Objective Measures of Retinal Image Degradation Due to Refractive Corrections

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PURPOSE: The purposes of this study are to examine the current status of quantitative descriptions of retinal image blur and find optimal characterization of image degradation.

METHODS: A variety of indexes of image degradation are computed for a typical eye and polychromatic light, in and out of focus, and as exemplars of sophisticated wave shaping, when the pupil transmission has been modified to a truncated Bessel amplitude function and to a “fractal” phase function.

RESULTS: Figures are shown for the optical transfer, point- and edge-spread functions, and Koenig bar and optotype letter blur for the various imaging and defocus conditions, and the relative values of several blur indexes are compared graphically and in a correlation table.

CONCLUSIONS: No single index captures the many ways in which the image can deviate from the diffraction-limited ideal. Among the incomplete descriptors of image degradation, the light distribution at a sharp edge stands out as optimally informative and economical, and, when condensed to just two values, one representing central image sharpness and the other outlying light spread, allows for a quick survey of the imaging deficit.

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The aim of a refractive correction, be it in the form of spectacles, contact, or intraocular lenses, is to render the retina optically conjugate to the desired object distance without introducing any optical defects beyond those inherent in the eye itself. In a given eye under limited conditions, some aberrations are in theory capable of amelioration, but the interest here is the change in retinal image quality encountered when some optical parameters are modified within the general framework of ophthalmic corrections.

The task of quantifying such image changes arises on many occasions. It has been studied extensively to help identify the best lens power in an autonomous refractive procedure,1,2; there is a need for it in specifying the eye’s depth of focus, that is, how rapidly the image quality deteriorates with changing object distance,3 and it is relevant when estimating expected performance with the new kinds of optical corrections that modern optical technology is beginning to make available,4 often frankly intended to enhance the range of object distances for which some acuity decrement is accepted at the expense of optimal image quality.

The ultimate interest in all this work is in the effect on vision; that is the reason why the eye’s depth of focus is traditionally gauged by means of subjective blur. Nevertheless, there are good reasons for objective approaches to quantifying deficiencies in the optical image on the retina. Subjective techniques, such as test letter acuity5 or contrast detection thresholds,6 always involve factors that depend on physiological and other stimulus parameters, necessarily detracting from their generality. For example, letters can be an uneven test especially in out-of-focus imagery with multipeaked point-spread functions; contrast detection at low luminance and in the periphery has quite different properties from good foveal pattern discrimination. There is therefore virtue in seeking measures that are somewhat before and thus detached from the actual visual process which the stimuli are intended to entrain. In addition, the rapid development of many new kinds of optical refractive corrections, especially intraocular ones, usually proceeds in a manner that makes their empirical evaluation impractical and forces reliance on computational resources for their evaluation.

For these reasons, this study is devoted to objective indicators of image degradation, reachable via computation from the known optical parameters of the corrections, in particular the deterioration that defocus imposes on the retinal image and that in turn result in visual deficit.

Any retinal image degradation, be it due to aberrations, to deliberate wave-front shaping, or merely to focus error, is necessarily superimposed on diffraction spread, whose lower limits are set by the pupil size and wavelength of light. Describing the degree of deviation from this ideal is, however, not simple: no single measure uniquely captures all the possible ways in which image quality can be compromised. The question formulated and addressed here then becomes the following: given an optically degraded retinal image and using computational rather than empirical resources, what are the most meaningful measures of the resulting spatial visual deficit? This study features an examination of some of the more promising indexes of deficit with emphasis not so much on the detection of the presence of light than on the discriminability of patterns.

According to the standard diffraction formulation here adopted, the light pattern on the retina is determined by the amplitude and

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The phase of the wave front of the electromagnetic disturbance emerging from the exit pupil into the eye's image space. No generality is lost by considering initially a single plane wave (a point object at infinity) because all other image situations can be regarded as the linear superimposition of such plane waves; this in turn amounts to the summation at each point on the retina of the effect of the disturbance from each of the wave fronts. A single wave is, by definition, monochromatic so that the treatment of the more usual polychromatic targets requires the additional consideration associated with light in a range of wavelengths. One ordinarily assumes incoherent illumination in object space, allowing the summation at the retina in the domain of intensity, as has been done here. When extended objects are illuminated by lasers, it is in the domain of amplitude, relative phase having to be taken into account in the process of summation.

