VisionCare Product News
Volume 6, Number 9 • September 2006

Fundamentals of Progressive Lens Design

By Darryl Meister, ABOM

Progressive Lens Surfaces

A *progressive addition lens* (or "PAL") is a type of multifocal lens that employs a surface with a continuously smooth increase in addition (Plus) power. The curvature of the surface increases from its minimum value in the *distance* zone to its maximum value in the *near* zone (Figure 1). The total increase in surface power between these two zones is equal to the specified Add power of the lens. This gradual increase in power also results in a variable focus intermediate zone.

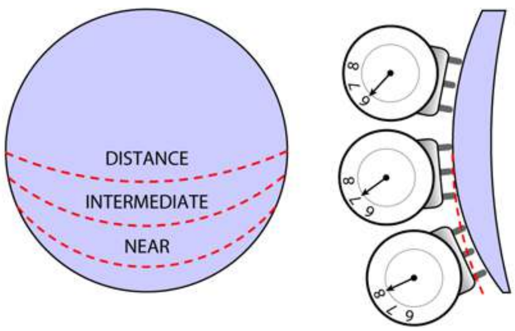

Figure 1. The surface power of a progressive lens design increases smoothly in order to produce a gradual change in Add power from distance to near.

Progressive lenses provide the desired Add power without any breaks, ledges, or lines by "blending" the transition between the distance and near zones. In fact, the transition between these zones is "smooth" enough to prevent abrupt changes in prism and magnification—or *image jump*—as well. This blending is achieved by incorporating varying amounts of *cylinder power*, oriented at an oblique axis, in the lateral regions of the surface (Figure 2).

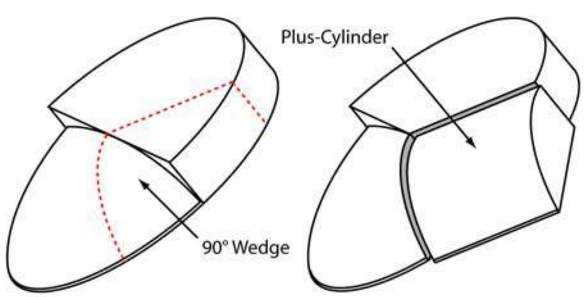

Figure 2. The ledge at the junction between a flatter curve and a steeper curve can be eliminated using cylinder power, as demonstrated by removing a 90° wedge from an Executive-style bifocal and replacing it with a section of a Plus-cylinder.

With the use of Plus-cylinder power at an oblique axis, it is possible to join a flatter distance zone curve into a steeper near zone curve without breaks in the surface. However, the geometry of a progressive surface is considerably more complex, with cylinder that varies in both magnitude and orientation. Traditional general-purpose progressive lenses possess four structural features (Figure 3):

1. *Distance Zone*: A stabilized region in the upper portion of the lens provides the specified distance prescription.
2. *Near Zone*: A stabilized region in the lower portion of the lens provides the specified Add power for reading.
3. *Progressive Corridor*: A corridor of increasing power connects these two zones and provides intermediate or mid-range vision.
4. *Blending Region*: The peripheral regions of the lens contain non-prescribed cylinder power and provide only minimal visual utility.

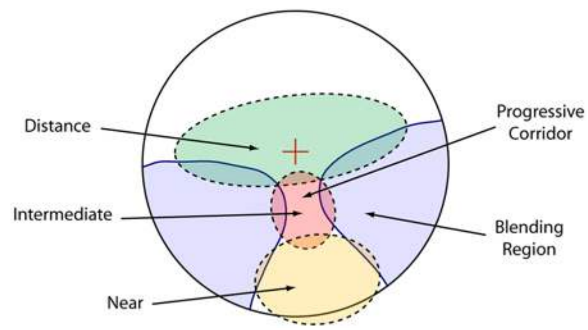

Figure 3. The structural features of a general-purpose progressive lens

Characterizing Progressive Optics

While the *central* regions of a progressive lens surface are *relatively spherical*, most points across the lens surface actually have some degree of *cylinder*. This means that the curvature actually varies locally from meridian to meridian at these points. The cylinder at each point on the lens surface is often referred to as *surface astigmatism*, since cylinder power produces an *astigmatic* focus instead of a point focus.

