Optical quality of the eye lens surfaces from roughness and diffusion measurements

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The Purkinje-Sanson images and the image of the anterior lens surface, formed by coherent light, are studied in this paper. The roughness and the diffusing behavior of the anterior lens surface are studied by two complementary methods: measurement of the scattering halo in the third Purkinje image and speckle-contrast measurements in the image of the anterior surface (lens epithelium). The scattering properties of the anterior lens surface are represented by an equivalent Gaussian diffusing surface defined by the standard deviation of the surface height, $\sigma_h = 0.143 \mu\text{m}$, and the correlation length, $r_0 = 7 \mu\text{m}$. The relative contribution of this surface to the intraocular scattering has been evaluated, and it depends strongly on the age of the subjects.

INTRODUCTION

The Purkinje-Sanson images, formed by reflection in the optical surfaces of the eye, have been known for a long time.¹ They have been used to evaluate geometrical parameters such as curvature radii, angles, and positions, and also they have been used to study the changes in these parameters with accommodation^{2,3} and night myopia,⁴ and, more recently, to study ocular movements⁵ and the evolution of refractive indices of the lens with the age.⁶ The major advantage of the Purkinje images is that nondestructive *in vivo* measurements can be made, although in those applications only measurements based on paraxial optics and on relative positions and magnifications are made. In this sense quantitative studies of their internal structures have not been carried out.

It is well known that the third and the fourth Purkinje images, formed by reflection in the anterior and the posterior lens surfaces, respectively, differ greatly in appearance. The third Purkinje image is diffuse and shows a speckled structure, whereas the fourth image is practically specular.⁷ This fact is explained by the different anatomical structure of both lens surfaces. The anterior lens surface is covered by the subcapsular lens epithelium, whereas the posterior surface is in direct contact with the smooth fibers of the lens.^{8,9} Thus the diffuse nature of the reflection on the anterior lens surface should be attributed to the roughness of the epithelium surface.

In this paper an objective method for the study of the optical quality of the eye lens surfaces is proposed. A point source is used to obtain, by photographic recording, the point-spread function (PSF) of the optical surfaces of the eye acting as catadioptrics. At the same time, coherent images of the anterior lens surface (lens epithelium) are obtained and studied.

After a preliminary qualitative study of the coherent Purkinje images, the diffusing behavior of the lens epithelium is studied by two complementary methods: measurement of the scattering halo in the third Purkinje image and speckle-contrast measurements in the image of the lens epithelium. For this purpose, the diffusing behavior will be characterized by a Gaussian surface that would produce the same

scattering halo as the lens epithelium. By applying the Beckmann theory of scattering of electromagnetic waves from rough surfaces,¹⁰ the roughness parameters of this equivalent Gaussian diffuser are determined. This artifice is used to give a simple description of the structure of the anterior lens surface that is actually likely to be more complicated.

RECORDING AND MEASURING SYSTEMS

The photographic recording system is represented in Fig. 1. A 4-mW He-Ne laser filtered and expanded by a spatial filter (SF) is collimated by a lens (L). The beam illuminates the fixed eye under an angle $\theta = 30^\circ$ to avoid overlapping of the Purkinje images. The light reflected in the optical surfaces of the eye is focused onto a photographic film by the imaging lens (IL), which is a standard photographic objective 50 mm $F/2$. It has been reversed in order to obtain a better optical quality when magnifications greater than 1 are used (usually $4.5\times$). The imaging lens and the camera are moved together to focus without changing the magnification. In this way it is easy to focus different planes, such as the anterior lens surface or each Purkinje image. The line of sight and the accommodation are fixed by a test, which is placed off axis to compensate the extra-axial position of the fovea. A high-density neutral filter (NF) is used to avoid eye damage. This filter, controlled by the camera, is removed only during exposure time (1/125–1/30 sec). The radiant power entering into the eye during the exposure time is 2 mW/cm^2 . This power is reduced to $2 \mu\text{W/cm}^2$ by the neutral filter, except during the exposures. The shutter (S) acts as an additional safety element and is released after the camera shutter to avoid speckle blurring due to vibrations of the camera body.

