Published in final edited form as:

Ophthalmic Physiol Opt. 2014 May ; 34(3): 331–345. doi:10.1111/opo.12110.

Impact of contact lens zone geometry and ocular optics on bifocal retinal image quality

Arthur Bradley, Jayoung Nam, Renfeng Xu, Leslie Harman, and Larry Thibos

School of Optometry, Indiana University, Bloomington, USA

Abstract

Purpose—To examine the separate and combined influences of zone geometry, pupil size, diffraction, apodisation and spherical aberration on the optical performance of concentric zonal bifocals.

Methods—Zonal bifocal pupil functions representing eye + ophthalmic correction were defined by interleaving wavefronts from separate optical zones of the bifocal. A two-zone design (a central circular inner zone surrounded by an annular outer-zone which is bounded by the pupil) and a five-zone design (a central small circular zone surrounded by four concentric annuli) were configured with programmable zone geometry, wavefront phase and pupil transmission characteristics. Using computational methods, we examined the effects of diffraction, Stiles Crawford apodisation, pupil size and spherical aberration on optical transfer functions for different target distances.

Results—Apodisation alters the relative weighting of each zone, and thus the balance of near and distance optical quality. When spherical aberration is included, the effective distance correction, add power and image quality depend on zone-geometry and Stiles Crawford Effect apodisation. When the outer zone width is narrow, diffraction limits the available image contrast when focused, but as pupil dilates and outer zone width increases, aberrations will limit the best achievable image quality. With two-zone designs, balancing near and distance image quality is not achieved with equal area inner and outer zones. With significant levels of spherical aberration, multi-zone designs effectively become multifocals.

Conclusion—Wave optics and pupil varying ocular optics significantly affect the imaging capabilities of different optical zones of concentric bifocals. With two-zone bifocal designs, diffraction, pupil apodisation spherical aberration, and zone size influence both the effective add power and the pupil size required to balance near and distance image quality. Five-zone bifocal designs achieve a high degree of pupil size independence, and thus will provide more consistent performance as pupil size varies with light level and convergence amplitude.

Keywords

zonal bifocal; apodisation; pupil size; diffraction; annular pupils; spherical aberration

Introduction

Patients cannot use eye rotation to select the appropriate (near or distance) power of a bifocal that is either attached to (e.g. contact lenses, CL) or implanted in (e.g. intra-ocular lenses, IOLs) the eye because these lenses move with the eye^{1, 2}. A zonal bifocal CL or IOL solves this problem by distributing distance and near optical powers into small adjacent zones, such that light forming the retinal image will pass through both optics simultaneously^{3, 4}. For either near or distant targets, therefore, some proportion of the light will be well focused while some will be significantly defocused. Although many zone patterns have been proposed and produced⁵⁻⁷, concentric annular designs with a central circular optic surrounded by one or more annular zones dominate the contact lens market⁸, but a recent modelling study shows that angularly segmented designs may outperform these more traditional radially segmented designs⁹.

Two-zone concentric zonal bifocals have a central circular zone containing a distance correction surrounded by a second annular zone containing a near “add”, or vice versa (e.g. Proclear Multifocal CL, CooperVision, <http://coopervision.com>), while others have three zones^{3, 10, 11}, five zones (e.g. ARRAY and ReZOOM IOLs, AMO, <http://www.amo-inc.com>, and Acuvue Bifocal CLs, Vistakon, <http://www.acuvue.com>) or seven zones (Morcher, 53F-Bifo7¹²). Because of the concentric design, the near and distance optical zones must have different shapes and the effective size of the outer zones (OZ) will vary with pupil size. Images generated by annular optics exhibit different diffraction effects from those produced by circular apertures¹³⁻¹⁷, and because the pupil function of the eye has radially varying amplitude and phase, the images created by each radially separated zone will be affected differently by Stiles Crawford apodisation¹⁸⁻²¹ and ocular spherical aberrations²². These optical factors complicate the relationship between pupil size and image quality generated by the near and distant optics. For example, although most studies report a familiar pattern showing improved image quality^{23, 24} and visual performance^{25, 26} with pupil sizes that maximize the amount of light in the focused image of two-zone annular bifocals, there are reports showing no obvious visual effect of changing pupil size²⁷.

For typical pupil sizes²⁸, diffraction is generally thought to have a limited role in human vision because natural pupil sizes are almost always significantly larger than those required to produce diffraction-limited (DL) behaviour^{22, 29}. However, the width of annular optical zones employed in concentric bifocal designs can be very small (e.g. <0.5 mm in ReZOOM³⁰), and wider annular zones within the lens can be made very narrow if the eye's pupil is only slightly larger than the inner diameter of the annulus. Also, calculations by Charman and Jennings¹⁷ emphasise that diffraction effects can dominate for narrow annular pupils even in the presence of typical levels of ocular spherical aberration.

Several previous studies have employed computational optics to investigate the imaging properties of zonal bifocal lenses, but some have either omitted the effects of diffraction^{3, 31}, ocular apodisation^{3, 9, 31-35}, or ocular aberrations^{32, 36}. A few studies have systematically examined the impact of pupil size^{7, 34, 35, 37, 38} on multifocal image quality, but only one of these included ocular pupil apodisation⁷.

We have applied computational wave-optics methods systematically to explore the individual and combined effects of zone geometry, pupil size, diffraction, ocular apodisation and spherical aberration on the images generated by two-zone and five-zone annular bifocals, and therefore quantify the factors that modulate the role that pupil and zone size play in determining image quality in eyes fit with bifocal optics. We hypothesise that although diffraction and apodisation have little impact on monofocal vision³⁹, and spherical aberration has little impact on monofocal refractions⁴⁰, diffraction, apodisation and spherical aberration will have a significant impact on the behaviour of concentrically designed zonal bifocals because of the radially-separated aperture geometry. Also, because diffraction, apodisation and spherical aberration can selectively degrade images generated by the annular outer zone(s), they should increase the pupil diameters required to balance distance and near image quality.

Methods

An important clarification of terminology is warranted. First, we have modelled lenses as perfect bifocals that are analogous to a lens with a distance correction placing the far point at infinity, and a near correction with +2 dioptres more power than the distance correction. We did not include transition zones in our model, and thus we are modelling true bifocals and not “multifocals”. We label the lens regions containing the distance and near corrections as distance optical zones and near optical zones. These terms are distinct from the distant and near object distances also critical to the understanding of bifocal optics. When referring to a “distance image” we are describing the image of a distant object for which the distance optic produces a well-focused image but the near optic also produces a blurred image. A “near image” describes the image of a near object (where the near optic produces a well-focused image but the distant optic produces a blurred image). It is also important to realize that the optical characteristics of a zonal bifocal and aberration-free optics can be characterized by defining the zone that is focused, e.g. the image quality generated when the inner zone (IZ) is focused can be achieved with a “centre distance” (CD) design and a distant target, or with a “centre near” (CN) design and a near target. This equivalence fails when spherical aberration is added to the model.

