Aspheric Lenses: Optics and Applications

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Lens Talk
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BACKGROUND

The principal use of aspheric lens designs is the reduction or elimination of optical aberrations produced by looking through an ophthalmic lens obliquely. We will begin our discussion of aspherics by exploring some of these optical aberrations and their effects. For ophthalmic lenses, a *lens aberration* occurs when rays of light fail to come to a point focus at the ideal image position of the eye (called the *far point*) as it rotates about its center.

OFF-AXIS PERFORMANCE

There are several lens aberrations that can affect the quality of peripheral vision through a spectacle lens. However, we will concentrate mainly on **oblique astigmatism**, which is one of the principal lens aberrations that must be corrected when designing ophthalmic lenses. This *astigmatic* focusing error, which is illustrated in Figure 1, results when rays of light from an object in the periphery strike the lens obliquely. Two focal lines are produced from each single object point. The dioptric difference between these two focal lines is known as the **astigmatic error** of the lens.

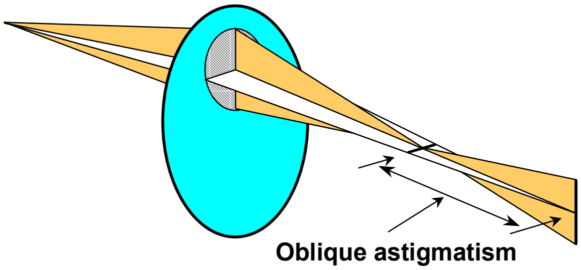

Figure 1. Rays of light from an object point strike the lens obliquely and are focused into two separate focal lines, instead of a single point focus, when *oblique astigmatism* is present.

Rays of light striking the **tangential**, or *radial*, plane of the lens come to a line focus at the **tangential focus**. The resultant focal line is perpendicular to the actual tangential plane. Rays striking the **sagittal**, or *equatorial*, plane of the lens come to a line focus at the **sagittal focus**. This focal line is perpendicular to the sagittal plane. Both of these planes are shown in Figure 2.

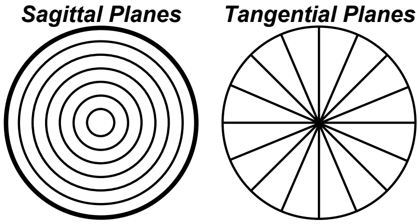

Figure 2. The *sagittal* (equatorial) and *tangential* (radial) planes of a lens.

Lens aberrations occur as the wearer gazes away from the **optical axis** of the lens, which is an imaginary line perpendicular to the optical center, to use his or her peripheral vision. Consequently, we often refer to the peripheral performance of a spectacle lens as its *off-axis* performance. The peripheral vision through a lens that suffers from oblique astigmatism is blurred, and the wearer experiences a limited field of clear vision.

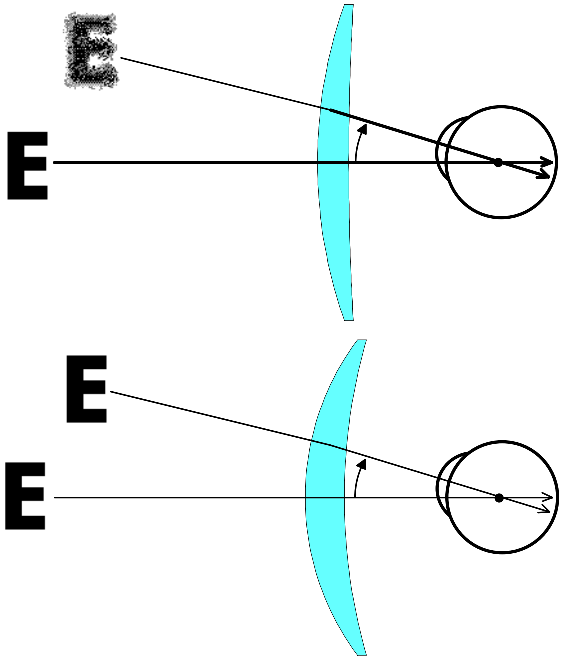

Figure 3. A comparison between steeper and flatter lenses. The steeper lens provides better off-axis optics, while the flatter lens provides better cosmetics.

