

Power Profiles of Multifocal Contact Lenses and Their Interpretation

Sotiris Plainis*, David A. Atchison†, and W. Neil Charman‡

ABSTRACT

Purpose. Many contact lens (CL) manufacturers produce simultaneous-image lenses in which power varies either smoothly or discontinuously with zonal radius. We present in vitro measurements of some recent CLs and discuss how power profiles might be approximated in terms of nominal distance corrections, near additions, and on-eye visual performance.

Methods. Fully hydrated soft, simultaneous-image CLs from four manufacturers (Air Optix AQUA, Alcon; PureVision multifocal, Bausch & Lomb; Acuvue OASYS for Presbyopia, Vistakon; Biofinity multifocal- "D" design, Cooper Vision) were measured with a Phase focus Lens Profiler (Phase Focus Ltd., Sheffield, UK) in a wet cell and powers were corrected to powers in air. All lenses had zero labeled power for distance.

Results. Sagittal power profiles revealed that the "low" add PureVision and Air Optix lenses exhibit smooth (parabolic) profiles, corresponding to negative spherical aberration. The "mid" and "high" add PureVision and Air Optix lenses have bi- aspheric designs, leading to different rates of power change for the central and peripheral portions. All OASYS lenses display a series of concentric zones, separated by abrupt discontinuities; individual profiles can be constrained between two parabolically decreasing curves, each giving a valid description of the power changes over alternate annular zones. Biofinity lenses have constant power over the central circular region of radius 1.5 mm, followed by an annular zone where the power increases approximately linearly, the gradient increasing with the add power, and finally an outer zone showing a slow, linear increase in power with a gradient being almost independent of the add power.

Conclusions. The variation in power across the simultaneous-image lenses produces enhanced depth of focus. The through-focus nature of the image, which influences the "best focus" (distance correction) and the reading addition, will vary with several factors, including lens centration, the wearer's pupil diameter, and ocular aberrations, particularly spherical aberration; visual performance with some designs may show greater sensitivity to these factors.

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Key Words: contact lenses, multifocal, addition, spherical aberration, presbyopia, pupil

Numerous designs of contact lens have been produced in an effort to satisfy the visual needs of presbyopes.¹ In particular, many manufacturers produce simultaneous-image (vision) lenses in which the power varies with rotational symmetry about the lens center, i.e., it varies either smoothly or discontinuously with zonal radius.²⁻⁶ Although these manufacturers

may describe their multifocal lenses as being center-near or center-distance designs, and may assign them distance-correcting and add powers, commercial secrecy makes it unusual for the power profile to be described in detail, making it difficult to properly assess the likely merits and disadvantages of any particular product.

Various methods have been used for measuring the power profiles of lenses of this type, including small-aperture focimetry⁷⁻⁹ and instruments based on Moiré, interferometric, Schlieren, and Hartmann-Shack methodologies.^{7,10-14} With most of these, soft lenses are placed in a saline-filled wet cell, the derived powers being corrected to air values using a factor which allows for the different immersion index.^{7,9} Apart from the problem of avoiding lens distortion in the cell, major limitations often include modest lateral resolution and, with the Hartmann-Shack method, difficulties in relating the image spots to the appropriate lenslets, particularly when the lens power profile displays abrupt discontinuities.¹⁵ A promising new diffraction-based method, which is used for

*MSc, PhD

†PhD, DSc, FAAO

‡PhD, DSc

Institute of Vision and Optics; Faculty of Life Sciences, University of Manchester, UK (SP), University of Crete, Greece; Faculty of Life Sciences (WNC), University of Manchester, Manchester, United Kingdom; and Institute of Health & Biomedical Innovation and School of Optometry and Vision Science (DAA), Queensland University of Technology, Brisbane, Queensland, Australia.

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the measurements in this paper, is the Phase Focus Lens Profiler (Phase Focus, Sheffield, UK) instrument, which claims a lateral resolution of $7\ \mu\text{m}$ and a power sensitivity $<0.02\ \text{D}$.¹⁶

It is important to consider what is usually plotted in a power profile. For any lens whose power is a smooth function of zonal radius y , any small circular region of the lens has spherocylindrical power in which the principal meridians are oriented radially and circumferentially (Fig. 1). If the tangential (radial) and sagittal (circumferential) powers are P_T and P_S , respectively, and y is the zonal radius, it can be demonstrated¹⁷ that

$$P_T - P_S = y(\partial P_S / \partial y) \quad (1)$$

It can be seen from Fig. 1 that the sagittal (circumferential) focal point corresponds to the focus of the rays from an annular zone of negligible width and radius y in the lens, or from any arc comprising part of this annulus. The power profile is usually plotted in terms of this power. Note from equation (1) that if the lens is decentered, some astigmatic power will be introduced, its value depending upon both the decentration and the sagittal power gradient.

Assuming that a power profile has been measured, an important question is how can we best define the “distance correction” and “near addition” provided by the lens? While this is straightforward with a two-zone bifocal design, where a central circular region has one unique power and the outer annular surround a different constant power, either in a center-near or center-distance arrangement, the position is more confused with designs having more complex profiles, e.g., those with a power gradient such that the power increases or decreases steadily from the center to the edge

of the optical zone. Clearly, there is no unique “distance” or “near” correction. Moreover, the correction provided by such a lens will vary with the pupil diameter and with its centration.

We present here measurements made on some recent designs of concentric presbyopic contact lenses and discuss how their power profiles might be approximated in terms of nominal distance corrections and near additions.

METHODS

Instrument

The fully hydrated lenses were measured with a Phase Focus Lens Profiler. This instrument uses the technique of ptychographic^{18–20} imaging in which a series of diffraction patterns is recorded from neighboring points on the lens and is used to reconstruct the lens thickness profile, and hence its power profile.¹⁶ Ptychography has been demonstrated to improve resolution of scanning transmission x-ray microscopy (STXM)²⁰ by measuring complete diffraction patterns at each point of a STXM scan and is becoming an important new method for high-resolution imaging^{18,19} between light microscopy and electron microscopy. The instrument can successfully measure abrupt step changes in power. However, although lateral (side-to-side) resolution is good (typically $7\ \mu\text{m}$) and power measurement can be very accurate, the algorithms used in the data analysis may make measurements subject to artifacts over the central area of the lens ($y < 0.5\ \text{mm}$). This is normally not a major drawback because this region usually corresponds to only a small fraction of the area of the lens used by the eye pupil. The lenses were measured in a wet cell and the powers were then corrected to powers in air. Each lens was allowed to equilibrate

