Light Scatter Causes the Grayness of Detached Retinas

Implications for Vision Loss in Retinal Detachment

Shizhuo Yin, PhD; Thomas W. Gardner, MD, MS; Tanu O. Thomas, MD; Keith Kolanda, COT

Objective: To investigate the cause of the gray appearance of the detached retina.

Methods: The effects of ex vivo bovine retinas and Scotch (3M, Minneapolis, Minn) tape on light scattering were predicted based on mathematical modeling and examined empirically on an optical bench. Images were collected with a CCD [charged-coupling device] camera connected to a microcomputer with an image grabber. The clarity of the image was calculated as the standard deviation, $\sigma$.

Results: Calculations predicted a gaussian distribution of laser light scattering with increased diffusion with increasing distance from the medium to the target. The image clarity, $\sigma$, increased rapidly in the first 50 µm of separation of the retina and tape from the test target and the rate of increase diminished thereafter. Removal of the outer retina with an excimer laser improved retinal transparency.

Conclusions: Data explain that the gray appearance of the detached retina results from light scattering. This phenomenon likely results, at least in part, because of the irregular outer retinal surface at the level of the photoreceptors.

Clinical Relevance: The findings suggest that visual loss in retinal detachment may result, in part, from optical properties of the detached retina and have implications for visual recovery and subretinal surgery.

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The primary physical features of retinal detachment that lead to the diagnosis are a gray discoloration of the elevated retina, which increases with height of the detachment, and reduced visibility of the underlying choroidal orange-red and vascular details. Rhegmatogenous, exudative, and tractional retinal detachments all share these features. Retinal shagreen is an undulation of the detached retina.¹

Detached retina is translucent whereas attached retina appears transparent, but the cause of this change in appearance has not been explained. One possible explanation is an intrinsic abnormality of the retina due to impaired metabolism leading to retinal edema. Although retinal edema certainly occurs in detachments,² at least 1 day is required to develop after experimental separation from the pigment epithelium and it does not resolve immediately upon reattachment.³ By contrast, detached retina regains its transparency as soon as it is reattached, whether by external or internal subretinal fluid drainage, or with perfluorocarbon liquids. Moreover, cystoid macular edema does not impair retinal transparency in attached retina.

A second possibility is retinal hypoxia. Although detached retina is probably relatively hypoxic because of its separation from the choroid, hypoxia alone is not likely to cause loss of transparency because central retinal artery closure for up to 30 minutes does not cause retinal whitening (T.W.G., unpublished data, 1992). Thus, an intrinsic retinal metabolic abnormality does not likely account for the grayness.

A third possible explanation for retinal grayness could be a loss of clarity of the subretinal fluid. However, in rhegmatogenous detachment, the subretinal fluid is contiguous with and as clear as the vitreous fluid and has the same refractive index (except in long-standing inferior detachments). In exudative detachment the fluid is usually a clear transudate. Fibrin may contribute to cloudy subretinal fluid in severe cases of central serous chorioretinopathy,⁴ but the retinal grayness is analogous to a similarly elevated rhegmatogenous detachment. Therefore, we examined the optical properties in an experimental model.
of retinal detachment to test the hypothesis that the detached retina scatters (diffuses) light. A MEDLINE search using the term retinal detachment yielded no publications that provide data on the topic. Both mathematical modeling and experimental studies demonstrate that detached retina and Scotch tape (3M, Minneapolis, Minn) tape scatter light depending on the height of elevation. These findings appear to account for the gray appearance of the detached retina and provide novel insights into the mechanism of the visual loss in retinal detachment.

METHODS

MATHEMATICAL MODELING

To examine the mechanism of the grayness of the retina in retinal detachment the properties of the normal attached retina must first be considered. The attached retina appears transparent because it lacks pigment (except for hemoglobin in blood vessels and luteal pigment in the fovea) and has an orderly cellular architecture. In addition, the photoreceptors interdigitate with the underlying pigment epithelium to provide for a smooth transition from one tissue to the other. These features minimize light scattering.

We hypothesized that inherent optical properties of the elevated retina alter its light transmission and change the normally transparent retina into a translucent structure. By analogy, transparent retina becomes a diffusive media-like “cloud” after detachment. As illustrated in Figure 1, experimental retinal detachment causes irregularities of the photoreceptors and pigment epithelium so light is diffused (or scattered) by the disordered photoreceptors. This is a volume scattering effect in which the light is scattered across the increased 3-dimensional space of the light path of the elevated retina. That is, since the photoreceptors are not in their natural parallel arrangement the light is scattered throughout the increased volume of the retina and subretinal space.

