Identifying sources of verification errors in progressive addition lenses

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Background: Occasional disagreement over spectacle lens prescription accuracy between the optical laboratory and the practitioner is to be expected, especially with a progressive addition lens (PAL). The PAL continues to evolve in design, yet retains some unique, inherent problems. The purpose of this study was to determine if the source of these problems results from the lens design, laboratory error, or verification procedures.

Methods: Six Varilux Comfort Orma Supra® progressive addition lenses were surfaced to plano distance power, and then verified using manual and automatic lensmeters. The same lenses were then re-surfaced for various sphere and cylinder powers, and verified in the same manner. The results of each trial were spherocylindrically averaged, and compared to the desired result. The lenses were also verified by several incorrect methods to investigate positional tolerance during verification and possible verification errors.

Results: The averages for the lenses surfaced to the "prescribed" power were not far from the expected power by all measurement techniques when measured at the central DRP location. Positional errors of as little as 2 mm from the DRP center, however, can lead to erroneous results.

Conclusions: Unless correct verification procedures are carefully followed, progressive lenses can be mistakenly identified as being in error when they are not.

Key Words: Addition lenses, lens design, lenses, prescription accuracy, progressive addition lenses, verification procedures

The very first progressive addition lens was designed by Owen Aves in 1907. Very few advancements were made on that lens until 1951, when the original Varilux lens was first released in France, and then in the United States in 1965.[1,2] Progressive addition lenses are now several generations removed from this original lens, with many companies in the race to manufacture improved designs. Progressive addition lenses have gradually become more accepted by the general population and continue to comprise a larger and larger share of the spectacle lens market.3,4

Historically, there have been two general design classes of progressive lenses: "*hard*" and "*soft*" (*see* Figure 1, *A* and *B*). The "*hard*" design (such as the Sola VIP®, Rodenstock Progressive R® designs, and some of the newer short corridor progressives that are designed for frames with a narrow "B" dimension) restricts unwanted aberrations to more-compacted areas in the lower temporal and nasal portions of the lens. This design attempts to achieve high image quality throughout areas of the lens in which distance and near vision are most often used. The "*soft*" design (such as the AO TruVision Omni® and Varilux Infinity®) incorporates a longer progressive zone and spreads a resulting lower amount of aberration more evenly throughout the lens surface, including the upper half of the lens, allowing a decreased "adaptation time."[2,5] However, with such designs, aberrations—mostly astigmatism—may "bleed" into the distance portion of the lens.[1,6,7] The Varilux Comfort®, the lens used in the current investigation, is a lens with asphericity that occurs by design over much of the lens surface, more comparable to that of a softer design.

Just as with any spectacle lens, progressive lenses—when received from the laboratory—should be verified before being

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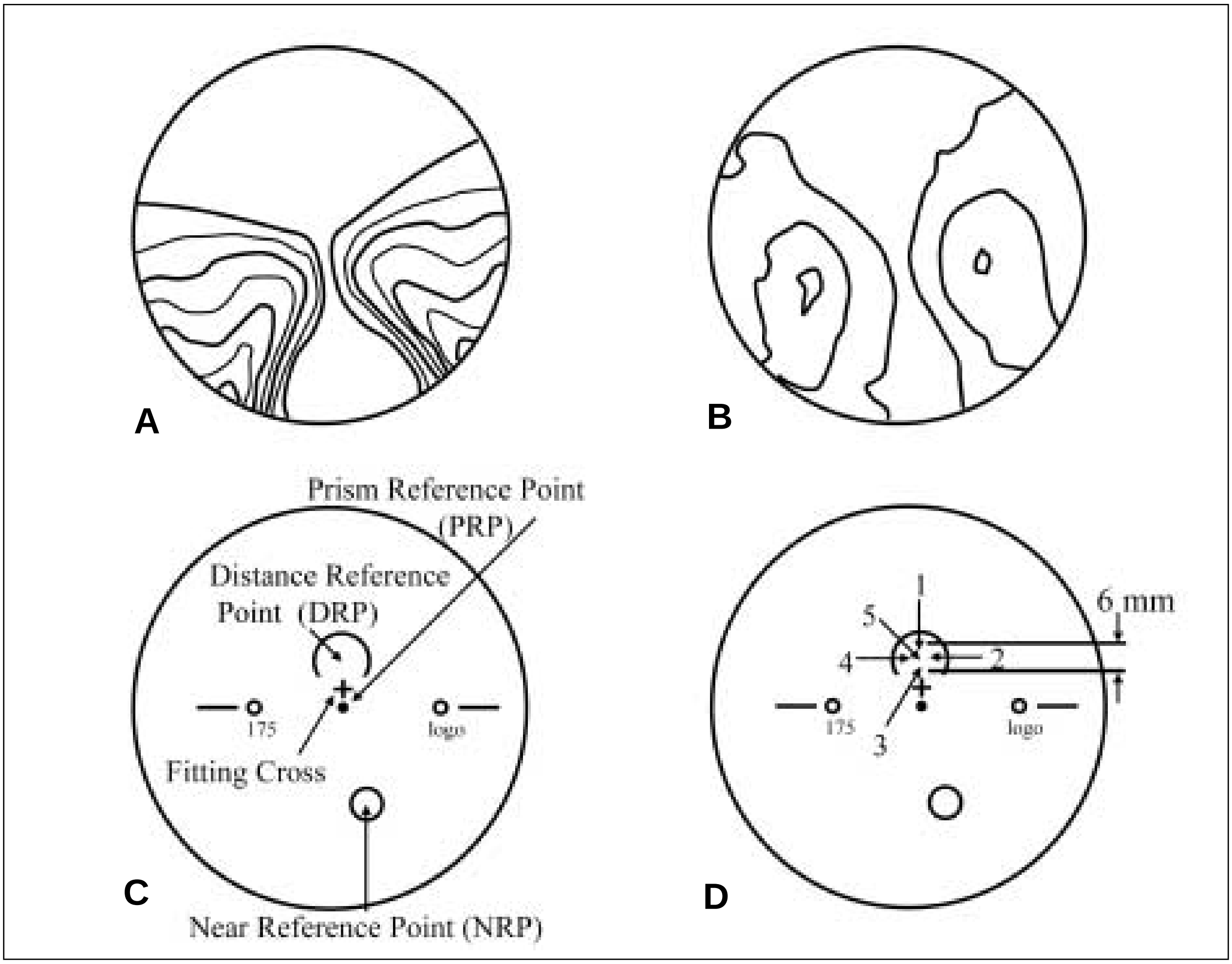