For conventional lenses, **base** (front) **curve** selection is one of the primary tools used to reduce lens aberrations. Flatter base curves produce better looking lenses that are flatter, thinner, and lighter weight. Flatter lenses are often more easily retained in frames, as well. However, flattening the base curve introduces significant aberrations in the periphery of the lens, as illustrated in Figure 3.

BEST FORM LENSES

When the base curve is chosen in an attempt to produce a lens form with a minimum of lens aberrations, the resulting lens is referred to as a **corrected curve lens**. Since corrected curve lens forms will have the least amount of the most detrimental aberrations, they are also called **best form lenses**. In 1909, Marius Tscherning demonstrated that there were two recommended *best form* base curves for each lens power. *Tscherning's ellipse*, which is depicted in Figure 4, is the locus of points that plot out the recommended front curves for each lens focal power.

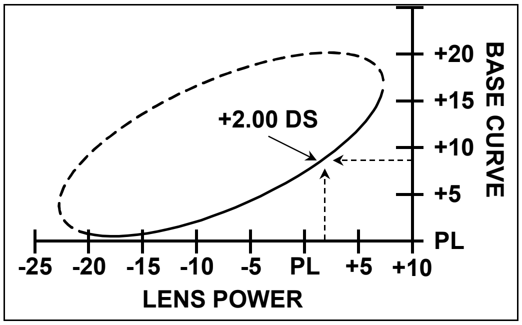

Figure 4. Tscherning's ellipse. Note that a +2.00 D lens requires roughly a 7.50 base curve to minimize aberrations.

It is important to note that modern lenses employ the flatter branch of Tscherning's ellipse. Ideally, a separate front curve would be required for each individual lens power to minimize lens aberrations, as shown in Figure 4. Practically speaking, this would require a massive, costly inventory. Manufacturers now group small prescription ranges together upon common base curves to keep inventories requirements minimal. It is important to note, though, that reducing the number of base curves utilized for a given range of lens powers also reduces the accuracy of the off-axis correction of the lens series.

So how much astigmatic error is generated by using flatter base curves? Figure 5 below is a graph of the *tangential* and *sagittal* power errors of a +4.00 D lens—at 30° off-axis—plotted against a range of front base curves. Oblique astigmatism is eliminated with a front curve of 9.75 D, since the tangential and sagittal errors are equal for that curve. Note that there is still some residual power error. It is generally not possible to completely eliminate all lens aberrations simultaneously; some residual error will generally remain. Unfortunately, this is a rather steep base curve to use; this lens will be thicker, heavier, and more bulbous than the same power made using a flatter base curve.

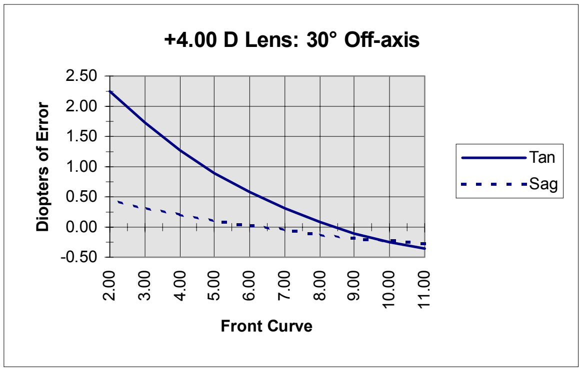

Figure 5. The off-axis performance for a +4.00 D lens at 30° off-axis.

Recall that a *best form*, or *corrected curve*, lenses use the optimum base curve for optical performance. Unfortunately, lenses that provide good cosmetics (i.e., flatter lenses), typically provide poor optical performance in the periphery. This is the primary conflict that lens designers have to balance when designing ophthalmic lenses: *optical performance* versus *cosmetics*.

