33

EVALUATION OF IMAGE QUALITY USING COMPUTATIONAL WAVEFRONT METRICS

Harilaos Ginis, PhD

Refractive error and astigmatism are the main aberrations present in the average healthy eye.[1,2] Refractive error is detrimental to retinal image quality even when its magnitude is small. Usually, the effect of refractive error on vision is analyzed in the context of far vision; however, the effect of defocus due to inaccurate or inadequate accommodation in the retinal images of near objects is similar.

Two main strategies in the surgical treatment of presbyopia are approaches that aim to restore the eye's ability for voluntary change of refractive state and others that extend the depth of focus (DOF), either by small-diameter diaphragms or by introducing multifocality (ie, optical aberrations). In both cases, the outcome can be evaluated both in terms of its primary optical effect and the corresponding functional (visual) performance. Although improved visual performance is the ultimate criterion of success, the difficulty in its systematic and thorough evaluation, as well as the inherent intersubject variability in visual performance and tolerance to blur, suggest that purely objective optical criteria should also be established.

EVALUATING THE RESTORATION OF ACCOMMODATION

Numerous procedures aim to restore accommodation; in other words, to restore or increase the eye's ability to change its refractive state to focus on near stimuli. These procedures are described in detail in Chapters 15 to 29. Naturally, the effectiveness of these procedures must be evaluated in terms of the total systematic dioptric change that can be achieved in the operated eye. Win-Hall and Glasser[3] have described appropriate objective procedures that measure the actual refractive change in pseudophakic eyes when an accommodative effort is made (see Chapters 31 and 32).

EVALUATING IMAGE QUALITY IN MULTIFOCAL SYSTEMS

Given the limited effectiveness of the IOLs that are designed to accommodate, several "static" designs of multifocal lenses or corneal treatments have been proposed to treat presbyopia. These, unlike spectacle progressive lenses, introduce multifocality within the

Pallikaris IG, Plainis S, Charman WN.
Presbyopia: Origins, Effects, and Treatment (pp. 275-280).

pupil of the eye. The rationale in these approaches is that certain types of multifocality (aberrations) may produce an increased DOF without having a catastrophic impact on retinal image quality. Although it is clear that the wavefront aberrations associated with the multiple foci will degrade retinal image quality, it is reasonable to investigate whether some designs are more efficient than others and whether it is possible to achieve a useful DOF capable of yielding acceptable image quality for both far and near vision. Clinical experience[4] shows that many patients are satisfied with multifocal IOLs, especially when they are willing to sacrifice (to some extent) retinal image quality to avoid the use of reading spectacles.

Image quality metrics are quantities that are calculated based on the optical properties of the system. Their value can be used as a quantitative indicator of the quality (or the suitability for a specific task) of the optical system. All the metrics, and their variation with focus, will, of course, change with pupil diameter.

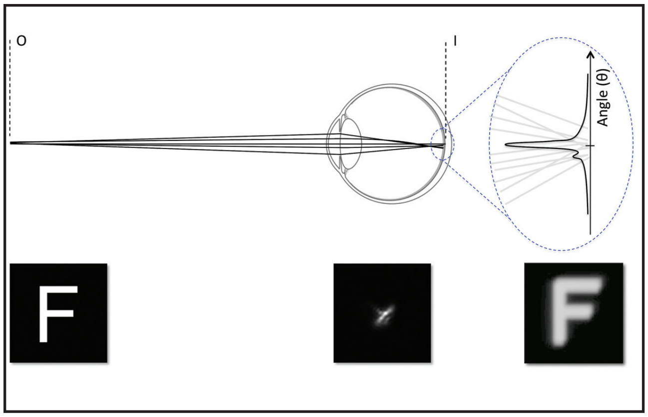

Figure 33-1. (Top) A point source imaged onto the retina. The PSF describes the 2-dimensional light distribution on the retina and is typically expressed as a function of visual angle and meridian. (Bottom) An extended object, such as an optotype, can be envisaged as a superposition of point sources. If the PSF is known (center square), the resulting image (right-hand square) can be calculated as the sum of the individual PSFs corresponding to each point in the object, weighted if necessary by the relative luminance of each point.