Figure 1 ***A*** shows an example of a hard progressive lens design (with a +2.00 D add). The contour plot indicates isocylinder lines (0.50 D steps) of incrementally increasing unwanted astigmatism that occurs over the lens surface. Notice a fairly wide near zone with the isocylinder lines narrowly spaced surrounding this zone, indicating a rapid change in power. (Redrawn with permission from CW Brooks and IM Borish. System for ophthalmic dispensing. Boston: Butterworth–Heinemann, 1996:298.)

B presents an example of a soft progressive lens design (with a +2.00 D add). The contour plot again indicates isocylinder lines (0.50 D steps) of incrementally increasing unwanted astigmatism that occurs over the lens surface. Notice the near zone appears narrow, but the contour lines demonstrate a more gradual change in induced power peripherally when compared with the hard design shown in ***A***. (Redrawn with permission from CW Brooks and IM Borish. System for ophthalmic dispensing. Boston: Butterworth–Heinemann, 1996:299.)

C depicts the basic design of a typical progressive addition lens. The distance power is located in the superior portion of the lens. The manufacturer determines this exact location and marks it with a semicircle. Prism is verified at the prism reference point (PRP). It is important to note that the fitting cross, which is centered in the patient's pupil, does not correspond with the PRP. The add power of the lens is verified in the location set by the manufacturer, marked with a circle, and called the near reference point (NRP). (Redrawn with permission from CW Brooks and IM Borish. System for ophthalmic dispensing. Boston: Butterworth–Heinemann, 1996:311.)

D depicts the five locations where measurements were taken for each of the lenses (1 = *Top*, 2 = *Right*, 3 = *Bottom*, 4 = *Left*, and 5 = *Center*).

dispensed. On verification, many progressive addition lenses appear to have a slightly incorrect sphere power, cylinder power, or axis, and are then returned to the manufacturer.[8] This is particularly true of designs with asphericity in the upper portion of the lens. Optical laboratories report that returns of progressive lenses with low sphere and cylinder powers are the most common.[9] This report was confirmed from manual (Reichert®) lensmeter measurements of an unsystematic sample of seven Varilux Comfort® lenses that had been recently returned to the manufacturer after apparently "failing" verification (*see* Table 1).

In addition to the above reports from the optical industry, optical theory also provides insight into this problem. Since the lensmeter measures back vertex power, measured astigmatism in a progressive addition lens is the (vector) sum of the front and back surface optics. Thus, the astigmatic power in the front surface, resulting from the progressive design, can alter the measured amount of the lens astigmatism.