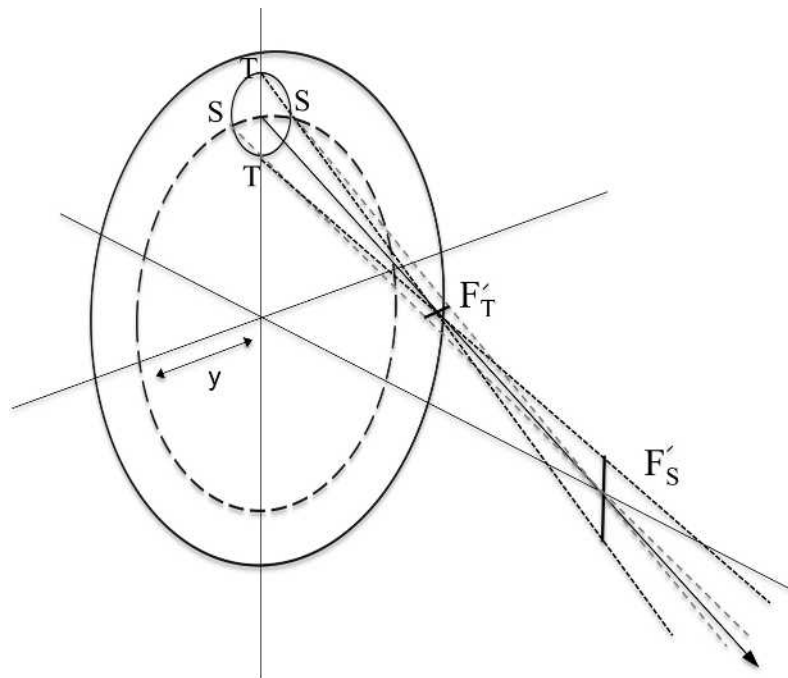


FIGURE 1.

Schematic section of an aspheric contact lens whose positive power increases with zonal radius. For any small circular area of the lens there are two astigmatic focal points F'_T and F'_S . However, if we consider the rays from a very narrow annular zone of radius y , or rays from any part of that annulus, there is a single axial focal point at F'_S . This is the sagittal (circumferential) focus for that zone.

overnight in saline solution at a temperature of 23.3°C. All measurements were made in the laboratories of the manufacturer of the instrument.

Contact Lenses

A selection of single examples of soft, multifocal contact lenses from four manufacturers was measured. All lenses had plano (0.00 D) labeled power for distance. The lenses and their basic characteristics were

1. Air Optix AQUA (AO) multifocal (Alcon, Fort Worth, TX, USA)—low-, medium-, and high-add lenses (center-near aspheric/bi-aspheric designs)
2. PureVision (PV) multifocal (Bausch & Lomb, Rochester, NY, USA)—low- and high-add lenses (center-near aspheric/bi-aspheric designs)
3. Acuvue OASYS for Presbyopia (Vistakon, Division of Johnson & Johnson Vision Care, Jacksonville, FL, USA)—low-, medium-, and high-add lenses (several concentric aspheric distance/near zones)
4. Biofinity multifocal (Cooper Vision, Fairport, NY, USA)—+1.50, +2.00, and +2.50 D add lenses. The lenses were of the “D” design in which the “distance” correction is at the lens center (center-distance). Note that the “N” design is also available, in which the “near” correction is at the lens center (center-near).

RESULTS

Figs. 2 and 3 are color-coded power maps for all the lenses as measured with the Phase Focus Lens Profiler.

Aspheric and Bi-aspheric Multifocal Lenses

Fig. 4 presents sagittal (circumferential) power profile data, obtained by averaging the power around each annular zone of the lenses, for the AO (left) and PV (right) aspheric multifocal lenses. These profiles are very similar to those published earlier by Vogt et al,¹⁴ who used a high-resolution Hartmann-Shack instrument. It is evident that, assuming that the increase in power at the center of the low-add PV lens is an instrumental artifact, the powers for the “low-add” PV and AO lenses exhibit smooth, continuous, parabolic profiles and can therefore be fitted²¹ by the following equation:

$$P_y = P_0 + by^2, \quad (2)$$

where y is the radial distance from the center of the lens (mm), P_0 is the paraxial power (at $y = 0$), P_y is the power at radius y , and b (D/mm²) is a constant which characterizes the power changes as a function of y (see Appendix A, available at <http://links.lww.com/OPX/A139>). Because in Fig. 2 the values of b are negative, this parabolic change in power corresponds to negative primary Seidel spherical aberration (SA).

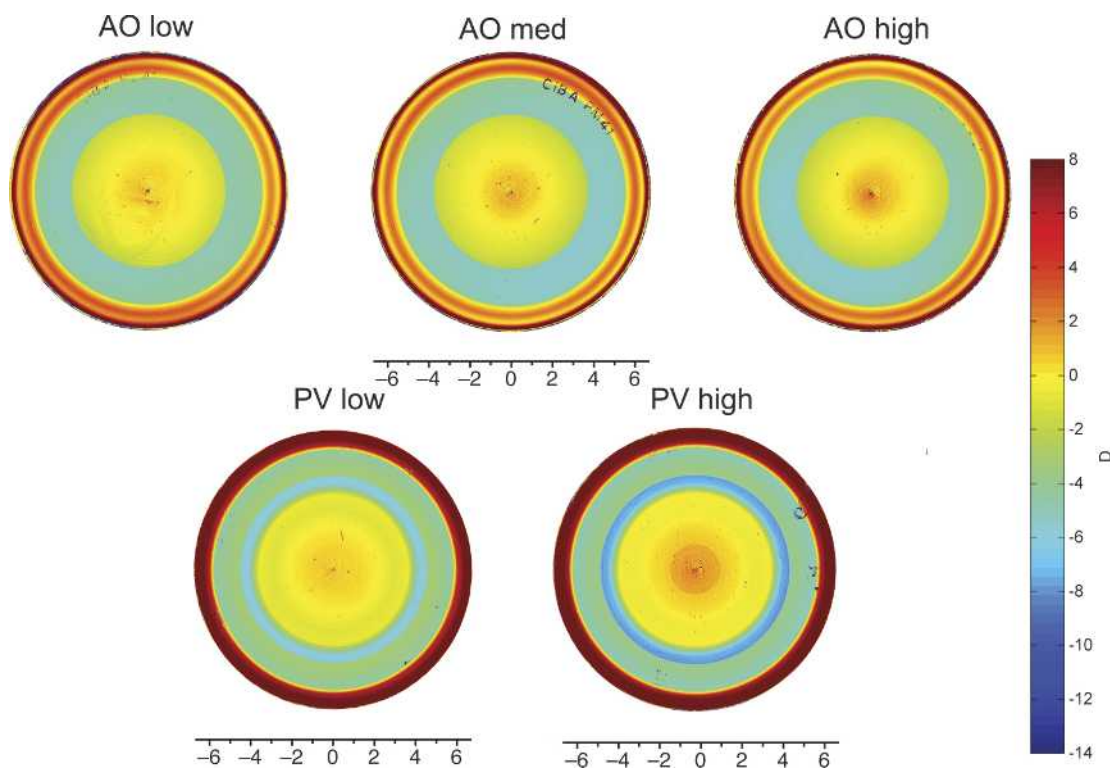


FIGURE 2.

Color-coded power maps for the aspheric/bi-aspheric multifocal lenses measured in this study with the Phase Focus Lens Profiler (Phase Focus Ltd, Sheffield, UK): AO multifocal lenses (Alcon, Fort Worth, TX, USA) (upper) and PureVision multifocal (Bausch & Lomb, Rochester, NY, USA) (lower). The full areas of the lenses are mapped (the horizontal scales give distances in millimeters, the right-hand vertical scale the powers). The optical zones correspond to the sharply bounded, central yellow/orange tinted areas (diameters about 6–7 mm).

