Contact Lens SPECTRUM

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WAVEFRONT

Seeing Into the Future With Contact Lenses

Wavefront technology measuring optical aberration may lead to the "ideal" contact lens correction.

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As we all know, the optics of the human eye, whether diseased or normal, are not perfect. In addition to diffraction and scatter, the eye suffers from optical errors called aberrations. For the past 400 years, we have known about and attempted to correct with glasses or contact lenses "lower order" aberrations of defocus and astigmatism. Not until the last 40 years have we even been able to measure (Smirnov 1961) "higher order" ocular aberrations beyond defocus and astigmatism.

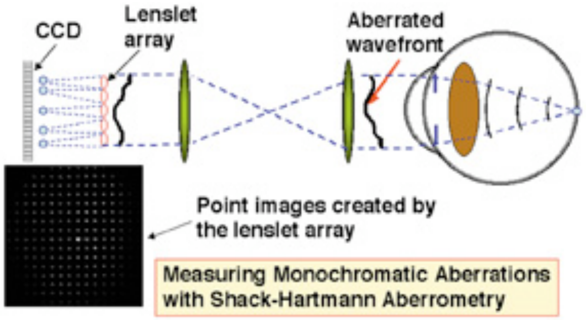


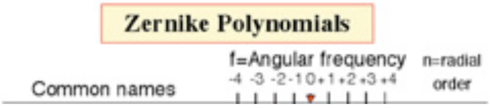
Figure 1. Measurement method.

Following the work of Smirnov, methods for measuring higher order aberrations have improved dramatically, becoming more efficient, accurate and patient-friendly. Today, one of the more common methods of aberration measurement uses Shack-Hartmann wavefront technology (Smith, Applegate et al 1996; Liang and Williams 1997; He, Marcos et al 1998; Salmon, Thibos et al 1998; Burns 2000; Moreno-Barriuso, Marcos et al 2001). This technology was originally developed in the study of astronomy, and then applied to the eye by Liang in the mid-1990s (Liang et al 1994). Since this time the ocular uses of Shack-Hartmann wavefront sensing, as well as other types of aberration measurement (such as ray tracing, scanning slit refractometry or more subjective methods), have opened the door to refractive corrections far superior to those traditionally available.

Measuring Monochromatic Aberrations

The principles of the Shack-Hartmann wavefront sensing aberrometer are shown in Figure 1. In the well-corrected eye, a narrow beam of light (usually infrared wavelength) is focused as a point source on the retina by the eye's optics. This image then becomes a source for reflected light exiting the eye. In an optically perfect eye focused at infinity, this point source would generate a plane wavefront (collimated beam of light) outside the eye. In the aberrated eye, this wavefront would not be completely flat, but deviated, as is shown in Figure 1. This wavefront is then sampled by a series of small inter-connected lenses called a lenslet array. This lenslet array focuses the exiting light wavefront as an array of points onto a camera or sensor. An aberrated wavefront will deviate the location of these points. It is possible to use the locations of these point images to calculate the wavefront shape and thus the aberrations of an eye.

The shape of this wavefront is typically fit by a series of mathematical functions called Zernike polynomials (Liang, Brimm, Goelz and Bille, 1994). These polynomials have varying radial orders and meridional frequencies. Figure 2 shows a pictorial



representation of these Zernike polynomials as a pyramid of terms. Although the mathematics of Zernike polynomials can be quite complicated, they provide a convenient method of representing wavefront shape in an algebraic form, which can then be easily programmed to control a lathe or refractive laser.

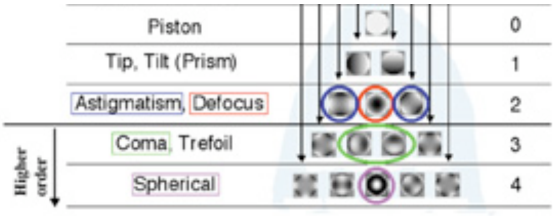


Figure 2. Aberration representation as a pyramid of Zernike polynomials.

As an alternative to describing the details of the wavefront as a series of Zernike polynomials, wavefront shape is often quantified by a single number describing the amount that it deviates from a plane wave. One of the most commonly used methods to describe the magnitude of the wavefront deviation is the root mean square wavefront error or RMS error. RMS is the standard deviation of the wavefront from a plane wavefront (Figure 3). In an optically perfect eye, RMS would be zero. Even though this is one of the most commonly used methods for quantifying optical quality, it may not effectively represent the effect of aberrations on vision, as retinal image quality and vision may not be maximized when RMS is minimized (Thibos et al 2002).