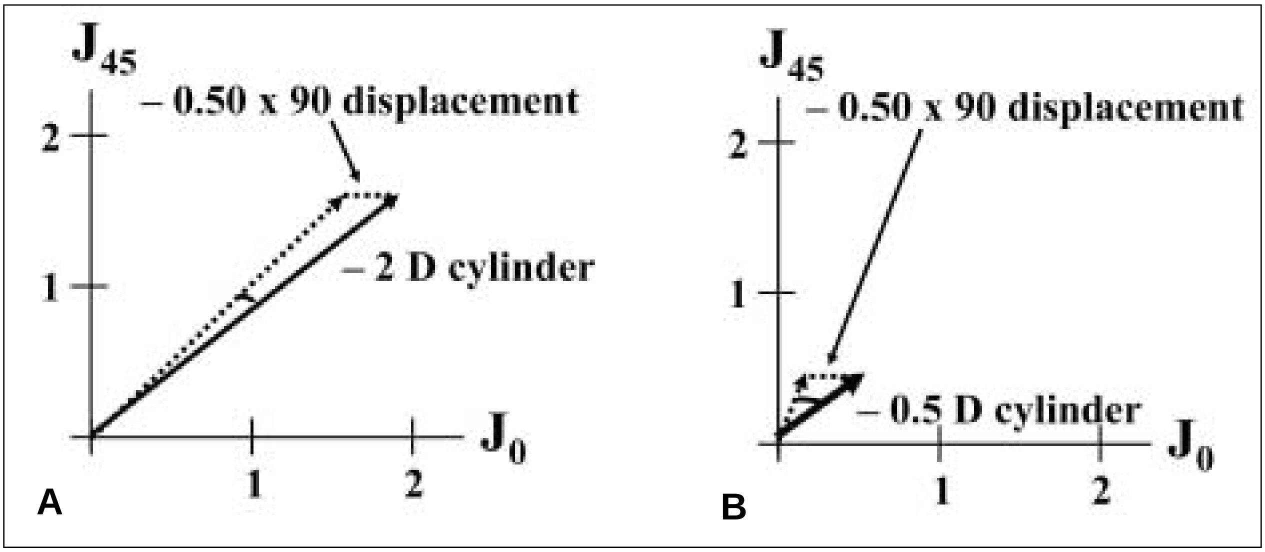

Figure 2 ***A*** shows the effect of a small –0.50 D × 090 induced cylinder power for a –2 D × 045 cylinder. ***B*** depicts this same small amount of induced cylinder on a –0.5 D × 045 cylinder. As can be seen, the same small induced cylinder will have a much larger effect on the small (–0.5 D) cylinder than on the larger (–2 D) cylinder, as the axis of the –2.00 D cylinder is changed only about 7 degrees, whereas the axis of the –0.50 D cylinder is changed about 22 degrees. This is a likely explanation of why the induced cylinder effect seems to be more prevalent in small cylinder powered lenses.

Table 1. Individual measurements of returned lenses with regular-sized aperture on a Reichert® lensmeter measured to the nearest 0.25 D

Lens	Power
1	+0.25 –0.25 × 063
2	–0.25 –1.50 × 003
3	–0.25 –0.25 × 106
4	–2.50 –0.25 × 005
5	–0.25 –0.25 × 103
6	+1.00 –0.75 × 085
7	+0.25 –0.25 × 029

Table 2. The plano lenses were resurfaced according to the following intended prescriptions

Lens	Power
1	–2.00 –0.50 × 180
2	–3.00 –2.00 × 180
3	+1.50 –0.50 × 180
4	+1.00 –0.75 × 180
5	+0.25 –0.25 × 180
6	Plano –2.00 × 180

This is particularly true for lower astigmatic powers (*see* Figure 2). The present study examined progressive addition lenses, and recorded the impact of position and measurement errors on the astigmatic power and axis measured during verification.

Methods

We assumed that front surface cylinder power can be measured directly with a lensmeter for a plano-powered lens. Six new Varilux Comfort Orma Supra® progressive addition lenses, all with +2.00 diopter (D) additions, were surfaced to plano distance power.* Lens power was then measured, first with a standard manual (Reichert®) lensmeter to the nearest 0.25 D and then with an automated Humphrey® Lens Analyzer to the nearest 0.01 D with a contact lens aperture in place. The contact lens aperture limits the area being measured to about 1.5 mm on the lens. Measurements were taken in the area at and surrounding the manufacturer's Distance Reference Point (DRP) (*see* Figure 1, *C*). The specific points measured were (1) directly on the DRP; (2) 3 mm above; (3) below; (4) to the left; and (5) to the right of the DRP (*see* Figure 1, *D*). Fifteen measurements were taken at each of these five points and spherocylindrically averaged using vector analysis.[10] The same plano lenses were then resurfaced to standard thickness for a variety of low sphere and cylinder powers (*see* Table 2). Then, in the same manner as before, measurements were taken in the same five locations on these resurfaced lenses using both lensmeters.

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* Lenses were surfaced thicker than normal, so that they could later be resurfaced to the desired thickness (2.0 to 2.5 mm) for refractive power.

