Degradation of vision through a simulated cataract

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Most cataracts, apart from the dense nuclear sclerotic type, interfere with vision by scattering the incident light. The scattering, and therefore the image degradation, may be simulated by a glass lens with petroleum jelly spots pressed on the surface. With such a system, "per cent of cataract" can be controlled by the amount of surface of the glass lens covered with petroleum jelly. The simulated cataract was part of an F-5 lens system which best simulated the eye's geometric optical system with a 3.5 mm. pupil. The study determined the transfer function of the simulated cataractous lens as a function of the per cent of cataract. Photographic and microdensitometric techniques are used. The results show the precise relationship between per cent cataract, resolution, and contrast. For example, contrast is first noted to drop for bar targets of small angular subtense with a 40 per cent cataract whereas, contrast remains constant until an 80 per cent cataract is reached if bar targets of large angular subtense are viewed.

Key words: cataract simulation, light scattering, image contrast, image resolution, transfer function, microdensitometry.

Very often a patient tested for visual acuity with the Snellen Eye Chart receives credit for good visual acuity, although the equality of the imagery is reported as "watery" or of low contrast. Thus the parameter of contrast discrimination, taken together with resolution is necessary for a full description of vision. Since most standard acuity tests measure only resolution, the full assessment of the visual quality cannot be obtained in the standard test situation. Early corneal edema, cataracts, or retinal edema are but a few of the possible causes of lowered contrast. Specifically, such pathology causes a narrowing of the eye's transfer function.

In this paper we shall construct a simple laboratory model to study the effects of cataracts on image degradation. In basic terms, a cataract may be thought of as an optical element containing a random distribution of scattering centers. The scattering centers are simply regions of appropriate size within the lens whose index of refraction differs from that of the surrounding matrix. Light passing through such a medium will therefore undergo scattering, and imagery will be aberrated. Put another way, the aberrations introduced by the randomly-distributed scattering centers...
cause any incident light wavefront to suffer distortions so severe that only hazy large angular subtense objects (low spatial frequency) images are seen.

In attempting to quantify just how much image resolution and contrast is lost due to a cataract, we are immediately faced with the problem of controlling the amount of cataract. Therefore, this study has developed a cataract model in which the degree of cataract can be varied. In what follows we shall first present evidence to the effect that, in so far as light propagation is concerned, our model reproduces the effects of actual cataracts. Having established the validity of our simulation, we shall then determine the effect of different degrees of cataract upon contrast discrimination and visual resolution. In particular, we shall determine the cataractous transfer function as a function of the percent of cataract.

**Cataracts—a phase model.** Fundamental to the validity of this work is the assertion that, by far the major effect of the cataract on imagery is to produce phase aberrations on the optical electromagnetic wave front propagating through the eye’s cornea and lens. Since the work of Maurice1 on light scattering in the cornea, and more recently the elegant observations of Benedek,2 and of Hart and Farrell3 on the theory of ocular transparency, it is generally accepted that light scattering alone, as distinct from absorption processes, is capable of accounting for the image characteristics of cataractous eyes. Specifically, their calculations2,3 indicate that a decrease in object contrast is the result of having the components of the optical field scattered randomly by the cataract. Similarly, random scattering centers can account for the effects of glare sensitivity and resolution decreases. These considerations, and the fact that the overall intensities with and without cataracts striking the entire retina are comparable1,4 strongly suggest that the cataract introduces random phase aberrations on the optical wave front by virtue of the fact that portions within the cataract have a different index of refraction than the adjacent portions. If this were not the case, and a cataract was instead composed primarily of randomly-distributed, light-absorbing regions, far less light would reach the retina. Furthermore, image contrast and resolution would be higher than observed.

This assertion is demonstrated in Figs. 1...
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Fig. 2. Image of an “E” (same as Fig. 1) through a lens apodized with a random array of phase distorting centers.

Fig. 3. In Fig. 1, we simulated the case in which the cataract is supposed to be a random collection of opaque areas. The object is black “E” on a white background, subtending 18° at an F/5 lens. A clear mask containing a random assortment of opaque spots of mean size 50 μ was placed over the lens. The “E” was imaged through the lens under illumination with a floodlight. In Fig. 2, we replaced the absorbing mask with a phase mask. The mask is simply a piece of flat glass with a random assortment of pits and ripples on its surface. The mean size of the random pits is also 50 μ. Fig. 3 shows the image of the “E” taken through an excised human lens mounted in silicone oil and placed in a Rose chamber. Visual acuity through the cataract had been finger counting at three feet. Care was taken to insure that the apertures and exposures were the same in all cases. Figs. 2 and 3 are obviously more comparable than Figs. 1 and 3, which lends credence to the phase model in that Fig. 2 more nearly reproduces the situation obtained in situ. Undoubtedly, however, there is a complementary principle here in that the cataract is neither wholly phase nor absorbing, but rather somewhere in between and weighted more nearly to the phase model.

