# The Prospects for Perfect Vision

Larry N. Thibos, PhD

Refractive surgery and other high-tech methods for correcting the optical aberrations of the eye aim to make the eye optically perfect. The notion that perfect vision may be within our grasp is a distinctly 21st century concept which is a quantum leap forward from the foundations of ophthalmic practice in the 20th century. Throughout history the assumption has been that the chief cause of poor vision is poor optical quality of the retinal image. From this basic principle, the following line of argument leads one to contemplate the prospects for perfect vision through refractive surgery or other means. Refractive errors are common, at least in the developed countries of the world, and these uncorrected refractive errors cause the retinal image to become blurred. This uncorrected optical blur reduces visual performance on almost every visual task imaginable because it reduces contrast in the retinal image. The successful history of ophthalmic clinical practice in the 20th century is proof that elimination of sphero-cylindrical blur with spectacles, contact lenses, intraocular lenses, and refractive surgery is a miracle cure that literally restores sight to the blind. Therefore, it stands to reason that the 21st century goal of eliminating all traces of optical blur due to higher-order aberrations of the eye, which clinicians sometimes call "irregular astigmatism," suggests the prospect of perfect retinal images producing perfect vision.

If the goal is to achieve retinal images of such high quality that they are no longer limited by the optical imperfections of the eye, then the only remaining optical limitation will be the unavoidable effects of diffraction. This is the meaning of the phrase "diffraction-limited retinal images." When contemplating the prospects for achieving diffraction-limited retinal images even under night-time viewing conditions when pupils are dilated, three questions immediately come to mind.

1) Is this quest for diffraction-limited image quality really possible, or is it just wishful thinking?

2) What would be the potential benefits of perfect retinal images, if they can be obtained?

3) What are the potential penalties? In other words, is there a down side to having perfect retinal images?

The purpose of this brief article is to frame these questions in terms that are understandable to clinicians and visual scientists alike, and at the same time to expose some of the complexity of the issues raised.

## ARE PERFECT RETINAL IMAGES REALLY POSSIBLE?

Other papers in this feature issue address the technical issues relating to perfecting retinal surgery, so here I will make the optimistic assumption that refractive surgery is going to become absolutely perfect. In other words, I will assume that modern technology is going to make it possible for a clinician to diagnose all of the optical imperfections of a patient's eye, and that these aberrations can be corrected exactly, without error, by a laser surgeon.

Despite this optimistic assumption, there are at least two good reasons to be skeptical that perfect retinal images and perfect vision will follow. First, the higher-order optical aberrations of eyes are a moving target that may prove difficult, or impossible, to hit. Second, to reap the benefits of correcting higher-order aberrations we must first eliminate the lower-order refractive errors of defocus and astigmatism, which may be difficult, or perhaps impossible, to achieve.

Aberrations are a moving target because of variability which may occur over time scales ranging from seconds to years. For example, the magnitude of ocular aberrations varies with the state of accommodation of the eye[1] and micro-fluctuations around

*From the School of Optometry, Indiana University, Bloomington, Indiana.*

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*Correspondence: Larry N. Thibos, PhD, School of Optometry, Indiana University, Bloomington, IN 47405.*