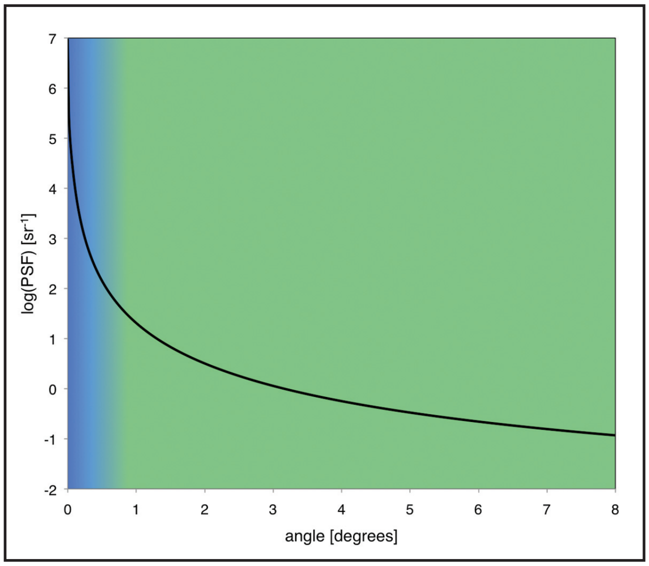

Figure 33-2. Profile of the PSF of the human eye. The central part is determined by the optics (aberrations), and it influences the resolution of the system. The peripheral part is determined by light scattering and is described in a statistical manner by empirical laws. (Based on data compiled and replotted from Vos JJ, van den Berg TJTP. Report on disability glare. *CIE collection*. 1999;135:1-9.)

The Point-Spread Function

The optical imperfections of the optical system of the human eye pose limitations on light focusing and, consequently, blur the image of the observed object even at the optimal focus. The theoretical light distribution corresponding to the image of a point source at the object space on the retina is the point-spread function (PSF; Figure 33-1).

The basic PSF can be calculated from the geometrical and optical properties of the eye. These can be collectively expressed by the wavefront aberration, to which must be added the effects of any light scattering in the eye media. Typically, clinical instruments that measure wavefront aberration express it with respect to a planar wavefront, which is appropriate for far vision. However, for near objects, the correct vergence must be considered. The PSF carries essentially all the information about the imaging quality of the eye. Practically, its spatial extent corresponds to the finest object detail that the optics can reproduce. The PSF itself provides the most direct and intuitive qualitative information about the image quality. Optics (wavefront aberrations, including refractive error) determine the central part of the PSF, whereas light scattering usually dominates the peripheral part (larger angles; Figure 33-2).[5] The PSF is usually normalized so that the volume under it is equal to unity. This expresses mathematically the fact that no light is lost (or generated) in the imaging process; it is simply redistributed according to the shape of the PSF.

A system with a narrow PSF can successfully image finer object details (higher spatial frequencies). Aberrations (and, of course, refractive error) broaden

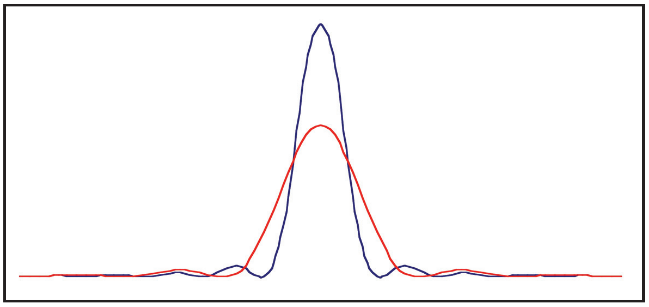

Figure 33-3. The blue line shows the profile of the PSF of a diffraction-limited system. Note that even in this aberration-free case, diffraction results to a spread of the light called the Airy pattern (after George Biddell Airy). The red line shows the profile of the PSF of a nearly-perfect system that has a Strehl ratio of 0.6 (the volumes under the red and blue surfaces are both equal to unity, and the ratio of the magnitude of the peaks is 0.6).

the PSF and limit the system's performance, especially at higher spatial frequencies (such as in objects with fine details and edges). The PSF is not generally rotationally symmetric, due to ocular defects, such as astigmatism and coma, which results in different degradations to image quality for object details at different orientations.