To quantitatively describe this process, a simplified approach is used to illustrate the quantitative effects of light scattering by the retina. This complicated volume scattering problem is treated as 2 separated plane problems. One plane simulates the diffusive media (retina or tape) and the other simulates the photoreceptor absorption. Because the scattering and absorption by photoreceptors may happen at different locations (photoreceptors, pigment epithelium) as shown in Figure 1, we assume there is a distance, d, between the diffusive media and the pigment epithelium layer. In the case of light passing through the attached retina as also shown in Figure 2A, d=0. In the detached retina, d increases and light scatters (Figure 2B). We further treat the diffusive media like a 2-dimensional, random-phase plate (transparent tape model). Mathematically, the transmittance of this diffusive plate can be described as

\[ t(x,y) = e^{\phi(x,y)}, \]

where \( \phi(x,y) \) is a random 2-dimensional distribution. Figure 2 illustrates the incoming light passing through this diffusive media first before reaching the photoreceptors.

Let us assume that the incoming light will form an image in the photoreceptor plane with a spatial distribution \( f(x,y) \).
dimension as the vertical distance, \( d \), increases.

scattered) with a smaller \( d \) and more scattered with a greater horizontal

through the translucent tape with distance, \( d \). The light is more focused (less

separation distance, \( d \), from 0.1 to 0.5. B, Output light intensity distributions

\( (\text{range, 0.1-0.5}) \), where

\[
\rho = \sqrt{x^2 + y^2}.
\]

To illustrate this distance effect, Figure 3B shows the output light intensity distributions when a point light source (coming from a helium-neon laser) passes through a Scotch tape with different distances to the plane upon which it is projected. It is shown that the greater the separation distance, \( d \), the worse the spatial resolution of the image. In other words, the image is more blurred. In particular, when \( d \) is small, a small change in the separation distance can result in a large change in FWHM. For example, as shown in Figure 3A, there is a much bigger change in FWHM when \( d' \) changes from 0.1 to 0.2 than when it changes from 0.2 to 0.3. This is consistent with the experimental results to be described in next section.

**EXPERIMENTAL STUDIES**

Translucent Scotch adhesive tape becomes essentially transparent when pressed against a smooth surface, much like a detached retina. This tape was used first as a model of the detached retina by placement on an optical hold in front of an AF-51 test target on an optical bench, as shown in Figure 4.

The distance between the hold and the test target with the tape or retina in place was adjusted via a translation stage. The tape was illuminated by tungsten white light. Images were collected by a CCD camera and a microcomputer with an image grabber (Figure 4).

Bovine eyes were acquired from a local abattoir and kept on ice for 48 hours until the experiments were performed. During this period the corneas became hazy, but the retinas retained their normal transparency while attached to the underlying pigment epithelium (not shown). The retinal transparency did not equal 0, based on equations 2 and 3, one can estimate that, in this case, the spatial resolution of the final image is about the full width half maximum (FWHM) of the point spread function. Figure 3A shows a set of point spread functions \( h(x,y) \) with different distance \( d' \) (range, 0.1-0.5), where

\[
h(x,y) = \frac{e^{-x^2 + y^2}}{d'^2},
\]

where \( d' \) is a constant proportional to the separation distance \( d \)

(ie, \( d = d' \times \epsilon \), where \( \epsilon \) is another constant). When \( d \) approaches...
RESULTS

SCOTCH TAPE MODEL

During retinal surgery the transparency of attached retina changes to translucency immediately on retinal detachment and back again to transparency after reattachment, irrespective of the method of reattachment. Therefore, we hypothesized that the optical properties of the retina depend on its position in relation to the pigment epithelium to determine retinal clarity rather than on a metabolic defect. Translucent Scotch tape was placed on the optical bench setup and the effect of its distance from the test target on image clarity was determined. Figure 5 shows the blurring effect of Scotch tape with different separation distances, d. In Figure 5A, the small distance (2 mm) between the tape and the resolution chart causes the details of the underlying chart to be blurred. In Figure 5B the distance is 0 so a clear picture is obtained. This observation demonstrates that the distance between an optically transparent medium and an image affects the appearance of the medium and the underlying image.

BOVINE RETINA MODEL

Bovine retinas retain their transparency despite up to 48 hours of postmortem exposure even though the corneas of the same eyes become edematous (not shown). However, the retinas immediately appear gray when elevated or folded. Thus, we used sections of retinas in an ex vivo preparation to further investigate the relationship between retinal position and clarity. Figure 6 shows a series of images with increasing separation distances between the AF-51 resolution chart and segments of bovine retina. Like the Scotch tape it is apparent that the greater the separation distance, the more blurred the image.