The photographic film (Kodak Technical Pan Film 2415) is previously pre-exposed in such a way that linear conditions are ensured. The measurements on the film have been made by a computer-controlled microdensitometer, programmed to make automatic measurements and computations, in such a way that scattering-halo or speckle-contrast values are obtained directly, depending on the case. For the

Fig. 1. Experimental system for the recording of the Purkinje images in coherent light: SF, spatial filter; NF, neutral-density filter; S, shutter; L, collimator; IL, imaging lens; C, camera. κ is the angle between the optical axis and the line of sight.

speckle-contrast measurements, a previous polynomial fitting is made to avoid possible errors caused by a nonuniform illumination.

PRELIMINARY RESULTS

Figure 2 shows typical records corresponding to a young subject. Images a) and b) have been obtained by focusing on

the anterior surface of the lens (epithelium) and correspond to very close focusing planes, although differences between them can be observed. The first and the second Purkinje images can be seen on the left; the first is very bright and partially masks the second Purkinje image. In the middle of Figs. 2a) and 2b) the lens epithelium appears as a rough surface and it looks like ground glass (the suture lines can also be observed). The fourth Purkinje image, on the right of these figures, is specular but shows some "defects" that could be attributed to the suture lines from the posterior surface. Astigmatism is present in these images, since the recording has been made off axis. Figures 2c) and 2d) show the third Purkinje image. This image is virtual and is placed in a posterior plane inside the vitreous. For this reason the first Purkinje image, which is 2 orders of magnitude brighter, is defocused and appears as a bright circle on the left in these figures. Both figures correspond to very close focusing planes: c) is at the best image plane and d) at the sagittal focus. Figure 3 shows the Purkinje images for a 57-year-old subject. In this case, a striated halo, produced by diffusion on the inner layers of the lens, appears. The contrast and the quality of the image of the lens epithelium are now very poor [Fig. 3a)]; the degradation of the images is mainly due to the blurring produced by the light scattered inside the lens.

The first and the fourth Purkinje images can be considered specular images, whereas the second and the third are diffuse. The first image is specular because, in spite of the roughness of the corneal epithelium, the reflection takes place in the surface of the tear layer that covers the anterior surface of the cornea. The second Purkinje image, on the

Fig. 2. Photographic records showing the Purkinje images and the image of the anterior lens surface. Subject MI (25 years old). Original magnification 4.5 $\times$. a) and b) show the first, second, and fourth Purkinje images and the anterior lens surface. c) and d) show the third Purkinje image. The brightest circle on the left is the defocused first image.

Fig. 3. Photographic records with the Purkinje images and with the image of the anterior lens surface. Subject AP (57 years old).

contrary, is diffuse because of the roughness of the corneal endothelium. The study of this image is difficult, because it is partially masked by the first Purkinje image, which is 2 orders of magnitude brighter.⁷ The third and the fourth images are also different. The posterior surface of the lens is smooth since there is no epithelial layer, and both capsula and lens fibers are smooth.⁹ On the contrary, the rough nature of the anterior lens surface is clearly visible in Figs. 2a) and 2b). In consequence, the study in what follows will be centered on the determination of the roughness and the diffusing behavior of the anterior lens surface.

ROUGHNESS OF THE ANTERIOR LENS SURFACE

The roughness and the diffusing characteristics of the anterior lens surface has been studied by two complementary methods. The first method, based on the measurement of the scattering halo of the third Purkinje image, will allow a determination of the roughness of the equivalent Gaussian surface that would produce the same scattering halo as the anterior surface. This equivalent diffuser is used to represent, in a simple way, the probably more complicated structure of the actual surface. In fact, effects such as small refractive-index discontinuities or multiple scattering could be present, and, on the other hand, the probability density function of the profile of the anterior lens surface could be non-Gaussian. To obtain more information about how the roughness of the equivalent diffuser relates with that of the actual surface, speckle-contrast measurements are also made.