We modelled two-zone and five-zone concentric designs with a +2 dioptres of add power imaging targets located at various viewing distances (quantified by target vergence). We set the two-zone design inner zone diameter to 3 mm and the outer zone diameter up to 6 mm, we examined both CD and CN two-zone designs. We also investigated a five-zone CD model with annuli of similar widths to the Acuvue Bifocal (Vistakon, <http://www.acuvue.com>) multi-zone bifocal design⁸. The zone diameters were, consecutively, 2.0, 3.2, 4.4, 5.3, and 6.0 mm.

Zonal bifocal optics were implemented computationally by first computing two wavefront error (WFE) maps across the entire pupil area, each containing the focussing error associated with either distance and near optics associated with a given target vergence³⁶. The reference surface for computing WFE was a sphere centred on the object point. Next we subdivided these wavefront maps into 2 or 5 zones (depending on the bifocal design under consideration) which were interleaved to assemble a single, composite wavefront with zero

phase discontinuities at the interface between neighbouring zones, thus mirroring the physical reality of zonal bifocals^{6, 41, 42}. Spherical aberration (SA) was added to the pupil function by adding Zernike primary spherical aberration with $C_4^0 = 0.15 \mu\text{m}$ (over a 6 mm diameter pupil^{22, 43}) to the composite wavefront. The resulting wavefront comprised the phase portion of the eye + bifocal pupil function, specified relative to the ideal spherical wavefront that converges onto the retina. Experimental studies have confirmed that eye and contact lens aberrations do add, at least approximately^{44, 45}.

To take account of Stiles-Crawford apodisation we defined the amplitude transmission (T) portion of the pupil function using the Gaussian formula

$$T_r = e^{-\sigma \cdot r^2} \quad \text{Equation (1)}$$

where r is pupil radius (mm) and $\sigma(\text{mm}^{-2}) = 0.5 * \ln(10) * 0.05^{18}$. This apodisation function is concentric with the eye's pupil. Pupil functions were defined over a 1024×1024 array, for a 550 nm source. Points outside the pupil circle were made opaque by setting $T = 0$.

Examples of the phase portion of pupil functions for three levels of target vergence are shown in Figure 1 with and without primary Seidel spherical aberration ($C_4^0 = 0.15$ microns, $C_2^0 = 1515 \times 0.15$ microns). Note that the composite wavefronts generated by the zonal bifocals in the absence of SA, for either distance or near targets, have alternating regions that are either flat or spherical (Fig. 1 A, B, E, F). When faced with an intermediate object distance, wavefronts in each successive zone has opposite sign curvatures (Fig. 1 C, D) indicating negative defocus in the distance zone and positive in the near zone. Adding positive Seidel SA contributes a positive shift in the wavefront error that increases as the 4th power of r .

Optical transfer functions were computed by standard Fourier methods^{46, 47} using custom Matlab software (Mathworks, <http://www.mathworks.com>) created at Indiana University. The optical characteristics of individual zones could be examined by setting the amplitude function to zero for all pupil locations outside of the zone(s) of interest. Image quality was quantified using the area under the radially-averaged modulation transfer function (MTF) bounded by the human neural contrast threshold function⁴⁸.

In the following analysis, aberrations, apodisations, and bifocal zone sizes, are located at the eye's corneal plane, where add powers and pupil diameters are defined. However, because IOLs are located deep in the eye, and the beam defined by the pupil is converging, the effective pupil and zone sizes at the IOL plane will be reduced by 13% to 17% (depending on exact axial location of IOL)^{3, 49} and the required add power at the IOL plane must be about 30% larger than that required at the CL plane⁵⁰. It is for this reason, that zonal IOLs will generally have smaller zones and greater add powers than bifocal zonal CLs.

Results

Effect of aperture geometry on diffraction limited performance

As shown previously^{13, 14, 17, 51-54}, image modulation decreases as the annulus thins at all but the very lowest and highest spatial frequencies, whereas bandwidth remains unchanged (see diffraction limited MTFs for zones C and E in Figure 2). Zonal bifocals with multiple annuli and a central circular zone effectively generate a bull's-eye optical aperture made up of a small central circle, and two or more concentric annuli. Figure 2 shows diffraction limited MTFs generated by each individual sub-aperture and the combined three-zone distance optic aperture from the five-zone bifocal design. The central 2mm circular aperture has the lowest bandwidth, whereas the 5.3 to 6 mm annulus has the greatest bandwidth. However, the increased bandwidth does not come with increased image modulation over the spatial frequency range most important for vision (<40 cycles per degree). In combination, the light from zones 1, 3 and 5 that make up the distance optic interacts coherently to generate an oscillating diffraction limited MTF with increased image modulation at medium spatial frequencies, and with a bandwidth determined by the outer diameter of the largest annulus, which in this example is 6 mm.

Impact of zone geometry and pupil size on bifocal images

The above analysis considers the distance and near optical zones separately, but in situ the near and distance zones are both imaging the same object point simultaneously. In Figure 3 we compare the MTFs for individual focused zones of bifocals with the full bifocal MTFs when the one zone is focused and the other defocused by 2 dioptres. In both the two-zone (Figure 3A) and five-zone (Figure 3B) examples, the outer diameter was 6 mm. In the two-zone case (3mm inner-zone diameter), this leads to a 75%/25% split in the area covered by the annulus and central circular aperture, respectively, and we can see that the bifocal MTFs (dotted lines) are reduced to approximately 75% and 25% versions of the focused individual apertures (solid lines). In this example of a two-zone bifocal geometry, the individual annular and circular apertures have almost identical MTFs (solid lines) over the visually significant range of zero to 50 cycles per degree, but when focused as part of the full aperture (dotted lines) they differ mostly because of the different proportions of the pupil covered (75% vs. 25%). In the five-zone lens case (Figure 3B), the separate distance optic (zones 1, 3 and 5) and near optic (zones 2 and 4) have similar MTFs (solid lines) over the full spatial frequency range, with the distance optic having slightly higher values for all spatial frequencies above 15 cycles per degree, which reflects the slightly larger distance optic (it covers about 58% of a 6 mm pupil). The bifocal phase transfer function remains zero in these examples, because image contrast is dominated by the optical zone that is well focused and has correct phase.

Models of the 2-zone designs confirm that the bifocal MTF (Figure 3) approximates an area-weighted average of the signed MTFs generated by the separate focussed and defocussed zones (average difference <1%). Bifocal images appear, therefore, as contrast-attenuated versions of the images generated by the focussed aperture, where the amount of contrast attenuation is determined by the proportion of defocused light. The focussed aperture becomes the effective aperture for bifocal imaging at distance and near, and the proportion

of the pupil it covers determines the absolute magnitude of the MTF. Therefore, the proportion of the pupil area covered by the distance and near optic, as well as the effects of diffraction, both affect bifocal image quality as pupil size changes. This can be seen by plotting the MTFs for a two-zone centre distance design (IZ= 3mm) as pupil diameter increases from 3 to 6 mm (Figure 4). For example, for a 3 mm pupil the lens is essentially monofocal, and in this diffraction limited example it produces a diffraction limited MTF for a distant target (solid line), and a 2D defocused MTF (dashed line) for a near target. As pupil size increases, the distant target MTF retains the same diffraction limit (about 90 cycles per degree) determined by the 3mm inner-zone diameter, but suffers from demodulation because of the increasing proportion of defocused light passing through the annular near optic. However, as pupil size increases, the effects of diffraction on the image of a near target generated by the surrounding annular optic vary with pupil diameter, and at the same time the demodulating effects of the out of focus image from the inner-zone are reduced because of the increased amount of light forming the focused outer-zone image. Notably, by examining the 4 mm pupil example with the outer annulus focused (this annulus is 0.5 mm across, and has an area 78% that of the central 3 mm pupil), diffraction demodulates the image contrast within the visible range of spatial frequencies, e.g. diffraction limited image modulation at 30 cycles per degree is <0.1 .