For purpose of gauging the impact on the image formed when an eye has an ophthalmic correction added to or in part substituted for its own optics, three different formulations completely define the retinal image distribution and allow for the full expression of any deviations in it from the aberration-free ideal: (a) pupil aperture, (b) optical transfer, and (c) point-spread functions. Their relationship is shown schematically in Fig. 1.

In the analysis at the level of the pupil aperture function, that is, before the computational steps that lead to the retinal light distribution, the various components contributing to degradation of the retinal image, for example, defocus and deliberate wave-front modifications introduced by the ophthalmic correction, can be identified and characterized separately. They can then be added to any defects in the eye's refractive apparatus, native or supplemented or partially substituted for by implants. However, once the next stage is entered, which always involved Fourier transformation, these components are conflated in the computational operations, and it is no longer possible to consider them in isolation. For example, the effect of a focus shift in one set of optical parameters now does not predict what it would be in another.

In this examination of measures of image degradation, the effect on vision is of primary concern, but it is multifaceted and would need to be targeted to the specifics of particular visual tasks. In general, however, of the three approaches listed, one is more direct than the others. Whereas the deviation of the pupil aperture function from uniformity and flatness, and the reduction of the optical transfer function from the diffraction limit afford the capability of fully specifying the imagery, they do not allow for the intuitive grasp of the reduction of visual performance that can be gained from the point-spread function's shape because it takes various forms when the eye is subjected to defocus and nontraditional pupil aperture functions. For example, because each pupil entrance point and each spatial frequency contribute light to all locations of the point image, these two do not singularly inform about, say, the sharpness of the peak of the image or the extent of its outer spread. For this reason, this study concentrates on the analysis of image degradations in the domain of the point-spread function, within which several measures of retinal image degradation will be compared with each other and with one put forward here, the edge spread. This will enable, on hand of some examples, a nuanced approach to an appreciation of computationally derived retinal image deficits and the eye's depth of focus.

**Single-index Measures of Point-spread Deformations**

The encyclopedic enumeration of single-value blur metrics by Thibos et al.\(^1\) lists 11 of their 33 as referring to the light intensity in the image plane. Of these, the somewhat esoteric ones of...
correlation width and image entropy will not be considered here, nor those that include neural factors, which would depend on the stimulus conditions and therefore lack generality. That the point-spread function can, on occasion, exhibit a dip rather than a peak in the center (see hereinafter for examples) makes it evident that measures based on the presence of a single central lobe would fail to provide a realistic guidance to the image quality. That applies to the Strehl ratio and the half width at half height, although both are superior measures for small deviations from the best-focus aberration-free image.

To evaluate their utility, four of the remaining single-value indexes of quality deficit in the list of Thibos et al., plus two additional ones, as well as some image visualizations, are here studied in a few representative cases where it is practical to express the point-spread function in radial \((r,\theta)\) coordinates centered on the intersection of the chief ray with the retina. The formulas for their analysis are based on knowledge of the light intensity \(I(r,\theta)\) on all elements of area \(r \cdot dr \cdot d\theta\) in the image of a point object over the affected retinal space, using for purposes of normalization \(I_{\text{max}}\), the peak light intensity wherever it is located within the point spread, and \(I_r\), the total light volume in the whole of the point image, the integral of the light spread centered on the Gaussian image point up to the maximum radius \(R\).

\[
I_T = \int_0^{2\pi} \int_0^R I(r,\theta) r \cdot dr \cdot d\theta
\]

Also examined is the light distribution in the image of a sharp straight edge, the step response of the imaging system, derived from integrating the line-spread function, which in turn is the one-dimensional integral of the point-spread function.

A list of the measures is given in Table 1. Except for the Strehl ratio and the equivalent energy, all metrics are in units of retinal distance, typically expressed as visual angle in arcmins; the larger the value, the more extended the light spread and the poorer the image quality. To conform with that trend, the edge gradient, which is higher the sharper the image, is represented by its reciprocal.

