Optical density of the human lens

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Optic disk reflectance was measured from 27 normal observers with their physiological lenses (aged 21–74 yr) and from two pseudophakic observers (aged 69 and 70 yr) with use of a Utrecht fundus reflection densitometer. Psychophysical heterochromatic flicker photometric luminance matches (10° field) were obtained on the same group of the observers. A four-parameter model incorporating lens density, hemoglobin absorption, optic disk reflectance, and superficial stray light was used to fit the reflectometric data. A model incorporating lens density and the Judd revised spectral luminous-efficiency function was used to fit the psychophysical data. The lens-density spectrum used the two-factor aging model of Pokorny, *et al.* [Appl. Opt. **26**, 1437 (1987)]. The lens density for each normal observer was estimated through a least-squares fitting procedure yielding an estimated lens age. For the reflectometric data the observer's chronological age agreed with estimated lens age with a correlation coefficient of 0.92. The reflectometric regression line underestimated chronological age by approximately 5 yr. The mean reflectance of the optic disk was 0.047 with standard error of the mean of 0.0044. Data from the pseudophakic observers were well described when corneal density was used to replace lens density. The lens density was also estimated from the psychophysical data. The observer's chronological age agreed with psychophysically estimated lens age with a correlation coefficient of 0.92. It was concluded that the *in vivo* lens density can be estimated from the reflectance spectrum measured off the optic disk. The reflectance spectrum of the optic disk was inferred to be close to spectrally neutral. © 1997 Optical Society of America [S0740-3232(97)00705-9]

1. INTRODUCTION

The light incident on the cornea traverses the ocular media before it reaches the retina. The ocular media (cornea, lens, and optic humors) attenuate the light through the effects of reflection, absorption, and scattering. The cornea absorbs primarily in the ultraviolet.[1] It is considered age invariant.[2] Aqueous and vitreous humors are considered to have the spectral density of water. Thus most of the ocular media light loss is attributed to the lens absorption. Absorption in the crystalline lens is both wavelength and age dependent. The lens is relatively transparent to long-wavelength light but absorbs significantly at short wavelengths. The density of the lens increases with the age of the observer, with the greatest increase occurring in the short-wavelength region.[3–10] The accepted published media-density functions are derived from whole-eye measurements[10,11] and thus should be considered to include both the corneal and the lens spectral density. Nonetheless, the function is frequently termed the lens spectral-density function.

There are numerous studies of the age dependence of the lens. Raeder[12] suggested a linear relation between lens thickness and age, a concept finding some support.[13–15] Other studies from different disciplines contradicted this linear model. Zigman[16] compared the lens-weight curve of van Heyningen[17] with the lens-density curve of Zigman *et al.*[18] and noted that the two curves showed markedly different variation with age. He argued that lens growth and increase in lens absorption with age followed different time courses. Weale's excised lens data also showed that increase of absorption in the lens accelerated at older ages.[19] Weale proposed an exponential function to describe the data. Tan's[20] analysis suggested an early change in the ultraviolet in the first decades of life, attributed to lens growth, followed by a second change in the short-wavelength region, which could be ascribed to accumulation of pigment due to aging. Pokorny *et al.*[21] proposed a two-factor lens-density spectrum to describe the nonlinear course of lens aging. In this model, the total lens-density function was separated into two components, $TL_1(\lambda)$ and $TL_2(\lambda)$, to represent the adult aging and stable portions, respectively. Average spectral lens density could be estimated for adult observers aged 20–80 by equations incorporating the two spectra and age coefficients. Scattering was considered to have a negligible contribution to the $TL_1(\lambda)$ relative spectral density function.[21] The two-factor model has been found to fit the lens-density change with age better than do simple linear models.[22,23] The dual change of lens absorption seems rooted in the changes of the structure protein in the human lens. Two chromophores of human lens in the visible region have been identified: kynurenines and aged proteins. The amount of kynurenines remains nearly constant after the first decade, while the amount of the latter increases with age.[23]

