Vision through an abnormal cornea: a pilot study of the relationship between visual loss from corneal distortion, corneal edema, keratoconus, and some allied corneal pathology

R. F. Hess* and L. G. Carney

Visual function was assessed by classic acuity measures as well as contrast thresholds over a wide spatial frequency range for subjects with experimentally induced corneal distortion and induced corneal edema. These results were compared with similar results for patients with unocular keratoconus, bilateral keratoconus, and allied corneal pathology. Distortion and edema were found to produce characteristically different types of contrast attenuation at threshold (amplitude) and have quite different suprathreshold abnormalities (phase) for objects within the resolution limit and therefore could form the basis of a useful functional classification of the visual degradation from corneal pathology.

Key words: contrast sensitivity, spatial frequency, distortion, edema, keratoconus, cornea

Assessment of vision within the clinical environment has traditionally been limited almost exclusively to measurement of the limit of resolution (visual acuity). A number of recent studies1-4 have proposed that a more complete picture of visual function should include assessment of the quality of vision for object sizes within the resolution limit. The contrast threshold function5 which quantifies the relationship between threshold visibility and object size in terms of contrast threshold satisfies all the requirements of a thorough visual assessment; both the acuity and contrast dimensions of visual function are investigated.

Although corneal abnormalities are very diverse in their physical appearance and pathophysiological basis, they may be able to be considered in terms of one or more basic causes of visual degradation. For example, one such classification might include the distinction between the visual effects resulting from corneal distortion and corneal scattering. Some conditions will clearly involve an interaction between both of these extreme components of degradation (i.e., corneal scarring). Similar types of dichotomous classifications have been shown to be useful for optical2,3 as well as neural4 visual abnormalities and have yet to be applied to corneal abnormalities. If this approach can be shown to be valid for specifying visual loss from corneal abnormalities, it may help clinicians to...
more accurately assess visual improvement from treatment (more sensitive than acuity changes) as well as develop a better appreciation of the nature of specific types of residual vision and their perceptual consequences.

In the present study, contrast thresholds were compared over a wide frequency range (9 octaves) for experimentally induced corneal distortion (with minimal edema) and induced corneal edema (with minimal distortion), keratoconus, and allied corneal abnormalities. The results suggest that distortion and edema (scattering) produce quite different types of contrast attenuation within the resolution limit and that it may therefore be useful to specify visual loss from corneal abnormalities in terms of these two characteristically different types of responses.

**Apparatus, methods, and subjects**

Vertical sine wave gratings were generated on the screen of a specially constructed 30 by 40 cm, high-resolution video monitor (P4 phosphor). The mean luminance was set to 50 cd/m²; contrast modulation which occurred about this mean luminance was adjusted by the subject with an 80-position switched logarithmic attenuation. A white 100 by 150 cm surround screen was illuminated to the same luminance. Care was taken to ensure the surround luminance was even and matched the mean luminance of the monitor screen. The contrast linearity and frequency response of the monitor screen were measured with a PIN photodiode, and testing was confined to within the linear and flat regions of these respective curves. The viewing distance was changed from 114 cm for low to medium spatial frequencies (0.12 to 4 c/deg) to 570 cm for high frequencies (>4 c/deg).

Corneal edema was experimentally produced by the wearing of a sealed, tight-fitting haptic lens (corneal clearance) filled with distilled water for 6 hr. Corneal distortion was experimentally produced by the wearing of a tight-fitting corneal contact lens over which 100% oxygen was passed (monocular goggle) for 2 hr (L. G. Carney, unpublished data). Corneal thickness was measured with a modified Haag-Streit pachometer attached to a Nikon photo-slit lamp. Corneal topography was measured before and after these conditions for a normal observer (R. F. H.) with an autocompensating photo-keratoscope which, following computer analysis of the data obtained from the photokeratograms, gave a three-dimensional plot along four meridians of the deviation of the corneal shape from the best-fitting reference sphere. Photokeratoscopy as well as slit-lamp photography was performed on all patients with corneal abnormalities.