Further evidence for the validity of cataract simulation by phase-aberrating media, insofar as light propagation is concerned, is obtained by observing the coherent scattering pattern which occurs on passing a laser beam through a cataract and a simulation. In Fig. 4 we see the image of the actual cataract. We illuminate the cataract with a collimated laser beam (1 mW He-Ne) and observe the scattered radiation in the farfield of the scattering centers. This simply requires photographing the scattered light in a plane more than 1 cm. from the cataract. The result is shown in Fig. 5.

The speckled appearance is due to interference of the coherent light from the randomly-distributed scattering centers, i.e., the pattern is produced by the random fluctuations in index of refraction within the cataract. Such a pattern is a quantitatable demonstration of the aberrating power of the cataract.

Thus we see that coherent scattering patterns such as shown in Fig. 5 give a char...
Fig. 3. Image of an "E" (same as Fig. 1) through an excised human cataract of counting fingers vision.

Fig. 4. An excised human cataract (incoherent illumination), characteristic signature to the scattering medium which reflects the nature of the medium's physical parameters. In Fig. 6 we see our simulation, namely an F/5 lens whose surface was covered randomly with petroleum jelly dabs whose mean phase step was 50 μ. Illuminating our simulation with the same laser as for the cataract, we see the scattering pattern of Fig. 7. Not only are the images of the cataract and simulation comparable (Figs. 4 and 6, respectively), but their characteristic scattering patterns are also quite similar (Figs. 5 and 7, respectively).

It appears quite reasonable then to assert that insofar as image degradation is con-
cerned, as long as the statistics of the optical path length variations are the same in different media, then on the average, the image degradations will be the same. This simply means that as long as two different media affect the optical wavefront in the same way, images seen through those media will have the same quality.

Method

Preparation of the simulated cataract. Having established a correspondence between an actual cataract, and a simulated cataract consisting of a lens of appropriate F/number covered with a random-phase medium, we can now control the amount of cataract. If we dab petroleum jelly onto the lens then the per cent cataract will be defined as the per cent of the lens surface thus
To ensure that the petroleum jelly is applied at random, we divided the lens into a 10 by 10 grid. The coordinates of a dab are obtained by reference to a pair of digits in a random number table (the last digit of a pair of numbers in a telephone book will do). Thus, with each dab equal to about 1/100 of the aperture area, twenty dabs for example gives a 20 per cent cataract. The dab is applied in a thin layer such that the phase heights are about 0.5 mm and the phase steps 20 to 50 μ within the area of the spot.

**Data collection.** We employed a standard United States Air Force three-bar resolution target as shown in Fig. 8, A. As the bars get smaller, and closer together, the spatial frequency (i.e., the number of bars per millimeter) increases until the resolution cutoff of the lens is reached. Note also that as the spatial frequency increases the contrast of the bars decreases. Thus the transfer function of the cataract model (the contrast of the target as a function of spatial frequency) will be obtained by measuring the contrast of the three-bar groups using microdensitometry as described below.

The United States Air Force resolution target was photographically enlarged by 13 times onto a photographic glass plate and positioned 24 meters from the lens. It was back-illuminated through a green Wratten filter with diffuse light. This procedure minimizes chromatic aberration and allows us to image the target in the focal plane of the lens, thus simulating the case of the eye's lens focused on infinity. All recordings were made on Kodak microfilm, number AHU 5460, after having exposed a sensitometric step wedge onto the leading edge. In this way film processing effects (as described below) could be monitored.

The data collection proceeded as follows. The film is positioned in the plane of best focus of the resolution target (the lens focal plane). The lens was then covered with petroleum jelly dabs in 20 per cent increments from 0 to 100 per cent. At each per cent cataract, the resolution target is exposed. Several different exposures for each per cent cataract were made. After the lens was completely covered, it was cleaned and the process repeated. Thus several members of the ensemble of degraded images were available for averaging. Typical results are shown in Figs. 8, A through 8, F. Note how the resolution and contrast of the images decreases as we proceed from 0 to 100 per cent cataract. It is our purpose to quantitate these decreases.

**Effects of film processing.** Since we shall ultimately reduce our data using microdensitometric scanning, it is necessary that we present photographic information to the microdensitometer as free from film processing artifacts as possible. Since a microdensitometer responds to the intensity of light transmitted through a photographic transparency, it is necessary to record a signal on film proportional to the exposure.