APPLICATIONS OF ASPHERIC LENSES

Fortunately lens designers have another tool at their disposal when designing lenses: asphericity. In the strictest sense, *aspheric* simply means 'non-spherical.' Yet this definition could include quite a few lenses (including any lens with cylinder power). We can be a bit more precise, and define an **aspheric surface** as a rotationally-symmetrical surface that gradually varies in surface power from the center towards the edge in a radial fashion. This change in surface power produces surface astigmatism that can counteract and neutralize the oblique astigmatism. Aspheric surfaces free lens designers from the constraints of *best form* lenses. Lenses can be made flatter, thinner, and lighter, while maintaining excellent optical performance.

The first application of aspheric spectacle lenses dates back nearly ninety years ago (hard to believe, isn't it?). Early aspheric lenses were originally employed to provide acceptable vision in high-plus, *post-cataract* lenses that exceeded the +8.00 D limit of Tscherning's ellipse. The *crystalline lens* is responsible for nearly a third of the refracting power of the eye. When the lens is removed from the eye as a result of a **cataract** (opacity of the lens), extremely high-plus spectacle lenses can be used to supplement the loss of refracting power. Because of surgical advances and *intraocular lens implants*, such lenses are now all but obsolete.

This lens design technology has lived on; though it has evolved to fit the needs of modern eyeglass wearers. Today, aspheric surfaces mainly allow lens designers to produce flatter, thinner lenses with the superior optical performance of the steeper corrected curve, or best form, lenses. This is even accomplished in low-powered lenses. In addition to superior cosmetics, the flatter profile of aspheric lenses provides less magnification/minification than steeper best form lenses (especially in plus powers). The makes the eyes appear more natural looking.

ASPHERIC LENS DESIGN

To produce a three-dimensional aspheric surface, non-circular curves are rotated about an **axis of symmetry**. The central curvature, or **vertex curvature**, of an aspheric surface will be nearly spherical. The vertex curvature of an aspheric surface will be the front curve value utilized for lens power and surfacing calculations. Away from the vertex curvature, the amount of surface astigmatism smoothly increases. The rate of increase in surface astigmatism depends upon the degree or type of asphericity.

Figure 6 demonstrates the surface created by rotating an ellipse about an axis of symmetry. Notice the changing radii of curvature in both the tangential and sagittal planes of the lens. This surface astigmatism is designed to neutralize the oblique astigmatism produced as the wearers looks away from the center of the lens. Original aspheric designs utilized **conicoid surfaces**, which are produced by rotating a conic section about an axis of symmetry to produce a three-dimensional surface. Modern aspheric lenses, however, often employ *higher order* surfaces that allow for more complex shapes than the simple conic sections.

Since flattening a lens introduces astigmatic and power errors, the peripheral curvature of the aspheric surface should change in a manner that neutralizes this effect. For instance, *plus* lenses with asphericity on the *front* surface require a *flattening* of curvature away from the center of the lens to reduce the effective gain in oblique power and astigmatic error. Asphericity on the *back* surface will require a *steepening* of curvature away from the center of the lens. The opposite holds true for *minus* lenses, which can also benefit from asphericity.

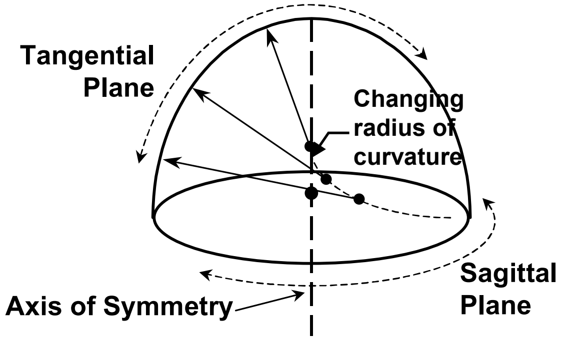

Figure 6. Anatomy of an aspheric surface. This elliptical curve has a radius of curvature that gradually changes away from the center. Once the ellipse has been rotated about the axis of symmetry, it produces a three-dimensional *conicoid* surface. The tangential radius of curvature, from point C_{TAN}, is longer than the sagittal radius of curvature, from point C_{SAG}. This results in surface astigmatism that can be utilized to control lens aberrations.

