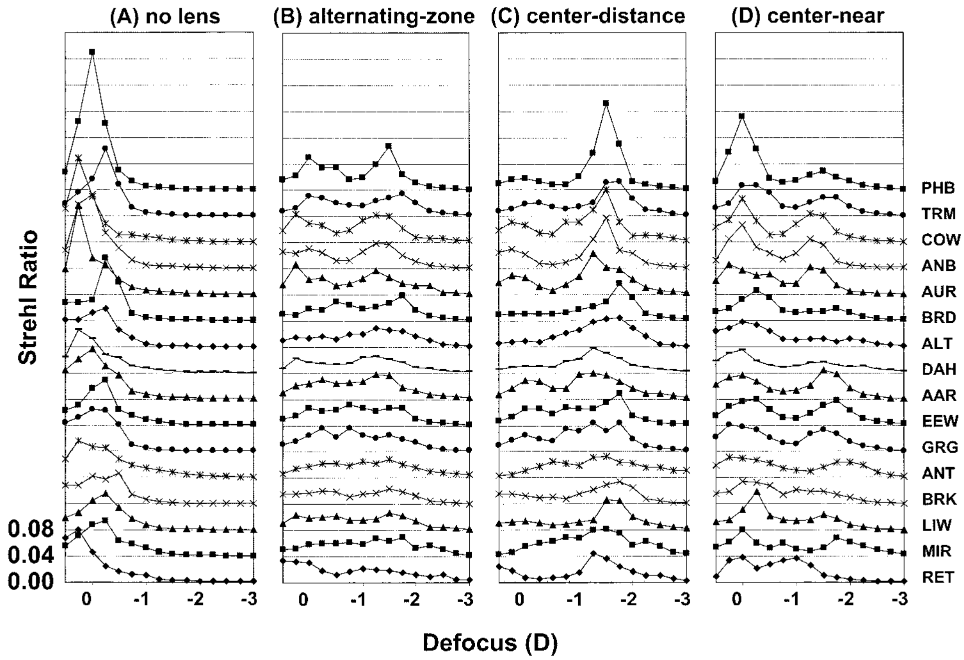

FIGURE 5.

Predicted Strehl ratio as a function of defocus for all subjects (A) without a contact lens or with an (B) alternating-zone, (C) center-distance, and (D) center-near contact lens design. The higher predicted Strehl ratio values at near for (C) center-distance zone design occurred due to the 5-mm pupil size used in simulations allowing for more light from the near correction portion of the lens in the image formation. The reverse also occurred for the higher predicted Strehl ratio values at distance for (D) center-near zone design.

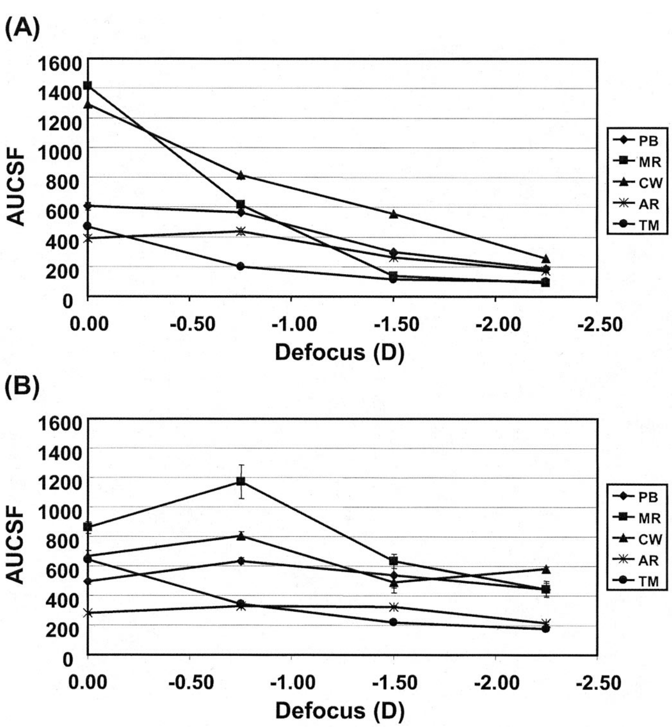

FIGURE 6.