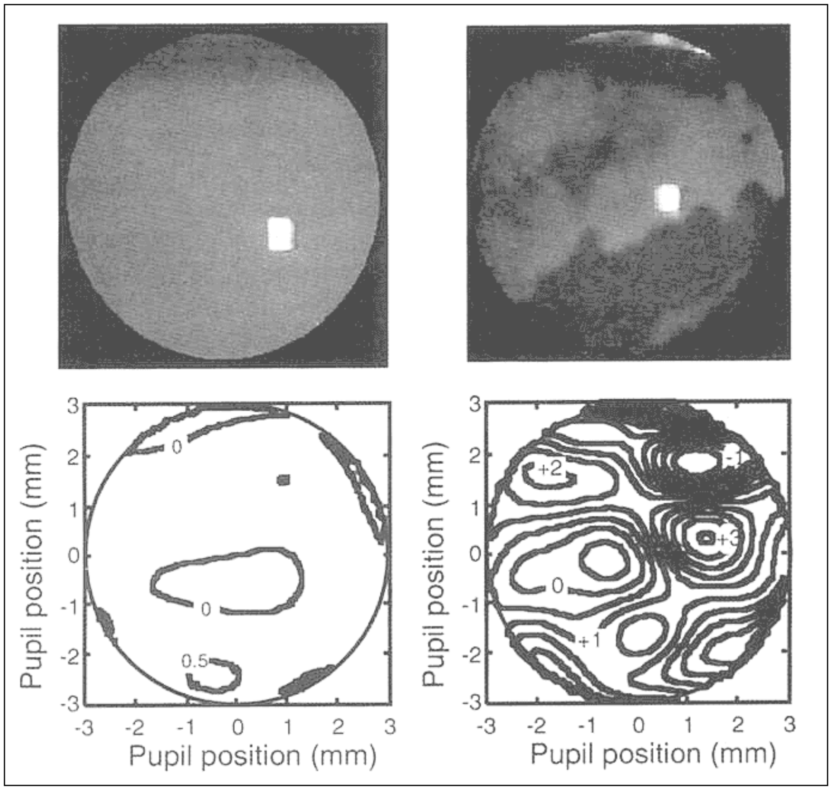


**Figure 1.** Effect of drying of tear film on optical aberrations of the eye. Upper row contains fluorescein images, bottom row shows contour maps of the optical pathlength to the retina through each point in the patient's pupil. Data in left column were obtained immediately after a blink. Data in right column were obtained after 40 seconds of blink suppression. Contour interval = 0.5 µm. Test wavelength = 0.633 µm.

a fixed state of accommodation causes instability in the aberration structure of eyes on a time scale of seconds, or less.[2] Additional instability may arise from evaporation of the corneal tear film, which has been shown to be capable of producing huge optical aberrations.[3,4] As illustrated in Figure 1, blink suppression causes large optical aberrations to appear when the tear layer becomes disrupted.[5] Because tears have a higher refractive index than air, rays of light traversing a relatively thin region of tear film propagate faster and so arrive at the retina slightly sooner than rays passing through the intact tear film. In optical terminology, this time (or phase) difference is an optical aberration which may be quantified by constructing a map of the optical path length through the eye to the retina for every point in the eye's pupil. Iso-metric contours of such maps illustrated in Figure 1 show that blink suppression increased the range of optical path lengths in this eye about 10-fold (from 0.5 µm to 5 µm). The magnitude of this effect varies greatly between subjects and between blinks in the same subject. Nevertheless, this is potentially a large effect which

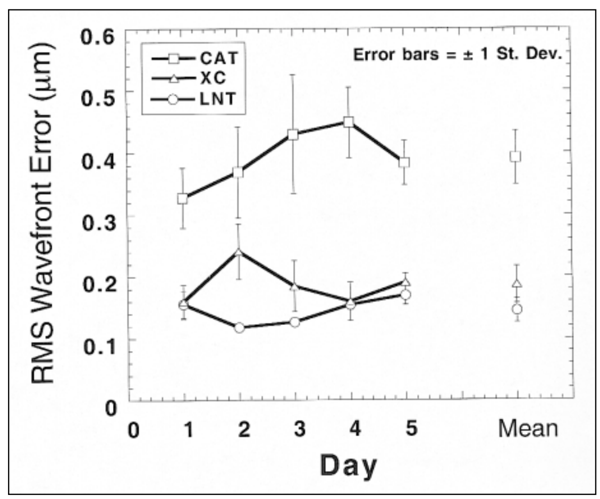


**Figure 2.** Day-to-day and trial-to-trial variability in higher-order aberrations measured with a Shack-Hartmann aberrometer for three subjects. Symbols show root-mean-squared (RMS) wavefront error accounted for by higher order aberrations (Zernike orders 3 through 7) in each patient's left eye. Error bars show ± 1 standard deviation of 5 repeated measurements over a time span of several minutes.

would be expected to have a major impact on the quality of the retinal image and on visual performance for tests of contrast sensitivity and visual acuity.[3]