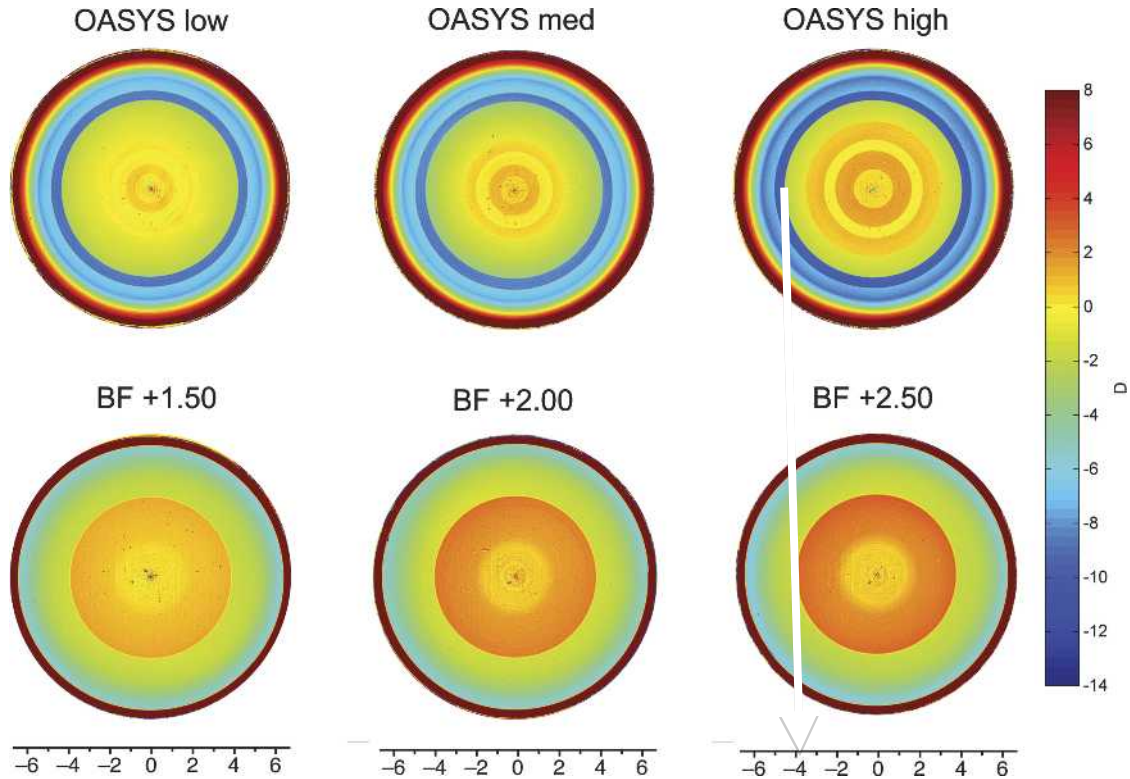


FIGURE 3.

Power maps of the multifocal lenses, with aspheric/step changes, measured in this study with the Phase Focus Virtual Profiler (Phase Focus Ltd, Sheffield, UK): Acuvue OASYS for Presbyopia (Vistakon, Division of Johnson & Johnson Vision Care, Jacksonville, FL, USA) (upper) and Biofinity multifocal (Cooper Vision, Fairport, NY, USA) (lower). Note the abrupt changes in power for the annular zones of the OASYS lenses and the central distance zone of the Biofinity lenses. The full area of the lens is shown in all cases.

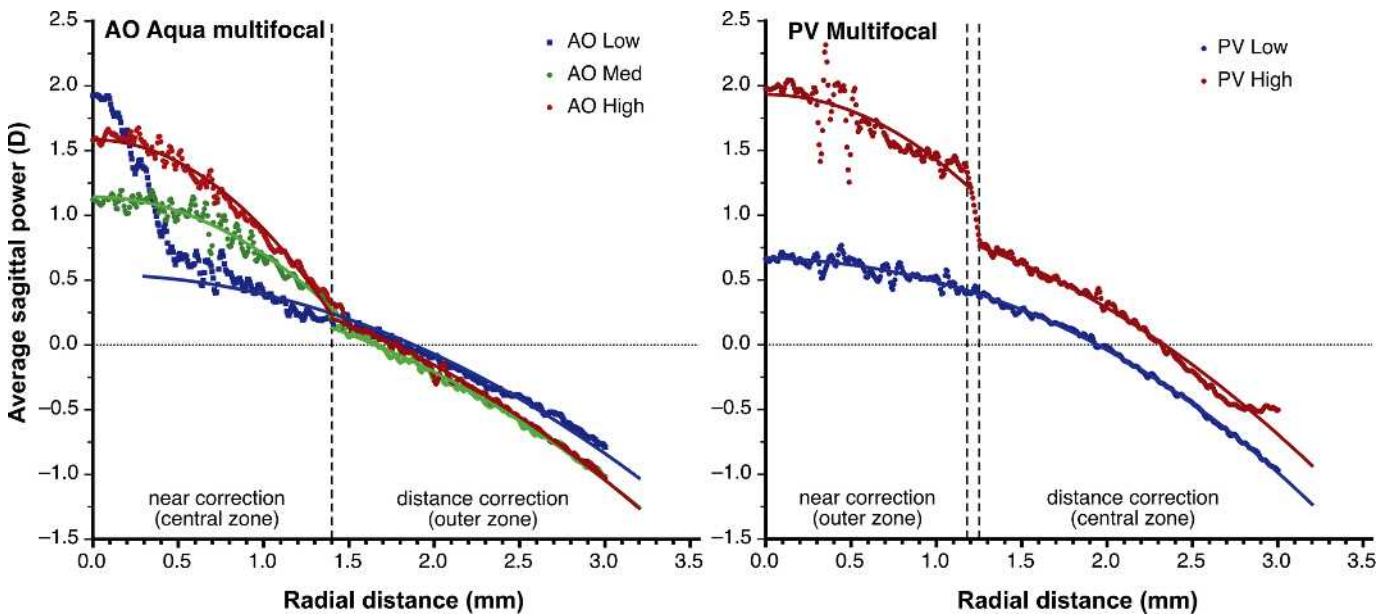


FIGURE 4.

Power profiles for Air Optix AQUA (left) and PureVision (right) multifocal lenses (vertical lines have been drawn to indicate the positions of step changes and thin lines show the fitted parabolas). Note that, according to Phase Focus, the abrupt increase in measured power over the central 0.3 mm zone of the AO Low is an artifact caused by dirt or a defect at the center of the lens. The algorithm used in deducing the power exaggerates the defect due to the small zonal radius. A color version of this figure is available at www.optvissci.com.

TABLE 1.