The diffusing behavior of a rough surface is characterized

by the first- and second-order statistics of its profile, which are defined by the probability density function (PDF) and the autocorrelation function, respectively.¹⁰ A rough surface is Gaussian when its PDF is Gaussian; then the first-order statistics (PDF) are determined by a single parameter, the height variance σ_h^2 . In the same way, the autocorrelation function is defined by the correlation length r_0 , whether that function is Gaussian or exponential. These parameters, the height variance (or its square root σ_h) and the correlation length r_0 , represent the roughness and the mean grain radius of the surface, respectively.

Measurement of the Scattering Halo of the Third Purkinje Image. Equivalent Gaussian Diffuser

The scattering halo of the third Purkinje image is obtained by microdensitometric measurement of the photographic recordings. The measurements (see Fig. 4) show that the third Purkinje image has a Lorentzian intensity distribution modulated by a random distribution (speckle) and that the specular component is masked by the scattering halo.

To obtain the roughness of the equivalent Gaussian diffuser, we have applied a reformulation of the Beckmann theory of scattering of electromagnetic waves from rough surfaces.¹¹ The Beckmann model gives the mean intensity distribution at the focal plane of a collecting lens for the light scattered from Gaussian surfaces.

In our case, the third Purkinje image is the intensity distribution at the focus plane of the anterior lens surface, acting as a diffusing conical reflector. Hence the anterior lens surface acts as the diffusing surface and as the collecting optical system at the same time. The imaging lens (IL) is used to reimage the virtual image formed by the anterior lens surface in a plane outside the eye. The curvature of the anterior lens surface causes the focusing of the light and generates aberrations in such a way that the third Purkinje image is the result of the convolution of the scattering halo, which is due to the roughness of the anterior lens surface, with the aberrated PSF of the conical surface. As we have mentioned above, the astigmatism is the most important aberration in this case, the spreading of the image being different depending on the focusing plane [see Figs. 2c) and 2d)]. To minimize the spreading that is due to the astigmatism, the measurements of the intensity distribution have been made transversely on the sagittal focus plane.

Fig. 4. Typical intensity distribution of the third Purkinje image in arbitrary units.

Table 1. Half-Width of the Third Purkinje Image and Roughness of the Equivalent Gaussian Diffuser^a

Subject	Age (yrs)	Half-Width (μm)	Roughness σ_h (μm)
IG	23	108.5 $\pm$ 2.3	0.11 $\pm$ 0.0275
JC	24	153 $\pm$ 3.3	0.155 $\pm$ 0.0388
VR	24	132 $\pm$ 8	0.134 $\pm$ 0.0335
MI	25	134 $\pm$ 10	0.136 $\pm$ 0.034
FC	25	147 $\pm$ 9.5	0.149 $\pm$ 0.0373
PA	30	148 $\pm$ 5.5	0.15 $\pm$ 0.0375
JM	30	115 $\pm$ 3	0.116 $\pm$ 0.029
CM	30	148 $\pm$ 7.7	0.15 $\pm$ 0.0375
JV*	32	251 $\pm$ 35	0.254 $\pm$ 0.0635*
MG	32	152 $\pm$ 5.5	0.155 $\pm$ 0.0388
AM	37	115 $\pm$ 9	0.116 $\pm$ 0.029
JB	37	148 $\pm$ 9	0.15 $\pm$ 0.0375
JS	37	137 $\pm$ 37	0.14 $\pm$ 0.035
AA	40	139 $\pm$ 1	0.14 $\pm$ 0.035
AP	57	160 $\pm$ 5.8	0.16 $\pm$ 0.04
LI	58	172 $\pm$ 7	0.174 $\pm$ 0.0435
LP	59	142 $\pm$ 16	0.144 $\pm$ 0.036
SC	59	158 $\pm$ 5.5	0.16 $\pm$ 0.04

^a Asterisks denote amblyopic eye.**Table 2. Averaged Equivalent Epithelium Roughness**

