i.Scription® by ZEISS:
Setting the New Standard of Vision Correction

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Aberrometry is elevating the standard of refractive eyecare by allowing clinicians to evaluate the optical characteristics of the eye more thoroughly, including both low-order and high-order wavefront aberrations. Determining the endpoint of refraction by taking into account the effects of high-order aberrations on retinal image quality can yield improved vision corrections that deliver optimal visual performance over a broader range of luminance levels, even under demanding viewing conditions like night driving. i.Scription® by ZEISS represents a "wavefront-guided" vision correction derived from aberration data captured by the i.Profiler^{plus}® aberrometer. Each i.Scription is then combined with a precisely fabricated, fully customized lens design in order to deliver the ultimate visual experience for wearers.

The Evolution of Refraction

Traditionally, the final or *manifest* refraction that serves as the basis for an eyeglass prescription is the result of a two-part process: The refractive errors of the eye are first estimated *objectively*, using either retinoscopy or an autorefractor, and then the prescription is *subjectively* refined by comparing the vision of the patient through trial lenses, using either a refractor head or trial frame. Many of the tools and techniques commonly used during refraction procedures have remained largely unchanged for over a century, since the pioneering work of Donders, Jackson, Copeland, and others.

Even today, with the widespread use of sophisticated autorefractors and photorefractors, manual subjective refraction is still considered the "gold standard" by clinicians. Nevertheless, traditional subjective refraction techniques suffer from certain inherent limitations. In particular, subjective refraction procedures often attempt to simulate ideal viewing conditions by using a brightly-illuminated, high-contrast visual acuity chart under normal room lighting, which causes the pupil of the eye to remain relatively small in diameter. Because a small pupil size restricts focusing to the central "paraxial" region of the eye, the influence of ocular aberrations upon vision is decreased, while variation in subjective responses from the patient due to the depth of focus of the eye is increased.

Now, with the recent advent of commercially-available *aberrometers*, which measure the "wavefront" aberrations of the eye, new enabling technologies may finally elevate the standard of refractive eyecare for the first time in decades. Evaluating the wavefront aberrations of an optical system has already become commonplace in high-performance optical fields such as astronomy. There has been increasing interest in the ophthalmic applications of this technology, driven by advances in laser refractive surgery. Refractive surgeons can now reduce more of the wavefront aberrations of the eye, in addition to the traditional spherical and cylindrical refractive errors, in an effort to achieve *supernormal vision* with better than average visual acuity. Although the "high-order" wavefront aberrations of the eye cannot be eliminated with a spectacle lens, without introducing even greater aberrations when the eye rotates behind the lens, instruments such as i.Profiler^{plus} by ZEISS have made possible a new generation of vision correction solutions that should yield improved clinical outcomes (Figure 1).

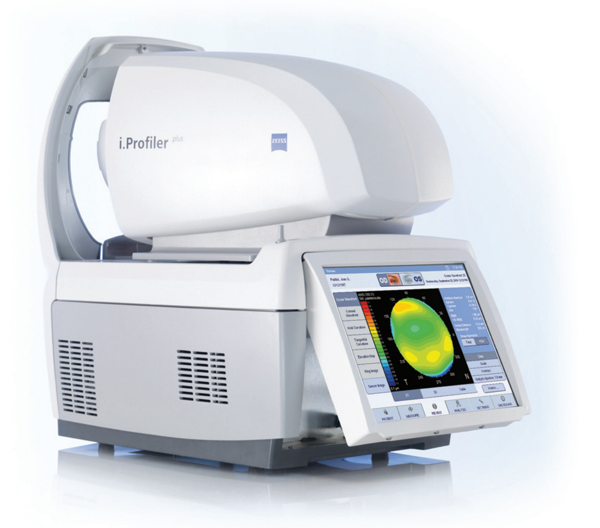


Figure 1. i.Profiler^{plus}® by ZEISS is a "3-in-1" instrument that incorporates the functionality of an aberrometer, corneal topographer, and autorefractor in a fast, compact, and easy-to-use system.

Wavefront Aberrations

The propagation of "light" has been described as a rapid movement of energy particles—or *photons*—that travel in a wave-like manner. The propagation of light from an object point can be represented conceptually using either *rays* or *waves* emanating outward from the light source. Just as rays of light diverge from an object point, waves of light spread out like ripples of water traveling away from a stone that has been dropped into a pond. At any given distance from the original object point, a *wavefront* exists that represents the envelope bounding waves of light that have traveled an equal distance from the object.

As the distance from the object increases, the curvature of these wavefronts becomes progressively flatter, eventually appearing flat beyond "optical infinity" (6 meters). The object point serves as the common center of curvature of these wavefronts. Conversely, light converging to a point focus can be described using spherical wavefronts that become progressively smaller, converging to the image point. Further, a ray of light from the same object point remains perpendicular to the corresponding wavefront as both propagate away from the object or toward the image (Figure 2).

An *aberration* is essentially an error in focus. There are several ways to characterize the aberrations produced by a lens or optical system. In geometrical optics, ray tracing is often utilized to calculate the path of a bundle of rays from an object point as the rays are refracted at the various surfaces of each lens or optical element. Aberrations are then determined by calculating the distance of these refracted rays from the intended focal point. Alternatively, the deformation of the corresponding wavefront of light as it passes through the optical system may be also determined.