### Computational Approach

The most convenient approach, computationally, is via the optical transfer function in the meridian under consideration. From the pupil aperture function, the transfer function is obtained by autocorrelation, which is real if the pupil function is circularly symmetrical. More generally, the transfer function will be complex, the value at each spatial frequency in the image being subjected to both amplitude and phase changes.

From the optical transfer function, the computation proceeds by cosine Fourier transformation to the line-spread function in that meridian, and the point-spread function is reached by circular Fourier or Hankel transformation. The edge-spread function is the integral of the line-spread function. When normalized, it necessarily goes monotonically from 0 to 1 in some sort of ogive form. For characterization by a single value, the slope at the 50% point is used.

To visualize the image degradation in specific instances, some target patterns were convolved with the point-spread function to obtain the retinal light spread. Köenig bars are a pair of parallel strips, three times as long as wide and separated by their width. The cross-sectional light distribution through the center of black Köenig bars on a bright background was calculated for two bar widths and illustrates the shape and depth of contrast available to the retinal processing apparatus with its cellular compartmentalization, the Stiles-Crawford effect, photochemical transduction, and ultimate neural stages. It has become customary to portray image blur by displaying gray-scale images of optotype letters that have been convolved with the point-spread function. This is equivalent to viewing the spatial pattern of excitation of the receptor population, although the impression that is conveyed does not necessarily match the observer’s blur experience of such an image degradation to which neural factors in the retina and cortex contribute.

### Specific Applications

The concepts laid out here are intended to assess retinal imaging in specific situations of known optical degradation, with the

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**TABLE 1. Metrics of retinal image degradation based on PSF**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
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<tbody>
<tr>
<td>Strehl</td>
<td>Height of the central lobe of the PSF relative to that of the diffraction-limited case with the same pupil and wavelength parameters</td>
</tr>
<tr>
<td>HWHH</td>
<td>Half width of the central lobe of the PSF, measured at half its height</td>
</tr>
<tr>
<td>D50</td>
<td>Radius within which half of the total light in the PSF is contained, that is, the value of (d) in the equation:</td>
</tr>
<tr>
<td>(I_T = 2\pi \int_0^a \int_0^\infty I(r,\theta) r \cdot dr \cdot d\theta)</td>
<td></td>
</tr>
<tr>
<td>ME</td>
<td>If all the light in the PSF were concentrated in a single ring, what would be its radius for the effect to be equivalent to each element (I(r,\theta) r \cdot dr \cdot d\theta) of the PSF being weighted by (r), its distance from the Gaussian image point (first moment), which is the value of (a) in the equation:</td>
</tr>
<tr>
<td>(I_T = 2\pi \int_0^a \int_0^\infty I(r,\theta) r^2 \cdot dr \cdot d\theta)</td>
<td></td>
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<tr>
<td>RadGy:</td>
<td>The light measure equivalent of the radius of gyration in dynamics, that is the distance (a) from the Gaussian image at which, were all of the light located here, it would have the same second moment as the actual distribution, that is, the value of (a) in the equation:</td>
</tr>
<tr>
<td>(I_T = 2\pi \int_0^a \int_0^\infty I(r,\theta) r^3 \cdot dr \cdot d\theta)</td>
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<tr>
<td>EE</td>
<td>The fraction of the total flux in the PSF that is contained in the area occupied by the Airy disk in the equivalent diffraction-limited imagery</td>
</tr>
<tr>
<td>Edg-Grad</td>
<td>The steepness of a light cliff, identified as the reciprocal of the slope at the inflection point in the image of a sharp black/white border (expressed as (1/(\text{proportional rise in the edge-spread function in 0.1 arcmin})). The optical response function to a retinal illuminance step (“brightness cliff”) is well represented in natural scenes (the horizon, still water surfaces, smooth edges in plant life).</td>
</tr>
<tr>
<td>Edg-Out</td>
<td>This represents the percentage of the light at a sharp edge that falls beyond 1 arcmin from the geometrical image. The larger the more extended the light spread.</td>
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</table>

All measures except the Strehl ratio and the EE are based on units of retinal image distance; the larger the value, the poorer the image quality. Edg-Grad = edge-gradient; EE = equivalent energy; HWHH = half width at half height; ME = mean equivalent; PSF = point-spread function.
examples serving as illustration of the range of answers that the various indexes might be expected to provide.