Subject Age (yrs)	Roughness σ_h (μm)
23–25	0.1366 $\pm$ 0.017
30–32	0.143 $\pm$ 0.018
37–40	0.1365 $\pm$ 0.014
57–59	0.16 $\pm$ 0.012

The roughness is determined by adjusting the experimental and theoretical halos. The best fit was found when a exponential for the autocorrelation and the very rough surface approximation ($K^2\sigma_\psi^2 \gg 1$) were assumed. With these assumptions, the mean intensity distribution has been calculated by following the Chandley–Welford reformulation¹¹ of the Beckmann model and using an exponential autocorrelation function instead of the Gaussian function used by them. For the case of rotational symmetry the mean intensity distribution is as follows:

$$\langle I(\rho) \rangle \simeq A^2 \frac{2\pi r_0^2}{S k^2 \sigma_\psi^2} \frac{1}{\left(1 + \frac{r_0^2 \rho^2}{\sigma_\psi^2 f'^2}\right)^{3/2}}, \quad (1)$$

where A is a constant, S is the pupil area, f' is the focal length of the Fourier-transforming lens, k is the wave number, ρ is the spatial radial coordinate, and $k^2\sigma_\psi^2 = 4k^2n^2 \cos^2 \theta \sigma_n^2$ is the phase variance (n is the refractive index and θ the incidence angle). So the roughness (or σ_h) can be computed by the expression

$$\sigma_h = \frac{r_0 \delta}{n \cos \theta f'}, \quad (2)$$

where δ is the half-width of the experimental halo. The correlation length is assumed to be the mean radius of the epithelial cells ($r_0 = 7 \mu\text{m}$),^{8,9} and the refractive index $n = 1.3374$ and focal length $f' = 6.34 \text{ mm}$ are taken from the

Gullstrand–Le Grand theoretical eye.⁷ The angle of incidence is 30° .

The equivalent epithelium roughness has been measured for 18 subjects (see Table 1) distributed among four different age groups; $\sigma_h = 0.143 \mu\text{m}$ was obtained as the mean value. Note that $\sigma_h \simeq \lambda/4$ for the middle wavelength of the visible spectrum. The uncertainties (errors) attributed to σ_h in Table 1 have been estimated by considering the maximum deviation of the five parameters involved in the computation. The parameters δ and θ have been directly measured in each case; thus their uncertainties are due to measurement errors; however, the uncertainties of r_0 , f' , and n have been estimated from anatomical statistical deviation. The following formula was used to compute the total error (convolution of Gaussian errors):

$$\Delta_{\sigma_h}^2 \simeq \Delta_{r_0}^2 + \Delta_{f'}^2 + \Delta_{\delta}^2 + \Delta_{\cos\theta}^2 + \Delta_n^2, \quad (3)$$

where Δ is the percentage of the uncertainty. The values used in the computation are $\Delta_{r_0} = 21\%$ from $r_0 = 7 \pm 1.5 \mu\text{m}$ (Ref. 8); $\Delta_{f'} = 14.2\%$ from $f' = 6.34 \pm 0.9 \text{ mm}$ (Ref. 7); $\Delta_n = 1\%$ (estimated); $\Delta_{\cos\theta} = 2.5\%$ from $\theta = 30 \pm 2^\circ$; and Δ_{δ} (calculated from the values of Table 1). The computed upper limit of the uncertainty is $\Delta_{\sigma_h} = 25\%$. In fact, all values in Table 1 fall within the interval 0.143 ± 0.033 ($\Delta_{\sigma_h} = 23\%$), except that for the amblyopic eye (subject JV). Moreover, if the subjects are grouped according to their ages (Table 2), the statistical deviation is about 10% for middle-aged subjects, increasing for the younger and decreasing for the older. Table 2 shows the average roughness for the four groups; the uncertainties of the table are statistical deviations. Roughness seems to increase slowly with subject's age; however, the differences are not statistically significant. The amblyope (subject JV) is the only one who shows a significant difference with respect to the others, and so he was not considered within the average roughness was computed.