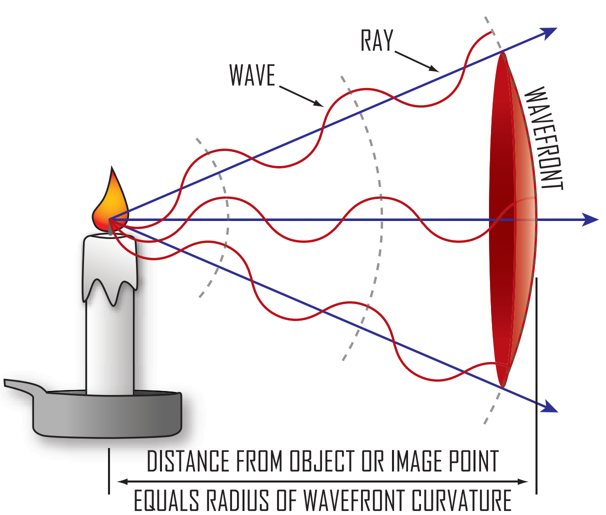


Figure 2. Light diverging from an object point or converging to an image point can be represented using either rays or wavefronts representing the envelope that bounds waves of light that have traveled in unison or phase.

In a perfect optical system, wavefronts of light from an object point should converge to a single point focus at the desired image location, such as the retina of the eye, after refraction through the system. In the presence of focusing errors or aberrations, however, these wavefronts become either too steep, too flat, or distorted from their ideal shape. Accordingly, the rays of light corresponding to these wavefronts are spread out at the plane of the desired focus, instead of intersecting at a single, sharp point. Consequently, optical aberrations may be represented using rays, wavefronts, or even the spread of light intensity at the image plane (Figure 3).

At any point across the aperture of the optical system, such as the pupil of the eye, the *wavefront error* is the effective optical separation between the actual wavefront and the ideal spherical wavefront centered on the desired focal point. Wavefront errors are usually expressed in micrometers or microns (µm), which are equal to one-thousandth of a millimeter (0.001 mm). For simple wavefront aberrations, differences in curvature between the aberrated and ideal wavefronts may also be used to quantify the aberration. The curvature of a wavefront, expressed in *diopters*, is simply equal to the reciprocal of its radius of curvature, in meters. The sphere and cylinder powers of a prescription actually indicate the differences in curvature between the aberrated and ideal wavefronts of the eye. For more complex wavefront aberrations, curvature, alone, does not sufficiently characterize the aberration.

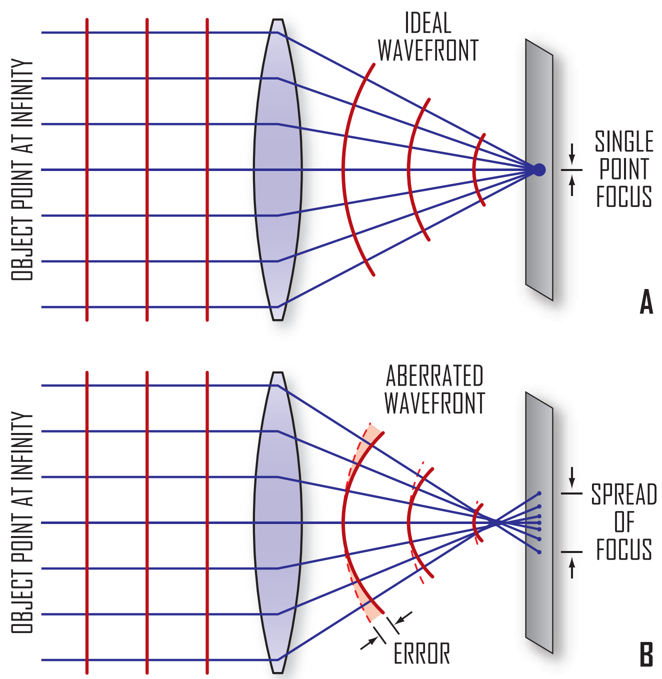


Figure 3. An optical system should produce wavefronts of light that eventually converge to the intended point focus (A), although wavefronts of light do not converge to a sharp focus at the desired point in the presence of aberrations (B).

Zernike Polynomial Series

Quantifying more complex wavefront aberrations often relies on more descriptive mathematics. Once the wavefront errors have been measured across the aperture (or pupil) of an optical system, these measurements can be "modeled" mathematically for easier analysis and manipulation. Most commonly, the shape of an aberrated wavefront is modeled by "fitting"—or closely approximating—the measurements with a series of polynomial functions using mathematical curve fitting techniques. This allows even complex wavefront aberrations to be represented as a combination of more basic shapes, often associated with traditional optical aberrations.

The *Zernike polynomial series* is commonly used to fit wavefront measurements. This is a set of functions that each represent individual optical aberrations, known as *modes*. Zernike polynomials are typically grouped by their *radial order*, which indicates how rapidly the aberration increases with pupil size (Figure 4):

- *Low-order* aberrations include *defocus* and *astigmatism*, broken into components at axis 45/135 (oblique) and at axis 180/90 (WTR/ATR), which are associated with the spherical and cylindrical refractive errors of the eye, respectively.
- *High-order* aberrations include third-order aberrations, such as *coma* and *trefoil*, fourth-order aberrations, such as *spherical aberration*, and aberrations of successively higher radial orders, which increase more rapidly as the pupil size increases.