Equations for the power profiles of the bi-aspheric AO and PV lenses

Lens type	Central power	Outer power
AO med	$P_y = 1.14 - 0.44y^2$ ($0 < y < 1.4$)	$P_y = 0.46 - 0.17y^2$ ($1.4 < y < 3.5$)
AO high	$P_y = 1.58 - 0.69y^2$ ($0 < y < 1.4$)	$P_y = 0.55 - 0.18y^2$ ($1.4 < y < 3.5$)
PV high	$P_y = 1.93 - 0.50y^2$ ($0 < y < 1.2$)	$P_y = 1.10 - 0.20y^2$ ($1.3 < y < 2.8$)

The range of zonal radii for which each equation is valid is given in brackets. The units for power are diopters (D) and for y are millimeters (mm).

Using equation (2), we find that the dioptric power profiles, and their extent, for the low-add lenses are

$$\text{AO Low: } P_y = 0.54 - 0.15y^2 \quad (0 < y < 3.5) \quad (3)$$

$$\text{PV Low: } P_y = 0.67 - 0.18y^2 \quad (0 < y < 3.0) \quad (4)$$

The two profiles are similar. Both lenses, which nominally provide a plano distance correction, have low positive paraxial power. Their power fall to zero at a radial distance of about 1.9 mm from the lens centers, so that a pupil diameter of at least 3.8 mm is required for inclusion of the zero-power zone.

The changes in the power as a function of lens zonal radius for “med” and “high” addition lenses (Fig. 2) cannot be fitted by a single second-order function. These lenses have bi-aspheric designs, leading to different rates of power change for the central and peripheral portions. Moreover, there is an abrupt discontinuity in the profile for the PV high lens. However, the data for the central and peripheral zones can be well fitted by separate parabolic functions, each valid for the appropriate range of zonal radii. The fitting equations are given in Table 1.

Note from Fig. 2 that the power of the PV “high-add” lens does not fall to the 0.00 D value of the nominal distance correction until a radial distance of about 2.4 mm from the center of the lens is

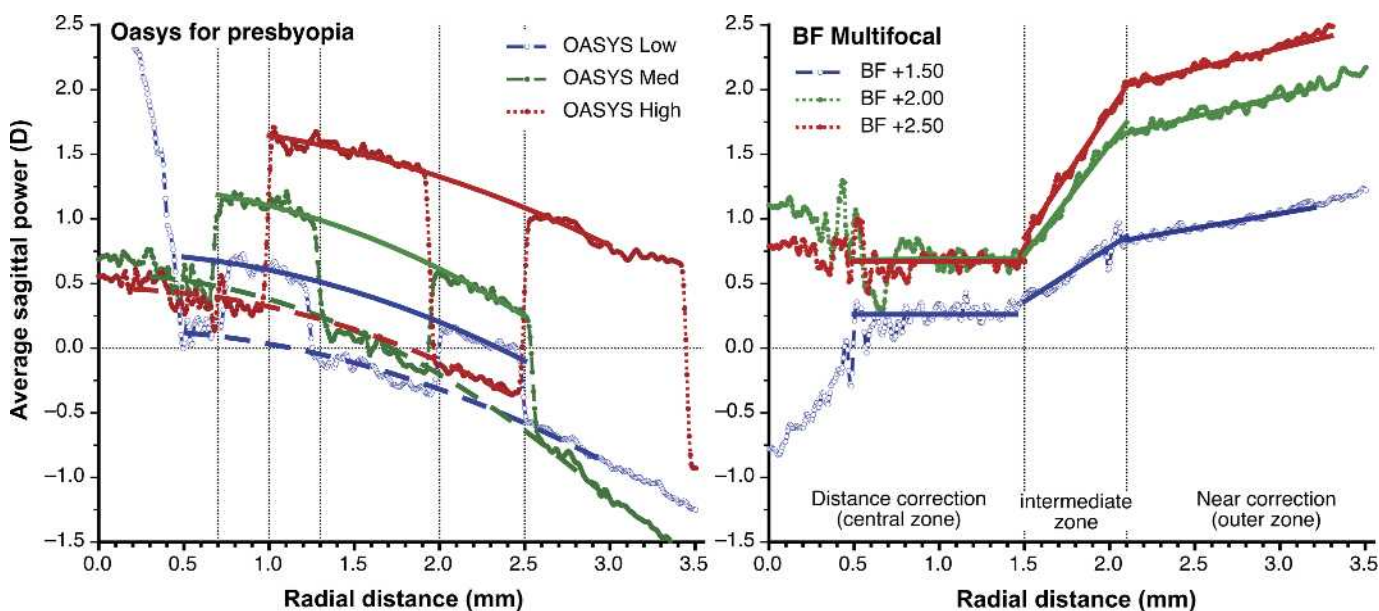
reached, whereas this occurs at a distance of about 1.7 mm for the “med” and “high” add AO lenses. Thus, with well-centered lenses, no part of the pupil will receive the nominal 0.00 D correction unless the pupil diameter exceeds about 4.8 mm with the PV high lens or about 3.4 mm with the AO lenses. At all zonal radii, the power of the “high” PV lens is slightly more positive than its AO counterpart. This shift affects the refractive corrections achieved with the two lenses but does not alter their “additions”.

Other Multifocal Lenses (Combined Aspheric/Step Changes)

As can be seen from Fig. 5, these lenses (OASYS for Presbyopia; Biofinity multifocals) have more complex power profiles.

OASYS for Presbyopia

The OASYS lenses display a series of concentric zones, separated by abrupt discontinuities (Fig. 5). The center of the lens is of lower positive power. The zone widths vary with the nominal add: it is not obvious why the zone widths are broader in the “high-add” design. Within each zone, the power is approximately constant and it might be surmised that the basic intention is that the powers

**FIGURE 5.**

Power profiles for OASYS for Presbyopia (left) and Biofinity multifocals (right) (note that vertical lines have been drawn to estimate step changes). Artfactual increases and decreases in power associated with the measurement technique occur for very small values of zonal radius (less than about 0.5 mm) for the OASYS Low-add and the Biofinity +1.50 D add lenses. A color version of this figure is available at www.optvissci.com.

TABLE 2.

Expressions for the parabolas which limit the power profiles of the OASYS for Presbyopia, and their ranges of validity (i.e., the inner and outer radii of the power zones)

Lens type	Lower parabolic fit	Upper parabolic fit
Low add	$P_y = 0.15 - 0.12y^2$ $0 < y < 0.7$; $1.3 < y < 2.0$; $2.5 < y < 3.5$	$P_y = 0.74 - 0.13y^2$ $0.7 < y < 1.3$; $2.0 < y < 2.5$
Medium add	$P_y = 0.58 - 0.19y^2$ $0 < y < 0.7$; $1.3 < y < 2.0$; $2.5 < y < 3.4$	$P_y = 1.27 - 0.17y^2$ $0.7 < y < 1.3$; $2.0 < y < 2.5$
High add	$P_y = 0.46 - 0.14y^2$ $0 < y < 1.0$; $2.0 < y < 2.5$	$P_y = 1.75 - 0.11y^2$ $1.0 < y < 2.0$; $2.5 < y < 3.5$

The units of power, P_y , are diopters (D) and for zonal radius, y , are millimeters (mm).

should alternate between the distance and the near correction. However, this is modified by a gradual overall change in power in the negative direction as the zonal radius increases. This presumably helps to smooth the optical performance as the viewing distance of tasks is changed through far, intermediate, and near, but it is more probable that the design is intended to allow for the effects of the usually positive spherical aberration of the eye (see below). The changes in power at the edge of each zone are about 0.50, 0.70, and 1.30 D for the low-, medium-, and high-add lenses, respectively.