Next, to determine how much error would be induced through improper lens verification procedures, measurements were also taken at other locations on the surfaced lenses at points at which someone might incorrectly verify the lens. These points were: (1) the fitting cross and (2) the prism reference point (PRP) (*see* Figure 1, *C*). These measurements were also taken 15 times with a Humphrey Lens Analyzer, set for 0.01 accuracy in combination with a contact lens aperture, and averaged.

Finally, the lens positioning tolerance was determined by observing the changing Humphrey Lensmeter readings as the lens was moved laterally and vertically, noting how far the lens could be moved from center before ANSI standards were exceeded for one of the three components: sphere, cylinder, or axis.

Results

The back vertex power measurements for the plano-surfaced lenses are shown in Figure 3, *A* and *B*. Equivalent sphere (M) results (*see* Figure 3, *A*) show that measurements of all lenses at the five locations were within 0.20 D of plano [mean magnitude (D) ± SD = 0.0783 ± 0.0576]. Interestingly, sphere did exceed the 0.13 D ANSI standard for two lenses (lenses 1 and 5), each at two peripheral DRP measurement locations. At the central measurement location, all lenses had equivalent sphere error measurements of less than 0.10 D [mean magnitude (D) ± SD = 0.0640 ± 0.0281]. These central error measurements also showed less variation between lenses than the peripheral error measurements.

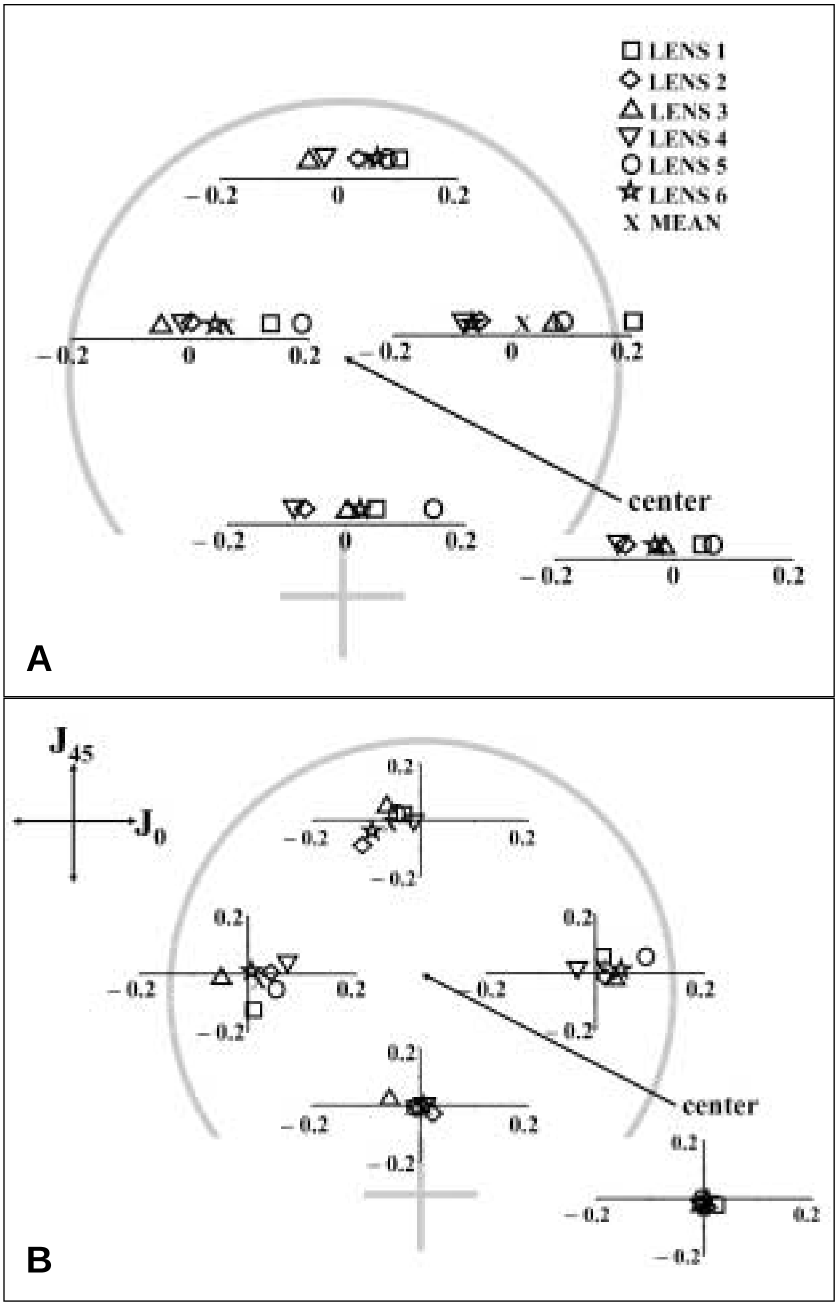

Figure 3 ***A*** shows a single-dimension description of the difference in sphere power (M) in diopters between the ordered plano prescription and that actually measured at each of the five locations at and surrounding the DRP. Each point on the graph is the vector average of 15 individual trials. ***B*** depicts a vector description in diopters of the difference between the ordered power of plano and the power measured. Again, each point on the graph is the vector average of 15 individual measurements. The difference measured in horizontal/vertical (J_0) astigmatism is graphed along the horizontal meridian, and oblique (J_{45}) astigmatism is graphed along the vertical meridian.