Low-order aberrations are detrimental to vision quality at both small and large pupil sizes. These aberrations are typically corrected by eliminating the refractive errors of the eye using sphero-cylindrical lenses. High-order aberrations become more detrimental to vision quality when the pupil size is large. Although often less severe than the low-order aberrations of an eye, these aberrations can also degrade visual acuity and reduce image contrast (Figure 5).

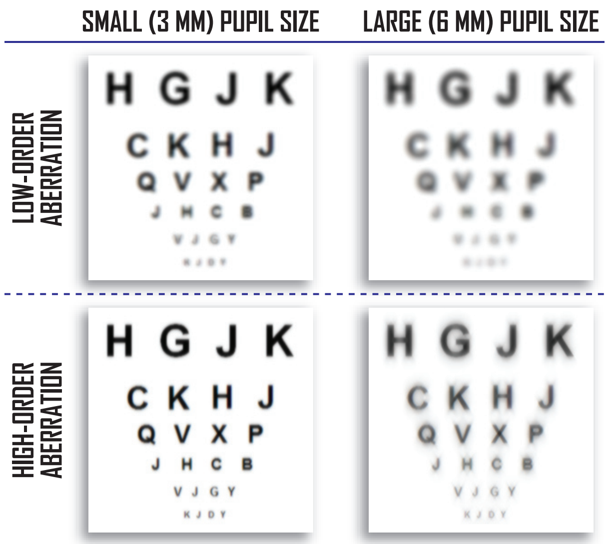
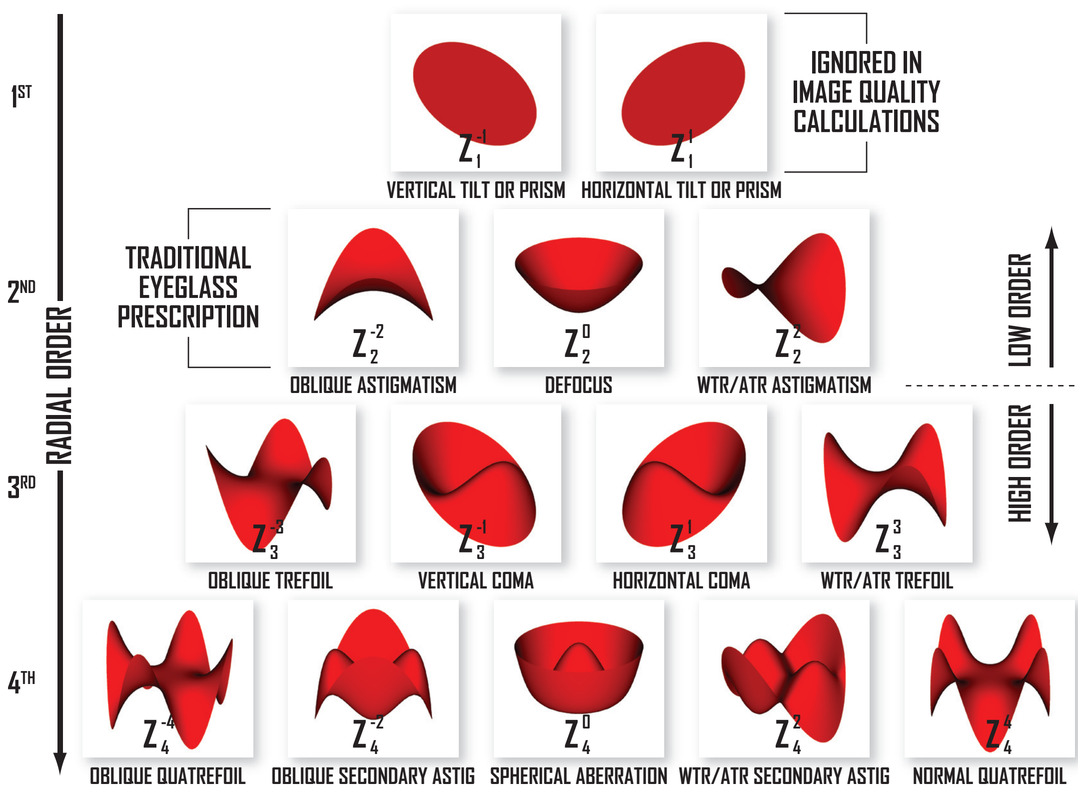


Figure 5. Low-order aberrations degrade vision quality even at smaller pupil sizes, whereas high-order aberrations become more detrimental at larger pupil sizes.