The standard exercise of conducting the computations on monochromatic diffraction-limited systems is not practical because even normal eyes deviate somewhat from the aberration-free ideal and do so in widely different ways; moreover, stimuli are rarely monochromatic. Hence, a mode of imagery that represents a more typical visual situation has been devised. Small, circularly symmetrical phase perturbation generated by a random process in the pupil plane has been introduced, and the retinal image is composed of the superposition of light at five wavelengths in 25-nm steps in the range of 500 to 600 nm weighted by the photopic luminosity curve with axial chromatic aberration taken into account. As a first approximation, circular symmetry in the pupil has been retained, which renders the calculations invariant with azimuth (meridional orientation). The resultant optical transfer function, the middle curve of the left panel in Fig. 2, fits in with the consensus for typical normal eyes.

The performance of this “typical normal eye” with a 4-mm diameter round pupil in focus and 1.25-D defocused is shown in Fig. 2, using two measures, the optical transfer function in the left panel and the cross-sectional light distribution through the center of the Gaussian image in the right. For comparison, the transfer function of a diffraction-limited aberration-free model of such an eye is also shown.

To gauge the behavior of the various indices of image degradation and allow for the evaluation of their relative merits, the light distribution in the retinal image was computed in focus and with some sample defocus situations for a plane wave (point target at infinity) light incidence in the “typical normal” case, as defined previously, and with two kinds of modified pupil apertures, selected as exemplars of the many possible ways in which contact and intraocular lenses can be expected to incorporate technical developments in modern optics, Bessel and “fractal” beams.

The essence of these modifications of the pupil transmission is illustrated in Fig. 3. Fig. 3A depicts the case when the pupil aperture transmission is that of Bessel function of the first kind and zero order, truncated between the first and second zeroes. As was developed in greater detail earlier, many properties of the retinal light distribution, particularly at various defocus levels, can be shaped by appropriate truncation. That this is associated with loss of total light admitted into the eye is an inevitable consequence. Fig. 3B represents an example of a purely phase modification with no change in the amplitude across the incident wave front. Of the various kinoform patterns, the one selected is based on the concept of a quasifractal zone plate, known to enhance depth of focus. The specific form here is the one implemented in the intraocular lens design of Remón et al. with the phase scaled up to a maximum of 0.4 mm and has the property that the Cantor set fractal progression is by pupil area rather than radius.

Fig. 4 depicts, for the three cases of unobstructed, Bessel beam and fractal phase pupil aperture functions, respectively, a detailed characterization of the image light distribution shown as the intensity level along one meridian within 6 arcmin either side of the axis in planes normal to the axis and 0.25 D apart from −2.5 to 2.5 D defocus. This manner of presentation, although densely packed, gives an immediate overview of the salient property of each mode of imagery. It should be remembered that specifics of these image space light distributions depend quite substantially on the particular pupil diameter and the parameters of the modifications. Nevertheless, because they are exemplars of nontraditional ophthalmic corrections, they serve well to test how blur indexes can act as probes of the kind of image degradation that their users would confront.
The situation in Fig. 4B, whose promise was foreshadowed in an earlier study, has a very rich potential; the example has been chosen to highlight the remarkable property of featuring two separate good focus zones. This is an unusual “bifocal” property—unusual because, unlike conventional spectacle bifocal lenses, the two zones occur along the same line of sight. The fractal pupil (Fig. 4C) has a similar property; the image light spread is more disseminated.

The main results of this study are shown in Fig. 5. In six side-by-side panels are characterizations of the light distribution on the retina of a typical normal eye with 4-mm diameter pupil, for three steps of defocus, 1.25 D apart. The leftmost is the optical transfer function, normalized to the zero spatial frequency position. Second from left is the cross-sectional profile through its center of the point-spread function, which in all cases contains the same volume of light, but with the graph’s vertical scale adjusted for better appreciation of its shape. Of wider practical utility is the light distribution in a sharp black/white straight edge; its virtue is that any multiple bumps in point-spread function have now been smoothed out and that the integration process by which it is arrived at assured that it is robust to contrast, always by definition reaching the light level of a uniformly lit field, to which it is normalized. Contrast

**FIGURE 3.** Aperture functions over the 4-mm-diameter round pupil used in the examples. (A) Truncated Bessel amplitude function. (B) Circularly symmetrical fractal distribution, according to simplest Cantor triadic program, the deviation of the wave front from planarity in 0.1 mm. Phase of electromagnetic disturbance is the distance $\text{mod} \frac{2\pi}{\lambda}$.