Figure 7 shows the standard deviation, σ, an index of image clarity as a function of a separation distance, d, for the bovine retina and Scotch tape, respectively, in which σ of the bovine retina was calculated using the same data as shown in Figure 6. Two observations can be made. First, the image through the bovine retina reaches the same level of clarity when in contact with the AF-51 chart as does the transparent tape. Thus, although 48 hours had elapsed from the time of death, the optical properties remained largely intact. Second, when the separation distance increases, the standard deviation, σ (i.e., the image clarity), drops rapidly then gradually declines. After an initial rapid increase further reductions in transparency with further increases in distance produce gradual declines in σ. This result agrees well with the clinical observation that shallow detachments reduce the clarity of the underlying choroidal vessels, and that the grayness of the detachment increases with the height of the detachment up to a point but reaches an apparent maximum. The most highly elevated portion of a given detachment appears gray (less transparent) than the less elevated area. The variation of the grayness with the detachment height further suggests that a metabolic effect is not a major factor. If that were the case, the retina should have a uniform appearance. This experimental observation is also consistent with the theoretical model as described by Figure 3.

The next step involved experiments designed to investigate whether the photoreceptor layer contributes to light scattering. Pieces of bovine retina were placed on glass microscope slides that were, in turn, laid on a near vision card. When the outer retinal surface faced the laser, successive laser exposures caused the characters of the near vision chart to become progressively clearer (Figure 7). By contrast, laser treatment of the inner retinal surface to the same extent did not alter the retinal transparency or the appearance of the near vision chart. After laser ablation, the retinas were fixed in 10% formalin, paraffin-embedded, and stained with hematoxylin-eosin. Sections through the retinas ablated with the outer retina facing the laser reveal progressive removal of the photoreceptors and part of the outer nuclear layer (Figure 8). These studies confirm the prediction that photoreceptors contribute to retinal light scattering (Figure 9).
In this report we present a new model to explain the gray appearance of the detached retina. The mathematical modeling and experimental findings show quantitatively that the retina scatters light when it is elevated from an adjacent surface—the optical plate in this model and the pigment epithelium in vivo. These data are consistent with the several well-recognized clinical observations. First, the change in retinal transparency occurs immediately on retinal detachment and reattachment; the rapid temporal course largely excludes a fundamental change in retinal metabolism as a reason for loss of transparency. Second, the grayness of the retina increases with the height.

Figure 5. The Scotch tape (3M, Minneapolis, Minn) blurs the image of the AF-51 resolution chart. A, When the tape is held 2 mm above the chart, the image is blurred. B, The tape is pressed flat against the AF-51 chart, and the lines are seen clearly.

Figure 6. Bovine retina blurs the AF-51 resolution chart. Images obtained with progressively less separation distances between the AF-51 resolution chart and the detached bovine retina show decreased blurring.
of the detachment; bullous detachments, whether rhegmatogenous, exudative, or tractional, are grayer than shallow detachments. Third, detachment blurs the image of the underlying choroidal vessels. Fourth, chronic, atrophic detachments are less gray than acute ones and retinoschisis elevations are nearly transparent. These points are further discussed below.

Light scattering (diffusion) occurs if the medium contains opacities or an irregular surface. Intraocular light scatter occurs with cataract, corneal, or vitreous opacities because light is deflected from its path and not focused onto the retina. The Scotch tape model demonstrates light scattering when the surface of the medium is irregular. In this case irregularities in the posterior (adhesive) surface of the tape are greater than the wavelength of visible light passing through it so tape held free in space is translucent or light gray. In addition, tape held over a formed image such as text blurs the view of the image. When pressed against a smooth surface the tape immediately appears transparent because the irregular posterior surface is smoothed. Likewise, when the retina is detached, photoreceptor outer segments no longer interdigitate with the pigment epithelium and create an irregular surface as shown in electron micrographic studies by Kroll and Machemer. Thus, scatter occurs if the irregularities of the outer segments exceed the wavelength of light. In these experiments we used white light. The model predicts that longer thickness of visible light would scatter less and would be less subject to changes in retinal or tape position. Future experiments will address this point.

The tape and bovine retina models used in this study differ from the situation in the intact globe. In the model light passes through the tape or retina only once. In contrast, light passes through the retina in both directions inside the globe. The model used in this study was chosen because it is technically impossible to make measurements in vivo. However, our observations strongly suggest that only a single pass of light is required to induce light scattering.