Aspheric lenses are generally more sensitive to the range of prescriptions that they have been optimized for. Consequently, aspheric lenses typically have more base curves available, in smaller increments of surface power. Proper base curve selection, as recommended by the manufacturer, is critical. Substituting aspheric base curves can often have a negative impact on the off-axis performance of the lens. Furthermore, the further a lens form is flattened from its optimum, best form base (spherical) base curve, the more asphericity (or surface astigmatism) will be required to properly compensate for the off-axis optics.

Flatter base curves produce thinner lenses. It is interesting to note that the actual geometry of an aspheric surface helps reduce lens thickness, as well. This is a consequence of the fact that the *sag* (or depth) of an aspheric surface differs from the sag of a spherical surface. Consider the comparison made in Figure 7.

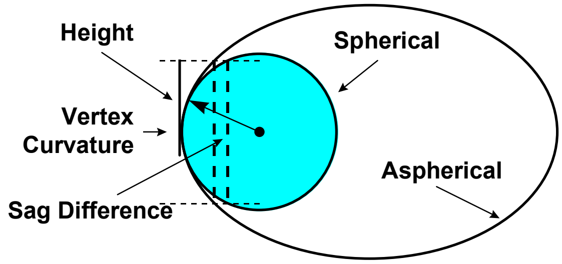

Figure 7. Difference in sags between spherical and aspherical curves. For a given diameter, the aspheric surface is more shallow than the spherical surface. The central portion, or *vertex curvature*, of an aspheric surface is nearly spherical.

At a given diameter, the aspheric surface has a shallower sag than the spherical surface. Further, the thickness reduction is maximized when the surface with the highest surface power is made aspheric (e.g., the back surface of a minus lens). It is also interesting to note that surfacing laboratories have to compute *block compensations* when generating aspheric lenses, as a result of this sag difference.

ASPHERIC LENS PERFORMANCE

We can now compare the physical and optical properties of a steep *best form* lens, a flat lens with a spherical base curve, and a flat *aspheric* lens. Careful consideration of Table 1 below shows that a +4.00 D best form lens can be produced having no astigmatic errors. The prescription off-axis closely matches that which is called for. A flat lens can also be made, which would be cosmetically superior, but the power off-axis departs significantly from the desired prescription. However, using an aspheric front surface, a lens can be produced that also eliminates the astigmatic error while providing an even thinner center.

Table1 +4.00-D lens design comparison

+4.00 D Lens Design Comparison*	Best Form Lens	Flat Lens	Aspheric Lens
Front Curve	9.75 D	4.25 D	4.25 D
Center Thickness	6.6 mm	5.9 mm	5.1 mm
Weight	20.6 grams	17.7 grams	14.8 grams
Plate Height	13.7 mm	6.0 mm	5.1 mm
Rx off-axis	+3.78 DS	+5.18 DS -0.99 DC	+3.77 DS

* These are CR-39 lenses that have been computed with a 70-mm diameter, and a 1-mm edge at 30° off-axis.

MEASURING AN ASPHERIC SURFACE

Unfortunately, because of the fact that the curvature of an aspheric surface varies away from the center, normal measuring instruments can not measure the front curve value—or vertex curvature—of an aspheric lens accurately. This is demonstrated in Figure 8. Some laboratory **sag gauges**, for instance, which are used to measure the curvature of a surface, have a measuring diameter of 50 mm. The 4.25 D aspheric lens from our previous example would actually measure 3.81 D at this diameter. Even *lens clocks* are only slightly more accurate since their outer pin spacing is smaller at 20 mm. Our aspheric would measure 4.17 D using a lens clock. It is equally difficult to detect asphericity using such devices, as well. The change in surface curvature towards the edge of the lens is often quite subtle with low-powered aspherics, and difficult to verify with these instruments.