We computed a series of images obtained with either the distance or near optic focused for a model without spherical aberration and a uniform pupil weighting (Figure 5) as a function of pupil diameter, from 3 to 6 mm. With the two-zone design, as pupil diameter increases, the high contrast well focused inner-zone image gradually decreases in contrast, whereas the focused outer-zone image gradually increases in contrast (Figure 5A). This dramatic alteration of the relative near/distance image quality with pupil dilation is virtually absent for the five-zone design (Figure 5B), which exhibits stable image quality with both distance and near focus irrespective of pupil diameter.

Impact of ocular factors on Bifocal Image Quality

The different apertures investigated in the above sections necessarily cover different parts of the eye's pupil. Thus, when in combination with the eye, the overall optical characteristics will be affected by Stiles-Crawford Effect apodisation and ocular aberrations. In this section, we examine the impact of these factors on the images created by different optical zones of two-zone and five-zone bifocals.

Impact of Stiles-Crawford Effect apodisation

As anticipated, apodisation by ocular SCE will have little effect on the diffraction limited MTF of a small central circular aperture (e.g. 3 mm), and a small but noticeable effect on the diffraction limited MTF of a 6 mm circular pupil^{19, 20, 39, 55}. The impact of SCE apodisation becomes significant for annular zonal bifocals by altering the relative weights of the radially separated focussed and defocused zones within a bifocal (Figure 6). For example, for the two-zone lens with a central 3 mm diameter inner-zone and an outer-zone (OZ) of 6 mm, the relative areas covered by the outer and inner zones are 75% and 25% without SCE apodisation, but these proportions change to about 65% and 35% when apodisation is added. Thus, the bifocal MTF when the inner-zone is focused increases by

approximately 35/25 because of apodisation, whereas the bifocal MTF obtained with a focussed annulus is reduced by approximately 65/75. This will be true for CD and CN two-zone designs. With a five-zone design, although apodisation alters the weights of the more peripheral zones, there are both distance and near optics in the more peripheral pupil, and therefore we find little impact of SCE apodisation on bifocal image quality generated with these lenses.

Impact of ocular spherical aberration on power distributions of zonal bifocals

The optical characteristics of 2-zone and 5-zone bifocal lenses were determined in combination with ocular SA levels typically encountered in human eyes. Two scenarios are considered in which the refraction of the eye prior to prescribing a bifocal lens either achieves paraxial focus or one that minimizes the wavefront root mean square error (minRMS focus). Monofocal subjective and objective spherical refractions in the presence of spherical aberration produce a near paraxial focus, unless spherical aberrations levels are low when a refraction closer to a minRMS refraction is preferred^{22, 40, 56-59}. When fit with the zonal bifocal, the dioptric refractive state of the corrected eye is displayed as a power map (Fig. 7) rather than a conventional wavefront phase map (Fig. 1). Optical power (in dioptres) at any point in the pupil is equal to wavefront slope at that point divided by radial distance r (in meters) to the pupil centre

$$V = \frac{dW/dr}{r} \quad (2)$$

The dioptric difference (ΔD) between a paraxial and minRMS refractive correction is equal to²²:

$$\Delta D = 12 \sqrt{5} \quad C_4^0 / R^2 \quad (3)$$

where R is the pupil semi-diameter. Thus, for a representative eye with 0.15 microns of primary spherical aberration⁴³ and a pupil diameter of 6mm, the difference between a paraxial and minRMS refraction is 0.45 dioptres. The calculated vergence errors for a model eye with a 6mm diameter pupil, distant target and $C_4^0 = +0.15$ are shown in Fig. 7 for either a two-zone CD lens design (Figure 7A), a two-zone CN design (Figure 7B), and a five-zone CD design (Figure 7C). Vergence errors (power in dioptres relative to that required to focus the distant target) are calculated for the bifocals assuming the eye's distance refractive correction was based on a minRMS (blue dotted line) or paraxial (red dotted line) criterion, although the latter is more likely to represent typical refractions^{40, 56}. The aberration-free case (solid black lines) is included for comparison.

When SA is added to a two-zone CD design, and paraxial refraction is obtained (Figure 7A), the eye is approximately focussed in the pupil centre for a distant object, and has between +2.25 and +2.8D of additional power in the annular surround. If the distance power of the bifocal was selected to achieve minRMS across the full pupil in the presence of spherical aberration, an annulus 0.7 of the distance from the pupil centre to the pupil margin will be focussed ($r=2.1$ mm in this case). When employing a minRMS distance refraction, the eye fit with the centre distance bifocal will have a central zone that is significantly hyperopic

(0.45D of negative defocus on axis). This minRMS distance correction does, however, produce approximately +2 dioptres of add power in the annular zone. For the two-zone CN design (Figure 7B), a paraxial refraction produces almost exactly +2D of defocus paraxially (as expected from a +2D add bifocal), but because of the positive spherical aberration, the annular distance zone is rendered slightly (about 0.45 D) myopic (positive defocus). With a minRMS refraction, the central near zone has about 0.5D less than the planned 2D of add power, but the annulus is approximately focused when viewing a distant target. In the presence of typical levels of spherical aberration, therefore, the average difference in optical power (difference in vergence error) between zones 1 and 2 for the two-zone design is approximately 2.5 dioptres for the CD design (Figure 7A), but only 1.5 dioptres for the CN design (Figure 7B).

In the case of the five-zone lens (Figure 7C) for which the zones 1, 3 and 5 contain a distance correction, the positive vergence error toward the edge of the pupil (for the paraxial refraction criterion) or hyperopia centrally (for the minRMS criterion) is distributed into both the distance and near optics. Interestingly, by including ocular spherical aberration we see different vergence values (and thus refractive errors) in zones designed to have equal power. For example, the distance optic is about 0.35 and 0.7 dioptres more myopic in zones 3 and 5 than in zone 1. Thus, in the presence of ocular spherical aberration, the multi-zone lens behaves as a multi-powered (true multifocal) lens, with each zone having a slightly different optical power.

Combined Impact of SA and SCE on Image quality of zonal bifocals

Because the inclusion of SA in the bifocal model changes the effective power of different optical zones, the effect of SA on image quality can best be revealed by examining image quality as a function of target vergence (see also ⁶⁰). This through-focus analysis identifies the target vergences that produce peak image quality, and the level of image quality achieved at these peaks. The dioptric separation of the two image quality peaks also reveals the effective add power of the lens. In Figure 8, we quantify the quality of the image by summing the area under the radially-averaged MTF bounded by the neural threshold ⁴⁸, which quantifies the MTF for the visually significant spatial frequencies. This image quality metric is normalised to monofocal diffraction limited optics. We model the case of an unaberrated eye, and an eye with ocular SA that is paraxially focused both with and without SCE apodisation (Figure 8).