Retinal grayness varies with the height of the detachment. Data in Figure 7 show that the loss of transparency begins in the first 50 μm of tape and retinal separation from the optical plate, and declines at a nearly linear rate thereafter. In this model the retinal grayness reached a plateau after approximately an 800-μm elevation. Although the detached retina probably reaches maximum grayness at a greater height in vivo (>1 mm), the overall trend of the ex vivo model data parallel the clinical situation. At this point, it is technically infeasible to measure retinal light scattering in vivo.

A common feature of all types of retinal elevation is loss of the clarity of choroidal vascular details. Figure 3, the calculations in equation 3, and the empirical data suggest why this is the case. The incident light is scattered in 3 dimensions (volume effect) so less is reflected to the viewer and the underlying tissue appears less clearly defined.

The model also seems to explain why chronic detachments are less gray than acute detachments. Longstanding detachments lead to photoreceptor outer segment atrophy; so, if the outer segments become shorter and more uniform than they are immediately after detachment, light scattering will be less. Indeed, in retinoschisis the photoreceptors remain in contact with the pigment epithelium and the separation plane occurs between the receptor inner segments and outer nuclear layers, so less irregularity of the cellular layers may occur. Hence, the retina remains nearly transparent unless accompanied by a rhegmatogenous retinal detachment.

The purpose of this study was to investigate the factors that could account for the appearance of the gray detached retina. The results strongly suggest that light scattering is a major factor. To investigate the role of the photoreceptors in the retinal transparency, additional studies showed that ablation of the outer retina increased the view of letters of a near vision card viewed through an elevated portion of retina, whereas similar ablation of the inner surface did not. Histologic examina-
tion confirmed the level of retinal ablation. These results provide strong evidence for the role of the irregular posterior retinal surface as a major factor in retinal light scattering. Indeed, irregular photoreceptor alignment has been shown to account for the gray appearance of the retina after blunt trauma7 (Berlin edema or commotio retinae) even without detachment, and the retina becomes clear when receptor alignment improves.

While the metabolism of the detached retina changes rapidly,8 neither retinal edema nor hypoxia fully account for the observed clinical features detailed above. Moreover, the subretinal and vitreous fluids are interchangeable and a differential refractive index between the retina and subretinal fluid, or a difference in subretinal fluid clarity is an unlikely explanation.

In addition to explaining the physical signs of retinal detachment, the results also suggest that light scattering may contribute to visual loss in retinal detachment because the image formed on the photoreceptors is blurred due to the scattering effect. In support of this concept, Friberg and Eller9 demonstrated that patients with macula-off detachments who had poor Snellen visual acuities often had surprisingly good acuities measured with the Guyton-Minkowski Potential Acuity Meter. Patients with visual acuities of finger-counting or less often had potential acuity meter results between 20/50 and 20/200. They also found that a large disparity between the Snellen visual acuity and the potential acuity meter measurement predicted a high likelihood of postoperative improvement in visual acuity. Although part of the good results with the potential acuity meter may have been because of the brightness and high contrast of the projected eye chart, the findings also suggest that the neural retina maintains some synaptic function even when detached. Therefore, reduced Snellen visual acuity could result in part from the shifting of the detection plane out of the perfect location (with shifting distance in the order of d) in the detached retina.

To maximize visual recovery after retinal detachment, the scattering effects must be eliminated. That is, the retinal must be reattached in its native position so that photoreceptors realign and have a smooth interface with the pigment epithelium. Indeed, psychophysical evidence for photoreceptor misalignment in patients with retinal detachment has been shown by the Stiles-Crawford effect10 and macular electoretinography in central serous chorioretinopathy.11 Retinal reattachment does not immediately restore visual function; so diffusion by the detached retina is but one factor in visual impairment. Other factors include photoreceptor and pigment degeneration and macular edema.2,3 However, as photoreceptors and pigment epithelium regenerate and regain their original contour and alignment, vision can continue to improve for many months.

Together the findings from these models provide a novel explanation for the phenomenon of retinal grayness and the mechanism of visual loss due to detachment. Further work will be required to validate the results in vivo. Improved visual outcome in detachment surgery will require improved understanding of the optics of the detached retina and means to enhance photoreceptor realignment. Optical “tweezers”12 may be one means to address this problem.

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Corresponding author and reprints: Thomas W. Gardner, MD, MS, Department of Ophthalmology, Pennsylvania State University, 500 University Dr, H097, Hershey, PA 17033 (e-mail: tgardner@psu.edu).

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