The methods to measure the spectral-density function of the lens have included direct transmission of the excised lens.[4] Optical reflectance methods of the living lens have used either the Purkinje image[8,24] or retinal reflectance.[25,26] Psychophysical methods have included comparison of the spectral sensitivity of aphakic and phakic eyes,[3,5] comparison of scotopic spectral sensitivity with the rhodopsin spectrum,[14,20,27] color matching,[28–30] and photometric equality.[26]

In this study we compare two methods, retinal reflection from the optic disk and a heterochromatic flicker photometric match. A four-parameter model was developed to fit the optic disk reflectance data, and the lens age was estimated from the fitting parameters. The lens age was also estimated from the psychophysical match for the same observers. We compared the estimated lens age from the reflectometric data, the estimated lens age from the psychophysical data, and the observers' chronological age. We also made reflectance measurements on two pseudophakic patients to assess the reflectance spectrum of the optic disk.

2. MATERIALS AND METHODS

A. Observers

Twenty-seven human observers aged 22–74 yr participated in both the reflectometry study and the psychophysical study (see Table 1 for number of observers classified by age and gender). Fourteen were faculty, staff, and students at the Visual Sciences Center of the University of Chicago, and thirteen were recruited observers. In addition, measurements were conducted on two patients with pseudophakia. They (one female, 69 yr; one male, 70 yr) and the two oldest observers (70 and 74 yr) were referred by the Eye Clinic of the University of Chicago, Pritzker School of Medicine. The study protocol was approved by the University of Chicago Institutional Review Board, and written informed consent was obtained from all observers. One observer was later diagnosed as having cataract, and her data were not included in the results.

B. Experiment 1: Reflectometric Measurement of Optic Disk Reflectance

Apparatus: We used a Utrecht fundus reflection densitometer.[31] This device uses a chopper wheel to produce light pulses at different wavelengths for bleaching, measuring, and reference purposes. For this study the measuring wavelengths ranged from 430 to 740 nm. Acquisition was by means of a photomultiplier and photon-counting electronics and was computer controlled. Once per second, the number of counts collected was sent to the host computer by a microprocessor. Counts were encoded with wavelength as well as time information and were corrected for the dark output of the photomultiplier. The entrance aperture was a 0.8×1.1-mm rectangle, and the exit aperture was a semicircle 2.5 mm in diameter. The edges of the entrance and exit apertures were separated by 0.7 mm. The entrance and exit apertures were conjugate to the observer's pupil. We modified the densitometer for the purposes of our study by masking the inner side of the exit pupil, to separate the entrance and exit apertures so as to reduce the superficial stray light. The stimulus field size was 2.6°, and the measuring field size was 2.1°.

Calibration: The calibration included measurement of the light level, the fixation target position, and the reflection from an artificial eye. The latter measurement was used as a reference to translate measured counts from the real eye to a measured reflection value. The artificial eye had a surface coated with Kodak white diffusing paint and had no lens, thus avoiding problems with lens reflection and lens absorption. The internal stray light of the densitometer was also checked. The maximum retinal illumination for bleaching was 5.6 log photopic trolands (td). All wavelengths had stray light under 0.011% of the total measuring light after reflecting off the retina.

Measurement site: We measured reflectance at the optic disk to avoid contamination by macular pigment and melanin.[11] Only nonphotolabile ocular pigments might contribute to the reflectance that we measured, because photolabile pigments had been bleached away. These include the cornea, lens, optic humors, and hemoglobin. Hemoglobin is an important factor at the optic disk because of the presence of large retinal blood vessels.

Procedure: A half hour before the experiment started, one drop of 0.5% tropicamide was placed in the inner canthus of the observer's eye, and a mouth bite bar was made for the observer. The bite bar and a pair of temple pads were used during the experiment as an aid to immobilize the observer's head. The measurement started after the pupil was dilated to at least 6 mm. During the first several minutes of the experiment, observers were aligned under direct view of the optic disk. Three criteria were adopted to ensure a good alignment: (1) the measuring beam passed through the central part of the pupil; (2) the third Purkinje image was observed so that the light was focused at the anterior surface of crystalline lens; and (3) the measuring beam was directed at a region of minimum blood vessels. The actual measurement site at the optic disk varied among observers, ranging from 12° to 18° nasal of the fovea. Each measurement took 140 s. Data were saved between measurements, and during these periods observers could rest. Positioning was checked before the next measurement began. Occasionally, measurements were repeated if observers did not maintain fixation and/or blinking was excessive.