Surface astigmatism varies across the surface a progressive lens. It is virtually zero along the progressive corridor, but increases into the lateral blending regions of the lens. In these regions, the surface astigmatism produces significant levels of unwanted cylinder power, which—in sufficient quantities—is perceived by the wearer as blur, distortion, and image swim.

Since each point in the blending region of a progressive lens can be thought of as a small cylinder, it makes sense to evaluate the optics of a progressive lens by measuring the amount of cylinder power present at these points. These measurements are often represented using a *contour plot*, which is a map that indicates how the levels of an optical quantity vary across the lens (Figure 4). Astigmatism contour plots indicate regions of potential blur, image swim, and distortion, and are useful for predicting the size of the distance, intermediate, and near zones.

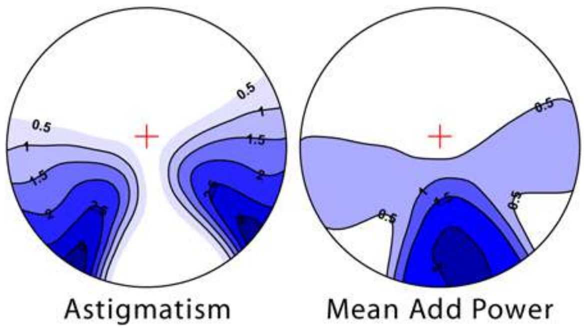

Figure 4. Contour plots show the distribution of an optical quantity across the lens by indicating its levels in fixed intervals (e.g., 0.50 diopters).

Generally speaking, progressive lenses have a unique astigmatism plot, so these plots serve as a kind of "fingerprint" of the lens design. It is also useful to evaluate the distribution of *Add power* across the lens. Since most points across the surface contain cylinder, the *spherical equivalent*, or *mean power*, is measured, which is the average power of the lens surface at each of these points. Mean power contour plots indicate the location of the near zone, as well as regions of excess Plus power that may interfere with clear distance vision.

While plots of surface astigmatism and mean Add power are the most common measures of optical performance, they fail to represent the *combined* interaction of these effects upon vision. Both unwanted cylinder power *and* excess—or insufficient—Add power contribute to blur. *RMS* (root-mean-square) *power* combines both the astigmatic and mean power errors into a single measure of power. RMS power is a more clinically meaningful measure of optical performance, and a useful predictor of blur and visual acuity.[1]

Although less common, it is also possible to characterize the optics of a progressive lens using *wavefront* analysis. Wavefront analysis evaluates "higher order" aberrations, including *spherical aberration* and forms of *coma*, in addition to mean power and astigmatism—which are the "lower order" aberrations that are usually more detrimental to vision. Wavefront aberrations are often represented using either a *Zernike series* or a *Taylor series*, which are mathematical functions whose terms represent quantities such as mean power error, astigmatism, coma, and so on.

Surface astigmatism and mean power contour plots provide a convenient way to represent various optical quantities, but they are only *indicative* of performance. Furthermore, contour plots of *surface power* are usually less visually meaningful than contour plots of *ray-traced* optical performance. These plots are calculated using lens-eye modeling to determine how the *wearer* actually perceives the optics of the lens.

Minkwitz's Theorem

In well-designed progressive lenses, unwanted cylinder power in the periphery is generally reduced to its mathematical limits. However, some level of unwanted cylinder power is ultimately necessary in order to blend any surface with Add power. Minkwitz showed that the rate of change in unwanted cylinder power (ΔCyl) at a small distance *away* from the centerline of the progressive corridor is nearly equal to twice the rate of change in Add power (ΔAdd) over an equal distance *along* the centerline of the corridor (Figure 5).[2]

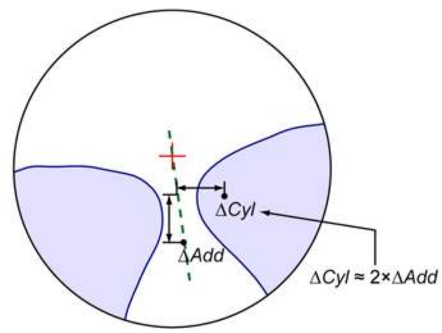

Figure 5. Minkwitz's theorem states that, in the vicinity of the progressive corridor, the cylinder power lateral to the corridor increases twice as fast as the Add power increases along the corridor—or $\Delta Cyl \approx 2 \times \Delta Add$.