Speckle-Contrast Measurements

The above results correspond to the equivalent Gaussian diffuser. However, the actual subcapsular lens epithelium is in contact with the lens capsula, which could flatten the peaks so that the actual PDF could be non-Gaussian but asymmetrical. Also, the structure of the anterior lens surface is more complicated. In this way the speckle-contrast measurements will provide additional information about

Fig. 5. Speckle-contrast measured in the image of the anterior lens surface versus the radius of the PSF of the imaging lens. Dashed curves are plotted from the experimental values of Table 3. The solid line shows the expected values for the equivalent Gaussian diffuser.

Table 3. Speckle-Contrast Measurements

Subject	Radius of the PSF (μm)				
	6	8.58	10.73	15.33	24.17
IG (23 yrs)	0.67 ± 0.07	1 ± 0.22	1.1 ± 0.18	1 ± 0.13	1.2 ± 0.28
JS (37 yrs)	0.6 ± 0.09	0.8 ± 0.1	0.83 ± 0.14	0.74 ± 0.67	1 ± 0.1
AP (57 yrs)	0.53 ± 0.09	0.59 ± 0.18	0.72 ± 0.16	0.7 ± 0.1	0.62 ± 0.17

epithelium roughness so that we can estimate how the equivalent Gaussian diffuser and the actual lens surface are related.

Speckle contrast on the image of a diffusing surface is defined as the standard deviation of the image intensity normalized to the mean intensity, and it depends on the surface roughness (surface-profile statistics) and on the aperture of the imaging lens.^{12,13} Speckle contrast on the image of the lens epithelium was measured after the measuring system was calibrated with a set of diffusers. Both diffusers and lens-epithelium images have been recorded and measured under the same conditions. In both cases the radius of the PSF of the experimental points has been computed as 1.22λ (numerical aperture) for each position of the stop diaphragm of the imaging lens. The calibration described in Appendix A includes speckle contrast for asymmetric diffusers, with flattened peaks, as is expected for the epithelium.

The calibration shows that (see Appendix A) (a) for the same roughness, diffusers with asymmetrical PDF's show greater speckle contrast than the Gaussian ones, (b) speckle contrast increases with asymmetry, and (c) the most asymmetrical diffuser shows greater speckle contrast than the roughest one. It follows that speckle contrast has a stronger dependence on the asymmetry of the PDF than on surface roughness. Figure 5 shows the speckle contrast versus the radius of the PSF of the imaging lens for three subjects of different ages: Subject IG, 23 years; subject JS, 37 years; and subject AP, 57 years of age. The expected curve for the mean equivalent Gaussian diffuser ($\sigma_n = 0.143 \mu\text{m}$, $r_0 = 7 \mu\text{m}$) has been extrapolated from the calibration data and is also included in the figure (solid line) for comparison purposes. Dashed curves have been plotted from the experimental values of Table 3. The experimental values and the measurement errors are not included in the figure for the sake of simplicity. The speckle contrast decreases with the subject's age. This should be attributed to the image blurring produced by the increase of scattered light inside the lens (compare Figs. 2 and 3) rather than to a structural change of the anterior lens surface. On the other hand, young and middle-aged subjects show considerably greater speckle contrast than the expected value, in the same way as is found in asymmetrical diffusers. This added to the fact that the capsula could flatten the peaks of the epithelium suggests that this surface is not Gaussian but is instead asymmetrical. The effect of the capsula would be similar to the flattening of the peaks caused to the 800P ground glass by incomplete repolishing (see Appendix A).

RELATIVE CONTRIBUTION OF THE ANTERIOR LENS SURFACE TO THE INTRAOCULAR SCATTERING

The equivalent roughness of the lens epithelium has been obtained by measuring the backscattering. In this section

the scattering in the forward direction is estimated, and its influence on the retinal image analyzed.