These advances in the science and technology of optical measurement are a necessary step before we can attempt to correct the higher order aberrations. However, the seemingly futuristic concept of correcting both the lower and higher order aberrations, and thus producing an "ideal" correction leading to "super vision" appears to be an attainable goal (Applegate 2000; Schwiegerling 2000; Thibos 2000; Applegate, Thibos et al 2001; Guirao, Porter et al 2002). For example, these new technologies now seek to correct not only the lower order aberrations of sphere and astigmatism, but also the higher order aberrations, and thus render the eye aberration free. Different methods of obtaining ideal correction have been proposed, including wavefront-guided refractive surgery (MacRae, Schwiegerling et al 1999; Mrochen, Kaemmerer et al 2000; Mrochen, Kaemmerer et al 2001) and aberration-correcting IOLs. Aberration correction can also be implemented with a contact lens correction (Atchison and Smith 1998; De Brabander, Chateau et al 1998; Marsack, Milner et al 2002).

Aberration-correcting Contact Lenses

To correct an eye's higher order aberrations with contact lenses requires the same approach as currently employed to correct lower order aberrations. For example, a myopic eye that has an excess of spherical power would be corrected with a negative power spherical lens. Likewise, an eye with positive spherical aberration would be corrected by a lens with negative spherical aberration.

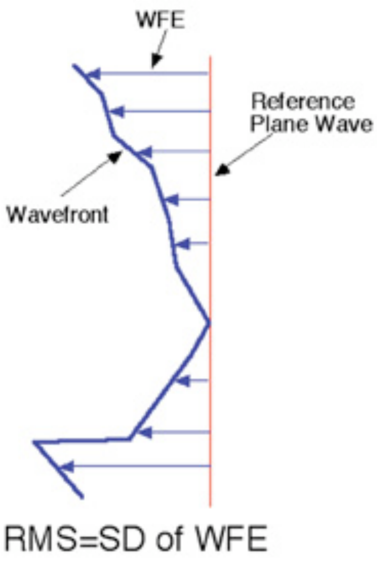


Figure 3. Root mean square wavefront error.

Aberrations were initially introduced into contact lenses (typically spherical aberration) not to correct the eye's aberrations, but to give the eye more aberration. These "multifocal" aberrated contact lenses were, and still are, used to expand the depth of focus in presbyopic contact lens wearers. Now, because we can measure the higher order aberrations of the eye, it seems plausible to use this approach to develop aberrated lenses to correct for the eye's aberrations. In contrast to the multifocal lenses, these aberration-correcting lenses would not expand depth of focus, but improve the quality of single vision.

It is important to realize that even a standard spherical contact lens (gas permeable or soft) can alter the aberration characteristics of an eye. This can be seen in the examples shown in the contour plots of Figure 4. This example shows an eye tested without a contact lens, with a spherical soft lens, and with a spherical GP lens. With an ideal aberration correcting contact lens on the eye, the contour plot would be free of any contour lines. In this example, both "spherical" contact lenses actually produce a slight reduction in the eye's higher order aberrations. However, the three-lobed structure (trefoil) seen in the aberration map of the naked eye (left panel) is also clearly visible when wearing the soft contact lens (middle panel). In fact, for a very thin, highly deformable soft contact lens, we might expect all aberrations of the naked eye to still manifest themselves when wearing the soft contact lens correction (Dietz 2003). However, because not all contact lenses are perfectly deformable, it is likely that specific contact lens designs will have a unique effect on the specific aberration structure when placed on the eye.

In a recent study of 200 well-corrected eyes, Thibos et al (Thibos 2002) found that the total amount of higher order monochromatic aberrations were equal to approximately 0.25D. This means that an aberration-correcting contact lens (or any ideal correction) must correct higher order aberrations much more accurately than ±0.25D. Also, in order to realize any benefit in optical quality from the correction of relatively small amounts of higher order aberrations, the larger amounts of lower order aberrations (sphere and cylinder) must be corrected to within a tolerance much smaller than levels currently acceptable in standard spectacle or contact lens corrections.

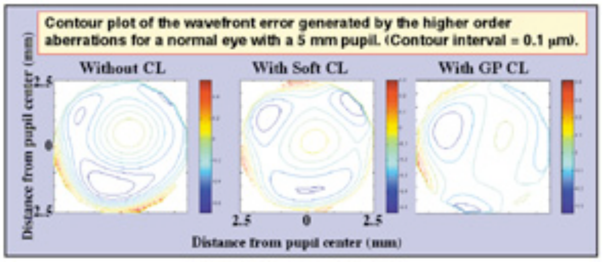
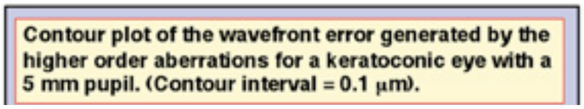


Figure 4. Aberrations of a normal eye without a contact lens, with a soft spherical lens and with a GP lens.