The *average* rate of change in Add power along the progressive corridor is equal to the total Add power divided by the corridor length of the lens (i.e., ΔAdd = Add ÷ Corridor). This means that the average rate of change in Add power is *proportional* to the Add power and *inversely proportional* to the corridor length of the lens design. Therefore, Minkwitz's theorem demonstrates two important guidelines regarding the optics in the central regions of a progressive lens surface:

1. The rate of change in cylinder power away from the progressive corridor increases as the length of the progressive corridor *decreases*. This means that lens designs with shorter corridors will produce more unwanted cylinder power or smaller viewing zones.

2. The rate of change in cylinder power away from the progressive corridor increases as the Add power of the lens increases. This means the unwanted cylinder power in the periphery increases at roughly the same rate as the specified Add power (Figure 6).

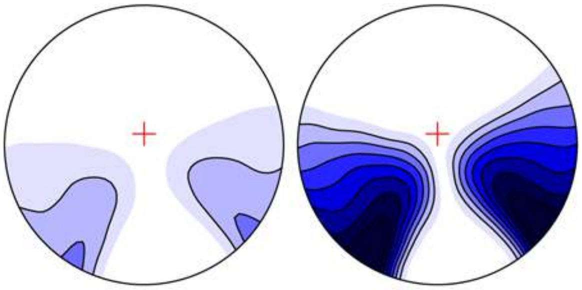

Figure 6. The surface astigmatism of a progressive lens is proportional to Add power, and the unwanted cylinder power of a +3.00 Add lens is roughly equal to three times the cylinder power of a +1.00 Add lens.

Distribution of Surface Optics

One of the most fundamental aspects of progressive lens design is the distribution of surface optics, including surface astigmatism and mean Add power. The magnitude, distribution, and rate of change of unwanted cylinder power and Add power define the gross performance of the lens design. Progressive lenses are often classified as "hard" or "soft" design based on the distribution of this astigmatism:

- **Harder designs.** A "harder" progressive lens design concentrates the astigmatism into smaller regions of the lens surface, thereby expanding areas of clear vision at the expense of raising unwanted cylinder power levels in the periphery. Consequently, harder progressive lenses generally offer wider distance and near viewing zones, but higher levels of blur and distortion in the periphery.
- **Softer designs.** A "softer" design spreads the astigmatism across larger regions of the lens surface, thereby reducing the overall magnitude of unwanted cylinder power at the expense of narrowing the clear vision zones. Consequently, softer progressive lenses generally offer less blur and distortion in the periphery, but narrower viewing zones.

As you increase the area of the lens used to "blend" the distance and near zones, you decrease the levels of surface astigmatism by spreading the blending region out over a larger area. Harder designs will generally work better for sustained viewing tasks requiring good visual acuity, while softer designs are better suited to dynamic vision. Additionally, softer designs tend to improve "comfort" and adaptation for emerging presbyopes, while harder designs offer the kind of utility current bifocal wearers enjoy (Figure 7).

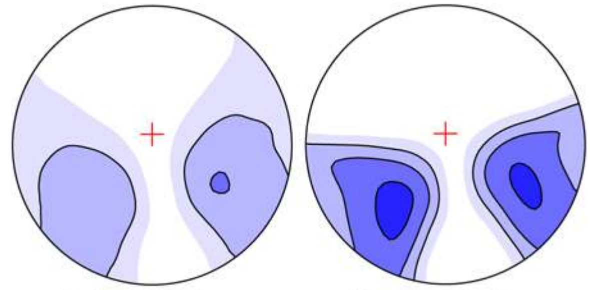

Figure 7. Astigmatism plots of "softer" lens designs exhibit more widely spaced cylinder power contours than plots of "harder" designs.

Modern progressive lenses are seldom strictly "hard" or "soft," but instead represent a balance between the two in order to achieve better overall utility. This balance may be tuned differently for certain Base curves and/or Add powers. The lens designer may also choose to combine *both* design philosophies. For instance, a softer distance periphery may be combined with a harder near periphery in order to improve dynamic distance vision while ensuring a wide field of near vision.