Consideration of Fig. 5 suggests that each of the OASYS lens profiles can be constrained between two parabolically decreasing curves, each giving a valid description of the power changes over alternate annular zones. The lower of the parabolas is similar for all three lenses. The equations for the parabolas and the ranges of zonal radii for which they are valid are given in Table 2. Note again that the zone widths for the high-add lens differ from those of the other lenses.

For simplicity, Table 2 assumes that the power changes at the zone boundaries are abrupt. It appears, however, from Fig. 3 that there may be transition zones of width about 0.05 mm which may scatter some light.

Biofinity Multifocal Lenses

According to the manufacturer, the “D” lenses measured should have a central distance zone, an intermediate annular zone of gradually increasing power for intermediate vision, and an outer “near” zone. This appears to be approximately the case (the manufacturer also produces center-near “N” lenses of broadly similar design). If we discount the measurements for $y < 0.5$ mm as being unreliable, it appears that all lenses do indeed have constant power over the central circular region of radius 1.5 mm, although this power is slightly positive rather than equaling the nominal distance correction of 0.00 D. There follows an annular zone ($1.5 < y < 2.1$) where the positive power increases roughly linearly, the gradient increasing with the nominal add power, and finally the outer zones of the lens show a slow, linear, positive increase in power with a

gradient which is almost independent of the nominal add power. The fits over the three zones of each lens are given in Table 3.

DISCUSSION

Reproducibility of Data With Phase Focus Instrument

Fig. 6 shows repeated measurements of the power profiles of additional OASYS lenses (low and high add). This lens design is illustrated because the abrupt discontinuities in power are likely to pose the greatest challenges to any measuring instrument. Repeated measurements of the power profiles of other lenses are given in Appendix B (available at <http://links.lww.com/OPX/A139>). In general, reproducibility is good, even across the boundaries of the power zones (≤ 0.05 D, except close to the lens center).

Evaluation of Distance Corrections and Add Powers

Given the power profiles of Figs. 4 and 5, how should we best evaluate the effective distance correction and the “add”? As noted earlier, unlike conventional simultaneous-image bifocals, there are no clearly defined and unambiguous “distance” and “near” powers for many of these lenses. Instead, the radial variation in power across the lens surface produces an enhanced depth of focus (DOF) over which reasonable image quality and on-eye, visual acuity can be achieved.^{22–24} The through-focus nature of the image will change with the pupil diameter and, within the DOF, the “best focus” will vary with the spatial frequency spectrum of the object viewed.^{4,13,25,26} However, it is clear that the “add” effect is not the same as the DOF because even a single-vision lens yields a non-zero DOF. It is the increase in DOF over what would be achieved with a single-vision lens that constitutes the “add” effect.²⁷

A further complication is the coupling of the aberrations of the eye, in particular its spherical aberration, with the power characteristics of the lens worn. The spherical aberration of the eye varies with the individual^{28–30} and tends to increase with age (see Fig. 7).^{31–33} For an early presbyopic age group, aged 40–59 years, the positive, primary Seidel spherical aberration has mean

TABLE 3.

Fits to power profiles of “D” type Biofinity multifocal lenses

Lens nominal “addition” (D)	Central area ($0 < y < 1.5$)	Intermediate zone ($1.5 < y < 2.1$)	Outer zone ($2.1 < y < 3.5$)
+1.50	$P_y = 0.25$	$P_y = 0.84y - 0.90$	$P_y = 0.23y + 0.36$
+2.00	$P_y = 0.68$	$P_y = 1.71y - 1.84$	$P_y = 0.32y + 1.00$
+2.50	$P_y = 0.67$	$P_y = 1.96y - 2.08$	$P_y = 0.32y + 1.36$

The units of power, P_y , are diopters (D) and for zonal radius, y , are millimeters (mm).

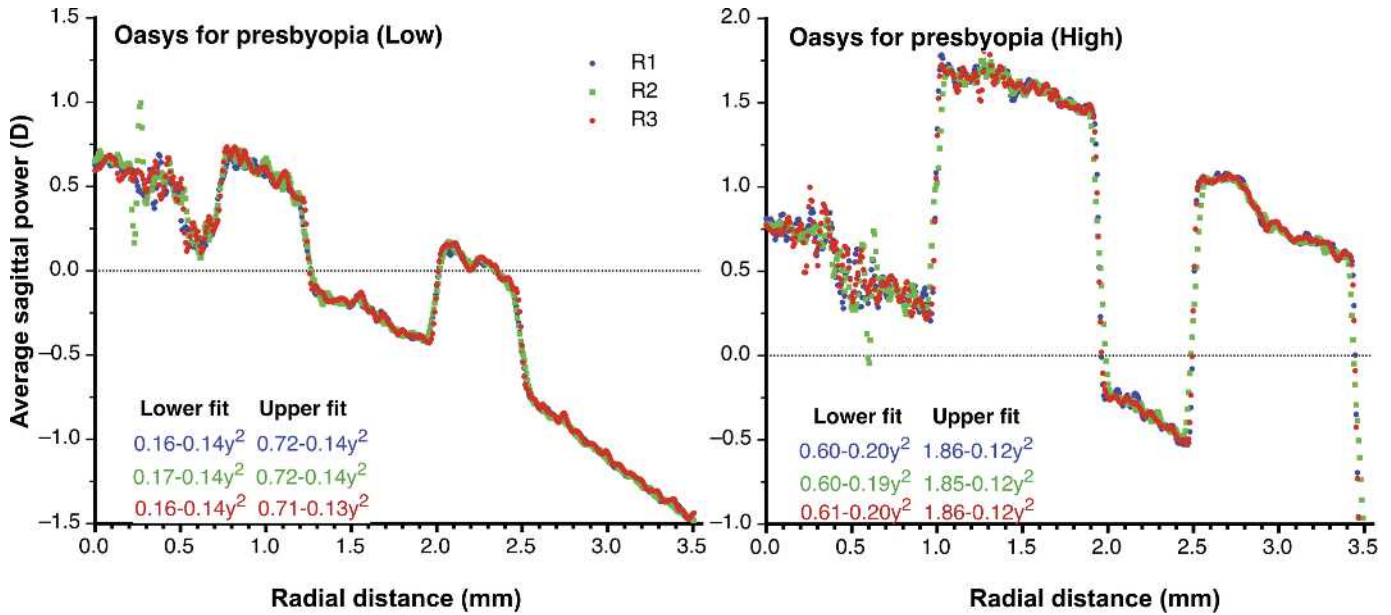


FIGURE 6.