In the absence of spherical aberration or SCE apodisation, the 75% outer-zone and 25% inner-zone distribution of areas for the two-zone bifocal with an inner zone of 3 mm and a 6 mm pupil creates the expected superiority of image quality when the larger outer zone is focused. This occurs with -2.0 dioptres of target vergence for the CD design (Figure 8A, solid line), and with 0.0 dioptres of target vergence for the CN design (Figure 8B). There is a much smaller imbalance seen with the five-zone lens (black lines, Figure 8C) between the peak image quality observed at the near and distance focus, revealing slightly better image quality for a distant target in the absence of ocular aberrations. The inclusion of spherical aberration (dashed lines) has little impact on two-zone image quality generated by a focussed inner-zone optic, but significantly degrades the peak image quality generated by

focussing the annular optical zone. Also, as predicted from the power profiles plotted in Figure 7, inclusion of SA changes the position of these peaks (effective refraction), and the separation between the peaks (effective add power). In the presence of +0.15 microns of Seidel spherical aberration (and a paraxial refraction), add power in the CD design increases to $> +2.5$ D, and thus the near peak in image quality shifts to a target vergence of less than -2.5 D (dashed line in Figure 8A), while the CN design has add power reduced to about $+1.5$ D (Figure 8B). Thus, the power distribution in the CD zonal bifocal adds to the effect of ocular SA and will produce approximately 1.0 D more add power than a design that includes a power distribution that is opposite to that of the human eye (CN design). Additionally, the eye fit with the CN bifocal may exhibit significant myopia at distance if the patient's initial refraction generated paraxial focus.

The impact of SA on the through-focus performance of the five-zone design is qualitatively different from that seen with the two-zone design. Because the distance and near optical zones exist at multiple eccentricities in the lens, the effective power of each zone differs in the presence of SA (see Figure 7C). Thus, each sub-zone within the distance and near optics of the five-zone design will manifest a different refractive state and predictably the through-focus image quality analysis exhibits multiple peaks at different target vergences. This effect is seen clearly in Figure 8C, where the inclusion of SA produces a clear broadening of the near and distance peaks of image quality, often with clear multi-lobe behaviour. As expected, this multi-lobed behaviour becomes more striking with increased ocular SA.

Adding SCE apodisation (Figure 8 dotted lines) in the presence of Seidel SA, increases inner-zone image quality due to an increase in the weight of the inner zone relative to the outer zone. Interestingly, in the presence of SA, apodisation generates a small improvement in image quality at both distance and near in the 5-zone design, indicating that the most apodised outer zones are least effective at generating images. Apodisation also slightly reduces the myopic shift seen in the outer zone refractions of the two-zone design. Similarly, with the five-zone design, a small hyperopic shift is seen in image peaks generated by both the distance and near optics when SCE is added.

The impact of diffraction, apodisation, and spherical aberration on the pupil size dependency of image quality

For any two-zone annular design, a pupil diameter that is $2 \times$ IZ diameter passes equal proportions of incident light through each zone⁶¹. Because two-zone annular bifocal lenses have been designed with a range of inner-zone sizes (e.g. Cooper Vision Frequency 55 Multifocal, inner-zone diameter of 1.7 mm (Cooper Vision, <http://coopervision.com>), and CIBA Bisoft (CIBA Vision, <http://www.cibavision.com>) with inner-zone diameter of 3.8 mm⁶²), the pupil diameter with twice the area of the inner zone will vary from about 2.4 mm to about 5.4 mm. Alternately, five-zone bifocals are designed to provide approximate balance over a wide range of pupil diameters (e.g. Acuvue CL, ARRAY or ReZOOM IOL). The sensitivity of two-zone concentric designs to pupil size, and the relative insensitivity of five-zone designs can be seen by plotting the proportion of the pupil area covered by the distance and near optic as a function of pupil diameter (Figure 9 A and B). For example, with a 3 mm inner-zone diameter area balance for the two-zone lens is achieved with a pupil

diameter of 4.24 mm, but because of decreased effectivity of the outer-zone due to apodisation, the balance point is increased to 4.6 mm (Figure 9A). Distance and near zone area balance is achieved with four different pupil diameters for the five-zone lens, and each is only slightly affected by pupil apodisation (Figure 9B). Similar unapodised data have been shown for the five-zone Array IOL by Kawamorita and Uozata³⁸ and a three-zone IOL³. MTF analysis (Figure 10), emphasizes that image quality can differ dramatically when inner-zone and outer-zone areas are matched. In this example, due to the combined effects of diffraction, apodisation and spherical aberration demodulating the outer-zone bifocal image, modulation when focusing the inner-zone is more than twice that achieved when focusing the outer-zone for all spatial frequencies above 5 cpd.

Our through focus analysis shows that image quality generated with the outer-zone optic is reduced by about a factor of two by the introduction of SA (Figure 8), which seems to contrast with the modelling results of Charman and Jennings (1979) in which they show adding spherical aberration had little impact on the MTF of an annular aperture. Clearly, as pupil size increases, the width of the annular outer-zone optic increases and thus demodulation due to diffraction will be less, but as pupil size increases the range of powers (longitudinal spherical aberration) within the outer-zone will increase (Figure 7). Therefore, we would expect that as pupil size was increased from one just larger than the 3 mm inner-zone to one that is significantly larger, there would be a shift in the primary factor determining peak image quality when focusing the outer-zone. Diffraction should dominate for narrow annuli and aberrations for wider annuli. This trend can be seen by comparing the effect of pupil diameter on peak near and distance image quality with or without SA (Figure 11).

Computing the impact of pupil size on near and distance image quality is straightforward in the aberration-free model, where image quality always peaks at zero and -two dioptres of target vergence. However, as shown in the 6 mm pupil example (Figure 8), adding spherical aberration changes the TVs that generate peak image quality. Therefore, in order to quantify the impact of pupil diameter on near and distance image quality, we first identified the near and distance image quality peaks by computing image quality for a range of target vergences in 1/8th dioptre steps. Adding spherical aberration to the model has little impact on distance image quality (image generated by the inner-zone optic) at any pupil diameter (Figure 11). For pupil diameters just larger than the inner-zone, adding spherical aberration to the model does not change the image quality when the outer-zone is focused, but SA can reduce near IQ to half when the outer-zone is expanded to 6 mm. This figure shows that, in the absence of spherical aberration, image quality for distant targets will be significantly higher with pupils < 5 mm, matched with a 5 mm diameter pupil, and superior for near target with pupils >5mm. That is, when IZ/OZ areas are equated with a 4.2 or 4.6 mm pupil for the uniform and SCE weighted pupils, respectively, focussing the inner-zone will produce superior image quality (see example in Figure 10). The difference produced by adding spherical aberration shows that as outer-zone diameter increases, spherical aberration begins to have a larger effect, but when outer-zone width is narrow, it is diffraction and not spherical aberration that dominates image quality generated by focussing the outer-zone. Notably, with typical levels of spherical aberration, the degradation in the outer-zone image produced

by spherical aberration is sufficient to overcome the expected increased image quality caused by the increased area covered by the outer-zone.