Using a similar graphic format, the two-dimensional astigmatic data are plotted in Figure 3, *B*. None of these plano lenses had measured cylinder amplitude (J_0 and J_{45}) greater than the minimum ANSI refractive standard of 0.13 D at any of the 5 lens locations [mean magnitude (D) ± SD J_0 = 0.0370 ± 0.0332 and J_{45} = 0.0286 ± 0.0408]. The measured cylin-

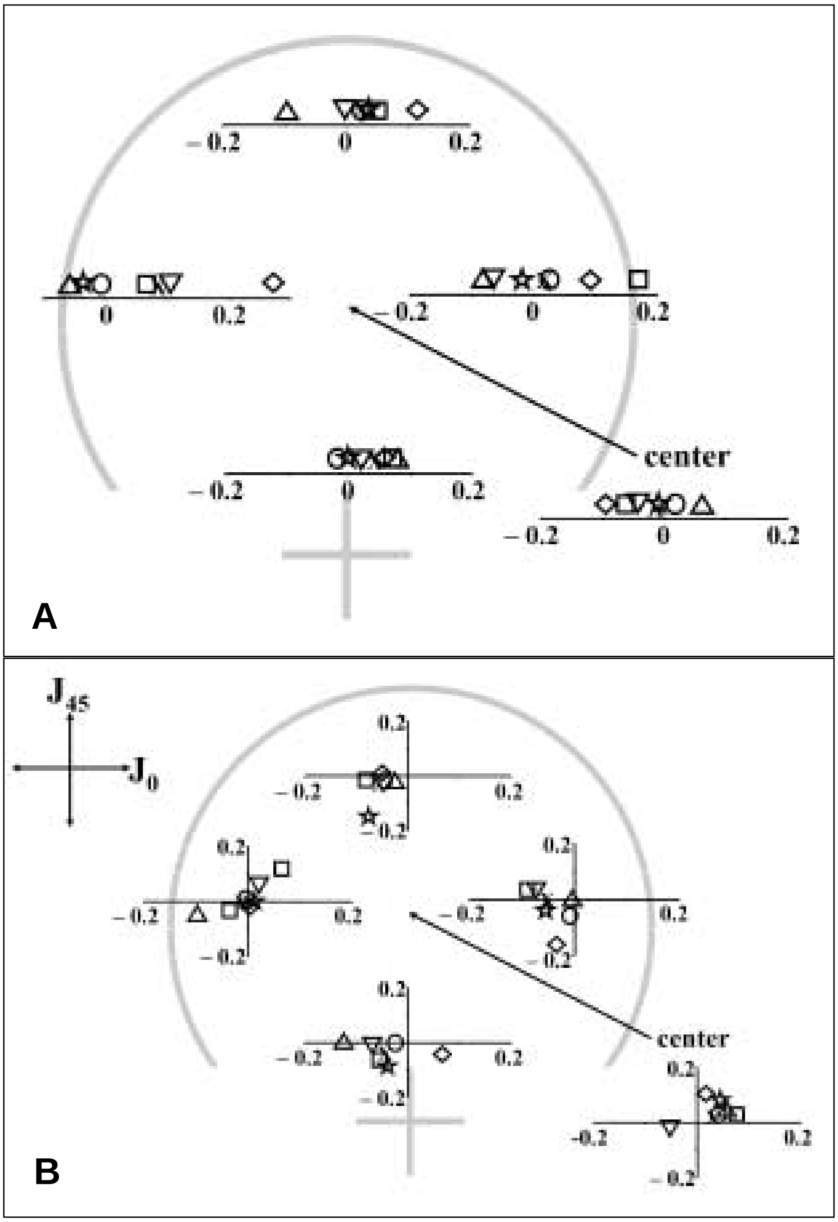

Figure 4 ***A*** shows a single-dimension description of the difference in sphere power (M) in diopters between the ordered (surfaced) prescription and that actually measured at each of the five locations at and surrounding the DRP. Each point on the graph is the vector average of 15 individual trials. ***B*** depicts a vector description in diopters of the difference between the ordered surfaced power and the power measured. Again, each point on the graph is the vector average of 15 individual measurements. The difference measured in horizontal/vertical (J_0) astigmatism is graphed along the horizontal meridian, and oblique (J_{45}) astigmatism is graphed along the vertical meridian.

der was less than 0.05 D at the central DRP location for all lenses (mean magnitude (D) ± SD J_0 = 0.0136 ± 0.0185 and J_{45} = 0.0052 ± 0.0100), suggesting that the astigmatism measured at the other locations may be due to the progressive lens design.