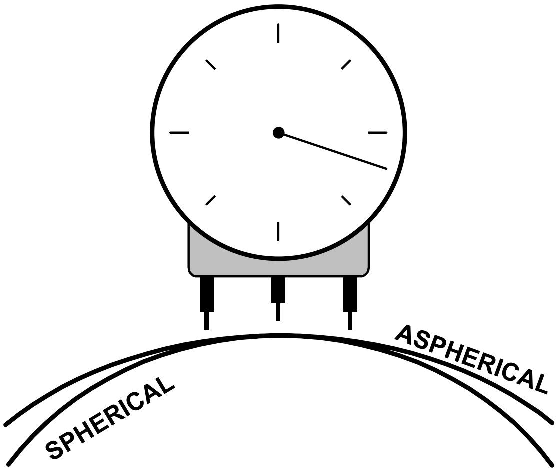

Figure 8. Aspheric surfaces can not be accurately measured with conventional instruments.

The geometry of an aspheric surface also prohibits the practice of grinding prism for decentration. However, prescribed prism can still be ground. Aspheric surfaces have a specific reference point—the axis of symmetry—which spherical surfaces do not. When prism is ground in an aspheric lens to decenter the optical center, the optical center is moved away from this reference point—which is typically located at the geometric center of the lens. Therefore, grinding prism to decenter the optical center (or decentering the optical center to induce prism) is not recommended in many cases. However, prescribed prism can be ground. It is best to consult the lens manufacturer for specific instructions in these cases.

Since the geometry of an aspheric surface can reduce the thickness of a lens, it becomes possible to use asphericity strictly for cosmetic purposes. By producing a highly-aspherical surface with a rapid change in curvature towards the periphery of the lens, the sag of the surface can be made much shallower. When asphericity is ‘exaggerated’ in this fashion, the off-axis optics are generally poor—since the lens has been optimized solely for cosmetics, with little regard for optics. Most modern aspheric lenses are designed to provide good optical performance, nonetheless.

ASPHERICITY AND HIGH-INDEX LENS MATERIALS

Since modern ‘thin & light’ lens materials often have lower Abbe values, proper lens design is critical. Materials with low Abbe values are more susceptible to **chromatic aberration**, or color dispersion and blur, in higher powers. Whenever possible, the *best form* base curve recommended by the manufacturer should be utilized. If the blur caused by *monochromatic* aberrations (like oblique astigmatism) is minimized with the proper selection of base curves, or with a well-designed aspheric surface, the wearer’s sensitivity to the *chromatic* blur may be kept below his or her threshold of tolerance. This can reduce the likelihood of a non-adapt.

I have heard many authors claim that the application of an anti-reflective coating will help reduce complaints related to low Abbe values and chromatic aberration. Although I have yet to discover any optical correlation between chromatic aberration and anti-reflective (A/R) coatings, I do think that A/R coatings enhance aspheric and high-index lenses. Aspheric lenses are often significantly flatter than conventional best form lenses. The surface reflections off flatter curves differ in size and clarity from the reflections off steeper curves. Further, high-index lens materials reflect more light than lower-index materials. This means that reflections will be slightly brighter and more noticeable to the wearer. If your patient is going into aspheric or high-index lenses for the first time, she may notice this change. By applying an anti-reflective coating beforehand, you are preventing this potential problem from becoming an issue.

Moreover, high-index lens materials reflect more light than CR-39 and crown glass. The application of an A/R coating more than compensates for any loss of transmittance. Besides, an anti-reflective coating is the perfect ‘premium’ add-on for your ‘premium’ aspheric and high-index lenses.

ASPHERICITY AND PROGRESSIVE LENSES

Because of their change in curvature, all progressive lenses are inherently *aspheric* (or non-spherical) in nature. Today, this term is used quite loosely and should probably be qualified with some additional details. For example, some manufacturers use base curves that are flatter than conventional *best form* base curves for their PAL designs. Asphericity is then applied in the peripheral portion of the lens to compensate for this; this is the same concept utilized for single vision aspheric lenses. Others may refer to their designs as aspheric, if the distribution of unwanted surface astigmatism produced by the progressive power encroaches significantly into the upper half of the lens. Still others may call any PAL design aspheric, if they are using the word in its strictest sense. When in doubt, a quick call to the lens manufacturer should alleviate any doubts.