It is evident that, for the presbyope, we would like to have a PSF whose dimensions remained small over as large a range of focus as possible, to maintain a large DOF. One of the challenges is achieving this for the different pupil diameters found under different lighting conditions.

THE STREHL RATIO

The Strehl ratio (named after Karl Strehl, a German physicist) is defined as the ratio of the peak illuminance of the system's PSF to the peak of the PSF of an ideal (ie, diffraction-limited) system with the same pupil diameter (Figure 33-3). It, therefore, gives an indication as to the extent to which the light is concentrated into the center of the PSF and should ideally be as close to unity as possible. In man-made optical systems, it is usually accepted that a value >0.8 should be achieved if the system is to have performance close to aberration free.

On average, the human eye has a Strehl ratio as low as 0.01 for a pupil diameter of 5.7 mm.[6] Although in the case of nearly perfect systems, the Strehl ratio can provide a useful quantitative characterization of image quality, but its validity is compromised when the system is severely aberrated, as in the human eye.

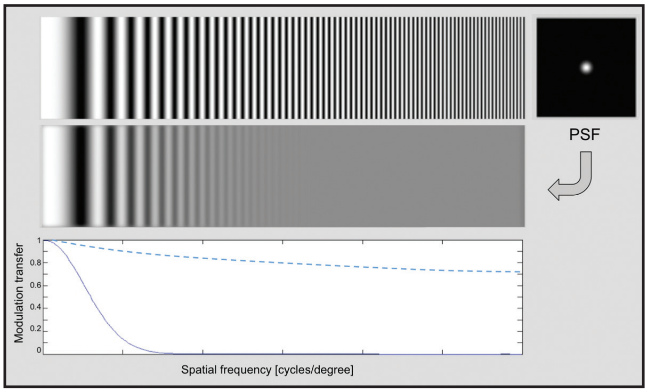

Figure 33-4. An object with variable spatial frequency (top) is imaged using a system characterized by the PSF shown at the upper right-hand part of the figure. The resulting image (middle) has its low spatial frequencies (left) almost unaffected, as the blur due to the PSF is narrower than the grating bars. As the spatial frequency increases (right), the blur associated with the PSF reduces the contrast of the image. At the point where the period of the modulation is comparable to the size of the PSF, the contrast is practically 0. The ratio of the image contrast to object contrast for each spatial frequency is the corresponding modulation transfer, and the whole plot for all spatial frequencies is the MTF (bottom). The dashed line shows the MTF of an ideal system limited only by diffraction.

The Modulation Transfer Function

As mentioned earlier, the more aberrated the wavefront, the wider the PSF and the lower the ability of the optical system to image detail (especially for higher spatial frequencies) with adequate contrast. The effectiveness of the optical system in imaging different spatial frequencies is quantified by the modulation transfer function (MTF). The MTF is the modulus of the optical transfer function (OTF), which is a 2-dimensional complex function equal to the Fourier transform of the PSF. The OTF carries information on both the modulation (contrast) and the phase (transverse spatial position) of the image of a hypothetical sinusoidal object for all spatial frequencies and orientations. Although the phase can be important, it is often ignored for simplicity when evaluating an optical system. An example of the practical meaning of the MTF (corresponding to a simple PSF) is shown for one orientation in Figure 33-4.