The difference between expected and measured back vertex power for the lenses surfaced to power (*see* Table 1) are shown in Figure 4, *A* and *B*. The difference in equivalent sphere (M) (*see* Figure 4, *A*) of all lenses at the five DRP measurement locations was less than 0.25 D [mean magnitude (D) ± SD = 0.0705 ± 0.05902]. Sphere error did exceed the 0.13 D ANSI refractive standard for two lenses (lenses 1 and 2), each at only one of the peripheral DRP measurement locations.

The two-dimensional astigmatic error data are plotted in Figure 4, *B*, using the same graphical format. All six lenses had astigmatism (J_0 and J_{45}) within 0.15 D of the desired result at all five measurement locations [mean magnitude (D) ± SD J_0 = 0.0556 ± 0.03905 and J_{45} = 0.0458 ± 0.0526]. Three lenses had measured cylinder errors greater than the minimum ANSI refractive standard of 0.13 D. (Each of these three lenses had a measured cylinder error of 0.15 D.) At the central DRP location the measured cylinder error was less than 0.10 D for all lenses [mean magnitude (D) ± SD J_0 = 0.0440 ± 0.0170 and J_{45} = 0.0432 ± 0.0374]. As with the plano-surfaced lenses, the small induced astigmatic error measured at the other peripheral DRP locations is probably an artifact of the progressive lens design.

Results outside ANSI standards were obtained when the lens was incorrectly verified at the fitting cross or prism reference point. A similar graphical representation of the error in equivalent sphere (M) for each of the six lenses is shown in Figure 5, *A*. The central error measurements are also depicted for reference. The sphere component at the fitting cross [mean magnitude (D) ± SD M = 0.1142 ± 0.0719] was outside ANSI refractive standards for only one lens, but the sphere component measured at the PRP

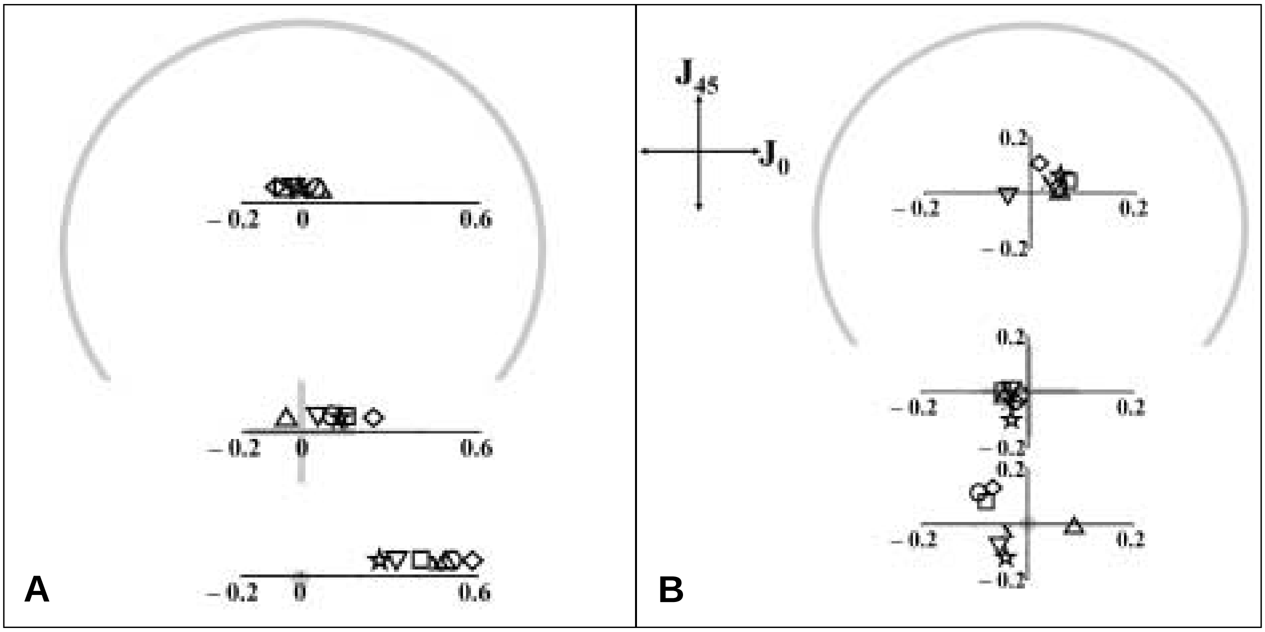

Figure 5 This chart represents, in the same graphical format, the difference between the prescribed surfaced power and the measured power for two locations on a lens where one may incorrectly verify a prescription, (1) the fitting cross and (2) the prism reference point (PRP). For a comparison, observed differences measured at the correct point (the DRP center) are also shown.