Little is known about how the aberration structure of eyes varies over the medium time scale of hours to days, but encouraging results shown in Figure 2 from a recent study by Cheng in my laboratory suggests the aberration structure of eyes is relatively stable over the course of a day, and between successive days. The average standard deviation of repeated measurements of monochromatic aberration coefficients for the 15 individual modes classified as 3rd, 4th, and 5th order Zernike aberrations was 20 nm, or about 1/30th of a wavelength of light on any given day, and was only slightly greater between days over a 1 week period for 3 different subjects. This small degree of variability is good news for those who aim to permanently correct the eye's aberrations surgically. However, on the longer time scale of years, aging trends in ocular aberrations suggest that surgical corrections made on an eye today might not be appropriate a few years later.[6,7]

The beneficial effect of correcting the eye's higher-order aberrations is greatest when the eye is well focused. However, perfect focusing by an eye is unlikely for several reasons: accommodative lag, micro-fluctuations in accommodation, variation in object distances in a three-dimensional world, presbyopia, or retinal motion due to vascular pulse or ocular rotations. Perhaps the most serious focusing problem of all is caused by the chromatic aberration of the eye, which prevents the simultaneous focusing of all visible wavelengths at the same time. We can get a sense of the relative importance of chromatic aberrations on retinal image quality by computing the polychromatic modulation transfer function (MTF) for a model eye. The MTF quantifies the optical quality of the eye in terms of its ability to reproduce in the retinal image those variations of intensity present across an object. For a sinusoidal grating object, modulation transfer is defined as the ratio of intensity modulation (ie, contrast) in the retinal image to the intensity modulation of the object and the MTF describes the variation of this ratio with spatial frequency of the grating. The Indiana Eye model is useful for this purpose because it was designed with a degree of chromatic aberration and spherical aberration typically found in human eyes.[8,9] When this model is configured to have neither chromatic aberration nor spherical aberration, it is diffraction-limited. Therefore the modulation transfer function for a large (6 mm) pupil is high throughout the visible range of spatial frequencies, as shown in Figure 3. Introducing chromatic defocus into the model reduces the modulation transfer function significantly, but the modulation transfer function suffers more when spherical aberration is introduced and performance is even worse when both aberrations are combined.

The vertical separation between the curves in Figure 3 tells us that by correcting the eye's chromatic aberration we could expect about twofold improvement in retinal image contrast over a broad range of spatial frequencies. However, the improvement would be 5-fold if we corrected the eye's spherical aberration. Finally, we could get a 30-fold improvement in contrast at 30 cyc/deg by correcting both types of aberration. Unfortunately, expected improvements in spatial resolution are not as dramatic. Cutoff spatial frequency is indicated graphically in Figure 3 by the intersection of the modulation transfer function with the neural threshold function.[10] This intersection occurs at 30 cyc/deg when both aberrations are included in the model, but this value increases at most to 60 cyc/deg, which is only a factor 2, when both aberrations are removed. Evidently the benefits of aberration correction are proportionally greater when measured in the contrast domain than when measured in the spatial domain.

In addition to the contrast attenuation caused by chromatic differences in focus, contrast is also

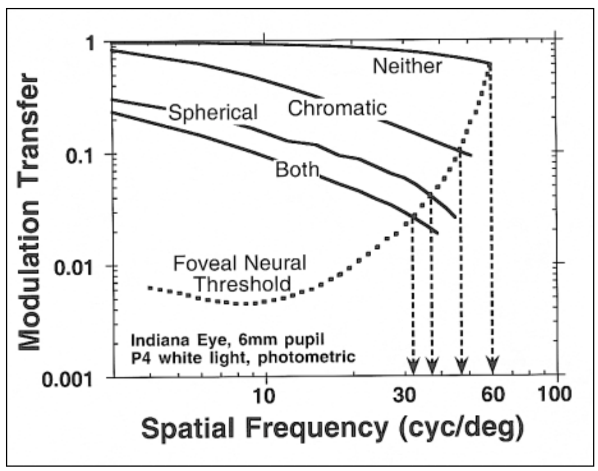


**Figure 3.** Modulation transfer functions for the Indiana Eye optical model of the eye configured with typical amounts of chromatic aberration, spherical aberration, or both. Dashed curve is the foveal neural threshold (treating ordinate as retinal contrast) reported by Campell & Green (1965). Predicted resolution limit (excluding neural undersampling) for high-contrast gratings is indicated graphically by the intersection of the modulation transfer functions with the neural threshold function.