The MTF is high for a wide range of spatial frequencies in an optical system with a narrow PSF, whereas if the PSF is wide (such as when defocus or other aberrations are present), the MTF quickly decreases to 0, indicating that the system cannot reproduce the higher spatial frequencies in the image. The MTF always eventually declines to 0 because, even in a system free of wavefront aberration, the PSF is blurred due to diffraction when it forms an Airy diffraction pattern. It should be remembered that the visual system cannot deal with spatial frequencies >60 cpd; therefore, optical performance at higher frequencies is of little interest.

Note that, rather than using the peak of the PSF, the Strehl ratio can also be computed in the frequency domain as the ratio of the integrals (for all spatial frequencies) of the OTF of the system to the integral of the OTF of a diffraction-limited system of the same pupil diameter. Several variants of this metric have been proposed, most notably the visually relevant Strehl ratio where both OTFs are weighted by the normal contrast sensitivity function. This suggests that it is sensible to calculate the metric on the basis of optical performance at the frequencies at which the human visual system is more sensitive.[7-9] Moreover, similar metrics, in which the weighting function favors higher spatial frequencies that presumably quantify the effectiveness of the optics in imaging fine optotypes, have been evaluated.[10,11] More elaborate metrics, which take into account the different contrast sensitivity along different orientations (the oblique effect), have also been proposed.[11,12] Finally, Watson and Ahumada[12] developed a model to link visual acuity and wavefront aberrations. They evaluated the effectiveness of the optical system in imaging letters by filtering optotype images by the OTF of the eye and a standard neural transfer function and adding arbitrary noise. They then determined the maximum of the cross-correlation of the resulting image to the intact image. This number (that was correlated to the probability of letter identification) can be considered as a task-specific metric, quantifying the suitability of the optics for the particular task (ie, imaging the particular optotype).

Wavefront Metrics

An ideal optical system should be characterized by a flat wavefront (in the absence of aberrations), resulting in a narrow PSF and an extended MTF. A variety of metrics can be derived from the wavefront aberration, which expresses the extent to which the actual 2-dimensional wavefront in the pupil departs from its ideal form. As in the case of PSF- and MTF-based metrics, all of the wavefront metrics will vary with the pupil diameter and the wavelength of the light because the eye suffers from longitudinal chromatic aberration.

The most common metric is the root-mean-square (RMS) wavefront aberration that quantifies the difference of the wavefront from a planar surface through the pupil of the eye. In the case of a near object, the difference is calculated in respect to a sphere centered at the object. The RMS wavefront aberration expresses the total wavefront error for the pupil diameter under consideration without taking into account the spatial distribution of this error within the pupil. In the case of systems with relatively high aberrations (such as the human eye), the RMS wavefront aberration is not always a suitable metric to describe image quality. It has been demonstrated[7-9] that, generally, the spherocylindrical correction that minimizes the RMS wavefront aberration does not correspond to the correction that is perceived by patients as optimal, in the sense that it is not strongly correlated to the refraction that maximizes visual acuity.[7] These findings can be explained based on the fact that different aberrations can result in different types of deterioration of image quality, even if they introduce the same RMS wavefront aberration.

More elaborate metrics than the RMS wavefront aberration have been introduced in an attempt to obtain a mathematical description of image quality that is more relevant to imaging and vision. These metrics have been evaluated in terms of their effectiveness in predicting best focus[9] and visual acuity.[7] Some of these metrics are still based on the flatness of the wavefront, such as the fraction of the pupil, where the wavefront aberration is smaller than a predefined threshold. Other metrics are based on the image plane properties of the optical system, such as the Strehl ratio (and variations of it), as well as the spatial characteristics of the PSF.[8]

SIMULATIONS OF IMAGE QUALITY

The metrics of image quality already discussed allow quantitative characterization of image quality. However, methods and metrics where the simulated image is compared and correlated to the object may prove more useful for the understanding of the actual optical performance of extremely aberrated systems, such as an eye with a multifocal element. Simulations of image quality in such systems provide valuable intuitive qualitative information on the retinal image. As examples, the following simulations (Figures 33-5