Figure 4. Complex wavefront aberrations can be represented as a combination of Zernike polynomial functions or "modes":

- *Each mode has a coefficient that specifies the magnitude of the aberration in the wavefront.*
- *A wavefront is reconstructed by adding together quantities of the various modes.*
- *Modes are grouped by their radial order, which indicates the "power" of the function.*
- *Radial orders are whole numbers that begin with the zeroth order and continue indefinitely.*
- *The total number of modes in each subsequent radial order increases by one mode.*
- *Modes in the second order are associated with spherical and cylindrical refractive errors.*
- *Modes in zeroth and first radial orders are typically ignored in calculations of image quality.*



Limitations of Subjective Refraction

Subjective refraction is a clinical procedure that determines the optimal prescription for correcting the refractive errors of an eye by having the patient compare vision quality through different spectacle lens powers, after establishing an estimate of the refractive status of the eye using objective refraction. Although the subjective refraction is considered the "gold standard" for judging the accuracy and precision of objective methods for performing refraction, the outcome can vary between different clinicians and between repeated measurements by the same clinician.[1] On average, refractions performed by different clinicians agree to within ±0.12 D, but for individual patients the discrepancies can be much larger (95% limits of agreement = -0.90 to +0.65 D).[2]

This variability is due to a variety of factors. The patient may use different perceptual criteria when choosing between lenses, such as sharpness, contrast, or legibility. The depth of focus of the eye may make it difficult for the patient to discriminate between small changes in image quality. The ideal refraction will often vary with pupil size and, therefore, luminance levels in the presence of high-order aberrations. With irregular corneas, sphere and cylinder powers can vary by up to 1.00 D or more between 3 mm and 7 mm pupil sizes.[3] Rounding errors due to the use of trial lenses in 0.25-diopter steps limit the precision of the refraction to ±0.12 D.

Moreover, high-order aberrations may result in irregular astigmatism or multiple combinations of cylinder power and axis that yield relatively good vision quality. Although the Jackson cross-cylinder technique will isolate one of these *local maxima* of vision quality, the technique may not necessarily converge to the combination of cylinder power and axis that yields the best vision quality or *global maximum* (Figure 6). Thus, the variability of subjective refraction undermines any attempt to validate objective refraction techniques, because the "gold standard" is, in effect, a "moving target."

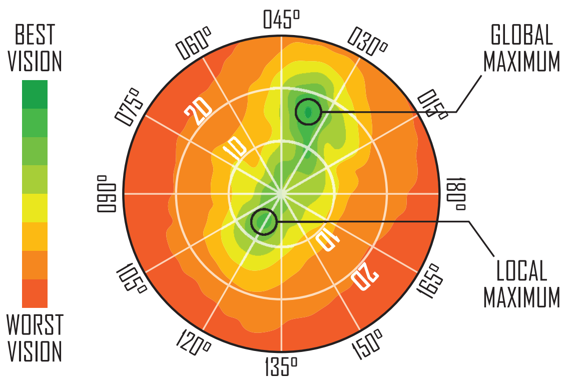


Figure 6. In the presence of high-order aberrations, a polar plot of retinal image quality as a function of cylinder power may reveal multiple combinations of cylinder power and axis that yield "good" vision quality, although the Jackson cross-cylinder technique may not necessarily converge to the "best" vision correction.

Although conventional vision corrections are intended to correct only the low-order aberrations of the eye, the optimal sphere and cylinder powers for these corrections are influenced by higher-order aberrations. In the presence of ocular high-order aberrations, the vision correction that maximizes the focus of *paraxial* rays of light passing through the central region of the pupil will differ from the vision correction that maximizes the focus of *marginal* rays passing through the periphery of the pupil. Further, both vision corrections will suffer from residual blur (Figure 7). Maximum retinal image quality will actually be achieved when blur is minimized using a balanced vision correction that represents a compromise between the defocus of the paraxial rays *and* the marginal rays.

In fact, experiments have shown that patients typically judge the optimal focus as lying somewhere between the paraxial focus and the marginal focus.[4] Because subjective refraction often involves viewing conditions that serve to restrict the pupil size, however, this procedure favors the paraxial focus. Additional information regarding the high-order aberrations of the eye should be applied in order to compute a sphero-cylindrical vision correction that optimizes image quality for the entire pupil. Determining the size of the patch of blur produced on the retina is one such method, but there are many ways to quantify image quality, each emphasizing a different aspect of the optical system and resulting image. Because the patient ultimately decides whether one retinal image is better than another, the best metric of image quality should reflect the image processing characteristics of the human visual system.

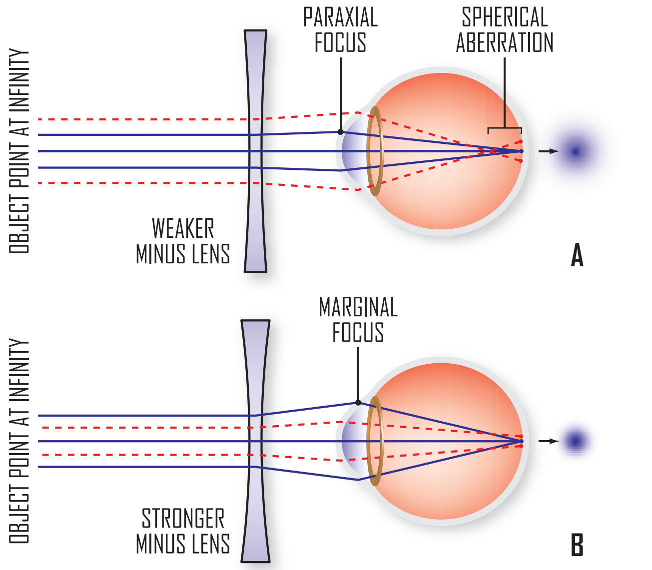


Figure 7. Because ocular high-order aberrations, such as spherical aberration, cause the best vision correction for focusing the paraxial rays (A) to differ from the best correction for focusing the marginal rays (B), the ideal vision correction for the entire pupil typically represents a compromise between these two extreme cases.