reduced by the transverse effects of chromatic aberration which induce phase shifts into the image which vary with wavelength. As a result, a polychromatic object with strong luminance contrast may end up on the retina with little luminance contrast. This happens because the various wavelength components of a color image shift laterally, filling in the dark gaps of a pattern. The magnitude of this effect depends on the degree of transverse chromatic aberration present for foveal vision, which in turn depends upon the accuracy of centration of the eye's pupil with the visual axis. A population study of young adult eyes has shown that the average person's pupil is displaced about 1/3 mm, but can be as high as 1 mm or more, which is enough to have a significant impact on image contrast.[11]

One of the curious features of chromatic aberration is that if an eye has a significant amount of transverse chromatic aberration, then image quality is actually better if the eye also has some chromatic defocus. The reason is because the defocus blurs the very wavelengths which are being phase-shifted by transverse chromatic aberration. Thus, chromatic defocus defeats the contrast-reducing mechanism of transverse aberration, and the net result is greater contrast in the retinal image when chromatic blur is present than when it is absent. The moral of this story is that for many eyes the quality of polychromatic retinal images may be better when the eye's natural chromatic aberration is left uncorrected, in which case the retinal image will always be defocused for most wavelengths of light, thus limiting the effectiveness of surgically correcting the monochromatic aberrations of eyes.

## WHAT ARE THE POTENTIAL BENEFITS OF PERFECT RETINAL IMAGES FOR VISION?

In general terms, vision should improve for any visual task for which human performance is limited by the amount of contrast in the retinal image, or by the distortions of spatial phase induced by optical aberrations, but not for those tasks for which performance is limited by the spatial grain of the retina. For example, the detection of visual objects by their luminance contrast is a visual task that is inherently contrast-limited. It follows that any improvement in retinal contrast achieved by reducing the eye's aberrations will improve contrast sensitivity for object detection in direct proportion to the improvement in the eye's modulation transfer function. This expectation has been confirmed experimentally for monochromatic light by using adaptive optics technology to reduce the eye's aberrations.[12] More recently, William's group has shown modest improvements in polychromatic letter acuity as well.[13]

In addition to the deleterious effects of optical aberrations on retinal image contrast, important effects occur also on the spatial phase of retinal images. Defocus can introduce phase-reversals into images so that dark regions become light, and light regions become dark, an effect sometimes called "spurious resolution." Similar effects occur for other aberrations besides defocus, and therefore one of the potential benefits of correcting ocular aberrations is the correction of spatial phase errors. This benefit is likely to be substantial. Tampering with the spatial phase of visual objects is known to have a very strong impact on spatial perception.[14] So, although the improvement in contrast achieved by aberration correction is certainly beneficial, eliminating phase shifts and phase reversals caused by optical imperfections may be even more important for spatial vision. For example, letter recognition is greatly hampered when optical defocus introduces phase reversals into some spatial frequency components of the target but not others. Experiments have shown that the phase shifts and phase reversals caused by optical aberrations are sometimes more important than loss of contrast.[15] Therefore, correcting aberrations should yield improvements in visual performance even greater than we might have predicted on the basis of contrast increases alone.

If the optical aberrations of an eye could be

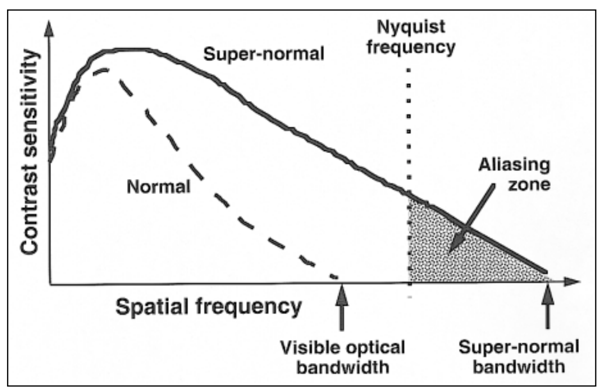


**Figure 4.** Schematic view of optical and retinal sampling limits to visual resolution. Broken and solid curves show contrast sensitivity functions for normal vision and for supernormal vision associated with improved optical quality, respectively. The highest spatial frequency that is above detection threshold for maximum stimulus contrast is a measure of the visible optical bandwidth of the eye, which is typically below the Nyquist frequency of the neural retina. Improved optical image quality will increase contrast sensitivity across a broad range of spatial frequencies, including a band of frequencies beyond the Nyquist limit, thereby increasing the visible optical bandwidth of the eye.