Examples of the reproducibility of three repeated measurements of the power profile. The lenses are low-add (left) and high-add (right) OASYS designs, with nominal plano distance powers. The equations of the lower and upper parabolic fits for the three measurements are also shown. A color version of this figure is available at www.optvissci.com.

and standard deviation across subjects of about $0.10 \pm 0.06 \text{ D/mm}^2$ (Fig. 7). Because the contributions of a soft lens and eye to the overall spherical aberration are additive³⁴ and in the case of center-near lenses their signs are opposite, the add effect for lenses with profiles like those in Fig. 4 is likely to be reduced. Moreover, the wide range of SA values found for different individuals helps to explain why some wearers may find the lenses helpful while others do not.⁶ In general, other monochromatic higher-order

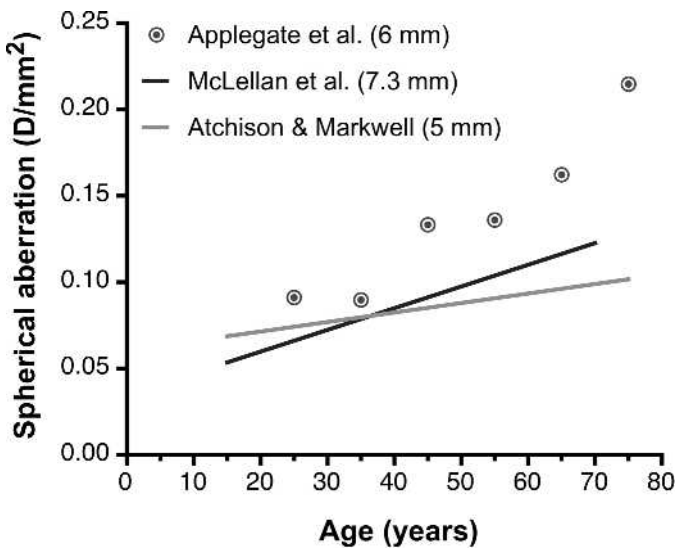


FIGURE 7.

Primary spherical aberration, expressed in diopters per square millimeter, as a function of age according to the authors indicated.^{32–34} The bracketed figures give the pupil sizes used by the authors in their estimates of the Zernike wavefront coefficient C_4^0 from which the values of primary spherical aberration were derived. The data from Applegate et al³² are mean values for 10-year age groups; those from the other authors are their regression line fits. Standard deviations are about 0.06 D/mm^2 in all cases at all ages.

aberrations are likely to further blur the image and extend the DOF when either single-vision or more complex lenses are worn. For simplicity, however, we shall assume that these aberrations have no influence on the “add” effect of the more complex lenses.

It is also clear that the on-eye effects of the lenses are likely to be strongly affected by the lens centration relative to the pupil and the pupil diameter. Well-fitting soft lenses usually show movement of $<0.5 \text{ mm}$ after a blink and centration to within about 0.5 mm ,³⁵ so that this effect may not be too important. Pupil diameter is probably much more significant. Pupil diameter will be affected by a variety of factors, the best known being the ambient illumination. Fig. 8 gives some typical experimental data for mean pupil diameter as a function of photopic light level for different

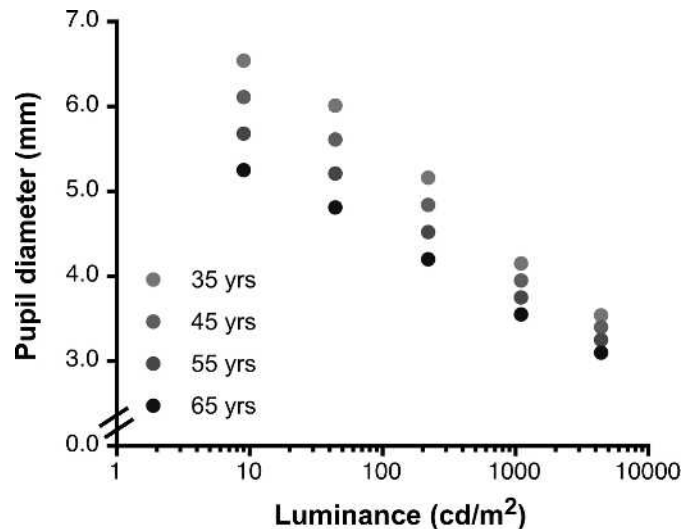


FIGURE 8.

Pupil diameter as a function of luminance, at various ages. The stimulus field was 10 degrees in diameter (based on data from Winn et al³⁷).

age groups under monocular conditions and with a 10-degree stimulus field.³⁶ Note that diameters become smaller as presbyopia advances. The range of luminance illustrated runs from the lowest photopic level to that encountered on a bright sunny day: for comparison, recommended luminance levels for internally illuminated ophthalmic test charts are usually around 120 cd/m². Fig. 8 suggests that the average presbyopic pupil is unlikely to be much greater than 5 mm in diameter under most well-lit conditions: a pupil diameter >6 mm would only be expected with younger presbyopes and under rather poorly lit conditions. In fact, the pupil diameter at any luminance level will often be smaller than those shown in Fig. 5 because it reduces with binocular observation, by around 0.5 mm, for the photopic range of luminance illustrated.³⁷ Moreover, for the same photopic range, the pupil diameter increases as the size of the stimulus field increases: for field diameters up to at least 25 degrees, the pupil diameter depends on the corneal flux density (i.e., the product of the field luminance \times its subtended area) rather than simply on the luminance.^{38,39} If, for example, we consider a sheet of white A4 paper in a well-lit office, its luminance will typically be around 100 cd/m² and, with a viewing distance of around 40 cm, its subtense will be a little in excess of 25 degrees, some $2.5 \times$ greater than the 10 degrees used in Fig. 5. This is equivalent to a $2.5^2 = 6.3 \times$ increase in luminance at the constant field size of 10 degrees, implying that under these conditions, pupil diameters might be about 0.8 mm smaller than those shown in Fig. 8, depending somewhat upon the age. Watson and Yellott⁴⁰ have recently attempted to produce a unified formula giving the expected pupil diameter in terms of the various relevant parameters.

Finally, we note that the value of the DOF (and hence the nominal “add”) will depend upon the criterion used to assess its boundaries, e.g., just-noticeable, troublesome or objectionable blur^{41,42} or criteria based on relative and absolute acuity levels (see for review⁶).

We now consider the characteristics of the lenses illustrated in Figs. 4 and 5.

Single Aspheric (Primary Spherical Aberration) Designs

Equations (3) and (4) give the single parabolic power profiles of the AO and PV “low” lenses. Experimental and theoretical studies suggest that, in the presence of spherical aberration of this form, conventional measurements of subjective refraction correspond closely to the paraxial focus, largely because this is optimal for objects whose spatial frequency spectrum is dominated by high frequencies, such as small letters.^{26,43,44} This arises from the nature of the associated point-spread function, where at the paraxial focus there is a compact central core, favoring imaging at high spatial frequencies, surrounded by a larger blurred area which primarily reduces image contrast.^{45,46}

Because the lenses have negative spherical aberration (i.e., are “center near”), the paraxial focus is presumably that used in near vision. This focus is independent of the pupil diameter. The problem lies in defining the distance correction because this must be provided by the pupil-dependent outer zones of the lens. Light from all zones within the pupil will be focused somewhere between the paraxial and marginal foci. Essentially, the “distance correction” must have a dioptric value such that the difference between the

paraxial (near) correction and the distance correction equals the reading addition (i.e., the enhancement in DOF over that achieved with a single-vision lens).