The logic behind these aberration-correcting contact lenses is in many ways quite simple. Assuming that a soft contact lens conforms to the corneal shape without any significant thickness changes (Dietz 2003), aberration-correcting soft contact lenses could be made by merely altering the thickness profile of the contact lens. We currently provide spherical power in contact lenses by varying lens thickness as a function of the radius squared (r^2). Using the standard method of describing aberrations (the Zernike polynomials described earlier), defocus is classified as a second-order aberration in which the wavefront varies as a function of r^2 (see red circle in center column of Figure 2). Thus, to correct this second order aberration we vary the thickness of the lens as a function of r^2. This same principle holds true for the correction of higher order (r to the power greater than 2) aberrations (see the lower two rows of Figure 2). The primary difference between aberration-correcting contact lenses and traditional spherical contact lenses would be the complexity of the contact lens thickness profile.



The "simple" case described above applies to a highly deformable soft contact lens. An added simplification of correcting higher order aberrations with such a soft contact lens is that knowledge of the

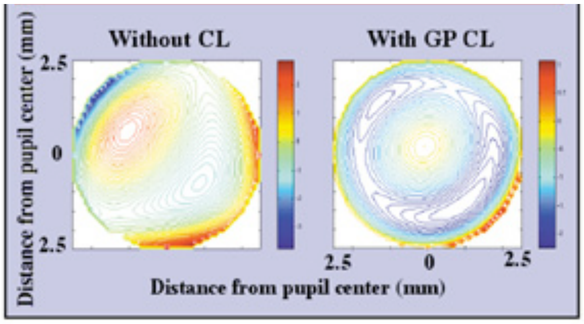


Figure 5. The aberrations in a keratoconic eye with and without a standard GP lens.

corneal shape is not required. However, for aberration-correcting gas permeable lenses, the process is slightly more complicated. With gas permeable contact lenses, the lens does not conform to the corneal shape, resulting in a new anterior optical surface, and creates a tear lens between the posterior gas permeable lens surface and the eye. Just as this tear lens contributes to the spherical power of the contact lens-wearing eye, it will also contribute to the higher order aberrations. Therefore, knowledge of the corneal topography is necessary in order to design an aberration-correcting contact lens.

The Need for Custom Correction

It would be simple for the contact lens manufacturers to produce a perfect aberration-correcting contact lens for everyone if all eyes possessed the same type and amount of higher order aberration. Unfortunately, this is not the case (Thibos 2002). And because each eye will have a different aberration profile, customized contact lenses may be necessary. In a research lab environment, custom correction has been shown to be successful at improving vision, although not equally so in all eyes. The amount of the improvement in image quality achieved by correcting monochromatic aberrations will depend on how large they are in a particular eye. For example, highly aberrated eyes (keratoconic, post-surgical, etc.) might be expected to experience the largest benefits from correcting higher order monochromatic aberrations (Williams 2000).

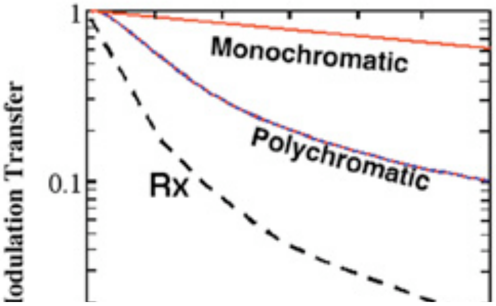
Lopez-Gil took the process one step farther, by using specially designed lathe-cut customized soft contact lens corrections on two normal, two post-penetrating keratoplasty (PKP), and two keratoconic eyes (Lopez-Gil 2002). They found no significant improvement in visual performance over a standard spectacle correction for the normal and PKP eyes, but did find a significant improvement for the two keratoconic eyes. However, no comparison was made in these cases to a standard GP lens correction, which clinically could be expected to significantly reduce aberration and improve visual performance in keratoconic eyes. An example of the reduction in aberration brought about by a standard GP lens in keratoconus can be seen by the aberration contour plot shown in Figure 5.

It appears from early experimental work that custom correction of higher order aberrations may be successful in improving vision in some eyes but not others.

The Polychromatic World

Currently, wavefront sensing technology measures only the monochromatic aberrations of the eye. Therefore, using the current technology an ideal correction could only be achieved for one wavelength of light. Yoon et al (Yoon 2002) have demonstrated that correcting the higher order aberrations leads to an MAR improvement of 0.20 log units (or two lines) in monochromatic light. However, in polychromatic light, this improvement in visual acuity was only 0.08 log units or (four letters). This failure to achieve perfect optical correction in polychromatic light is demonstrated by the MTF of Figure 6 (adapted from Yoon et al 2002). Although diffraction-limited or "perfect" optics cannot be achieved in polychromatic light, the improvement in retinal image contrast produced by correcting monochromatic aberrations can be quite dramatic.