Quantifying the impact of pupil size on near and distance image quality for the five-zone design is complicated by spherical aberration because of the multiple peaks seen in the through focus plots (Figure 8C), reflecting the different optical power associated with each zone. Therefore we plotted the effect of pupil diameter on image quality for near and distance targets for two refractive scenarios: one in which the model is focussed paraxially, and thus the inner zones are reasonably well focussed but the outer zones are significantly myopic (Figure 7C), and in a second scenario we focussed a more marginal pupil region (2.1 mm from the pupil centre) and thus the central zones are significantly hyperopic. These two scenarios are analogous to adding either Seidel (paraxial focus) or Zernike ($0.7r_{\max}$ focused) spherical aberration to a paraxially refracted eye (Figure 7C). With paraxial focus (Figure 12A), image quality with a distant target and a small pupil (2 mm) is high due to the 2 mm diameter zone 1 being well focused. Also, as zone 2 is exposed (pupil diameters from 2 to 3.2 mm) near target vergence image quality rises quickly (and distant target vergence image quality falls), but as anticipated recruiting the defocussed outer zones with additional pupil dilation fails to improve either distant or near image quality. This plot shows that for a paraxially refracted eye (Figure 12A) with typical levels of spherical aberration, image quality for distant (target vergence = 0) and near (target vergence = -2) is well matched for all pupil diameters ≤ 3 mm. Unlike the behaviour of the two-zone lens, apodisation has little impact on five-zone imaging, and predictably, therefore, produces a pupil dependency of image quality similar to that observed in a physical model lacking SCE and imbedded with the five-zone ARRAY IOL³⁸. In the second scenario, in which zones 3 and 4 are better focused (Figure 12B) we can see that when pupil size increases to expose zone 3 (pupil diameters from 3.2 to 4.4), image quality for the distant target increases and image quality for the near targets decrease. This trend is then reversed when zone 4 containing +2D add power is exposed (pupil diameters from 4.4 to 5.3 mm). We can see in Figure 12B that including significant spherical aberration into the model does not prevent the thin outer zones from contributing to image quality as long as they are well focussed. In this figure image quality is quantified by the area MTF metric in which all values are normalised to the area MTF generated by a diffraction limited 6 mm pupil.

Discussion

Our modelling of radially-organized zonal-bifocals has revealed significant interactions between optical zone dimensions, pupil size, Stiles Crawford apodisation, ocular spherical aberration and diffraction in determining refractive power and image quality. Consistent with earlier reports⁵⁶, if a single annular optical zone is made narrow either by lens design or by the eye's pupil blocking peripheral lens optics, the maximum achievable retinal image contrast over most of the visible spatial frequency range will be significantly attenuated by diffraction (Figures 2-4), even in the presence of ocular spherical aberration (Figure 11). As the outer annular aperture widens, the diffraction-dominated MTF initially improves due to increased effective area of outer-zone optic, but then is demodulated by aberration as pupil size increases still further (Figure 11), as observed by Applegate⁶³. These results suggest that there may be benefits from including a SA correction in the outer-zone of two-zone

bifocal lenses. In addition to the effects of aperture size and shape, image quality is demodulated by light from the second out of focus aperture, as seen in computational^{9, 32} and physical^{34, 64} models of zonal bifocals, but on the eye this effect is significantly modulated by the SCE (Figures 6 and 8). As predicted, the pupil diameters required to balance image quality for near and distant targets with a two-zone bifocal are increased by diffraction, SCE and by spherical aberration (compare Figures 4, 5, 10 and 11).

It is clear that although a near paraxial refraction might provide best image quality for a large pupil with monofocal optics^{22, 40, 56-58}, it will lead to a significant increase in add power for a two-zone centre distance design, and a myopic shift for the distance correction with a two-zone centre near design (Figures 7&8). This is not surprising, because both Koomen and Charman^{56, 57} showed that optimal refraction for annular pupils becomes significantly more myopic with increasing annulus diameter. These findings emphasise that, because of ocular SA, it is likely that a two-zone CD design will exhibit more add power than contributed by the lens alone. Also, a two-zone CN design should be prescribed with 0.5D extra minus in the annular zone distance correction (assuming the patient preferred a near paraxial monofocal refraction) to achieve image quality peaks for TVs of zero and -2D. The same phenomenon can convert a bifocal five-zone correction into a multifocal correction (Figure 5 & 6) providing increased depth of focus surrounding the image peaks observed at both distant and near target vergences, as seen experimentally with eyes fit with the Acuvue five-zone bifocal³³.

Although the five-zone lens shows a good degree of pupil size independency in its optical performance, balanced near and distance optical performance of two-zone designs can only be achieved with specific pupil sizes. However, identifying a two-zone lens geometry that will generate similar IQ for near and distant targets is complicated because pupil size varies with light level, age and with convergence. For example, early presbyopes (e.g. 45-55 yr.⁶⁵) viewing low light environments will tend to have the largest pupils of any patients likely to employ zonal bifocals (e.g. mean = 6.0 mm, SD=0.9²⁸), whereas pseudophakes (e.g. 70-80 yr.⁶⁶) viewing high light levels will have the smallest pupils (e.g. mean = 3 mm, SD=0.6^{28, 67}). The above pupil size data were collected with zero convergence, but Chateau⁶⁸ has shown that convergence miosis occurs in non-accommodating eyes and that it scales with pupil size. We extrapolated the Chateau data to estimate convergence miosis in mm for the large and small pupil ranges defined above for the presbyopes and pseudophakes (using least squares fitting, Convergence Miosis = $1.636 \times \ln(\text{pupil diameter}) - 1.1354$), and thus define the anticipated range of pupil sizes (mean $\pm$ SD) expected for these groups when viewing a 40 cm target. The 5.1 to 6.9 mm low light level presbyopic pupil range reduces to 3.6 to 4.9 mm when converged, and the high light level pseudophakic range drops from 2.4 to 3.6 mm down to 2.1 to 2.65 mm. Therefore, most presbyopes and pseudophakes would experience a significant distance bias at photopic light levels with a 3 mm diameter inner-zone, and a distance bias would also exist at low light levels when converged at near. These large pupil-size dependent biases can be minimized by employing a concentric five-zone lens design (Figure 12), and zone geometries that vary as a function of meridian rather than radial distance from the centre (e.g.⁷).

The computations described in this report have only included a single higher order aberration (primary spherical aberration), have employed only one wavelength, have assumed zero accommodation, and have assumed that both the lens and the SCE are centred on the pupil. Real eyes may have decentred pupils, decentred Stiles-Crawford, higher order aberrations other than spherical aberration, all of which were ignored. We have also ignored potential tear film disruptions which can degrade retinal image quality⁶⁹⁻⁷³ more so in eyes wearing contact lenses⁷⁴, and the possible, but small optical changes caused by lens flexure⁴⁵. Therefore, the conclusions from this modelling study must be considered provisional until confirmed by future studies with more clinically realistic conditions. However, our predicted imaging behaviour of the virtual zonal bifocals examined in this study has many parallels with experimentally measured images created by zonal bifocals in situ^{23, 24, 34, 75}, and both contrast sensitivity and visual acuity measurements from patients wearing zonal bifocals^{10, 25, 75} indicating that the factors included in our model (zone geometry, diffraction, SCE and spherical aberration) dominate bifocal image quality in patients' eyes.