Letter acuity was measured with single Landolt C targets (approximately 100% contrast) for which frequency-of-seeing was probit analyzed to obtain a 50% threshold. Each letter was presented eight times. The background luminance was set to 50 cd/m² to match that used for the contrast threshold measurements.

The method of adjustment was used for all settings (N = 3), and the eyes were alternately compared at each spatial frequency. In the case of the experimentally produced edema and distortion, the affected eye was compared to the fellow eye which acted as a normal control. In the case of the unilocular corneal pathology, the “abnormal” eye was compared to the normal fellow eye as a control. In the cases in which both eyes were affected, the results were compared to the thresholds for a normal, age-matched, untrained observer. A normal eye was defined as having normal acuity, no photokeratoscopic, biomicroscopic, or staining corneal abnormality of any other optical or ocular abnormality, and no history of general medical or ocular abnormality. All subjects were carefully optically corrected. Distortion in this context refers to visual loss due to irregular optical aberrations, i.e., not amenable to spherical or cylindrical optical correction.

**Results**

**Experimentally induced corneal disturbance.** The results of visual loss from induced unilocular corneal distortion (Fig. 1, A) and edema (Fig. 1, B) are illustrated in terms of the contrast threshold function. In each case the fellow normal, control eye (unfilled symbols) was alternately compared with the “abnormal” eye (filled symbols) at each spatial frequency. The ratio of these thresholds are compared for distortion and edema in the lower frame (Fig. 1, C). Inset in Fig. 1, A and B, are the relevant pachometric and photokeratoscopic results before and after contrast testing. These results show that for the induced corneal distortion (no appreciable thickness change but irregular topography change, see Figure insets) contrast thresholds were affected only for a limited band
Fig. 1. Contrast thresholds are compared over a wide range of spatial frequencies for the normal (unfilled symbols) and abnormal eye (filled symbols) of R. H. Contrast thresholds and pachometric and photokeratoscopic measurements are compared before and after experimentally induced distortion (A) and edema (B). Contrast attenuation is different for these two conditions (C). Standard errors are no larger than the symbol size used.

of medium to high frequencies. To the extent that low spatial frequencies were not affected, the visual effect from distortion was similar to that of a defocused or aberrant optical system. Induced corneal edema (marked thickness change, but with minor distortion, see Figure insets), on the other hand, produced depression of contrast thresholds for low- as well as high-frequency gratings. The low-frequency abnormality was relatively constant from 0.12 to 2 c/deg, after which it increased with spatial frequency. Acuity loss (extrapolation to abscissa) was approximately the same in these two experimentally induced conditions, yet vision for objects within the resolution limit was markedly different, indicating that edema was the major factor contributing to visual loss in the second case, at least for low spatial frequencies. A careful refraction was performed before contrast testing in each condition, and changes in apparent mean luminance were equated between the eyes with neutral density filters (0.1 ND). These two compensations isolate the results from induced overall (regular) corneal curvature changes and direct transmission losses due to scattering. From an examination of the image of the
keratoscopic mires (inset in each diagram) it is clear that distortion within the central area was more dramatic in Fig. 1, A, than in B, whereas corneal thickness change showed the reverse trend. These results therefore reflect contrast threshold changes from only distortion (Fig. 1, A) and from edema combined with minor distortion (Fig. 1, B).

**Keratoconus**

Essentially uniocular keratoconus. Results for three subjects who exhibited uniocular keratoconus with different degrees of acuity loss are illustrated in Fig. 2. In this figure the performance of the keratoconic eye (filled symbols) is compared at each frequency to that of the normal fellow eye (unfilled symbols). The contrast ratio function which more adequately describes the form of the visual loss from keratoconus for all three subjects is also illustrated in Fig. 2. Inset in each frame is a photograph of the keratoscopic mires for the normal eye and fellow keratoconic eye. These results demonstrate that even extreme forms of keratoconus affected the contrast function in a characteristic way; that is, low spatial frequencies were virtually unaffected for even gross forms of high frequency loss. This progressive collapsing of the contrast function from the higher frequency region followed the prediction from the experimentally induced corneal distortion results (Fig. 1, A). Furthermore, the suprathreshold appearance of gratings was also affected; severe frequency-dependent distortions oc-