Variability Problems



The preceding discussion has outlined the underlying theory of how higher order aberrations could be corrected using both soft and GP contact lenses. However, the success of correcting higher order aberrations with contact lenses may be further limited by the underlying variability in the eye-contact lens combination. The aberrations of the eye itself may vary over time, and also the lens position and shape may vary over time. Therefore, due to this variability, any single lens with a fixed built-in aberration structure will not fully correct vision at all times.

We already know that to correct astigmatism adequately, a contact lens must be rotationally stable. Indeed, the success of toric contact lenses hinges on their rotational stability. To correct higher order aberrations, a contact lens must also be rotationally and translationally stable. For successful correction of higher radial orders and angular frequencies (Figure 2), the lens stability demands will be even more critical Just as is the case with a toric lens that rotates, an aberration-correcting contact lens that either translates or rotates will not provide the appropriate correction.

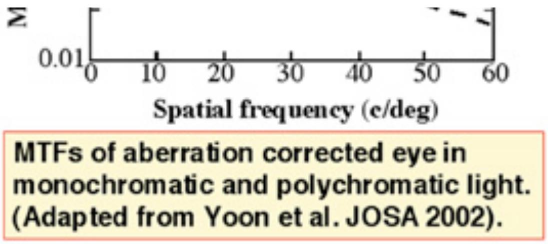


Figure 6. MTFs calculated for an aberration-corrected eye in monochromatic and polychromatic light.

Current soft contact lenses have been reported to have average translations of 0.6 mm and rotations of about 6 degrees with blinking (Tomlinson 1994). GP lenses may have larger translation values closer to 1mm to 2mm. The good news, however, is with theoretical simulations Guirao predicted that typical movements of soft contact lenses would not preclude successful correction of higher order aberrations (Guirao 2001). However, these lens movements will prevent this correction from being absolutely perfect.

Just as we saw with lens translation or movement, if the aberrations of the eye change, then the customized contact lens correction will no longer provide the appropriate correction for that eye. Our group at Indiana University has been studying the variability of higher order aberrations in human eyes. Any study of the variability of aberrations requires an instrument that can accurately and reliably measure higher order aberrations. Using a series of PMMA model eyes with known aberrations, we confirmed that our aberrometer (COAS, from Wavefront Sciences, Inc.) does accurately and repeatably measure an eye's aberrations. Higher order aberrations were found to be accurate within 0.01 microns and repeatable to within 0.002 microns (Cheng 2003).

Knowing that we can accurately measure aberrations, we proceeded to take repeated measurements on human eyes over seconds, hours, weeks, months and years. We quantified the variation that occurs in these measurements by comparing the variance in wavefront RMS (Figure 7, adapted from Cheng 2003).

We quantify this variability by comparing the variance in wavefront RMS over these several time scales (Figure 7, adapted from Cheng 2003). It is clear that as the time scale lengthens, the variability increases. These variations in the eye could be caused by tear film changes, fixational eye movements or accommodative changes during measurement acquisition (He 2000), as well as genuine long-term changes in the eye over time. In general, the longer an aberration-correcting contact lens is used, the less effective it may become at correcting the higher order aberrations. Even though these variations appear quite small in terms of the number of microns they represent, they can significantly impact the effectiveness of the aberration correction. For example, an aberration-correcting contact lens that provides diffraction-limited ("perfect") optics on the day it is fitted may produce only modest improvements in image quality a month or year later.

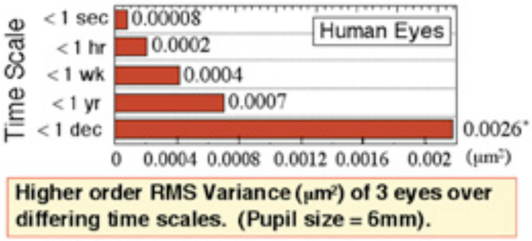


Figure 7. The variation in higher-order RMS that occurs in

Conclusion

With the availability of clinical aberrometers to accurately measure the eye's higher order aberrations and the ability to accurately lathe arbitrary contact lens surfaces, it is now feasible to produce customized aberration correcting contact lenses. However, the success of this approach will be limited due to the polychromatic nature of the real world and the inherent variability in the contact lens and eye. The ultimate effectiveness of this new approach is yet to be determined. Customized correction of higher order aberrations is being considered in a variety of modalities, but as of yet, none have proven successful. You can, however, anticipate normal human eyes.

seeing reports of new developments and any successes with customized contact lens corrections in the near future.

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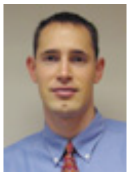

Dr. Kollbaum teaches a contact lens class and instructs in the contact lens clinic at Indiana University. He is currently working on a PhD in the area of aberration correction. He previously worked in private practice in Iowa.