Acknowledgments

This study was funded in part by the NIH grant NEI R01 EY 05109 awarded to Larry Thibos, and by a grant from Johnson & Johnson Vision Care, Inc. awarded to Arthur Bradley.

References

1. Wolffsohn JS, Hunt OA, Basra AK. Simplified recording of soft contact lens fit. *Cont Lens Anterior Eye*. 2009; 32:37–42. [PubMed: 19167261]
2. Golding TR, Bruce AS, Gaterell LL, Little SA, Macnamara J. Soft lens movement: effect of blink rate on lens settling. *Acta Ophthalmol Scand*. 1995; 73:506–11. [PubMed: 9019373]
3. Charman WN, Murray IJ, Nacer M, O'Donoghue EP. Theoretical and practical performance of a concentric bifocal intraocular implant lens. *Vision Res*. 1998; 38:2841–53. [PubMed: 9775330]
4. Charman WN, Walsh G. Retinal image quality with different designs of bifocal contact lens. *Transactions BCLA Conference*. 1986; 9:13–9.
5. de Carle J. A Refractive Multizone Bifocal. *Trans BCLA Conference*. 1989; 12:66–70.
6. McAlinden C, Moore JE. Multifocal intraocular lens with a surface-embedded near section: Short-term clinical outcomes. *J Cataract Refract Surg*. 2011; 37:441–5. [PubMed: 21333867]
7. Petelczyc K, Garcia JA, Bara S, Jaroszewicz Z, Kakarenko K, Kolodziejczyk A, et al. Strehl ratios characterizing optical elements designed for presbyopia compensation. *Opt Express*. 2011; 19:8693–9. [PubMed: 21643121]
8. Benjamin, W.; Borish, I. Correction of presbyopia with contact lenses.. In: Benjamin, W., editor. *Borish's Clinical Refraction*. Second ed.. Butterworth; St. Louis: 2006. p. 1274-319.
9. de Gracia P, Dorransoro C, Marcos S. Multiple zone multifocal phase designs. *Optics letters*. 2013; 38:3526–9. [PubMed: 24104805]
10. Knorz MC, Claessens D, Schaefer RC, Seiberth V, Liesenheff H. Evaluation of contrast acuity and defocus curve in bifocal and monofocal intraocular lenses. *J Cataract Refract Surg*. 1993; 19:513–23. [PubMed: 8355159]
11. Baikoff G, Matach G, Fontaine A, Ferraz C, Spera C. Correction of presbyopia with refractive multifocal phakic intraocular lenses. *J Cataract Refract Surg*. 2004; 30:1454–60. [PubMed: 15210222]
12. Hessemer V, Eisenmann D, Jacobi K. Multifokale Intraokularlinsen, eine Bestandsaufnahme. *Klin Monatsbl Augenheilkd*. 1993; 203:19–33. [PubMed: 8411889]
13. Linfoot E, Wolf E. Diffraction Images in Systems with an Annular Aperture. *Proc Phys Soc B*. 1953; 66:145–9.

14. O'Neill EL. Transfer function for an annular aperture. *J Opt Soc Am.* 1956; 46:285–88.
15. Rivolta C. Multiple annular circular aperture: maxima and minima of the diffraction pattern. *Appl Opt.* 1987; 26:3119–21. [PubMed: 20490018]
16. Tschunko HF. Imaging performance of annular apertures. *Appl Opt.* 1974; 13:1820–3. [PubMed: 20134576]
17. Charman WN, Jennings JA. Properties of annular artificial pupils. *Vision Res.* 1979; 19:947–9. [PubMed: 516467]
18. Applegate RA, Lakshminarayanan V. Parametric representation of Stiles-Crawford functions: normal variation and peak location and directionality. *J Opt Soc Am A.* 1993; 10:1611–23. [PubMed: 8350150]
19. Mino M, Okano Y. Improvement in the OTF of a defocused optical system through the use of shaded apertures. *Appl Opt.* 1971; 10:2219–25. [PubMed: 20111305]
20. Olsen T. On the Stiles-Crawford effect and ocular imagery. *Acta ophthalmol.* 1993; 71:85–8. [PubMed: 8475719]
21. Tschunko HF. Imaging performance of annular apertures. 3:Apodization and modulation transfer functions. *Appl Opt.* 1979; 18:3770–4. [PubMed: 20216692]
22. Thibos LN, Hong X, Bradley A, Cheng X. Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J Opt Soc Am A.* 2002; 19:2329–48.
23. Woods RL, Saunders JE, Port MJ. Concentric-Design Rigid Bifocal Lenses, Part 1: Optical Performance. *J British Contact Lens Ass.* 1993; 16:25–36.
24. Young G, Grey CP, Papas EB. Simultaneous vision bifocal contact lenses: a comparative assessment of the in vitro optical performance. *Optom Vis Sci.* 1990; 67:339–45. [PubMed: 2367087]
25. Bradley A, Abdul Rahman H, Soni PS, Zhang X. Effects of target distance and pupil size on letter contrast sensitivity with simultaneous vision bifocal contact lenses. *Optom Vis Sci.* 1993; 70:476–81. [PubMed: 8336909]
26. Jones B, Lowther GE. The Effect of Near Zone Size of a Center-Near ZOne Hydrogel Contact Lens Bifocal on Visual Acuity. *Int Cont Lens Clin.* 1989; 16:87–93.
27. Ravalico G, Baccara F, Bellavitis A. Refractive bifocal intraocular lens and pupillary diameter. *J Cataract Refract Surg.* 1992; 18:594–7. [PubMed: 1432673]
28. Winn B, Whitaker D, Elliott DB, Phillips NJ. Factors affecting light-adapted pupil size in normal human subjects. *Invest Ophthalmol Vis Sci.* 1994; 35:1132–7. [PubMed: 8125724]
29. Atchison DA, Smith G, Efron N. The effect of pupil size on visual acuity in uncorrected and corrected myopia. *Am J Optom Physiol Opt.* 1979; 56:315–23. [PubMed: 495689]
30. AMO. ReZoom Acrylic Multifocal Posterior Chamber Intraocular Lenses. Package Insert Technical Specifications. Abbott Medical Optics Inc. 2006
31. Charman WN, Saunders B. Theoretical and practical factors influencing the optical performance of contact lenses for the presbyope. *Journal of the British Contact Lens Association.* 1990; 13:67–75.
32. Klein SA, Ho Z. Multifocal Bifocal Contact Lens Design. *Proc SPIE.* 1986; 679:25–35.
33. Martin JA, Roorda A. Predicting and assessing visual performance with multizone bifocal contact lenses. *Optom Vis Sci.* 2003; 80:812–9. [PubMed: 14688544]
34. Choi J, Schwiegerling J. Optical performance measurement and night driving simulation of ReSTOR, ReZoom, and Tecnis multifocal intraocular lenses in a model eye. *J Refract Surg.* 2008; 24:218–22. [PubMed: 18416255]
35. Artigas JM, Menezo JL, Peris C, Felipe A, Diaz-Llopis M. Image quality with multifocal intraocular lenses and the effect of pupil size: comparison of refractive and hybrid refractive-diffractive designs. *J Cataract Refract Surg.* 2007; 33:2111–7. [PubMed: 18053913]
36. Chateau N, Baude D. Simulated in situ optical performance of bifocal contact lenses. *Optom Vis Sci.* 1997; 74:532–9. [PubMed: 9293522]
37. Terwee T, Weeber H, van der Mooren M, Piers P. Visualization of the retinal image in an eye model with spherical and aspheric, diffractive, and refractive multifocal intraocular lenses. *J Refract Surg.* 2008; 24:223–32. [PubMed: 18416256]