The scattering properties of a rough surface are quite different if they are studied by transmission (forward scattering) or by reflection (backscattering). The phase variance is different in both cases. When the incidence is normal ($\theta = 0^\circ$), it is related with the height variance by the expression:

$$k^2 \sigma_\psi^2 = \begin{cases} 4k^2 n^2 \sigma_h^2, & \text{reflection} \\ k^2 (n' - n)^2 \sigma_h^2, & \text{transmission} \end{cases} \quad (4)$$

To compute σ_ψ for the anterior lens surface, let us assume that $n = 1.3376$ (refractive index of the aqueous⁷) and $n' = 1.38$ (refractive index of the external layers of the lens⁷). Since the mean equivalent roughness is $\sigma_h = 0.143 \mu\text{m}$, it follows that $\sigma_\psi^{\text{reflection}} = 0.389 \mu\text{m}$ and that $\sigma_\psi^{\text{transmission}} = 0.006 \mu\text{m}$. It can be noted that, for $\lambda = 0.55 \mu\text{m}$, in the case of reflection $k^2 \sigma_\psi^2 = 30$ (very rough surface), whereas in the case of transmission $k^2 \sigma_\psi^2 = 0.0047$ so that the slightly rough surface approximation can be applied. The mean intensity distribution for the light scattered from a slightly rough surface with exponential autocorrelation function is given by the expression¹¹

$$\langle I(\rho) \rangle \simeq A^2 \exp(-k^2 \sigma_\psi^2) \times \left[F_0(\rho) + \frac{2\pi r_0^2 k^2 \sigma_\psi^2}{S} \frac{1}{\left(1 + \frac{k^2 r_0^2 \rho^2}{f^2}\right)^{3/2}} \right], \quad (5)$$

where $F_0(\rho)$ is the PSF (specular component) of the imaging lens. The factor $\exp(-k^2 \sigma_\psi^2)$ is the fraction of nonscattered light, and it results from the computed value of σ_ψ that only a 0.36% of the incident light is scattered by the anterior lens surface. This fraction of light causes the scattering halo [second term of expression (5)].

To estimate the relative influence of the anterior lens surface to the intraocular scattering, the phase variances, obtained by fitting two experimental veiling glare functions (Le Grand¹⁴ and Walraven¹⁵) with the Lorentzian function of expression (5),¹⁶ are compared with our transmission phase variances. The relative influence is evaluated by using the fact that the diffusing behavior of a composite diffuser is equal to that of a diffuser whose phase variance is the sum of the phase variances of the components $k^2 \sigma_\psi^2 = \sum k^2 \sigma_{\psi_i}^2$.¹⁷ Thus we estimate the relative contribution of the anterior lens surface to the intraocular scattering as the percentage of the phase variances. The phase variance computed from Le Grand's veiling glare function ($\sigma_\psi = 0.025 \mu\text{m}$) (Ref. 16) that corresponds to a young subject (less than 30 years old) (Ref. 14) is compared with our results from young subjects ($\sigma_\psi = 0.0047 \mu\text{m}$), and it results that the relative contribution of the anterior surface is about 3.5%. The phase variance corresponding to the veiling glare from the

results of Walraven ($\sigma_\psi = 0.05 \mu\text{m}$) (Ref. 16) has been used as representative of a mean eye and has been compared with our mean result ($\sigma_\psi = 0.006$). In this case the relative contribution is about 1.5%. This shows that the relative contribution of the anterior lens surface to the intraocular scattering decreases with the subject's age. This seems reasonable since the scattering inside the lens increases markedly, whereas the roughness of the anterior lens surface remains almost constant.

SUMMARY AND CONCLUSIONS

An objective and nondestructive method for the study of the diffusing behavior of the eye lens surfaces, based on the recording and measurement of the light reflected by the lens surfaces, is presented in this paper. Preliminary results have confirmed that the posterior lens surface is smooth, except for the suture lines, and that the anterior surface looks like ground glass with its corresponding diffuse Purkinje image.

The roughness and diffusing behavior of the anterior lens surface have been studied by measuring the scattering halo of the third Purkinje image and the speckle contrast of the image of the anterior lens surface (lens epithelium). The results show that the PDF is not Gaussian but asymmetrical. This seems reasonable because the capsula, which covers the lens, flattens the peaks of the surface.