Table 1. Number of Observers Classified by Age and Gender

Age	Male	Female	Total
20–30	3	3	6
30–40	6	3	9
40–50	1	1	2
50–60	3	3	6
60–70	1	1	2
>70	2	0	2
Total	16	11	27

C. Experiment 2: Psychophysical Heterochromatic Flicker Photometric Match

The psychophysical method to estimate lens absorption used heterochromatic flicker photometry. The choice of the pair of wavelengths was optimized by three constraints: (1) similar absorption of macular pigment at the two wavelengths, (2) similar ratios of long-wavelength-sensitive to middle-wavelength-sensitive (L/M) cones at the two wavelengths to minimize the effect of individual differences in cone ratios,[32–34] and (3) separation of the two wavelengths to allow robust estimation of lens density. We chose wavelengths of 430 and 495 nm: The macular pigment spectrum has approximately equal density (0.365, 0.360) (Ref. 10), and the L/M ratios according to the Smith–Pokorny fundamentals[35] are similar (0.735, 0.637). Thus the wavelengths are close to being a tritanopic pair. Finally, these wavelengths are sufficiently separated to allow precise estimation of lens density.

Apparatus: We used a two-channel system. Channel I provided a test light of 495 nm, and channel II provided a reference light of 430 nm. The two channels were combined with a rotating bowtie-shaped front-surface mirror. The lights then passed through an integrating bar[36,37] and a 10° field stop.

Calibration: The interference filter spectra were calibrated in the apparatus with a laboratory-constructed spectroradiometer placed on the observer's side of the artificial pupil. A 500-nm filter was tilted to an appropriate position to achieve a wavelength of 495 nm. Both the test and reference lights had half-height bandwidths of 10 nm. The neutral-density wedge was calibrated at 38 angular positions by measuring the radiance of the test light with an EG & G Radiometer/Photometer (model 550). Data were used to generate a look-up table.

Procedure: The method of adjustment was used. The observers adjusted the luminance of the test light until the perception of flicker in the field was eliminated or minimized. The alternation rate was under observer control and was set to be between 15 and 18 Hz. Practice was allowed for naïve observers. Observers were instructed to view the center of the field. Five measurements were averaged.

3. MODELS

A. Models of Reflectometric data

The reflectance off the optic disk can be modeled by combining the lens density and the hemoglobin density with an estimate of disk reflectance and an estimate of superficial stray light. We considered three versions of the lens-density spectrum: (1) the two-factor lens-density spectrum of Pokorny *et al.*,[21] (2) Weale's[19] exponential lens aging model, and (3) Savage *et al.*'s[15] linear model. These models are discussed below. The hemoglobin spectrum was obtained from standard tables. The disk reflectance was assumed to be wavelength invariant. The superficial stray light is light reflected from the corneal surface and is similarly assumed to be wavelength invariant.

We used the following equation to fit the reflectometric density spectrum:

$$D(\lambda) = -\log\{p_4 + (1 - p_4)p_3/10^{[2p_1L(\lambda, A)+p_2H(\lambda)]}\}, \quad (1)$$

where $L(\lambda, A)$ is the lens-density function; $H(\lambda)$ is the hemoglobin spectrum;[38] and p_1, p_2, p_3, and p_4 are free parameters. The lens density in this equation is doubled because of the double pass of the light through the lens. For the four free parameters, p_1 is related to the observer's age in the lens-density function, p_2 is the amount of hemoglobin, p_3 is the reflectance of the optic disk, and p_4 represents superficial stray light. The hemoglobin spectrum $H(\lambda)$ is given by

$$H(\lambda) = 0.05\ \mathrm{Hb}(\lambda) + 0.95\ \mathrm{HbO_2}(\lambda), \quad (2)$$

where $\mathrm{Hb}(\lambda)$ and $\mathrm{HbO_2}(\lambda)$ are the extinction coefficients of hemoglobin and oxyhemoglobin, respectively.[39]