38. Kawamorita T, Uozato H. Modulation transfer function and pupil size in multifocal and monofocal intraocular lenses in vitro. *J Cataract Refract Surg.* 2005; 31:2379–85. [PubMed: 16473235]
39. Atchison DA, Joblin A, Smith G. Influence of Stiles-Crawford effect apodization on spatial visual performance. *Opt Soc Am A J.* 1998; 15:2545–51.
40. Xu R, Bradley A, Thibos LN. Impact of primary spherical aberration, spatial frequency and Stiles Crawford apodization on wavefront determined refractive error: a computational study. *Ophthalmic Physiol Opt.* 2013; 33:444–55. [PubMed: 23683093]
41. Plainis S, Ntzilepis G, Atchison DA, Charman WN. Through-focus performance with multifocal contact lenses: effect of binocularity, pupil diameter and inherent ocular aberrations. *Ophthalmic Physiol Opt.* 2013; 33:42–50. [PubMed: 23199097]
42. Vega F, Alba-Bueno F, Millan MS. Energy distribution between distance and near images in apodized diffractive multifocal intraocular lenses. *Invest Ophthalmol Vis Sci.* 2011; 52:5695–701. [PubMed: 21659312]
43. Salmon TO, van de Pol C. Normal-eye Zernike coefficients and root-mean-square wavefront errors. *J Cataract Refract Surg.* 2006; 32:2064–74. [PubMed: 17137985]
44. Lopez-Gil N, Castejon-Mochon JF, Benito A, Marin JM, Lo-a-Foe G, Marin G, et al. Aberration generation by contact lenses with aspheric and asymmetric surfaces. *J Refract Surg.* 2002; 18:S603–9. [PubMed: 12361166]
45. Kollbaum P, Bradley A, Thibos LN. Comparing the optical properties of soft contact lenses on and off the eye. *Optom Vis Sci.* 2013 In Press.
46. Goodman, JW. Introduction to Fourier optics. Roberts & Company; Englewood: 2005.
47. Thibos LN. Principles of Hartmann-Shack aberrometry. *J Refract Surg.* 2000; 16:563–5.
48. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. *J Vis.* 2004; 4:329–51. [PubMed: 15134480]
49. Ravikumar S, Bradley A, Thibos LN. Chromatic Aberration and Pseudochromatic Image Quality with Diffractive Multifocal Intra-ocular Lenses. *J Cataract Refract Surg.* 2013 Submitted.
50. Lakshminarayanan V, Lang AJ, Portney V. The “Expected Visual Outcome” (EVO) model: methodology and clinical validation. *Optom Vis Sci.* 1995; 72:511–21. [PubMed: 8539016]
51. Barakat W, Houston A. Transfer Function of an Annular Aperture in the Presence of Spherical Aberration. *J Opt Soc Am.* 1965; 55:538–41.
52. Miller NJ, Dierking MP, Duncan BD. Optical sparse aperture imaging. *Appl Opt.* 2007; 46:5933–43. [PubMed: 17694146]
53. Tschunko HF. Annular apertures with high obstruction. *Appl Opt.* 1974; 13. [PubMed: 20125914]
54. Tschunko HF. Annular apertures with low and high obstruction. *Appl Opt.* 1981; 20:168–9. [PubMed: 20309084]
55. Zhang X, Ye M, Bradley A, Thibos L. Apodization by the Stiles-Crawford effect moderates the visual impact of retinal image defocus. *J Opt Soc Am A.* 1999; 16:812–20.
56. Charman WN, Jennings JA, Whitefoot H. The refraction of the eye in the relation to spherical aberration and pupil size. *Br J Physiol Opt.* 1978; 32:78–93. [PubMed: 737383]
57. Koomen M, Scolnik R, Tousey R. A study of night myopia. *J Opt Soc Am.* 1951; 41:80–90.
58. Zheleznyak L, Sabesan R, Oh JS, MacRae S, Yoon G. Modified monovision with spherical aberration to improve presbyopic through-focus visual performance. *Invest Ophthalmol Vis Sci.* 2013; 54:3157–65. [PubMed: 23557742]
59. Cheng X, Bradley A, Ravikumar S, Thibos LN. Visual impact of Zernike and Seidel forms of monochromatic aberrations. *Optom Vis Sci.* 2010; 87:300–12. [PubMed: 20351600]
60. de Gracia P, Dorronsoro C, Sanchez-Gonzalez A, Sawides L, Marcos S. Experimental simulation of simultaneous vision. *Invest Ophthalmol Vis Sci.* 2013; 54:415–22. [PubMed: 23233256]
61. Borish IM. Pupil dependency of bifocal contact lenses. *Am J Optom and Physiol Optics.* 1988; 65:417–23.
62. Gispets J, Arjona M, Pujol J. Image quality in wearers of a centre distance concentric design bifocal contact lens. *Ophthalmic Physiol Opt.* 2002; 22:221–33. [PubMed: 12090637]
63. Applegate RA. Acuities through annular and central pupils after radial keratotomy. *Optom Vis Sci.* 1991; 68:584–90. [PubMed: 1923334]

64. Kim MJ, Zheleznyak L, Macrae S, Tchah H, Yoon G. Objective evaluation of through-focus optical performance of presbyopia-correcting intraocular lenses using an optical bench system. *J Cataract Refract Surg.* 2011; 37:1305–12. [PubMed: 21700107]
65. Morgan PB, Efron N, Woods CA. An international survey of contact lens prescribing for presbyopia. *Clin Exp Optom.* 2011; 94:87–92. [PubMed: 21039845]
66. Tuft SJ, Bunce C. Axial length and age at cataract surgery. *J Cataract Refract Surg.* 2004; 30:1045–8. [PubMed: 15130642]
67. Kasper T, Bühren J, Kohnen T. Intraindividual comparison of higher-order aberrations after implantation of aspherical and spherical intraocular lenses as a function of pupil diameter. *J Cataract Refract Surg.* 2006; 32:78–84. [PubMed: 16516783]
68. Chateau N, De Brabander J, Bouchard F, Molenaar H. Infrared pupillometry in presbyopes fitted with soft contact lenses. *Optom Vis Sci.* 1996; 73:733–41. [PubMed: 9002089]
69. Himebaugh NL, Nam J, Bradley A, Liu H, Thibos LN, Begley CG. Scale and spatial distribution of aberrations associated with tear breakup. *Optom Vis Sci.* 2012; 89:1590–600. [PubMed: 23080060]
70. Himebaugh NL, Thibos LN, Bradley A, Wilson G, Begley CG. Predicting optical effects of tear film break up on retinal image quality using the Shack-Hartmann aberrometer and computational optical modeling. *Adv Exp Med Biol.* 2002; 506:1141–7. [PubMed: 12614042]
71. Himebaugh NL, Wright AR, Bradley A, Begley CG, Thibos LN. Use of retroillumination to visualize optical aberrations caused by tear film break-up. *Optom Vis Sci.* 2003; 80:69–78. [PubMed: 12553546]
72. Montes-Mico R, Alio JL, Munoz G, Charman WN. Temporal changes in optical quality of air-tear film interface at anterior cornea after blink. *Invest Ophthalmol Vis Sci.* 2004; 45:1752–7. [PubMed: 15161836]
73. Nam J, Thibos LN, Bradley A, Himebaugh N, Liu H. Forward light scatter analysis of the eye in a spatially-resolved double-pass optical system. *Opt Express.* 2011; 19:7417–38. [PubMed: 21503052]
74. Gruppeta S, Lacombe F, Puget P. Study of the dynamic aberrations of the human tear film. *Opt Express.* 2005; 13:7631–6. [PubMed: 19498790]
75. Holladay JT, Van Dijk H, Lang A, Portney V, Willis TR, Sun R, et al. Optical performance of multifocal intraocular lenses. *J Cataract Refract Surg.* 1990; 16:413–22. [PubMed: 2380922]