Wavefront-Guided Objective Refraction

An *aberrometer* measures the wavefront aberrations of the eye. Just as topographers now provide more detail regarding the surface characteristics of the cornea than conventional keratometers, aberrometers now capture more detail regarding the refractive characteristics of the eye than conventional autorefractors. Autorefractors typically measure only the low-order aberrations of the eye over a small region of the pupil, roughly 3 mm in diameter, which essentially restricts light to the paraxial region of the eye. Aberrometers, on the other hand, measure both the low-order and high-order aberrations of the eye over the entire pupil.

Many aberrometers utilize a Shack-Hartmann wavefront sensor. A point source of light—representing a distant object—is projected onto the retina. The retinal image of this point source then serves as the object point for measurement. After leaving the eye, light from this object point passes through an array of small lenslets that sample the optics of the eye over the entire pupil. Each lenslet brings light to a focus on a CCD sensor. Ideally, light from the retina should produce a plane (flat) wavefront after passing back through the optics of the eye. Any differences between the plane wavefront and the actual wavefront exiting the eye will cause light to deviate as it passes through the lenslets. The displacement of each focus is then measured and used to model the wavefront errors (Figure 8).

Once the wavefront errors have been modeled, often using the Zernike polynomial series, a vision correction can be determined. Because the eye remains in a constant state of movement, it is not feasible to correct the high-order aberrations of the eye with a spectacle lens. A conventional sphero-cylindrical vision correction eliminates the low-order aberrations of the eye. Nevertheless, it is possible to determine a *wavefront-guided* vision correction using a combination of conventional sphere power and cylinder power that minimizes the blur that results from the interaction between the low-order and high-order aberrations.

For instance, approximating a map of the vergence errors over the pupil of the eye with the best-fitting sphero-cylindrical map is a simple way to determine an ocular wavefront refraction.[5] Alternatively, diffraction and interference effects can be taken into account by approximating a map of the wavefront errors over the pupil.[6] Other methods are available to determine the optimal wavefront refraction as well. The refraction can be determined by iteratively optimizing the optical quality of either the retinal image of a point source using the *point spread function* or the image of sinusoidal gratings using the *modulation transfer function*.

These functions can be manipulated in a variety of ways to develop novel measures of optical quality. Some especially useful metrics, such as the *Strehl ratio*, have even been modified to account for the early stages of visual processing. Furthermore, other criteria may also prove beneficial when optimizing a wavefront-guided vision correction. For instance, experiments have shown that observers prefer a vision correction that maximizes the area of the pupil for which the vergence errors or the wavefront errors are negligible.[7]

Although refractive errors are determined clinically for distant objects, in everyday life the eye must form the retinal image for objects at a variety of distances, simultaneously. Thus, providing a large depth of focus is arguably more important than optimizing the focus for any single viewing distance. This is why the ZEISS *VoluMetric* merit function was developed to optimize the three-dimensional image intensity produced in the vicinity of the focus of the lens-and-eye combination. Rather than limiting attention to a single focal plane, this function integrates the beam intensity along the depth of the focus in addition to the cross-sectional area in order to minimize the *volume* of blur. The VoluMetric function therefore provides a superior wavefront refraction that is less sensitive to the frequent fluctuations in viewing distance, accommodation, and pupil size encountered throughout the day (Figure 9).

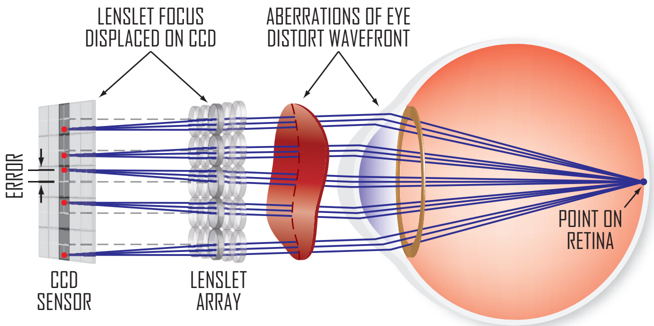


Figure 8. Many commercial aberrometers, like i.Profiler^plus by ZEISS, use a wavefront sensor that is based on the Shack-Hartmann principle, which measures the focusing errors of an array of small lenslets caused by the distorted wavefront originating from a point on the retina at the back of the eye (not to scale).