Any photographic transparency has an intensity transmittance \( T_i(x) \) given by,

\[
T_i(x) = 10^{-\frac{x}{10}}
\]
Fig. 8. United States Air Force 3-bar resolution target as seen through various degrees of simulated cataract. A. 0 per cent cataract. B. 20 per cent cataract. C. 40 per cent cataract. D. 60 per cent cataract. E. 80 per cent cataract. F. 100 per cent cataract.
Fig. 9. Representation of the D-log E relationship.

where \( D(x) \) is the optical density on the film at position \( x \), \( D(x) \) is related to the exposure \( E \) through the D-log E curve as represented in Fig. 9. As can be seen if the exposure is too low the film will not respond to changes of brightness in the object (the toe region), and if the exposure is too large the film saturates, again giving no response to object brightness changes. In the central region, however, there is a reasonably linear section where object brightness changes can be linearly related to density changes on the film. It is in this region that we wish to make our exposures. Specifically, the linear region is described by Equation 2,

\[
D(x) = D_o + \gamma \log E(x),
\]

where \( D_o \) is the extrapolated intercept of the straight line region, and \( \gamma \) is the slope. Both \( D_o \) and \( \gamma \) are determined by the type of film and the chemical processing procedures used. Substitution of Equation 2 into Equation 1 yields an intensity transmittance given by,

\[
T_i(x) = A \ (E(x))^{-\gamma}
\]

where the constant \( A \) is defined by,

\[
A = 10^{D_o}.
\]

Now if the slope \( \gamma \) equals -1, \( T_i \) will be proportional to the exposure \( E \). This is accomplished by reversal processing of the film. The resulting intensity transmission of the film is then equivalent to the aerial image that would appear at the retina. The procedure for reversal processing Kodak AHU 5460 microfilm to a \( \gamma \) of -1 is given in Table I. Fig. 10 shows the D-log E relationship for all the exposures shown in Fig. 8. This curve was obtained from the sensitometric step-wedge mentioned above. All of our data (Fig. 8) occupied the linear region of Fig. 10.

Microdensitometry. In Fig. 8, we have seen the decrease in object resolution and contrast as the per cent of cataract increased. To determine the contrast at which a given spatial frequency is seen as a function of per cent cataract, we employed a Joyce Lobel dual-beam scanning microdensitometer. To insure proper sampling by the scanning aperture (one must sample with an aperture whose size is no larger than the reciprocal of twice the spatial frequency being sampled) we used a 10μ square aperture for all our traces.

Fig. 11 shows a typical set of densitometric traces of various spatial frequencies of a three-bar target as seen through a 40 per cent simulated cataract. Density (bar blackness) increases downward. It can easily be seen how the density difference between the three bars and the clear background decreases with increasing spatial frequency. From such traces the contrast \( (C) \) of a given spatial frequency \( (\nu) \) may be calculated according to,

\[
C(\nu) = \frac{T_i^{\nu=0}(\nu) - T_i^{\nu=\nu}(\nu)}{T_i^{\nu=0}(\nu)} = 1 - 10^{-\Delta D(\nu)}
\]

where,

\[
\Delta D(\nu) = D_{\text{max}}(\nu) - D_{\text{min}}(\nu)
\]

and \( D_{\text{max}} \) and \( D_{\text{min}} \) are the maximum and minimum densities, respectively, of the spatial frequency.

This procedure was repeated twice for each spatial frequency at each degree of simulated cataract. When the contrast data for each degree of cataract is normalized to the contrast at zero spatial frequency, and plotted against resolution we finally obtain the desired transfer functions of the cataractous lens.

Results

We have seen in some detail the various procedures used to determine the transfer function of the cataractous lens. Our data, as calculated via the procedures of the last section, is presented in Fig. 12. From Fig. 12, A we see that the transfer functions forming 0 to 40 per cent cataract are quite similar. As we approach 60 per cent cataract (Fig. 12, B) the transfer function begins to narrow at the low frequencies and bow in the midrange of frequencies.