Fig. 2. Contrast thresholds are compared over a range of spatial frequencies for the normal (unfilled symbols) and keratoconic eye (filled symbols) of three uniocular keratoconus patients. Inset in each frame is the appearance of the keratoscopic mires for each eye. The form of the contrast attenuation is shown in the top right frame. Standard errors equal the symbol size used.
Fig. 3. Contrast thresholds are compared over a wide spatial frequency range for patients with bilateral keratoconus. These results (filled and unfilled symbols) are compared to a normal contrast function (unfilled circles). The appearance of the keratoscopic mires for each eye tested is inset in each frame. The form of the contrast attenuation for each eye is displayed in the top right frame. Standard error was equal to the symbol size used.

occurred above threshold for these subjects. For low spatial frequencies very little distortion occurred, whereas the distortions and/or discontinuities increased with spatial frequency at and above 1 c/deg.

**Bilateral keratoconus.** In Fig. 3 contrast threshold functions are presented for subjects in whom both eyes were affected to varying degrees from keratoconus. In all cases only refractive errors of an irregular (optically uncorrectable) nature remained. Photokeratoscopic profiles could not be obtained because the central corneal curvature was steeper than 5.5 mm radius; the photokeratograms do, however, allow an objective, albeit qualitative estimate of the degree of keratoconus. The results for these subjects are compared to a normal contrast sensitivity function for an inexperienced subject matched for age. The results exhibited a combination of the effects produced by experimentally induced distortion and scattering (see Fig. 1, B), in that, for some eyes, all spatial frequencies were affected. The presence of a low-frequency abnormality seemed to depend only partially on the severity of medium- to high-frequency degradation. In more advanced keratoconic cases opacities were present, and this was found to correlate well with the presence of a low-frequency abnormality. It is interesting to note that in some cases spatial frequencies close to the cut-off frequency were attenuated less than medium frequencies (Fig. 3, top right). Whether this is a true bandpass effect or merely spurious resolution remains to be determined.

**Allied corneal pathology.** In Fig. 4 contrast threshold functions are given for two unusual
Fig. 4. Contrast thresholds are compared over a wide spatial frequency range for a patient with unilateral epithelial pitting (top left frame) and one with bilateral corneal dystrophy (bottom right frame). In the bottom right frame the form of the contrast attenuation from these two types of corneal disturbance are displayed. Inset in each frame is the appearance of the keratoscopic mires for each eye tested. Standard error is equal to the symbol size used.

cases of corneal pathology: unilateral epithelial pitting and bilateral corneal dystrophy. In the patient with unilateral epithelial pitting* (Fig. 4, top left), thresholds for the affected eye are compared with those for the fellow normal eye. The topographical changes which typify this condition are shown in the keratoscopic mires in the figure inset and should be contrasted with that of the normal eye. In Fig. 4 (bottom right) the sensitivity ratios (contrast ratio) for the normal and abnormal eyes are plotted as a function of spatial frequency. These curves represent the contrast attenuation characteristics of the corneal disturbance. The patient with unilateral epithelial pitting exhibited only a contrast loss for high to medium spatial frequencies, and in this regard, the condition mimicks corneal distortion. Since low spatial frequencies are not affected, it can be concluded that isotropic scattering, as may be expected from edema, is not involved.

In Fig. 4 (bottom left) it is clear from the photograph of the keratoscopic mires that this patient exhibited a marked bilateral corneal dystrophy* which has left his corneal epithelium “moth-eaten” in appearance. The condition must necessarily exhibit both con-

*Slit-lamp examination and staining techniques revealed multiple discrete opacities localized in the corneal epithelium. Other corneal layers appeared normal; the condition has been stable in appearance and visual effect for some years.
real distortion and opacification, and yet contrast was attenuated for only medium to high spatial frequencies. This result was not predictable on the basis of the experimentally induced distortion and edema results or the keratoconic results. Such a finding illustrates how important it is to individually assess the nature of contrast loss for some more diverse types of corneal disturbance. This paradoxical result could indicate that only narrow-angle scattering was involved in this case.