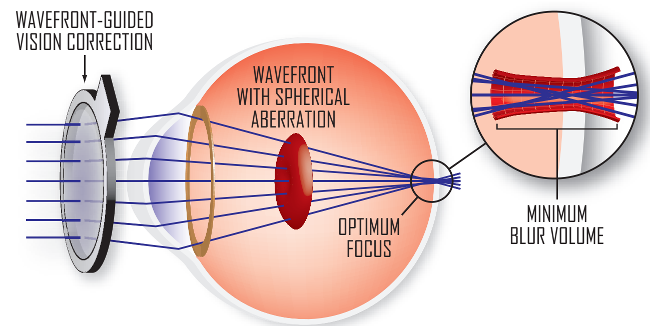


Figure 9. The ZEISS VoluMetric merit function utilized to calculate a wavefront-guided i.Scription seeks a combination of sphere and cylinder power that minimizes the three-dimensional "volume" of a focus distorted by high-order aberrations in order to maximize vision quality as well as the depth of focus of the eye.

i.Scription by ZEISS

Traditional subjective refractions are often performed under viewing conditions involving luminance levels that result in relatively small pupil sizes. Ambient light levels vary considerably, however, between *photopic* (or daytime), *mesopic* (or twilight), and *scotopic* (or nighttime) viewing conditions. Although most light adaptation occurs within the retina, the size of the pupil varies inversely as a function of luminance, becoming smaller as luminance increases in order to control retinal illumination and to maximize retinal image quality. The pupil size varies from a minimum of roughly 2 during photopic vision to a maximum of roughly 8 mm during scotopic vision (Figure 10).[8] Because of the increasing dependence on pupil size of the aberration modes in higher orders, the influence of high-order aberrations upon the ideal vision correction increases at low luminance levels when the pupil size is large.

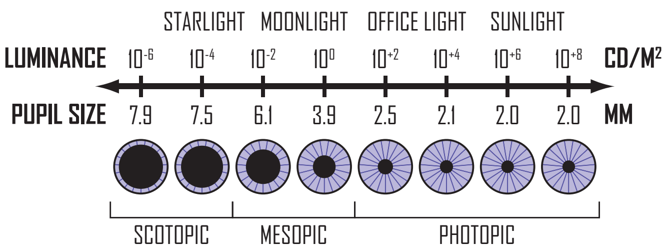


Figure 10. The pupil of the human eye varies from a minimum of roughly 2 mm during photopic vision to a maximum of roughly 8 mm during scotopic vision.

Although the low-order, sphero-cylindrical refractive errors will remain relatively constant in the absence of high-order aberrations, regardless of pupil size, all eyes suffer from at least some high-order aberrations. Normal eyes have on average a root-mean-square error (RMS) of 0.33 μm for high-order aberrations at a pupil size of 6 mm, which is roughly equivalent to 0.25 diopters of defocus.[9] Determining the endpoint of refraction by taking into account the effects of high-order aberrations on retinal image quality may therefore result in superior sphero-cylindrical vision corrections that deliver optimal vision over a broader range of luminance levels.

Using wavefront aberrometry data captured by i.Profiler^plus^, the ZEISS VoluMetric merit function calculates a wavefront refraction with sphere and cylinder powers that deliver the most optimal vision quality over a range of viewing conditions (Figure 11). The clinician must then conduct a standard subjective refraction as usual for assessing binocular vision, performing binocular balancing, and determining the near addition. Lastly, the wavefront refraction is reconciled against the subjective refraction using a unique subjective refinement algorithm in order to ensure that the spherical equivalent of the final refraction does not deviate excessively from the subjective findings. The result of this patented process is the patient's i.Scription: a precise, wavefront-guided vision correction.

Because the VoluMetric merit function maximizes depth of focus of the eye based on the interaction between the low-order and high-order aberrations, i.Scription should improve visual performance under more demanding viewing conditions. Wearers may experience improvements in contrast sensitivity, low-light vision, and night driving due to a reduction in "night myopia" caused by high-order aberrations and the *Purkinje shift* in ocular color sensitivity. Additionally, wearers may experience a reduction in the apparent effects of ocular chromatic aberration.

» i.Scription combines a wavefront refraction with the findings of the subjective refraction

Every i.Scription spectacle refraction comprises a sphere power, cylinder power, and cylinder axis. Unlike traditional eyeglass prescriptions, however, the i.Scription sphere and cylinder powers are calculated to the nearest 0.01-diopter step. Thus, i.Scription is more precise than a conventional prescription, which can result in rounding errors of up to ±0.12 D due to the use of trial lenses in 0.25-diopter steps. The use of more precise prescription values further enhances the optimized wavefront refraction of i.Scription.