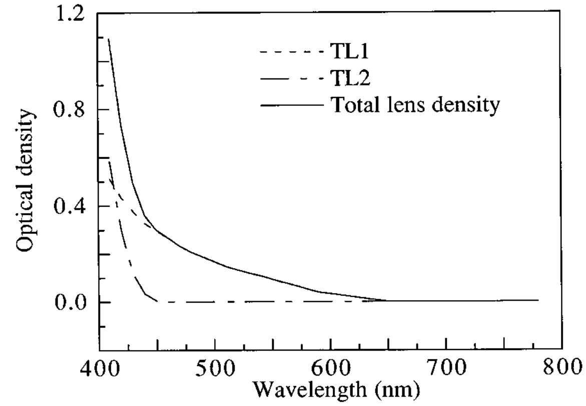

Fig. 1. Lens spectral density according to the two-factor lens-density model of Pokorny *et al.*[21]

The four parameters (p_1, p_2, p_3, p_4) in Eq. (1) were estimated with the Solver routine of Microsoft Excel, which minimizes the sum of the squared residuals of difference between data and model output. Thirteen measurement wavelengths (430–740 nm) were used to estimate the four parameter values; measurements at 380 and 410 nm were discarded because of poor signal-to-noise ratio.

1. *The Two-Factor Model*

Pokorny *et al.*[21] proposed a two-factor lens-density model that included age-independent and age-dependent components. One component, $TL_1(\lambda)$, representing the aging portion after the age of 20, was weighted to represent different ages. The second component, $TL_2(\lambda)$, represented the lens component that was stable after the age of 20. This component presumably includes the corneal spectral density. The total lens spectral density, $L(\lambda, A)$ was modeled as the sum of these two factors. Figure 1 shows the two factors and their sum as a function of wavelength; $TL_1(\lambda)$ is for a 32-year-old observer.

$$L(\lambda, A) = (\mathbf{k})[TL_1(\lambda)] + TL_2(\lambda), \quad (3a)$$

where $\mathbf{k}$ is a scalar, dependent on the observer's age. Experimental data[29] have shown that the rate of increase of lens density at a given wavelength after the age of 60 is approximately three times that at ages 20–59. Pokorny *et al.*[21] proposed that the scalar could be described by two functions: one corresponding to ages below 60 and a second for ages above 60:

$$\text{for } 20 < A < 60 \qquad \mathbf{k} = 1.00 + 0.02(A - 32),$$

$$\text{for } A > 60 \qquad \mathbf{k} = 1.56 + 0.0667(A - 60). \quad (3b)$$

When the two-component model is applied to Eq. (1), the free parameter p_1 replaces $\mathbf{k}$ in Eq. (3a).

2. *Exponential Model*

Weale[19] suggested that the lens density is exponentially related to the observer's age and linearly related to the lens density at birth:

$$L(\lambda, A) = L(\lambda, 0)\exp[\beta(\lambda)A], \quad (4)$$

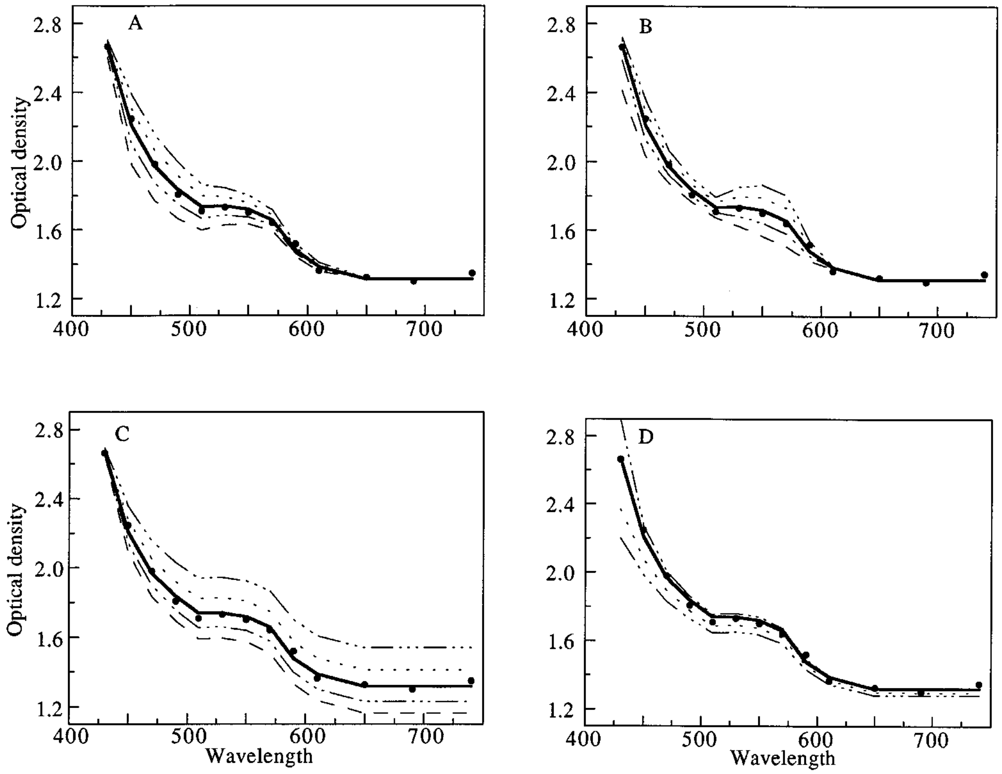

Fig. 2. Examples of model fits for the data of one observer. The model was Eq. (1) and the two-factor lens-density model. The four panels show the effects of varying one parameter around the best-fit value while the other three parameters are kept fixed. The best fit (solid curves) had the following parameter values: $p_1 = 1.25$, $p_2 = 0.017$, $p_3 = 0.047$, $p_4 = 0.002$. Broken curves from bottom to top in each panel: A, $p_1 = 0.75$, 1, 1.25 (fit value), 1.5, 1.75; B, $p_2 = 0.003$, 0.01, 0.017 (fit value), 0.024, 0.031; C, $p_3 = 0.067$, 0.057, 0.047 (fit value), 0.037, 0.027; D, $p_4 = 0.006$, 0.004, 0.002 (fit value), 0.001.

where $L(\lambda, 0)$ is the spectral density at birth, $\beta(\lambda)$ does not change very much with wavelength and has a dimension of year^{-1}, and A is the observer's age in years. The spectra of $L(\lambda, 0)$ and $\beta(\lambda)$ were read off graphs in Weale's paper; a tabulation is included in Ref. 19.

3. Linear Model

Savage *et al.*[15] proposed that lens density $L(\lambda, A)$ is linearly related to age:

$$L(\lambda, A) = [(A - 25.4)0.013 + 1]10^{[5.543-(0.013439\lambda)]}, \tag{5}$$

where A is the observer's age in years and λ is the wavelength in nanometers.

Figure 2 demonstrates the effects of the variation in each of the four parameters (p_1, p_2, p_3, and p_4), with use of the two-factor lens spectrum on the model output: The fit of the data with the model gave the estimates of the four parameters, and then one of the parameters was varied around the estimated value while the other three parameters were fixed at their estimated values (broken curves). The data (solid circles) in the four panels were from a 45-year-old male observer. The best fit (solid curves) had the following parameter values: $p_1 = 1.25$, $p_2 = 0.017$, $p_3 = 0.047$, $p_4 = 0.002$. Figure 2 shows that manipulation of the four parameters affects different spectral regions. The parameter p_1, for the aging component of the lens, affects the predictions below 550 nm. The factor p_2, for hemoglobin, has its major effect on the midspectrum plateau. The factor p_3, for overall reflectance, determines the long-wavelength asymptote, and the factor p_4, for superficial stray light, determines the limiting optical density at the short wavelengths.