Vision and Progressive Lenses

Progressive lenses must satisfy several visual requirements in order to deliver sufficient performance and overall utility:

1. Good critical vision
2. Good dynamic vision
3. Good binocular vision
4. Good ergonomic utility

These factors are generally interrelated. For instance, improving dynamic vision by "softening" the lens design may compromise critical vision by reducing the size of the central viewing zones. Similarly, because of the relationship between unwanted cylinder and corridor length, shortening the corridor to improve ergonomic utility may also result in smaller viewing zones. Lens designers must strive to find the best balance between these visual requirements in order to maximize performance for the wearer.

This balance must also be considered when evaluating progressive lenses. If only measures of critical vision performance are considered, without considering dynamic vision performance, it may be difficult to ascertain the overall utility of the lens across its full spectrum of use. Recent studies, for instance, have shown how the "rating" of a progressive lens can change markedly when measures associated with dynamic vision and comfort—such as the maximum level of unwanted cylinder power—are factored in along with central viewing zone size.[3]

Critical Vision

Critical vision generally involves sustained viewing tasks that require excellent visual acuity and a sufficiently wide field of clear vision. High visual acuity is only possible in the central viewing zones of a progressive lens. Since these zones are not well defined, their size and utility vary depending upon both the wearer's tolerance to blur and the nature of the viewing task.

The size of the central viewing zones can be increased by pushing the surface astigmatism of the lens design farther into the periphery. However, this trade-off results in higher and more rapidly increasing levels of unwanted cylinder power. Therefore, the size of the distance and near viewing zones should be no larger than necessary in order to avoid unnecessary compromises in optical performance. Further, the lens designer must determine the best visual balance between the relative sizes of these two viewing zones (Figure 8).

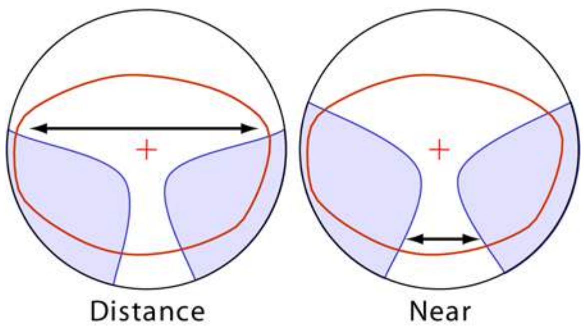

Figure 8. The lens designer must find the optimum balance between the size of the distance and near zones in a progressive lens.

The configuration of the central viewing zones should be consistent with the typical wearer's physiological interaction with the environment, including the viewing tasks the wearer is likely to perform throughout the day. This requires careful consideration of the range and nature of typical viewing tasks, as well as the relative frequency of those tasks. There are also progressive lenses available that have been designed for specific viewing tasks, such as computer use.

Additionally, the *object geometry* of those viewing tasks is equally important. The distribution of the surface optics and Add power of the lens design should correspond to the typical size, position, and orientation of the objects involved in these viewing tasks. For instance, the optics of the central viewing zones should be refined in order to ensure that the correct Add power is available to the wearer for the typical reading distance associated with each viewing task.

Dynamic Vision

The blur produced by the unwanted cylinder power in the periphery of a progressive lens is less consequential to dynamic vision, which often requires only recognizing and localizing objects. However, the progressively changing Add power and unwanted cylinder power in the periphery may also produce rapid variations in prism and magnification. These variations can produce an optical effect known as *image swim* in which objects appear to shift, distort, or even sway unnaturally.

The *vestibular apparatus*, which is an organ within the inner ear linked to the visual system, helps to maintain your sense of balance and to stabilize vision while in motion. An annoying visual phenomenon may arise when the *apparent* movement of the visual environment through the lens differs from the *physical* movement or orientation detected by the wearer because of image swim. This vestibulo-ocular conflict may produce an unpleasant "rocking" sensation similar to vertigo or motion sickness.