Figure 1.

Wavefront error profiles for two-zone (left) and five-zone (right) bifocal lenses produced by distant (A, B), intermediate (C,D) and near (E,F) target distances. A +2 dioptre add was used in each case. Gray indicates optical zone with +2 add power. Black lines show aberration-free case, red lines show WFE in presence of Seidel spherical aberration ($C_4^0=0.15$ microns, $C_2^0=\text{SQRT}(15) \times 0.15$ microns).

Figure 2.

Examples of diffraction limited MTFs for the individual circular and annular zones and combined apertures for the distance optic of a five-zone bifocal (zones A, C and E, see Figure 1). Inserts show schematic maps of zone geometry.

Figure 3.

MTF plots for individual and combined zones of zonal bifocal lenses: A, a 2-zone (6 mm diameter pupil, 3 mm inner zone diameter) and B, 5 zone (6 mm pupil, same zone geometry as described in Figure 1). For reference, the diffraction limited MTF of a monofocal diffraction limited 6 mm optic is also shown (black line). In both panels, solid lines show the diffraction limited MTFs for the focussed separate inner (blue) and outer (red) zone optics (A) and distance (red) and near (blue) optics of the five-zone design (B), while the dashed lines show the MTFs for the full 6 mm aperture with one optic focused and the other defocused by 2 dioptres. Aperture geometries are shown schematically, white=focused, black = defocussed, and gray is opaque.

Figure 4.

Radially averaged modulation transfer functions (MTFs) for a centre-distance two-zone bifocal with a 3 mm an inner-zone diameter and +2D add power for several pupil sizes. Solid lines show MTFs when the central distance optic is focussed, and dashed lines when the annular near optic is focused. Numbers on each curve indicate pupil diameter in mm. This model included diffraction and uniform pupil transmission.

Figure 5.

Sample images of a logMAR chart computed for a two-zone centre-distance +2D bifocal with 3 mm diameter inner-zone (A: top two rows). Row 1 and 2 show images calculated for distant (target vergence, TV = 0) and near (TV = -2) targets, respectively. The left to right series are calculated with pupil diameters of 3, 4, 5, and 6 mm. DHEVP line = logMAR of 0.3. Sample images of a logMAR chart computed for a five-zone centre-distance +2D bifocal are shown in the bottom two rows (B). Rows 3 and 4 show images calculated for distant (TV = 0) and near (TV = -2) targets, respectively.

Figure 6.

Impact of Stiles Crawford effect (SCE) apodisation on diffraction limited modulation transfer functions for a 6mm circular pupil, and for a two-zone bifocal with 3 mm and a 3 to 6 mm annulus. Add power is 2 dioptres. Modulation transfer functions computed with SCE (dashed lines) are compared to those w/o SCE (solid lines) when either the inner-zone (blue) or the outer-zone (red) are focussed.

Figure 7.

Wavefront vergence errors are plotted as a function of radial position in the pupil for a two-zone centre distance bifocal (A), a two-zone centre near bifocal (B) and a centre distance five-zone bifocal (C). In each case we plot the vergence error in the absence of any aberrations (solid black line), with Seidel spherical aberration added (red dotted lines, $C_4^0=0.15$ microns, $C_2^0=\text{SQRT}(15) \times 0.15$ microns) and with Zernike spherical aberration added (blue dotted lines, $C_4^0=0.15$ microns, $C_2^0=0$). Zones with the near add are indicated with gray in each panel.

Figure 8.

Through focus image quality (diffraction-limited normalized Area Under the MTF) was computed for three zonal bifocals (2-zone centre distance (A), two-zone centre near (B) and five-zone (C)) as a function of target vergence in dioptres. In each case a 6 mm pupil was used. MTFs for each bifocal lens were calculated with a +2 dioptre add power, and either without spherical aberration (black lines), or with 0.15 microns of Seidel spherical aberration (dashed lines) added. The combined impact of Seidel spherical aberration and Stiles Crawford Effect apodisation is also shown (dotted lines). Image quality is quantified

by the areaMTF metric in which all values are normalized to the areaMTF generated by a DL 6 mm pupil.

Figure 9.

Percentage of pupil area covered by the distance (blue) and near (red) optics as a function of pupil diameter in mm for a two-zone bifocal with a 3 mm diameter inner-zone (A) and a five-zone design with zones diameters of 2.0, 3.2, 4.4, 5.3, and 6.0 mm (B). Pupil area calculations are performed either with (filled symbols) or without (open symbols) Stiles Crawford Effect central weighting of the pupil.

Figure 10.

MTFs for a two-zone bifocal with +2D add power and a 3mm inner-zone diameter calculated for a 4.2 mm diameter pupil, which equates the area of the inner-zone and outer-zone. Blue shows MTF when inner-zone is focussed, and red when outer-one is focused.

Figure 11.

Peak near (red) and distance (blue) image quality (AreaMTF) obtained with through-focus analysis (see Figure 6) for a two-zone centre-distance bifocal is plotted as a function of pupil diameter in mm. In this example, the areaMTF metrics are normalised by the areaMTF for a diffraction-limited 6 mm pupil. Open symbols represent uniform pupil, while filled symbols show data for a Stiles Crawford Effect apodised pupil, the model includes 0.15 microns of primary spherical aberration (scaled for pupil diameters less than 6 mm).

Figure 12.

Image quality for a five-zone bifocal as a function of pupil diameter. 0.15 microns of spherical aberration was included. AreaMTF with (solid) and without (open) Stiles Crawford Effect apodisation are calculated for distant (blue) and near (red) target vergences. In this example, the areaMTF metrics are normalised by the areaMTF for a diffraction limited 6 mm pupil. Panel A shows data when the eye is paraxially focused, equivalent to adding Seidel spherical aberration to the lens, whereas panel B shows image quality for an

eye which had a minRMS refraction, which is equivalent to adding Zernike spherical aberration to the lens.