One possible theoretical approach to estimating the add is to view the lens as though it were a two-zone concentric bifocal and to divide the area covering the pupil into equal areas consisting of a central circular “near” zone and an outer annular “distance” zone. This would nominally ensure that equal quantities of light contributed to the distance and near images. The radius separating the zones is evidently $y_{\max}/\sqrt{2}$, where y_{\max} is the pupil radius. Just as we approximate the paraxial power, P_0 , as being that of the near correction, so the power at the inner edge of the annulus becomes the distance correction. Because the power varies with the square of the zonal radius, the power at radius $y_{\max}/\sqrt{2}$ lies midway between the paraxial and marginal powers of the overall lens: this is, in fact, the plane of focus that yields minimal RMS wavefront deviation. On this basis, the add effect is simply $(b \cdot y_{\max}^2)/2$, so that for a 6 mm pupil and using the values of the parameter “ b ” from equations (3) and (4) (i.e., -0.15 and -0.18 D/mm²), the “add” effects of the AO and PV “low” add lenses would be about 0.70 and 0.80 D, respectively, falling to around 0.30 D and 0.35 D for a 4 mm pupil. The nominal distance correction of both the low-add lenses in Fig. 2 is plano, and their power profiles pass through zero when $y = 1.9$ mm. If we assume that the distance correction is found at a zonal radius $y = y_{\max}/\sqrt{2}$, it could be argued that the lenses are designed for a pupil diameter of $2y_{\max} = 5.4$ mm. For this pupil diameter, the effective adds for the AO and PV designs would be 0.56 and 0.66 D, respectively. These values would, of course, reduce if we made allowance for the “typical” positive spherical aberration of the eye (about $+0.10$ D/mm²) because the effective combined lens-eye values of b would then be reduced to around -0.06 D/mm².

An alternative theoretical approach, adopted by Plainis et al,²¹ once more divides the lens into equal area circular “near” and annular “distance” portions but then calculates the area-weighted average power, P_a , for each portion. It is easy to show that $P_a = P_0 + (b \cdot y_{\max}^2)/4$ for the central “near” area and $P_a = P_0 + (3b \cdot y_{\max}^2)/4$ for the outer “distance” annulus (see Appendices A and C—available at <http://links.lww.com/OPX/A139>). The difference between these mean powers is again $(b \cdot y_{\max}^2)/2$, so that the estimated “add” effect is the same as before, although the values of the deduced distance and near corrections are more negative.

Do the estimates of add effects and corrective powers made in this way bear any relation to what is achieved in practice? Yi et al²⁸ and others^{22,47,48} have approached this problem experimentally using adaptive optics systems to introduce controlled amounts of spherical aberration (i.e., values of the parameter b) and defocus, and to eliminate the other monochromatic ocular aberrations. With a 6 mm pupil, Yi et al found that, with their “objectionable blur” criterion for the limits of the DOF, there was a linear enhancement in DOF as the spherical aberration was increased. The average increase in DOF was about 0.8D for ± 0.4 D/mm² of spherical aberration (equivalent to a value of $0.6 \mu\text{m}$ for the Zernike coefficient C_4^0). Benard et al^{22,47} found very similar results (0.85 D) for the increase in total DOF with the same level of SA and 6 mm pupils, but that the increase in DOF was much reduced for a 3 mm pupil, to around 0.3 D. Higher DOF estimates were found by Rocha and his colleagues.⁴⁸ However, in all studies,

TABLE 4.

Corrective powers and effective adds (diopters) for the bi-aspheric lenses of Fig. 2 and the fits of Table 1

Lens	Paraxial approach			Mean power method		
	Distance correction	Near correction	Add	Distance correction	Near correction	Add
AO med	+0.28	+1.14	0.86	-0.24 (-0.05)	0.71	0.94 (0.75)
AO high	+0.23	+1.58	1.35	-0.19 (0.02)	0.91	1.08 (0.88)
PV high	+0.73	+1.93	1.20	0.28 (0.50)	1.57	1.27 (1.05)

In the case of the “mean power” approach, the powers for the outer annuli are derived for both 5 mm and 4 mm (in brackets) pupil diameters.

the apparently beneficial increase in DOF was accompanied by a marked loss in optimal visual acuity, e.g., by about 0.2 logMAR in the Yi et al study.²⁷ A similar loss in acuity was found by Hickenbotham et al²³ when using 5 mm pupils and 0.38 D/mm² of spherical aberration, when the gain in DOF using a logMAR 0.2 (6/9, 20/30) criterion as the objectionable blur level was about 0.65 D.

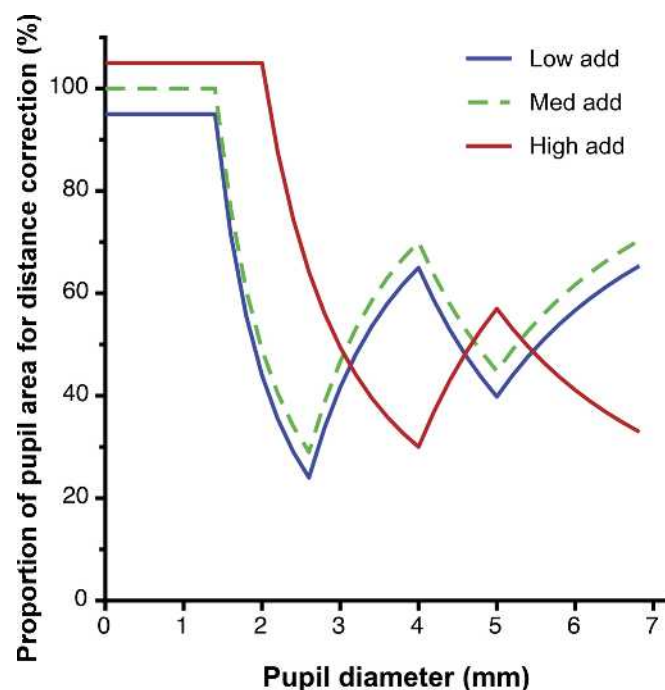
Our approach, taking the effective reading addition as $(b.y_{\max}^2)/2$, would yield expected additions of about 1.8 D for the 6 mm pupil and spherical aberration levels used by Yi et al²⁷ and Benard et al,²² and about 1.2 D for the conditions of the Hickenbotham et al study.²³ Thus, our estimates of the reading addition are about twice as high as the enhancements in DOF observed experimentally, suggesting that an effective reading add value of about $b.y_{\max}^2/4$ would be more realistic than $b.y_{\max}^2/2$. We assume that the discrepancy arises largely because the degradation in image quality caused by the introduction of the spherical aberration reduces the dioptric range over which adequate image quality is achievable.