Objects—such as straight lines—may also appear curved or skewed when viewed through the lateral areas of the lens. Since the unwanted cylinder power in the periphery of the lens is generally oriented at an oblique axis, unequal magnification occurs in oblique directions. This oblique magnification, which is referred to as *skew distortion*, causes the vertical and horizontal edges of images to tilt and stretch (Figure 9).

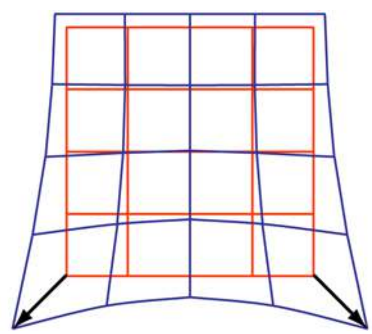

Figure 9. The magnification produced by the obliquely oriented cylinder power in the peripheral regions of a progressive lens results in an apparent shearing of objects and other potentially disturbing visual effects.

The distribution of surface optics in the periphery of a progressive lens should be carefully managed in order to minimize image swim, skew distortion, and other unwanted optical "side-effects." Image swim, which can result in the apparent acceleration of images, can be minimized by controlling the rates of change in prism and power. Skew distortion can be minimized by controlling the axis of the unwanted astigmatism in the periphery so that it is generally oriented at a less oblique angle.

Binocular Vision

Progressive lens designs were originally *symmetrical*, meaning that the right and left lenses were identical. To achieve the desired near inset, the lens blanks were rotated 9° to 11°. However, this raised the unwanted cylinder power in the nasal region of the lens well into the distance zone, resulting in both a disruption of binocular fusion as the wearer gazed laterally and a reduction in the *binocular field of view* (Figure 10). This also limited inset control for near vision, since the inset path of the progressive corridor would have to fall along a straight line.

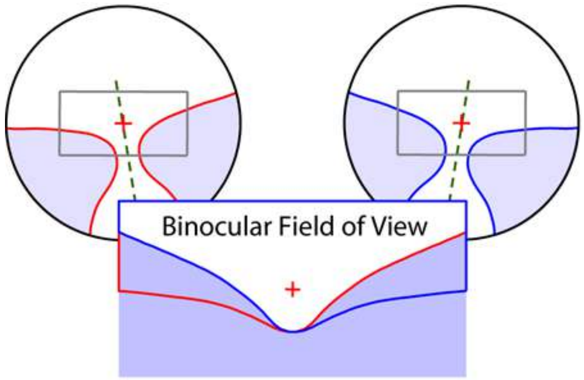

Figure 10. A symmetrical lens design results in a significant reduction in the binocular field of view and a disruption of binocular fusion as unwanted cylinder in the nasal side of the design is rotated up into the distance zone of each lens.

Most modern lens designs are now *asymmetrical*, using separate designs for the right and left lenses. The amount of cylinder power on either side of the progressive corridor is adjusted independently, which allows the near inset to be achieved without rotating the lens design. Instead, the progressive corridor is initially designed at an angle with the necessary nasalward inclination. This provides better binocular alignment between the right and left viewing zones, affording the wearer larger binocular fields of view (Figure 11).

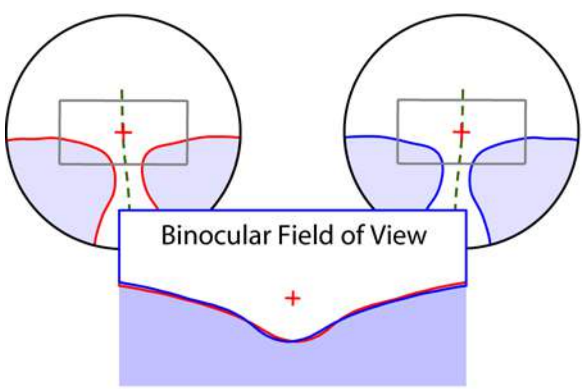

Figure 11. An asymmetrical lens design maximizes the total binocular field of view by maintaining better alignment between the right and left viewing zones.

While asymmetrical designs ensure wider binocular fields of view, levels of unwanted cylinder are often greater to the nasal side of the progressive corridor as a result of achieving the near inset without rotating the design. This produces differences in prism, magnification, and power between corresponding points on the two lenses as the eyes move across them in unison, which can make binocular fusion more difficult and less comfortable. Progressive lens designs with *horizontal symmetry* take asymmetry a step further by minimizing differences in power and prism between corresponding points to either side of the progressive corridor (Figure 12).