In Fig. 5, A, the acuity ratios (abnormal/normal eye acuity) for Landolt C (unfilled symbols) and gratings (filled symbols) are compared with the ratio of the low-frequency (0.12 + 0.24 c/deg averaged) threshold abnormality. Acuity loss (grating or Landolt C) was seen to be an unreliable predictor of the extent of the contrast attenuation for larger objects \( r = 0.4; p > 0.1 \). Fig. 5, B, illustrates the correlation between the grating and Landolt C acuity ratios. These results indicate that, in some cases, letter acuity can be affected more than grating acuity in keratoconus and allied corneal conditions.

Discussion

The results from experimentally induced corneal disturbance showed that distortion and edema produced characteristically different types of contrast attenuation for objects within the resolution limit. Distortion produced contrast attenuation which is restricted to high to medium spatial frequencies, whereas edema (11% thickness change) produced contrast attenuation for low as well as medium-high spatial frequencies. These results extend the findings of Hess and Garner² (6% thickness change) and substantiate their prediction which was made on the basis of simulated edema. Two caveats are noteworthy. First, it is virtually impossible to produce each of these conditions in complete isolation. In this experiment the major contributor to physiological change was monitored. Second, the edema produced was mainly stromal and cannot be generalized to any corneal edema. These experimental findings were then tested on patients exhibiting unilateral as well as bilateral keratoconus. In this condition, distortion is initially the major contributor to visual loss, but as opacities develop in the later stages, scattering also contributes to visual degradation. Low-frequency abnormalities were found to correlate well with opacification which is known to occur in well-established keratoconus.⁶

The prediction that these two types of corneal disturbance produce different visual effects and the suggestion that this could form
the basis of a classification of visual loss from corneal pathology were supported by the keratoconic results. This conclusion is in line with a number of recent studies\textsuperscript{1-4} which have suggested that a more complete picture of visual function can be obtained by supplementing the presently accepted "acuity" assessment of vision for object sizes within the resolution limit. Two studies in particular\textsuperscript{2,3} have pointed out that optical attenuation of low spatial frequencies may have an important role in everyday visual performance. For this reason it has been proposed that a functional classification should be adopted, based on whether only medium to high frequencies are affected or whether low as well as medium to high frequencies are affected. This could be done with a simplified clinical approach at only two spatial frequencies.

Because it is difficult to quantify the relationship between the physical nature of scattering produced by edema and punctate opacities, individual, empirical assessment of contrast thresholds are needed in addition to acuity measures.

The present contrast threshold results for low spatial frequencies could not be predicted on the basis of the visual acuity. This result which is supported by a number of allied investigations\textsuperscript{5-4} indicates the need to supplement the present acuity assessment of vision. Because all the contrast degradation occurs in the eye's optics (prior to any neural gain-setting mechanism), the measured contrast attenuation at threshold may also be relevant to suprathreshold stimuli. This is assuming that significant, secondary contrast gain changes do not occur in adult life.\textsuperscript{9} If this is so, these results also establish the suprathreshold contrast matching function for patients with optical defects. For this reason, combined with the possible perceptual importance of low-frequency loss,\textsuperscript{3} assessment of residual vision for legal and occupational needs should be based on the nature of any nonacuity abnormality (quantified in terms of contrast threshold) as well as classic acuity measures.

It should be realized that the fidelity of information transmitted through any media depends upon the amplitude and phase-transfer properties of the system. Contrast thresholds supply information directly only about the former parameter. It has also been shown that \textit{phase distortions} are introduced by corneal surface irregularity. This new suprathreshold dimension further strengthens the functional difference between distortion and scattering and may also explain the present finding that letter acuity may be more dramatically affected than grating acuity in keratoconus. Therefore quite different perceptual defects occur in both the amplitude and phase domains for distortion and scattering. Since most corneal disturbance may be considered in terms of either one or both of these two conditions, they could form the basic templates of a useful \textit{visual} classification (threshold as well as suprathreshold situations) for a wide spectrum of corneal pathology.

This project would not have been possible without the valuable discussions and support given by John Strachan, John Nathan, Geoff. Lennig, Barry Collin and Ed. Howell. We also wish to thank all our subjects and Patricia Collier for typing the manuscript.

REFERENCES