At 80 per cent cataract both the narrowing and bowing are enhanced. Not only is there a significant drop in contrast at low frequencies, but we also see about a 30 per cent increase in contrast from 30 lines per millimeter to 60 lines per millimeter with
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Table I. The procedure for obtaining \( \gamma = -1 \) on Kodak AHU 5460 film is as follows. Use fresh developer and distilled water at a temperature of 68° F.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Time</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop in DK-50 diluted 4:1</td>
<td>5 min.</td>
<td>agitate 15 sec. every 30 sec.</td>
</tr>
<tr>
<td>Rinse in water 3 times</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Bleach</td>
<td>2 min.</td>
<td>agitate 15 sec. every 30 sec.</td>
</tr>
<tr>
<td>Rinse 3 times</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Clearing bath</td>
<td>30 sec.</td>
<td>constant agitation</td>
</tr>
<tr>
<td>Rinse 3 times</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Re-expose by slowly running film back and forth in front of a high intensity, Lampette (front and back) 3 times</td>
<td>agitate 15 sec. every 30 sec.</td>
<td></td>
</tr>
<tr>
<td>Develop in D-95</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Rinse 3 times</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Fix bath</td>
<td>2 min.</td>
<td>agitate 15 sec. every 30 sec.</td>
</tr>
<tr>
<td>Rinse in running water</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Perma-wash</td>
<td>2 min.</td>
<td>agitate 15 sec. every 30 sec.</td>
</tr>
<tr>
<td>Rinse in running water</td>
<td>1 min.</td>
<td></td>
</tr>
<tr>
<td>Photo-flo and dry</td>
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marked fall-off at high frequencies. The marked bowing in the midrange of frequencies suggests an improved contrast relative to the adjacent lower frequencies. Such curves are typical of highly aberrated lenses. The phenomena may be heuristically understood as follows. A lens may be considered as a series of concentric zones of equal area. Each zone passes a different band of spatial frequencies associated with the object being imaged. Because of diffraction in the light propagating from the object to the lens, low spatial frequency information can be thought of as passing through the central zones, while high spatial frequency information passes through the peripheral zones. This is why, for example, a pinhole camera has poor resolution, while a large aperture lens gives high resolution imagery. Recall now that the phase scatterers were put down at random across the surface of the lens. Dividing the aberrated lens into such zones we can see that the mean distance between scatterers in any zone increases as we move toward the peripheral zones. This is why, for example, a pinhole camera has poor resolution, while a large aperture lens gives high resolution imagery. Recall now that the phase scatterers were put down at random across the surface of the lens. Dividing the aberrated lens into such zones we can see that the mean distance between scatterers in any zone increases as we move toward the peripheral zones. Thus we should expect somewhat less aberration in certain zones near the periphery than those closer in. The result would then be a relative improvement in contrast of the spatial frequencies passed by those zones.

At 100 per cent cataract the transfer
Fig. 11. Typical microdensitometric traces of various spatial frequencies seen through a 40 per cent cataract.

Fig. 12. Transfer function of a cataractous lens. A. 0, 20, and 40 per cent, cataract. B. 60, 80, and 100 per cent, cataract.
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Fig. 13. Contrast of various size objects as a function of per cent cataract.

function shows a marked drop in both resolution and contrast for all target frequencies except those near zero. In such a condition only very large objects may be seen.

These data may be translated into a family of curves showing how the contrast of various size objects varies as a function of the per cent cataract. This is done by considering the per cent cataract as an axis normal to the coordinate systems of Fig. 12, and plotting the contrast vs. the per cent cataract with the spatial frequency (object size) as the parameter. This is done in Fig. 13. For example, an image resolution of 15 lens per millimeter corresponds to an object subtending 9.2 minutes of arc at the lines. Thus from Fig. 13 we can see that for large objects as much as 80 per cent cataract may be tolerated before the image contrast decreases appreciably. However, for small objects the sensitivity to the amount of cataract increases. In particular, for objects subtending about 1 minute of arc there is a marked decrease in contrast after the lens is 40 per cent cataractous.

Discussion

This study has quantitatively demonstrated the relationship between image contrast and resolution as a function of the per cent of cataract present. This was accomplished using a simulated cataract after demonstrating (1) that image degradation due to a cortical-type human cataract is due to the phase-aberrating nature of the cataract; (2) the phase-aberrating characteristic of such cataracts may be simply reproduced by appropriately covering a suitable lens with a random phase scatterer.

By imaging a three-bar resolution target through our simulation for various degrees of cataract, it was then possible to construct the cataractous transfer functions using precise photographic and microdensitometric procedures. Finally, from these data the contrast at which a given size object can be seen was determined as function of the per cent cataract present.

It should be noted that there exist other, more direct methods, than those employed to obtain the transfer function of a lens. For example, the Ealing Optical Transfer Function Systems, "EROS 100," "EROS III," and "EROS IV," yield the transfer function of a test lens automatically. It would be of interest therefore, to repeat our experiments using such systems on human as well as simulated cataracts.

We have shown how the full assessment of visual quality requires the test of contrast discrimination as well as resolution. Further, it has been seen that such tests, when made in the presence of pathologic conditions leading to image degradation, might be used to quantitatively assess the degree of that pathologic state. Thus, in the standard test situation, the addition of variable contrast targets would offer the possibility of a more complete description of the patients' visual quality. Finally, from the point of view of the visual psychologist, the utilization of our procedures would enable data collection in the presence of image-degrading pathology.
REFERENCES
5. The far-field of a scatterer of size D is given by $D^2\lambda$ where $\lambda$ is the wavelength. In the case of a cataract the scattering centers are not larger than about 20 $\mu$ (40 $\lambda$). Thus the far field is about 800 $\mu$ from the scatterer.