B. Model of Psychophysical Data

For the Judd revised standard observer,[40] a luminance match between two wavelengths can be written:

$$P_e(495)V_J(495) = P_e(430)V_J(430) \tag{6}$$

where P_e refers to the radiance of the lights and $V_J(\lambda)$ refers to the Judd revised spectral luminous-efficiency function. For our choice of wavelengths that minimized both macular pigment and the L/M-cone ratio, an individual's sensation luminance $S_i(\lambda)$ can be related to the Judd revised observer by taking into account the difference in lens density between the Judd and the individual observer:

$$\log[S_i(\lambda)] = \log V_J(\lambda) + k_i[TL_1(\lambda)] - TL_1(\lambda). \tag{7}$$

Thus the individual scaling constant k_i can be derived from the sensitivity ratio at the match:

$$\begin{aligned}\log[S_i(495)/S_i(430)] &= \log[V_J(495)/V_J(430)] \\ &\quad + k_i[TL_1(495) - TL_1(430)] \\ &\quad - [TL_1(495) - TL_1(430)].\end{aligned} \tag{8}$$

The scaling constant is solved as

$$k_i = \{\log[S_i(495)/S_i(430)] - \log[V_J(495)/V_J(430)] + TL_1(495) - TL_1(430)\}/[TL_1(495) - TL_1(430)]. \quad (9)$$

C. Model for Reflectance Data from Pseudophakic Patients

When we modeled the reflectance data from normal observers, we made the assumption that the reflectance of the optic disk was spectrally neutral. To see whether the optic disk had a flat reflectance spectrum, we conducted a reflectance measurement on two pseudophakic patients. To fit the reflectance data from pseudophakic patients, we replaced the lens-density term in Eq. (1) with the sum of the corneal spectral density, $C(\lambda)$, and the density of the intraocular lens, IOL(λ). This change eliminates the free parameter, p_1.

$$D(\lambda, A) = -\log(p_4 + (1 - p_4)p_3/10^{\{2[C(\lambda) + \mathrm{IOL}(\lambda)] + p_2 H(\lambda)\}}) \quad (1a)$$

where $C(\lambda)$ was taken from the literature[1] and the IOL(λ) was estimated by measurement of an IOL provided by the manufacturer (IOLAB Intraocular lens, Model 4897B). The IOL was virtually transparent over most of the visible region. The density started to rise at wavelengths below 450 nm and reached high values in the near ultraviolet.

4. RESULTS

A. Reflectometric Data of Normal Observers

Figure 3 shows data for 26 observers. Raw optic disk reflectance data are expressed as density units. Each set of points shows data for one observer (solid circles). The solid curves running through the data are the fits from the four-parameter model incorporating the two-factor lens-density function (model 1). Both the data and the fits have been displaced vertically. Numbers within each panel are the chronological age of the observer (left) and the estimated lens age (right). Optical density was highest at short wavelengths and decreased to an asymptote at long wavelengths, with a plateau between 500 and 550 nm.

Figure 4 shows a scatter plot of the estimated lens ages plotted against the chronological ages. Panel A shows the estimated lens age from the model with the two-factor lens-density function; panel B shows estimated lens age from the linear lens-density model, and panel C shows the exponential lens-density model. Each data point represents one observer (solid circles). The dashed lines are 45° lines, and the solid lines are the linear regression lines. The correlation coefficients between the chronological and the estimated lens age were 0.92 (with the two-factor lens-density model), 0.87 (with the linear lens-density model), and 0.84 (with exponential lens-density model). The model incorporating the two-factor lens density underestimated chronological age by approximately 5 yr. The model with the linear lens density overestimated lens density in older observers and underestimated lens density in younger observers. The model with the expo-