In order to represent the scattering properties of the anterior lens surface in a simple way, an equivalent Gaussian rough surface has been considered. The equivalent roughness is $\sigma_h \approx \lambda/4$ for the central wavelength of the visible spectrum. In spite of this high value, the influence of the scattering produced by this surface on the retinal image is small, because the refractive indices involved are quite similar. The relative contribution of the anterior lens surface to the intraocular scattering has also been estimated, and it seems to depend markedly on the subjects' age. The estimation gives a relative contribution of about 3.5% for young subjects (23–25 years) and about 1.5% for middle-aged subjects (30–40 years).

Finally, the result obtained with an amblyope (roughness almost double than in normal eyes) suggests that it could be a direct relation between anterior lens roughness and visual-acuity deficiencies. However, further studies with amblyopes are needed to verify such a relation.

APPENDIX A: SPECKLE-CONTRAST CALIBRATIONS

The experimental system for speckle-contrast measurements has been calibrated by a set of ground-glass diffusers. The PDF and the autocorrelation function of each diffuser have been obtained by a computer-aided profilometer. Table 4 shows the roughness characteristics of six diffusers; four of them (Samples 800SA, 600SA, 500SA, and 400SA) have symmetrical, bell-shaped PDF's (Gaussian), and by contrast, the 800A and 800P diffusers have asymmetrical PDF's. As a measure of asymmetry, Pearson's skewness (defined as the difference between the mean and the maximum of the PDF) normalized to the standard deviation is also shown in the table. The asymmetrical diffusers were obtained by incomplete repolishing of 800-type ground glasses, so that the peaks were flattened. The 800A ground

Table 4. Roughness Characteristics of the Ground Glasses

Diffuser	σ_h (μm)	r_0 (μm)	Skewness of the PDF	
800SA	0.37	5.75	0.0442	(Gaussian)
600SA	0.385	6.6	0.03	(Gaussian)
500SA	0.58	7.3	-0.032	(Gaussian)
400SA	1.3	8.8	0.0056	(Gaussian)
800A	0.28	5.6	-0.225	(Small asymmetry)
800P	0.22	6.4	-0.673	(Strong asymmetry)

Fig. 6. Speckle contrast versus the radius of the PSF of the imaging lens for Gaussian diffusers.

Fig. 7. Speckle contrast versus the radius of the PSF of the imaging lens, corresponding to a Gaussian diffuser (800SA), to a slightly asymmetrical diffuser (800A), and to a very asymmetrical diffuser (800P).

glass was repolished during a very short time (small asymmetry) and the 800P during a longer time (strong asymmetry). The characteristics of the diffusers are given in Table 4, where the effect of the polishing in the 800 type diffusers can be noted. The roughness σ_h decreases and the asymmetry of the PDF increases after polishing.

After the mechanical contact measurements, the ground-glass diffusers were photographed and measured under the same conditions and with the same apparatus as the anterior lens surface. Figures 6 and 7 show the speckle contrast versus the radius of the PSF of the imaging lens for the six diffusers of the Table 4. The curves of Fig. 6 correspond to the 600SA, 500SA, and 400SA Gaussian diffusers and those of Fig. 7 to the 800-type diffusers. The figures represent the curves that have been plotted from the experimental measurements, and the experimental points and errors are shown in Table 5; these are omitted from the figures for the sake of simplicity. It can be appreciated that the speckle contrast increases with the roughness and with the asym-