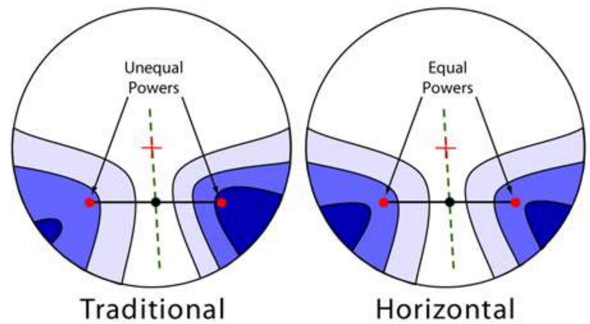

Figure 12. A horizontally symmetrical lens design minimizes differences in power, prism, and magnification between the two lenses for corresponding points to either side of the corridor, improving binocular fusion and comfort.

Ergonomic Utility

Theoretically, the *length* of the progressive corridor is the separation between the point that produces the *lowest* Add power along the corridor and the point that produces the *highest* Add power. The lowest Add power generally occurs at the *distance reference point* (DRP) of the lens, while the highest Add power is generally located at the *near reference point* (NRP). However, in practice, corridor length is usually defined as the distance from the *fitting point* of the lens to some point along the corridor producing a minimum percentage of the Add power (e.g., 85%).

Several factors must be taken into account when choosing the corridor length for a progressive lens design. For example, shorter corridor lengths offer the following advantages:

1. More near vision utility in smaller frames
2. Reduced eye declination during near vision

Every additional 1 mm of corridor length requires roughly 2° of additional ocular rotation to reach the near zone. If the corridor length is too long, the wearer may not be able to reach the full Add power without awkward or uncomfortable postural adjustments. Additionally, the minimum fitting height of the progressive lens may not allow for a wide selection of frame styles.

However, shorter corridor lengths have certain disadvantages:

1. Less intermediate vision and mid-range utility
2. More rapidly increasing levels of unwanted cylinder power and distortion

Consequently, the length of the corridor should be carefully chosen in order to offer the most utility with the least amount of optical compromise. Furthermore, the rate of change in Add power along the corridor is also important. Excess Plus power around the fitting cross should be kept minimal in order to ensure clear distance vision, and the ramp up in Add power as the corridor approaches the near zone should reflect how a typical presbyope holds materials while reading (Figure 13). ◄

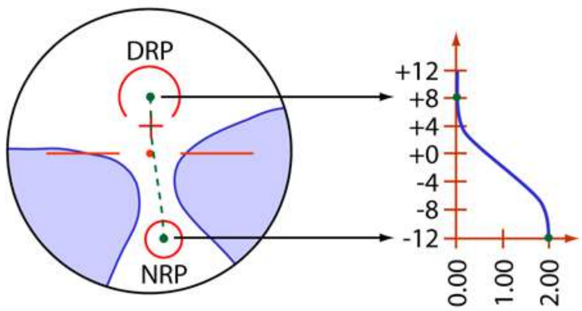

Figure 13. The Add power of a progressive lens must be carefully controlled in order to maximize the ergonomic utility of the lens design without unnecessary optical compromises.

Darryl J. Meister is a Certified Master Optician and the Technical Marketing Manager for Carl Zeiss Vision, a leading manufacturer of optical lenses and coatings.

1 Schwendeman, F, Ogden, B, Horner, D, & Thibos, L. "Effect of Sphero-Cylinder Blur on Visual Acuity." *Optometry and Vision Science*, 1997; Vol. 74, No. 12; pp 180-181

2 Sheedy, J, Campbell, C, King-Smith, E, and Hayes, J. "Progressive Powered Lenses: the Minkwitz Theorem." *Optometry and Vision Science*, 2005; Vol. 82, No. 10, pp 1-9

3 Sheedy, J, Hardy, R, & Hayes, J. "Progressive addition lenses – measurements and ratings." *Optometry*, 2006; Vol. 77, pp 34-36