[mean magnitude (D) ± SD M = 0.4200 ± 0.1240] was well outside ANSI refractive standards for all lenses (range, 0.27 D to 0.61 D). This is to be expected, however, as the PRP is located at the beginning of the progressive zone.

Table 3. Z80.1–1999 ANSI standards for sphere, cylinder, and axis*

	Power	Allowable range
Sphere	0.00 to ± 6.50 D	± 0.13 D
(meridian of highest power)	Greater than ± 6.50 D	± 2% of sphere power
Cylinder	0.00 to 2.00 D	± 0.13 D
	2.12 to 4.50 D	± 0.15 D
	Greater than 4.50 D	± 4% of cylinder power
Axis	0.00 to 0.37 DC	± 7°
	0.37 to 0.75 DC	± 5°
	0.75 to 1.50 DC	± 3°
	Greater than 1.50 DC	± 2°

* From *Prescription Ophthalmic Lenses—Recommendations*. Merrifield, Va.: Optical Laboratories; approved September 10, 1999. Copyright © 2000.

Results for the two-dimensional astigmatic error measured at the fitting cross and PRP are shown in Figure 5, *B*. The fitting cross measurements for all lenses [mean magnitude (D) ± SD M = J_0 = 0.0440 ± 0.0170 and J_{45} = 0.0432 ± 0.0374] were again closer to the desired results than those measurements taken at the PRP [mean magnitude (D) ± SD J_0 = 0.08120 ± 0.0163 and J_{45} = 0.0961 ± 0.0532] in all cases. No lenses were outside ANSI refractive standards for cylinder when measured at the fitting cross. However, two lenses were found to have an astigmatic error outside ANSI refractive standards when measured at the PRP (lenses 2 and 6). Though not recorded, quite erroneous measurements were also elicited by tilting the lenses vertically or horizontally, as may often occur with incorrect frame positioning or by not using the aperture stop appropriately. This procedural error of tilting the lens in the lensmeter caused extreme variability in results, as would be expected and could be predicted from conventional optical theory.†

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† Tilting a lens will change the effective powers in the tangential and sagittal lens meridians. These powers are $F_S = F\,[1 + (\sin^2 / 2n)]$ and $F_T = F\,[(2n + \sin^2\theta) / 2n \cos^2\theta)]$. ***F*** equals the power of the lens being tilted; ***n*** is the refractive index of the lens; and q is the angle of tilt. Thus, tilting the lens results in an induced cylinder equal to $F_T - 0_S$.