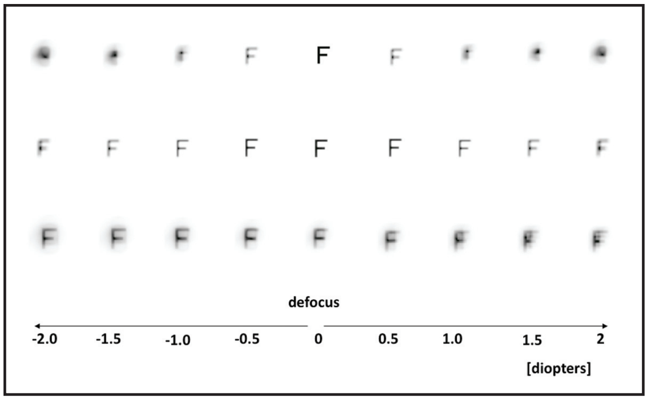

Figure 33-5. Simulated retinal image quality as a function of defocus of a letter corresponding to a 0.5 decimal acuity (6/12 equivalent). (Upper) Aberration-free system, pupil diameter 6 mm. (Middle) Aberration-free system, 2 mm pupil diameter. (Lower) Spherical aberration (0.55 μm introduced as the coefficient of the Z_4^0 Zernike polynomial), 4 mm pupil diameter.

through 33-7) are intended to demonstrate qualitatively the impact of defocus in different cases, including multifocality.

Considering Figure 33-5, we can see that, with an eye free of aberration, the image quality declines symmetrically on either side of best focus as the focus error increases. The image blurs more rapidly with defocus at the larger pupil size. Thus, a greater DOF is conferred with the smaller pupil. With spherical aberration, there is always some noticeable blur, which is different for equal positive and negative values of defocus. However, the letter can be read over a fairly wide range of defocus; that is, "best image quality" is sacrificed for increased DOF.

Now, consider a bifocal system that has a pupil diameter of 5.5 mm where a central addition of +2.00 D has been applied at a diameter of 3 mm (Figure 33-6). The images at the 2 foci are characterized by a superimposed blur resulting from the unfocused part of the incoming light that reduces the contrast of the letter.

The PSF in the bifocal system (shown in Figure 33-6) is characterized by a narrow peak surrounded by defocused light that is converging to the second focus. The existence of a pointed peak in the PSF results in the formation of an image with sharp edges and details, whereas the defocused part of the light results in a superimposed blurred image (Figure 33-7). The resulting image has reduced contrast at practically all spatial frequencies. However, if this image is fused with the sharp image from the fellow eye, the perceived binocular image may be less affected by the multifocality. Moreover, the visual system could, to some extent, compensate this loss of retinal contrast through adaptation mechanisms. The effects of multifocality are more evident in scenes with high dynamic range, such as in night scenes with artificial lighting (Figure 33-8). This is similar to the behavior of a system with light scattering; contrast is always reduced, but the effect is visible mostly at the presence of glare sources (images with high dynamic range).