A: Area under the contrast sensitivity function (AUCSF) for 1 to 24 cpd as a function of defocus for subjects not wearing a contact lens. B: AUCSF for 1 to 24 cpd as a function of defocus for subjects wearing an Acuvue Bifocal contact lens. Error bars represent ±1 SD.

vision with concentric-ring bifocal contact lenses, whereas others will experience an increase in depth of focus. Even though increasing the depth of focus of the eye might not be the intended effect of the lens, it is not necessarily a negative outcome for the patient. When we looked at the bifocal benefit only, we found that all of our subjects had improvements in near vision when wearing the bifocal contact lens. Our subjects experienced a bifocal benefit, even without bifocal vision. For example, although subject MR had higher than average aberrations and was predicted to have no bifocality from the lens, he demonstrated the largest calculated and actual bifocal benefit.

With an increase in depth of focus, the patient can have an increased range of moderately clear vision for the distances needed to function for most daily tasks. For example, a patient who has 20/25 to 20/40 distance, intermediate, and near visual acuity would be able to handle all but the most demanding tasks. The common phrase "20/happy" is often used to describe many bifocal contact lens wearers' vision[20] and could possibly be a good descriptor for a patient's satisfaction when experiencing an increase in depth of focus. Of course, many patients with high visual demands will need better visual acuity at distance or near. This could possibly explain why eye care providers are prescribing modified monovision in cases where the patient only has an increase of depth of focus with bifocal contact lenses.

This numerical model could be useful in the improvement or development of bifocal contact lens designs. The comparisons between predicted and actual visual quality demonstrated that part of the subjects' visual quality while wearing bifocal contact lenses can be predicted based on their aberrations. Analysis of the actual and calculated bifocal benefit shows that on average, our subjects had more net benefit gained at near from wearing the contact lens than was lost at distance. A bifocal contact lens design that would have

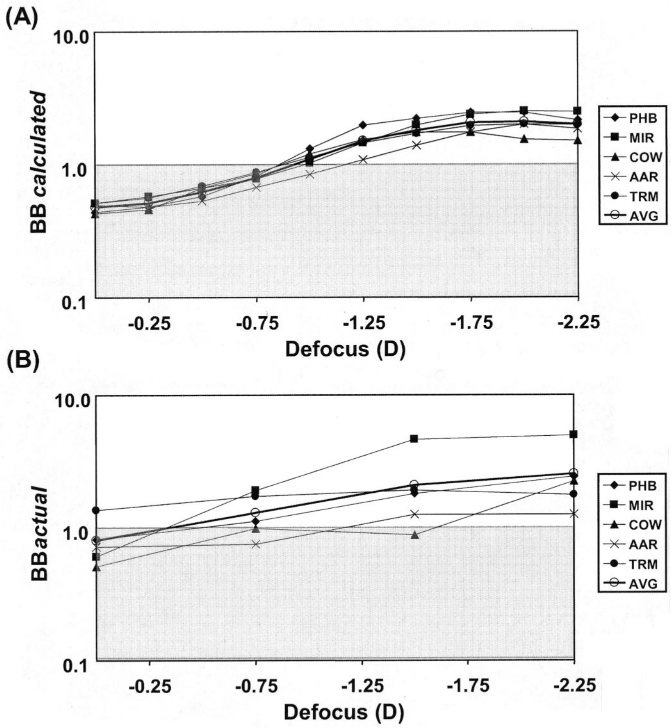

FIGURE 7.

A: Calculated bifocal benefit (BB) as a function of defocus. All subjects were predicted to have a benefit of wearing the contact lens for near viewing and a decrement (shaded area) in distant viewing. B: Actual bifocal benefit as a function of defocus. Decrements in visual quality are in the shaded area.