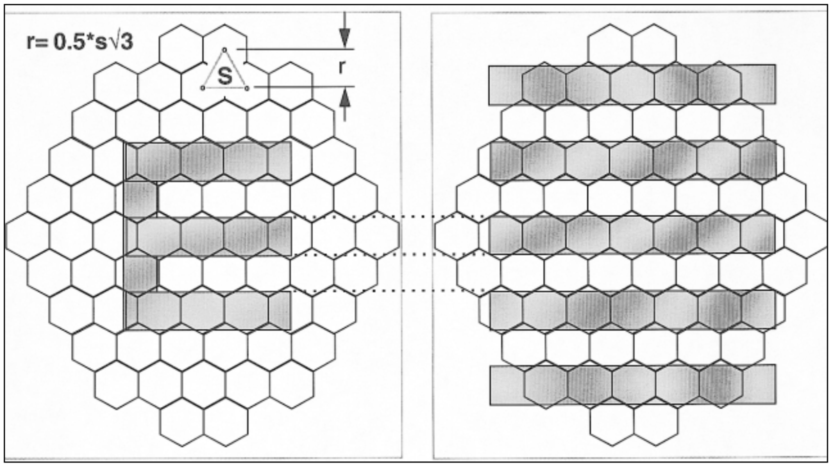


**Figure 5.** Retinal sampling limits to resolution. Left panel shows the letter E scaled such that the stroke width of the letter matches the bar width of a grating at the Nyquist frequency. For a photoreceptor lattice with center-to-center spacing *S* between adjacent cells, the Nyquist frequency is 1/(2r), where r = 0.5$S\sqrt{3}$.

reduced enough to eliminate insufficient contrast as the limiting factor for visual performance, then some other factor, such as the sampling density of retinal neurons, will surface as the limit to visual performance. The highest frequency that a neural sampling array can resolve is called the Nyquist frequency. Stimuli beyond the Nyquist frequency are undersampled and therefore are misrepresented by the neural visual system.[16] Thus, visual resolution is set by the lesser of the two parameters: optical bandwidth of the retinal image and sampling density of retinal neurons. As illustrated schematically in Figure 4, under normal circumstances the optical bandwidth of our aberrated eyes determines the resolution limit of foveal vision because optical bandwidth is typically less than the Nyquist frequency of the photoreceptor array. However, if aberration correction in the future by surgery or ophthalmic lenses succeeds in increasing the optical bandwidth beyond the Nyquist frequency, then neural sampling will replace optical filtering as the mechanism which limits visual resolution. When this happens, vision of objects that exceed the Nyquist frequency will become possible, but unfortunately such vision will be non-veridical and therefore unreliable. This is because neural undersampling misrepresents fine spatial details as coarse details, a phenomenon known as “aliasing.” Aliasing produces a kind of misperception in which objects appear to have a different spatial scale, orientation, form, or direction of motion compared to the physical stimulus.

The goal of achieving superior retinal images on the fovea with optical bandwidth in excess of the neural Nyquist limit is possible in the laboratory using interference fringes formed directly on the retina.[17] However, this condition is commonplace in peripheral vision where the eye's natural optical bandwidth typically exceeds the neural sampling density of the peripheral retina.[18,19] This suggests that studies of spatial aliasing and motion aliasing in the periphery may help predict the potential consequences of perfect foveal images achieved by future clinical treatment. Those prior studies predict there will be an improvement in contrast sensitivity for the task of visual detection, but not for the task of spatial resolution because of the ambiguity introduced by aliasing.[20-24]