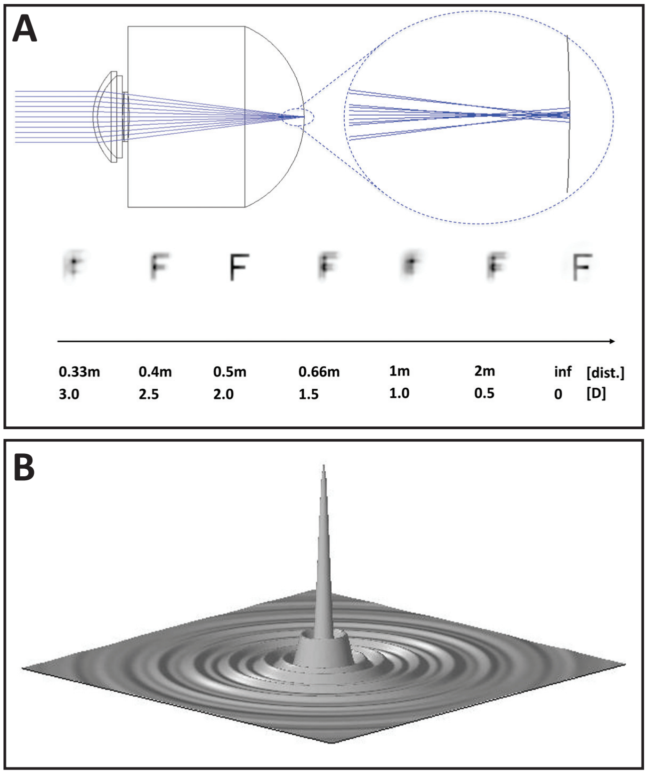

Figure 33-6. (A) Schematic of an eye model with a bifocal intraocular lens and a pupil diameter of 5.5 mm. The top shows a detailed view of the rays near focus, and the lower part shows a simulation of image quality for different object distances or dioptric vergences. (B) PSF (far object distance) for this system. The plotted area of the PSF is 10x10 minutes of arc. The central peak is the light focused by the peripheral part of the system, whereas the "ripples" are associated to the "defocused" part of the incoming light. PSF for the near focus is similar.

SUMMARY

Although clinical testing in patients with multifocal elements may indeed reveal loss of contrast sensitivity and far visual acuity in some cases, theoretical evaluation of the image quality in different multifocal designs, as well as simulations, may facilitate our understanding of the visual disturbances associated to the multifocality and help to optimize the design of such systems.

Figure 33-7. Simulated appearance of a daylight natural scene as imaged through the bifocal system as described in Figure 33-6 (5.5-mm pupil). Only the left-hand side of the image has been blurred by the bifocal PSF; the right-hand side is shown unblurred for comparison. Note that, although sharp image detail can still be seen in the bifocal image, its contrast is significantly reduced.

Figure 33-8. Simulated night scene with the bifocal system described in Figure 33-6. In scenes with higher dynamic range (such as night scenes with exposed sources of illumination), the multifocality becomes more apparent (eg, haloes around isolated lights). The assumed pupil diameter is 5.5 mm.

REFERENCES

1. Castejon-Mochon JF, Lopez-Gil N, Benito A, Artal P. Ocular wave-front aberration statistics in a normal young population. *Vision Res.* 2002;42:1611-1617.
2. Thibos LN, Hong X, Bradley A, Cheng X. Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J Opt Soc Am A.* 2002;19:2329-2348.
3. Win-Hall DM, Glasser A. Objective accommodation measurements in pseudophakic subjects using an autorefractor and an aberrometer. *J Cataract Refract Surg.* 2009;35(2):282-290.
4. Pepose JS. Maximizing satisfaction with presbyopia-correcting intraocular lenses: the missing links. *Am J Ophthalmol.* 2008;146(5):641-648.
5. Vos JJ, van den Berg TJTP. Report on disability glare. *CIE collection*. 1999;135:1-9.
6. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A*. 2001;18(8):1793-1803.

7. Cheng X, Bradley A, Thibos LN. Predicting subjective judgment of best focus with objective image quality metrics. *J Vision*. 2004;4:310-321.

7. Guirao A, Williams DR. A method to predict refractive errors from wave aberration data. *Optom Vis Sci*. 2003;80:36-42.

9. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. *J Vis.* 2004;4:329-351.
10. Plainis S, Ginis HS, Pallikaris, A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis.* 2005;5(5):466-477.
11. Kilintari M, Pallikaris A, Tsiklis N, Ginis HS. Image quality metrics for the prediction of subjective best focus. *Optom Vis Sci.* 2010;87(3):183-189.
12. Watson AB, Ahumada AJ Jr. Predicting visual acuity from wavefront aberrations. *J Vis.* 2008;8(4):17.1-17.19.