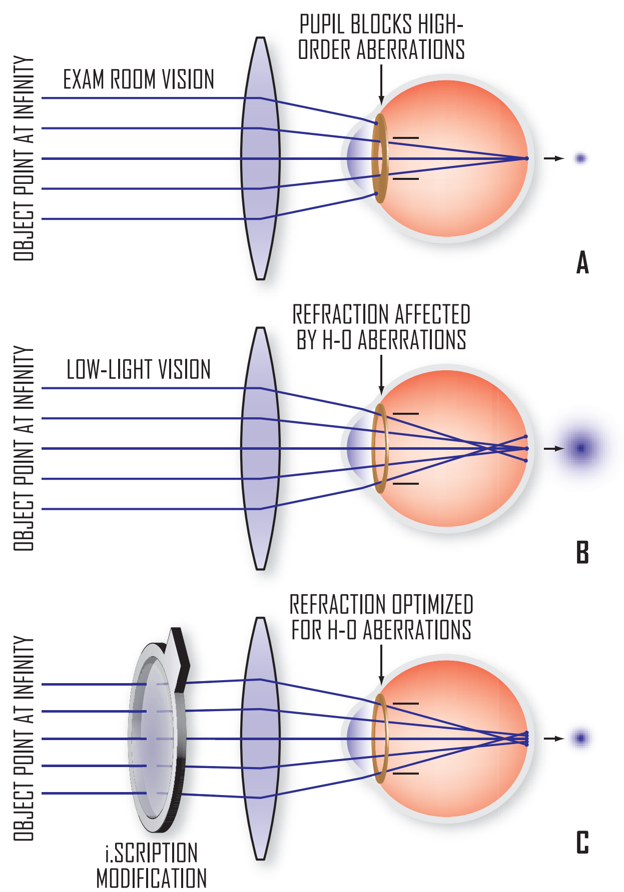


Figure 11. Conventional vision corrections often provide optimal performance under ideal viewing conditions (A), but may provide reduced performance under more demanding conditions due to high-order aberrations (B), whereas i.Scription maximizes visual performance over a broad range of viewing conditions (C).

Precision Customized Lenses

> » i.Scription lenses utilize precisely fabricated, fully customized lens designs

Once an i.Scription vision correction has been determined, a spectacle lens must be fabricated to the desired prescription powers. Unfortunately, traditional spectacle lenses often introduce additional wavefront aberrations that can compromise optical performance and vision quality for the wearer compared to the vision achieved during the eye exam (Figure 12):

- Residual low-order aberrations occur in traditional spectacle lenses because of oblique astigmatism as a result of either the tilt of the fitted lens (that is, *position of wear*) or the angle that the line of sight makes to the lens during peripheral vision.
- Residual low-order aberrations also occur in spectacle lenses due to the power rounding errors inherent in traditional lens surfacing, which typically relies on hard "lap" tools that are stocked in only 0.12-diopter increments of surface power.

Traditional, *semi-finished* lens blanks are typically available in only a handful of unique base curves or lens designs, which are factory-molded in mass quantity. Changes to the basic design of traditional spectacle lenses are limited to subtle variations in optical design across a small number of base curves that must work sufficiently well for relatively broad prescription ranges. Traditional spectacle lenses are therefore specifically designed for a few "average" prescription powers, using either "average" fitting parameters for progressive lenses or assuming a fitting condition free of lens tilt for single vision lenses. The use of average assumptions for each lens design results in uncorrected low-order aberrations for many wearers that can restrict, distort, and blur the fields of clear vision.

Fortunately, the advent of *free-form* or *digital surfacing* technology has freed many lens designers from the constraints of traditional, mass-produced spectacle lenses. This modern manufacturing platform relies on computer-controlled generators that can precisely grind surface curves of extremely high complexity, including aspheric and progressive designs, directly onto a semi-finished lens blank.

When combined with advanced optical design software, free-form lens designs can be calculated in "real time," using the wearer's specific prescription and fitting parameters, immediately prior to fabrication. Progressive and single vision lens designs with i.Scription by ZEISS can therefore be fully customized to the unique visual requirements of the individual wearer. Customized lenses preserve the intended optical performance of the lens design by minimizing residual low-order wavefront aberrations, while ensuring that every wearer enjoys the visual benefits of the i.Scription vision correction, regardless of his or her prescription requirements or position of wear (Figure 13). Additionally, free-form surfacing is not subject to the power rounding errors of traditional lens surfacing.

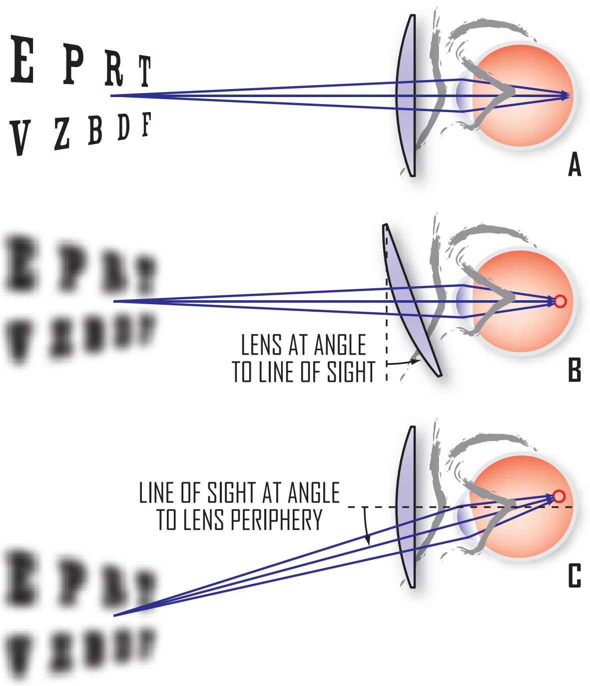
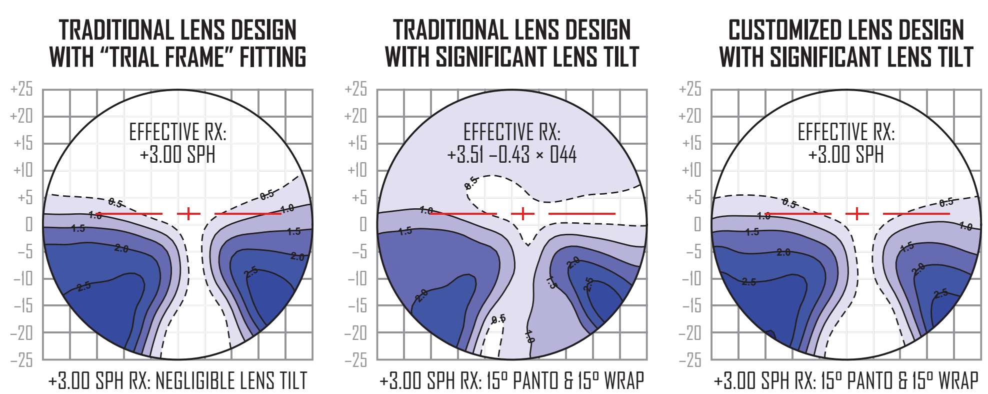