Table 5. Speckle Contrast of the Ground Glasses

Diffuser	Radius of the PSF (μm)					
	6	8.58	10.73	15.33	24.17	33.53
800SA	0.4 $\pm$ 0.06	0.48 $\pm$ 0.03	0.54 $\pm$ 0.03	0.66 $\pm$ 0.05	0.66 $\pm$ 0.04	0.84 $\pm$ 0.03
600SA	0.39 $\pm$ 0.05	0.51 $\pm$ 0.03	0.52 $\pm$ 0.04	0.64 $\pm$ 0.01	0.76 $\pm$ 0.065	0.08 $\pm$ 0.076
500SA	0.465 $\pm$ 0.01	0.54 $\pm$ 0.066	0.65 $\pm$ 0.085	0.79 $\pm$ 0.07	0.87 $\pm$ 0.08	0.97 $\pm$ 0.03
400SA	0.61 $\pm$ 0.07	0.65 $\pm$ 0.04	0.74 $\pm$ 0.04	0.92 $\pm$ 0.06	0.98 $\pm$ 0.02	0.1 $\pm$ 0.15
800A	0.56 $\pm$ 0.01	0.67 $\pm$ 0.05	0.73 $\pm$ 0.04	0.79 $\pm$ 0.05	0.99 $\pm$ 0.02	1.03 $\pm$ 0.07
800P	1.2 $\pm$ 0.29	1.39 $\pm$ 0.06	1.29 $\pm$ 0.15	1.16 $\pm$ 0.05	1.16 $\pm$ 0.09	0.97 $\pm$ 0.12

metry of the PDF. The 800P diffuser with the smallest roughness shows greater speckle contrast than even the roughest 400SA diffuser. There is a strong dependence of the speckle contrast on the asymmetry of the PDF of the diffusing surfaces. For equal roughness, higher speckle contrast must be expected in asymmetrical diffusers.

REFERENCES

1. M. Tscherning, *Optique Physiologique* (Carré et Naud, Paris, 1898); English translation, *Physiological Optics* (Keystone, Philadelphia, Pa., 1904).
2. E. F. Fincham, *The Mechanism of Accommodation* (Pullman, London, 1937).
3. A. Ivanoff, *Les Aberrations de l'Oeil* (Massou, Paris, 1953).
4. J. M. Otero and M. J. Aguilar, "La acomodación en la miopía nocturna," *An. R. Soc. Esp. Fis. Quím. Ser. A*, **49**, 127-129 (1953).
5. T. N. Cornsweet and M. D. Crane, "Accurate two-dimensional eye tracker using first and fourth Purkinje images," *J. Opt. Soc. Am.* **63**, 921-928 (1973).
6. M. Millodot and I. A. Newton, "A possible change of refractive index with age and its relevance to chromatic aberration," *Albrecht von Graefes Arch. Klin. Exp. Ophthalmol.* **201**, 159-167 (1976).
7. Y. Le Grand and S. G. El Hage, *Physiological Optics* (Springer-Verlag, Berlin (1980).
8. S. Duke-Elder and K. C. Wybar, *System of Ophthalmology*, Vol. II of *The Anatomy of the Visual System* (Kimpton, London, 1961).
9. R. C. Tripathi and J. B. Tripathi, "Morphology of the normal, aging, and cataractous human lens. I. Development and morphology of the adult and aging lens," *Lens Res.* **1&2**, 1-42 (1983).
10. P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces* (Pergamon, London, 1963).
11. P. J. Chandley and W. T. Welford, "A re-formulation of some results of P. Beckmann for scattering from rough surfaces," *Opt. Quantum Electron.* **7**, 393-397 (1975).
12. J. W. Goodman, "Dependence of image speckle contrast on surface roughness," *Opt. Commun.* **14**, 324-327 (1975).
13. H. Fujii, T. Asakura, and Y. Shindo, "Measurement of surface roughness properties by using image speckle contrast," *J. Opt. Soc. Am.* **66**, 1217-1222 (1976).
14. Y. Le Grand, "Recherches sur la diffusion de la lumière dans l'oeil humain," *Rev. Opt.* **16**, 240-266 (1937).
15. J. Walraven, "Spatial characteristics of chromatic induction; the segregation of lateral effects from straylight artifacts," *Vision Res.* **13**, 1739-1753 (1973).
16. R. Navarro, "Incorporation of intraocular scattering in schematic eye models," *J. Opt. Soc. Am. A* **2**, 1891-1894 (1985).
17. P. Beckman, "The scattering of electromagnetic waves from rough surfaces," in *Progress in Optics VI*, E. Wolf, ed. (North-Holland, Amsterdam, 1967), pp. 53-69.