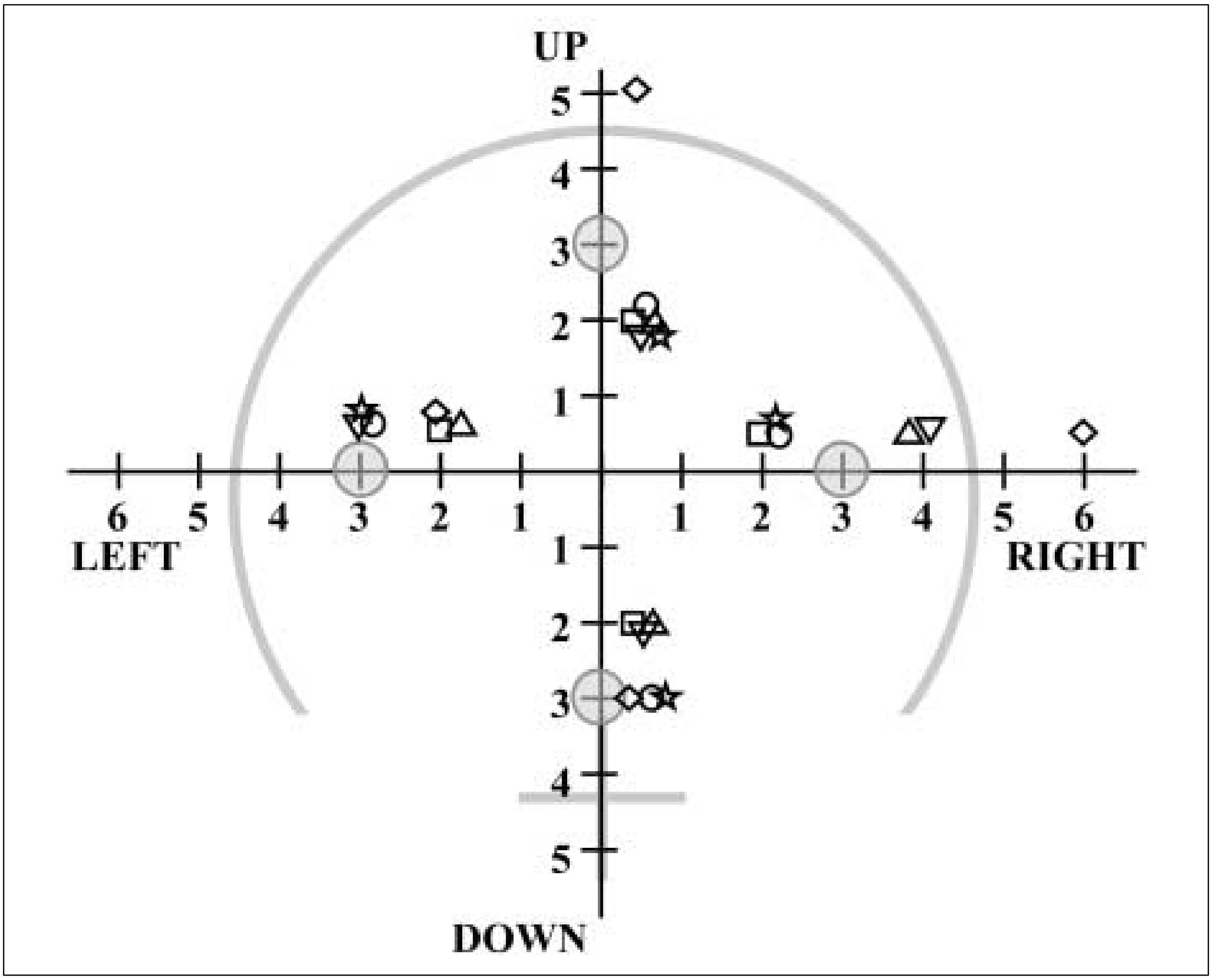

Figure 6 Figure 6 quantifies how many millimeters the lens could be moved from the point when it was correctly centered before going beyond ANSI Z–80 standards. The lens was moved upward, downward, left, or right until a single reading outside ANSI refractive standards could be obtained. The majority of the time, ANSI standards for cylinder axis were the first to be exceeded. For some lenses this could occur with as little as 2 mm of movement. Other lenses required 6 mm of movement. The locations of the previously discussed peripheral DRP measurements (± 3 mm) are highlighted with semitransparent circles.

Finally, we systematically de-centered the lenses behind the lensmeter until either the equivalent sphere, cylinder power, or cylinder axis errors exceeded ANSI refractive standards. Lens positional tolerance was found to be highly variable between lenses (*see* Figure 6). In the majority of the cases, ANSI refractive standards for cylinder axis were the first to be exceeded. Notice that the 2 mm of movement at which ANSI standards were exceeded for some lenses is closer to the DRP center than the 3-mm measurements shown in Figures 3 and 4. In those graphs, we identified the few lenses that exhibited cylinder magnitude errors in excess of ANSI refractive standards at the 3-mm locations, but from Figure 6 it is clear that cylinder axis errors were in excess of ANSI refractive standards, with smaller eccentricities for many of the lenses.

Discussion

Our results show that back vertex power of progressive addition spectacle lenses measured at the DRP center is virtually identical to the power intended. Erroneous measurements could be obtained in some instances if the lens was not correctly centered behind the lensmeter or if the measurement was taken at the incorrect location (such as the PRP). Therefore, our data suggest that verification “failures” that have been reported for these lenses must be a result of incorrect verification techniques, and not errors in the front or back lens surface.

These incorrect verification techniques may include: (1) not correctly marking the lens, and therefore not measuring at the correct central DRP location; (2) erroneously measuring outside of the distance reference circle (such as at the fitting cross or PRP); or (3) tilting the lens.

These verification errors have a financial burden associated with them, not only for the practitioner who loses productivity and efficiency (as well as patient satisfaction), but also for the laboratories and lens manufacturers. According to the industry estimates provided to us, roughly 7% of all types of spectacle lenses sold are returned for some apparent error. Looking into these apparent errors, roughly half of them are due to verification errors.

It is estimated that the spectacle lens industry, in the United States is a 1.2 billion dollar industry (wholesale, including all single-vision, bifocal, and multifocal lenses). The cost of these verification errors is staggering. The cost of these errors appears to be shared in many cases 50/50 between the laboratory and spectacle lens manufacturer—and the total is estimated to be roughly $84 million.[11]

Verification of progressive lenses requires care and precision. To reduce errors, it is wise to periodically review proper methods for measuring and marking progressive addition lenses with office staff. Merely guessing at the correct verification location may accidentally work in some instances, but in most cases is sure to cause difficulties and misunderstandings.

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