The above has assumed that the lenses are perfectly centered to the pupil of the eye. As noted earlier, this may not be true in practice and may result in an extension of the DOF and “add” effect. For example, in an experimental study with subjects having normal ocular aberrations, cycloplegia, and 4 mm artificial pupils, Plakitsi and Charman²⁴ found that two types of soft, single-aspheric lenses with about +0.18 and -0.38 D/mm² of spherical aberration both enhanced DOF over that achieved with the naked eye by about 0.8D. If we assume that, on-eye, the lenticular SA was combined with an ocular SA of 0.10 D/mm² the combined lens-eye SAs became +0.28 and -0.28 D/mm², so that for a 4 mm pupil the predicted gain in DOF of $(b.y_{\max}^2)/2$ would be about 0.60 D, somewhat less than that observed. It seems reasonable to attribute the higher practical value to the effects of small amounts of lens decentration which result in a wider range of lens power across the pupil, including some cylinder effects. However, even for early presbyopes, having some reserves of accommodation and who require a moderate additions,⁴⁹ near visual acuity with such single-aspheric lenses does not appear to be sufficient.⁵⁰

Bi-aspheric Designs

There is less ambiguity here because there are obvious “near” and “distance” zones in the lenses (see Fig. 4). As in the simple aspheric case, two approaches might be used. In the first, paraxial approach, we take the paraxial power of the central circular region as being the “near” correction and the power corresponding to the inner edge of the outer annulus as being the “distance”

correction. The reading addition then corresponds to the difference between these powers. Alternatively, we may take the near and distance corrections as respectively the area-weighted mean powers of the inner circular and outer annular regions of the lens. Whereas the first definition of the addition is independent of the pupil radius (provided that the pupil diameter is greater than the diameter of the inner circular zone), the second is obviously pupil dependent. Table 4 gives the distance and near corrections and “adds” for the three bi-aspherical lenses of Figs. 2 and 4, derived on the basis of these two approaches and, for the second method, assumed pupil diameters of 4 and 5 mm. It can be seen that, with these center-near designs, the second method tends to yield more negative values for the corrections, and the near additions and distance corrections become pupil dependent. The estimated “add” values agree with recent results in an experimental study,⁵¹ which assessed the on-eye performance with AO and PV high lenses concluding that the negative SA provided by these lenses is not enough to increase

**FIGURE 9.**

Percentage of the pupil covered by the distance correction as a function of the pupil diameter for the three OASYS adds. To avoid overlap between the curves, the “low-add” values have been decreased by 5% and the “high-add” values have been increased by 5%. A color version of this figure is available at www.optvissci.com.

DOF for a target placed at 40 cm, resulting in significantly reduced contrast sensitivity.

OASYS Lenses (Stepped Power Profiles)

There is much less ambiguity in specifying a distance correction and add power for each of these lenses. Although the power steps are constrained within upper and lower parabolic curves, rather than between constant values, it can be seen from Table 2 that the value of the coefficient b for all these parabolas is about -0.14 D/mm^2 . It will be recalled that the mean ocular spherical aberration for the 40- to 49-year-old age group was about $+0.10 \text{ D/mm}^2$. This figure rises to about $+0.11 \text{ D/mm}^2$ at the age of 55 years.^{31–33} Thus, when the soft lenses are placed on the typical eye, the two parabolic changes are almost equal and opposite in sign and the steps in the combined power profile are made between almost constant levels of zonal power. The lenses therefore have distance powers corresponding to the central powers, i.e., $+0.15$, $+0.58$, and $+0.46 \text{ D}$ for the low, medium, and high adds, respectively. The add powers correspond to the mean heights of the power steps and take the values 0.56 , 0.73 , and 1.48 D .

It is of interest to consider the fraction of the pupil covered by the “distance” correction as a function of the pupil diameter, assuming that the lenses are well centered. This is shown in Fig. 9. Evidently for pupil diameters larger than about 3 mm , the area of the pupil will be covered more or less equally by the distance and near corrections, ensuring that both the distance and near images have reasonable contrast.

Biofinity Lenses

As can be seen from Fig. 5 and Table 3, the central “distance” portion of these lenses has a diameter of 3.0 mm . All the measured lenses have low positive power in this area, rather than being plano. The intermediate annular zone of radially increasing positive power extends to a pupil diameter of 4.2 mm . The linear rate of increase of power with zonal radius is relatively low in the outer “near” annuli of the lenses (around 0.3 D/mm), so that even an increase in pupil diameter to 6.2 mm only increases the marginal power by 0.3 D in comparison with that for the 4.2 mm diameter zone. Thus, it seems reasonable to take the nominal “add” as being the difference between the power of the central, circular distance zone, and the inner edge ($y = 2.1 \text{ mm}$) of the outer “near” zone. The estimated adds are then 0.50 , 1.03 , and 1.18 D for the nominally $+1.50$, $+2.00$, and $+2.50 \text{ D}$ lenses. Thus, the estimated near additions are substantially lower than the manufacturer’s values. Under photopic conditions and with the contracted pupils of near vision, the actual add effect might be very small. Although it is true that the add effect might be enhanced with large pupils or, perhaps, by small amounts of lens decentration, it is clear that the performance of the measured “D” lenses is strongly biased in favor of distance vision. Presumably the manufacturer’s “N” design would be similarly biased towards near vision.

CONCLUSIONS

These measurements illustrate the diversity of power profiles found among current simultaneous image corrections and the

difficulties in summarizing their performance in terms of distance corrections and near addition powers. Because the measurements were made on single examples of each type of lens, we cannot claim that our plots are typical of all lenses of a particular type, although we have no reason to believe that they are in any way exceptional.

The imaging characteristics of stepped profiles of the OASYS type appear to be reasonably robust against pupil changes, unlike the other designs, whose performance is dependent upon pupil diameter, particularly in the case of the simple parabolic power profile. On the other hand, the presence of a number of abrupt changes in the power profile, with the possibility that ill-defined transitional zones may scatter significant amounts of light, may result in lowered image contrast. In the case where the extended DOF is due to primary SA, the introduction of greater amounts of aberration in attempts to increase the effective reading addition would be expected to be accompanied by substantial losses in visual acuity.⁵² Hickenbotham et al²³ have suggested that this loss in VA greatly diminishes the value of using additional spherical aberration in attempts to improve presbyopic vision.

In practice, exact centration to the eye pupil may not be achieved when any of these lenses are worn. From Figs. 4 and 5, it can be seen that such decentration may extend the range of powers within the eye pupil, and possibly the effective DOF. In most cases, however, any marked decentration will be accompanied by a loss in image quality, due particularly to astigmatism and coma.⁵² Moreover, it should be remembered that because a soft contact lens on the eye wraps the cornea, several changes in lens power may occur, due to lens flexure, lens dehydration, and tear lens effects, especially in cases where the fit is not acceptable.⁵³

Overall, power profiles give considerable insight into the performance of simultaneous image lenses.¹⁴ If combined with knowledge of the ocular aberrations and likely normal pupil diameter of the individual patient, power profiles can be valuable guides to the visual performance that the patient might achieve with different designs of lens.

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APPENDICES

Appendices A–C are available at <http://links.lww.com/OPX/A139>.

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Sotiris Plainis

Institute of Vision and Optics (IVO)

School of Health Sciences

University of Crete

PO Box 2208

Heraklion 71003

Crete, GREECE

e-mail: plainis@med.uoc.gr