Although vision is a complex sensory process that cannot be adequately measured by a single number, clinicians and the general public rely on letter acuity as an overall measure of visual quality. So the question on every one’s mind is: How good can acuity become if all optical aberrations are removed? To a first approximation, the smallest letter that can be resolved by a triangular lattice of photoreceptors will have a stroke width equal to the spacing between adjacent rows of receptors as illustrated in Figure 5. For this letter size, the spacing between letter strokes is the same as the spacing between bars of a grating at the Nyquist frequency. Psychophysical estimates of the Nyquist limit for the foveal cone mosaic are in the range of 50 to 60 cyc/deg[25], which is equivalent to a Snellen acuity of 20/10. Anatomical data suggest rather more individual variability, ranging from 46 to 83 cyc/deg[26], which corresponds to 20/13 to as high as 20/7. In fact, letters smaller than this might still be legible because the visual task of letter discrimination can usually be performed with those spatial frequency components lower than the “characteristic frequency” that I’ve used here to predict letter acuity from the neural Nyquist limit.[27] Nevertheless, it appears unlikely that letter acuity will increase by more than the factor 2 or 3 for the average person, even if retinal images are perfect.

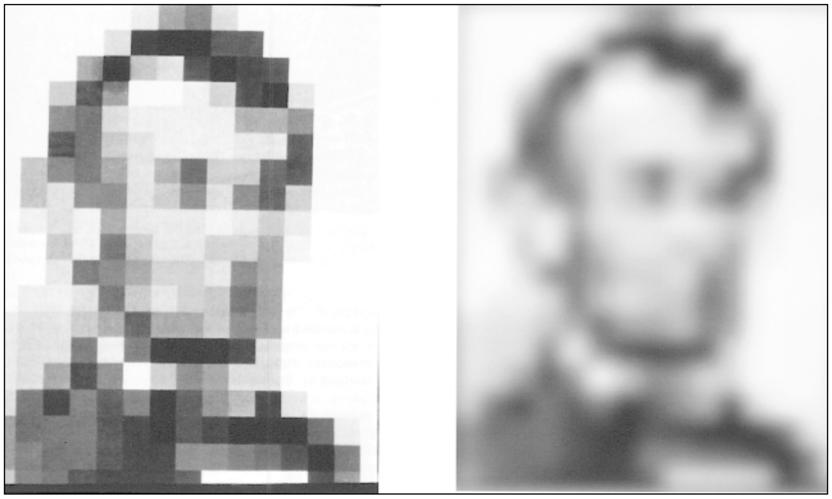

**Figure 6. Left)** The masking effect of high spatial frequencies introduced by half-toning and low-resolution printing may be objectionable for eyes with super normal optical quality. **Right)** In a normal eye the sharp edges are blurred by natural optical aberrations and residual defocus.

## WHAT ARE THE POTENTIAL PENALTIES OF PERFECT RETINAL IMAGES?

Ironically, the use of high-technology to increase optical bandwidth of eyes may clash with those high-tech industries that depend upon the eye's imperfections to make their product look good. For example, television and computer monitors use rasters which produce pixel patterns that are about equal to the resolution limit of the eye for viewing at arm's length. Similarly, the printing industry uses half-tone images which may become objectionable if the individual dots of the image are clearly visible to a person with "supernormal vision." The masking effect of high spatial frequencies introduced by half-toning and low-resolution printing can be severe, as may be seen by the well-known portrait of President Lincoln shown in Figure 6.

Finally, we should consider possible public health and safety issues associated with perfect retinal images. Current safety standards for lasers and other light hazards are based on the assumption that eyes are aberrated, so light from a bright point source is spread out across the retina, which helps dissipate the damaging heat. If we improve image quality significantly, we may be putting the retina at risk for accidental exposure to bright point-sources of light. We should also consider costs and benefits to the national and global communities of refractive surgery aimed at reducing the eye's higher-order aberrations. Is striving for marginal improvement in the vision of normal individuals who already have good vision more important than devoting our energies and resources to treating eye diseases and other visual disabilities, especially in the developing world?

In framing the issues relating to perfect vision I've emphasized the facts we already know, but many unanswered questions remain. How will normal visual mechanisms respond to non-physiological levels of contrast never before encountered by the retina and brain? Will we discover that we are all amblyopic to objects which exceed the optical bandwidth of normal eyes because we have been deprived of these stimuli all of our lives? Will motion aliasing and spatial aliasing become a significant problem when the optical quality of our eyes exceeds the neural sampling limits of the retina? Many such interesting and important issues will need to be addressed by future researchers before we will have an inkling of what vision will be like when retinal images become perfect.

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