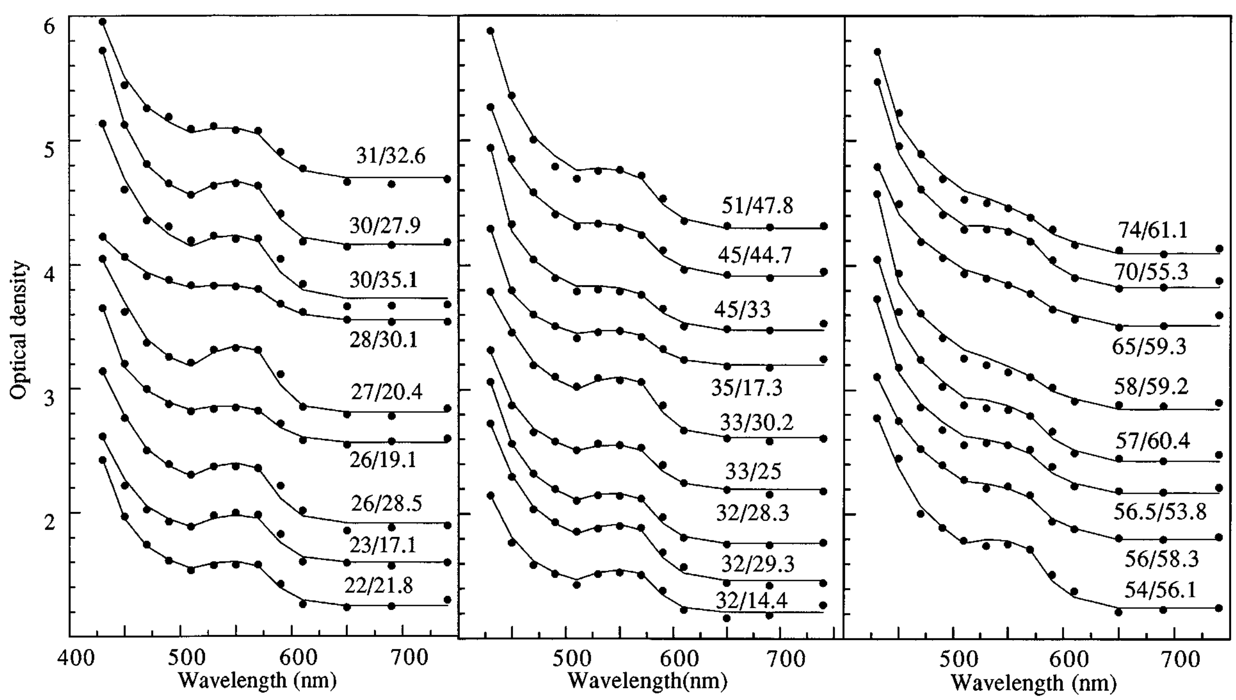

Fig. 3. Data and model fits for the 26 observers. Optic disk reflectance data are expressed as density units. Each panel shows data for one observer (solid circles). The solid curves are the fits from Eq. (1) with use of the two-factor lens-density function (model 1). Both the data and the fits have been displaced vertically for clarity. Numbers to the right of each curve give the chronological age of the observer (left) and the estimated lens age (right).