**FIGURE 4.** (A) Cross-sectional light intensity distribution through the center of point-spread functions in the typical normal eye with 4-mm-diameter pupil as a function of defocus is in the range of $-2.5$ to $2.5$ D. (B) The same as panel A but for the truncated Bessel pupil aperture function of Fig. 3A. (C) The same as panel A but with the fractal phase pupil aperture function of Fig. 3B. All graphs are drawn to the same scale, revealing in the middle graph the reduction in image intensity that is the consequence of the apodizing effect of the Bessel beam modification of the pupil aperture. Also shown vividly is the bifocal property of the truncated Bessel beam, with the two relatively sharp imagers separated by 2 D.
reduction due to image degradation, the variable underlying, for example, the Strehl ratio, can, however, be gauged in the next panel, which depicts the light dip in a large uniform field along the central axis (orthogonal of the length of its lines) of Koenig bar patterns with 1 and 3 arcmin parameter. This plot illustrates both contrast (depth of dip) and resolving capacity, that is, the extent to which the doubleness of the pattern remains represented in the image distribution. In a 3D plot of these data, for a 2′, that is, 20/40 or 0.3 logMAR, Koenig bar pattern can be seen in the panel second from right. On the far right, there is a figure in gray levels of Snellen optotype letters of five sizes (20/16, 20/20, 20/30, 20/40, 20/80) of Snellen letters. (Bottom) Magnitude at 0, 1.25, and 2.5 D defocus of six single-value metrics of image degradation (Table 1) in a form that allows meaningful comparison: ME (the weighted average distance of the light in point-spread function from the Gaussian image point), RadGyr (second moment of light distribution from Gaussian image point), EW (the diameter of light cylinder containing the volume under the point-spread function with height maximum of dotted line), D50 (diameter of disk within which half of the light is contained), EE (proportion of volume of point-spread function contained in the Airy disk for this stimulus condition, expressed as 1/30th of its reciprocal), and EG (expressed as reciprocal of derivative of edge-spread function at its inflection point). EE = equivalent energy; EG = edge gradient; EW = equivalent width; ME = mean equivalent; OTF = optical transfer function.

**Bessel Function Pupil Aperture Transmission**

Fig. 6 shows similar data for the case in which the wave front across the pupil had imposed on it a circularly symmetrical Bessel function illustrated in Fig. 3A. As can be seen by comparison with Fig. 5, this results in an inferior in-focus image quality in comparison with normal viewing, yet the falloff with defocus is much less.

**Fractal Pupil Apertures**

Similar data for the fractal pupil (Fig. 3B) can be seen in Fig. 7. The graphs at the bottom of Figs. 5 to 7 permit tracking of the six single-value indexes of image degradation. Some indication of their relative behavior under the imaging conditions is available.
in Table 2, their correlation matrix. There are some high correlations, but in general, no convergence toward a consensus is discernible, as might be expected in view of the high diversity among the point-spread configurations and the different weighting of their components in the computation of the individual indices.

Whereas citing single-value indices would seem to be insufficient as indicators of image degradation in a practical situation, display of the whole point-spread function would be unwieldy, although preferable to the optical transfer function because it is more immediately related to retinal light spread. As a compromise, the display of the edge-spread function presents itself. The double integration by which the edge spread is reached from the point-spread function smooths out any uneven peaks. Regarded as components of natural scenes, it actually represents a more universal visual situation. Except for stars and isolated distant lights in darkness, light points occur rarely in natural scenes, whereas edges are common: even 20/20 Snellen letters are made up mostly of edges several minutes long, by which length the characteristics here displayed have been fully developed.