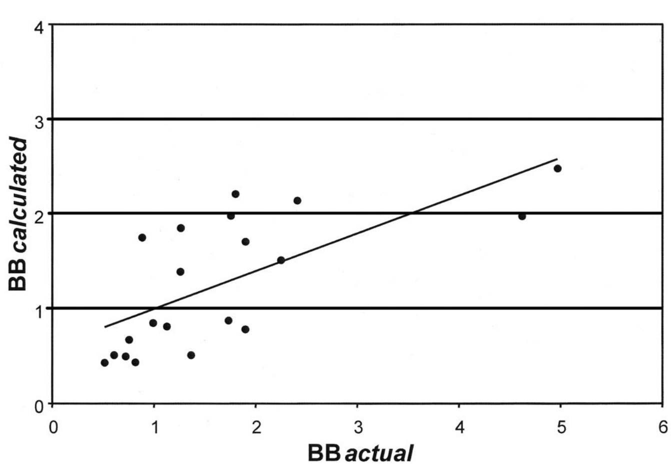

FIGURE 8.

Statistically significant positive correlation of actual bifocal benefit (BB_{actual}) vs. calculated bifocal benefit ($BB_{calculated}$) ($r = 0.685$, $p = 0.008$).

a predicted positive bifocal benefit for the largest range of defocus could be the most advantageous design for the presbyopic patient.

However, whether preferred visual performance is gained through increased depth of focus or through actual bifocality is still an uncertainty. If it is an increase in depth of focus that successful wearers of simultaneous vision contact lenses are experiencing, we should be able to understand how best to increase depth of focus at a minimal cost to vision at any distance. If bifocal vision is preferred, studies based on the typical aberrations[21, 22] and pupil size[23] of the presbyopic population could lead to contact lens designs that would provide true bifocal vision for more presbyopes. Furthermore, once the preferred lens design is determined, then the best method to manufacture the lens will need to be determined or, if necessary, developed.

Another possible benefit of this study's model could be the computer-based modeling and design of contact lenses based on the patient's aberrations. A future wearer of bifocal or single-vision contact lenses could have the best lens design for their particular aberration profile chosen for them before ever trying on a lens. This potential method would be highly beneficial, allowing the eye care practitioner to reduce contact lens fitting time and enhance their patient's satisfaction by providing improved visual quality and fewer follow-up examinations.

Limitations

The exact parameters of the contact lenses used in this study were not known. However, our model can be easily applied to any multizone concentric-ring bifocal contact lens once the lens parameters are known.

In this study, we did not consider the effect of lens decentration in our simulations. For the five subjects fitted in the Acuvue Bifocal contact lens, the horizontal decentration ranged from 0.0 to 0.35 mm, and the average was 0.09 mm. Vertical decentration was not measured. To test whether the lens displacement was important for the model, we computed the effect that the maximum decentration would have on the AUMTF from 1 to 24 cpd for a range of object vergences for two of the subjects. The differences between the centered and decentered lens models were small. The maximum difference was 11% (at one vergence), but the average difference was <5%. For some vergences, decentration of the lens improved the performance, whereas for others, the performance was degraded, but this did not occur in any systematic way. A prior objective analysis of decentered contact lenses by Woods et al.[12] does not provide similar data for comparison because we used a larger optical zone and we modeled the Acuvue design, which has alternating zones, as opposed to a two-zone design. However, one can extrapolate from Wood's data that when the decentrations are as small as we experienced in our study, then the expected changes in the AUCSF would be small. Thus, the metric we used to compare actual and predicted visual quality in our study was only minimally affected by horizontal lens decentration and does not change the findings of this study. We should add that the decentration did cause noticeable changes in the PSF.

Another possible limitation of this study is our assumption that the aberrations of soft contact lenses and the aberrations of the eye are additive (i.e., the contact lens does not alter the aberrations of the eye). Recent work by Lopez-Gil et al.[15] indicates that this is a probable assumption.

CONCLUSIONS

This study found that a model can be created to predict the patient's response to concentric-ring bifocal contact lenses based on the patient's optical aberrations measured with a Shack-Hartmann wavefront sensor. A positive relationship was found between predicted visual quality based on monochromatic aberrations and actual visual quality for concentric-ring bifocal contact lenses. This study also demonstrated that multizone bifocal contact lenses do not always provide bifocal vision.

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