Figure 12. Although vision through refractor-head or trial-frame lenses may be clear (A), low-order aberrations due to oblique astigmatism can occur in fitted spectacle lenses that will blur vision when viewing through a lens that is tilted in front of the eye (B) or when viewing through the periphery of the lens (C).

Figure 13. Contour plots of ray-traced astigmatism demonstrate that the optics of traditional progressive lens designs may be significantly influenced by the position of wear, resulting in residual low-order aberrations that can restrict, distort, and blur the zones of clear vision, whereas the fully-customized lens designs utilized for i.Scription lenses maintain the desired optical performance, regardless of the prescription or position of wear.



Clinically Proven Performance

Several clinical studies have demonstrated the efficacy of i.Scription for improving vision at night, color perception, and contrast sensitivity, without compromising visual performance during normal viewing conditions.[10] A randomized, double-masked clinical study comparing i.Scription to conventional spectacle refractions was conducted at InSight Eyecare, an independent optometric clinical research facility near Kansas City, Missouri. This wearer trial utilized a crossover design in which each of 40 subjects wore a pair of ZEISS single vision lenses with i.Scription and a pair of conventional single vision lenses for one week each, in random order. A variety of objective measures of visual performance and subjective measures of wearer preference demonstrated improved results for vision quality under demanding viewing conditions:

- Subjects rated ZEISS lenses with i.Scription higher for distance vision, night vision, and color perception.
- ZEISS lenses with i.Scription also performed better on average than conventional spectacle lenses in measures of mesopic visual acuity and contrast sensitivity.

A similar clinical study was also conducted by investigators at the prestigious Clinical Research Center of the School of Optometry at the University of California at Berkeley. Each of 30 subjects compared ZEISS single vision lenses with i.Scription to conventional single vision lenses in a randomized, double-masked wearer trial utilizing a crossover design. Once again, a variety of objective measures of visual performance and subjective measures of wearer preference demonstrated several positive outcomes:

- Subjects with low- to moderate-prescription powers preferred ZEISS lenses with i.Scription more often for distance vision, active vision, sharpness, changing focus, and overall vision.
- Subjects preferred ZEISS lenses with i.Scription more often for night vision, vividness of colors, and having less glare.
- ZEISS lenses with i.Scription also performed better than conventional spectacle lenses in measures of low-contrast, mesopic visual acuity—by approximately half a line of acuity.

» In clinical studies, i.Scription lenses perform better in more demanding conditions

Each i.Scription vision correction represents a synergy between a thorough wavefront refraction, a skillful subjective refraction, and a customized lens design. The product of this patented integration of optical science and clinical art is a uniquely calculated wavefront refraction, subjectively refined based on the judgment of the clinician, and precisely fabricated using digital surfacing technology. ZEISS lenses with i.Scription will deliver excellent vision, day or night, with improved contrast sensitivity compared to conventional spectacle lenses (Figure 14).

Automated refraction has not yet replaced subjective refraction. Many factors influence the final manifest refraction, including patient history, binocular balancing, and cosmetic appearance. Nevertheless, wavefront refraction technology can determine a starting point of refraction more quickly and reliably by optimizing retinal image quality more accurately. Subjective refinements can then be applied as needed based on the professional judgment of the clinician, in consultation with the patient. Because aberrometers characterize the optics of the eye so thoroughly, the expectations are high that this technology will yield improved clinical outcomes.

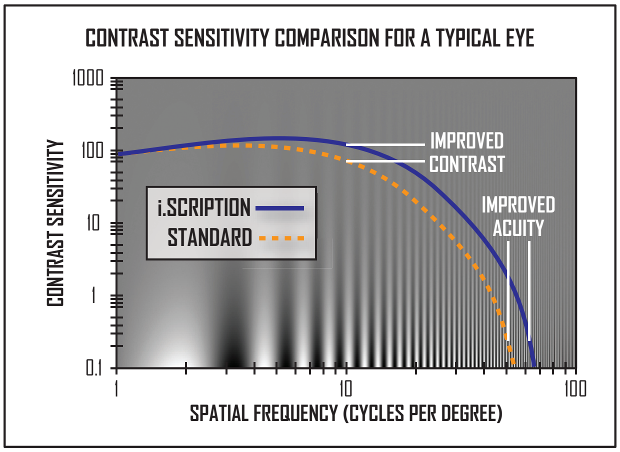


Figure 14. Calculations of the contrast sensitivity of a typical wearer for a conventional spectacle correction and an i.Scription wavefront-guided vision correction demonstrate the improvement in visual performance with i.Scription.

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