Fig. 8 shows how edge-spread functions can serve to characterize the image degradation, which a viewer would encounter for defocused targets with the kind of nontraditional ophthalmic corrections, which have just been dealt with. On the left is a sequence of edge-spread functions for targets with, in order, 0, 1.25, and 2.5 D defocus, seen through the Bessel lens (Figs. 3A, 4B, 6) drawn as dashed curves. For comparison purposes, each curve is accompanied by the equivalent one, drawn solid, for an ideal 4-mm pupil eye vision. On the right (Fig. 8) is a similar depiction of the situation with the fractal lens (Figs. 3B, 4C, 7), and it illustrates how this kind of lens maintains a steepness at the inflection point ( emblematic of sharpness of central peak of point-spread function) in defocused viewing, at the expense of wider light spread: the more gradual the slope toward the baseline and the steady field light level, the more extended the light spread and the consequent veiling glare.

DISCUSSION

The problem tackled in this article is the search for the most informative yet economical mode of representing how optical images on the retina have become degraded when viewing the world through ophthalmic aids under certain conditions, particularly changes in viewing distance. Although the best test is always actual visual performance, this is not always an option in experimental conditions especially for intraocular lenses. The attempt is therefore made here, using knowledge of the optical parameters of the devices, to find ways of computing the deficits encountered by a
typical normal eye for photopic foveal vision with an average pupil diameter. The aim is an overall guide and blueprint in exploring optimal configurations, as modern technology makes them available in clinical practice.

For computational convenience, circular symmetry in the pupil has been assumed. In many instances where this does not apply, for example, simple astigmatism, computation needs to be extended to just a pair of orthogonal axes, merely doubling the task. Other developments such as the “optical sword”\textsuperscript{12} can be handled within the $r, \theta$ formulation by integrating the pupil electromagnetic disturbance function in rings of radius $r$ and width $dr$ and amplitude and phase varying with meridional angle $\theta$. More generally, however, $x, y$ two-dimensional pupil integration would have to be followed (see Fig. 4.1 in Goodman\textsuperscript{13}), with the consequence that the optical transfer function becomes two-dimensional and complex (in the mathematical sense). It needs emphasizing that the computations here presented have not been extended to encompass changes in pupil diameters. In most instances, these would entail changes that are not qualitative, but rather result in some differences in the numerical values shown here, which in any case are meant to be largely illustrative of effects that are likely to be encountered. Such diffraction calculations would initially be carried out for a single wavelength of light. Whenever, as is usually the case, a wider range of wavelengths is involved, calculations would need to be replicated across the spectrum with chromatic aberration and receptor luminosity functions folded in, and final summation to reach an appropriately weighted point-spread function.

**TABLE 2.** Correlation matrix for the single-value degradation indexes (Table 1) computed for 15 focused and defocused imaging conditions with typical normal, Bessel, and fractal pupils

<table>
<thead>
<tr>
<th></th>
<th>ME</th>
<th>RadGyr</th>
<th>EW</th>
<th>D50</th>
<th>EE</th>
<th>Edg-Grad</th>
<th>Edg-Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>0.97</td>
<td>0.66</td>
<td>0.35</td>
<td>0.23</td>
<td>0.74</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>RadGyr</td>
<td>0.97</td>
<td>0.23</td>
<td>0.11</td>
<td>0.61</td>
<td>0.61</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>EW</td>
<td>0.66</td>
<td>0.49</td>
<td>0.62</td>
<td>0.85</td>
<td>0.85</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>D50</td>
<td>0.35</td>
<td>0.23</td>
<td>0.74</td>
<td>0.54</td>
<td>0.54</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>EE</td>
<td>0.23</td>
<td>0.11</td>
<td>0.62</td>
<td>0.54</td>
<td>0.77</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Edg-Grad</td>
<td>0.74</td>
<td>0.61</td>
<td>0.85</td>
<td>0.54</td>
<td>0.77</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Edg-Out</td>
<td>0.92</td>
<td>0.86</td>
<td>0.67</td>
<td>0.51</td>
<td>0.33</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.64</td>
<td>0.55</td>
<td>0.63</td>
<td>0.45</td>
<td>0.64</td>
<td>0.72</td>
<td></td>
</tr>
</tbody>
</table>

The six individual degradation indexes—ME, RadGyr, D50, EE, Edg-Grad, and Edg-Out—are defined in Table 1. Edg-Grad = edge-gradient; EE = equivalent energy; EW = equivalent width; HWHH = half width at half height; ME = mean equivalent.
Searching for the most informative single-value index of degradation is elusive because the various indexes weight different aspects of the point-spread function differently. There is generally a common trend among them, as can be seen in the panels of Figs. 5 to 7 and in their correlation matrix in 15 different imaging conditions for three pupil functions each in five focus settings (Table 2).

If single-value indexes are insufficient to reasonably inform about the nature of image degradation in a given situation, what might be the best compromise between economy and completeness in its description? As we have seen, the edge-spread function is both sufficiently detailed and intuitive. A first glance at it would concentrate on two regions, the steepness of the slope at the ogive's inflection point, representative of the edge sharpness and resolution capacity for small target changes, and the gradualness of its approach to its two limits of zero and full-field luminance, indicative of veiling of outlying zones. When the purpose is to survey the image degradation generated by some new type of correction, there may be some utility in restricting image degradation information to the easily assimilable form of a pair of parameters, one for steepness of gradient at the center and the other for outlying spread. Those chosen here, suitably scaled for ease of display, are (1) the reciprocal of the slope at the inflection point, expressed by the proportional contrast change in 0.1 arcmin from the inflection point, and (2) 1/10 the contrast at a distance of one arcmin from the geometrical image of the edge, which is a measure of the area under the line-spread function outside its 2 arcmin central zone.

In Fig. 9, these two measures are depicted side-by-side with the edge-spread functions from which they have been derived. They recommend themselves as a tradeoff between the full characterization of imagery in all its detail by the point-spread function and the admitted incompleteness of single-value indices. For example, they graphically show how, with substantial defocus, the fractal lens retains small-detail resolution while at the same time permitting extended light spread. The figure also reveals at a glance how, compared with normal viewing (bottom left), the Bessel beams hold moderate image quality over a wide focus range (bottom, middle).

Image degradation can, of course, be caused by many other optical defects or deliberate wave-front modifications, and it remains to be demonstrated how sufficient the approach sketched in this study is and how, where necessary, it can be usefully extended while at the same time retaining its conciseness.

The discipline of visual optics presents even more challenges in the description at the interface between patients and the geometrically and optically definably aspects of their visual world as it presents itself through their ophthalmic aids. Here analyzed was the obvious and most salient clinically diagnostic situation, the instant glance with the fovea at a finely textured target. Additional issues would be involved for peripheral or low-contrast viewing or where chromaticity plays a significant role. Even more elaborate analysis is needed for the moving eye behind a fixed ophthalmic correction like progressive multifocal lenses, not only when the instantaneous point-spread function is not circular symmetric but also where there are position-dependent spatial distortions caused by magnification changes.

CONCLUSIONS

As modern optical theory and technological practice open up the possibilities of modifying the optical properties of the light beam entering the eye in ingenious and sophisticated ways, there is the need of identifying their expected visual performance, both in the designated focal plane and for defocused targets. In vivo visual testing cannot always be attained, especially in the optical design stages of intraocular lenses. Here undertaken is a critical evaluation of the various suggested measures of the degradation.
FIGURE 9. (Left) Edge-spread functions for 0, 1.25, and 2.5 D defocus in sequence from left to right: (A) typical normal eye with 4-mm-diameter pupil, (B) the same as panel A but with the Bessel pupil aperture, (C) the same as panel A but with “fractal” pupil aperture. (Right) Measures for each of the ogives on the left: two bars of height proportional to degradation indexes derived from that edge-spread function. Dark bar, reciprocal of the ogive gradient at its inflection point (the lower the value, the sharper the edge and the better the resolution); light bar, the fraction of light beyond one arcmin from the edge.
with respect to an ideal aberration-free optical image on the retina that can occur while viewing in- and out-of-focus targets with these ophthalmic corrections. It is concluded that the edge-spread function, that is, the light in the image of a straight edge, provides at a single glance the most informative objective descriptor of the retinal image quality in a given viewing situation.

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