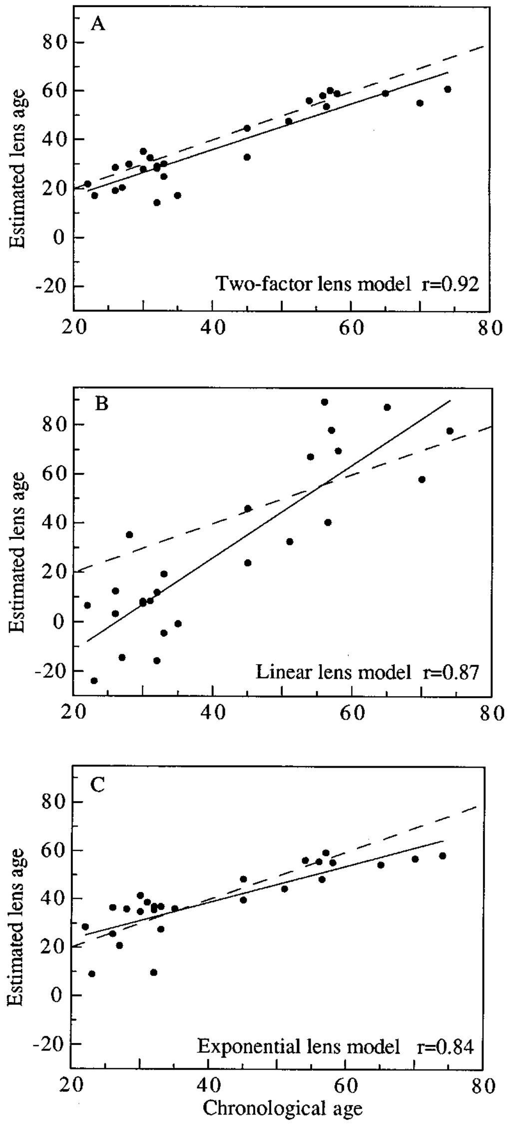

Fig. 4. Scatter plot of the lens age estimated from reflectance data versus the observer's chronological age. Solid lines show the linear regression. A, two-factor lens model; B, linear lens model; C, exponential lens model.

nential lens density overestimated lens density in younger observers and underestimated lens density in older observers by an amount comparable with that from the model with the two-factor lens density. We tested whether the absolute deviations of the estimated lens age from the chronological age by the three lens-density models were equal. First, the ominibus analysis-of-variance null hypothesis was rejected. This meant that at least one absolute deviation was different. The Fisher–Hayter test showed that the deviations by the two-factor lens-density model and the exponential lens-density model were not significantly different ($a = 0.05$), and both were significantly smaller than the deviation obtained with the linear lens-density model ($a = 0.05$).

Figure 5 shows the sum of squared residuals (SRS) from the models plotted against the chronological age. The three lines are linear regression lines: two-factor lens-density model (solid circles, solid line); exponential lens-density model (squares, dotted line); and linear lens-density model (open circles, dashed line). The SRS from the exponential model showed an increase with age (correlation coefficient 0.68). The other models did not have this tendency. Both the averaged SRS from the exponential model and the averaged SRS from the linear model are greater than the averaged SRS from the two-factor model.

The partial correlations among parameters in the model with the two-factor lens-density function were evaluated; the coefficients are shown in Table 2. The coefficients of the parameters and the chronological age are shown in the bottom line of the table. An asterisk indicates that the correlation between the two variables is significantly different from zero. The partial correlations among the four parameters, except p_1 with p_2 and p_1 with p_4, were low and not significant ($\alpha > 0.05$). The negative correlation ($r = -0.60$) between p_1 and p_2 suggests the hypothesis that the vascularity of the optic disk decreases with age. A similar significant partial correla-

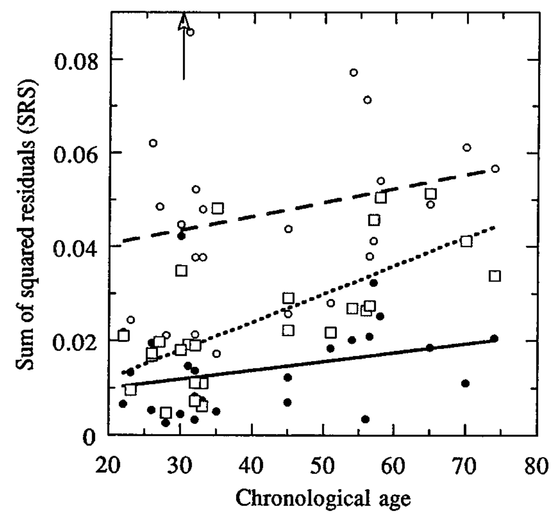

Fig. 5. SRS of the three models versus chronological age. Fit with the two-factor lens model (solid circles, solid line), $r = 0.18$; fit with the exponential lens model (open squares, dotted line), $r = 0.68$; fit with the linear lens model (open circles, dashed line), $r = 0.30$. The arrow indicates an SRS of 0.133 for the linear lens model, which is out of the display range.

Table 2. Correlation Coefficients among the Parameters in the Two-Factor Lens Model

	Parameter			
Parameter	p_1	p_2	p_3	p_4
p_1	—	−0.60*	0.14	−0.59*
p_2	—	—	−0.12	0.30
p_3	—	—	—	0.13
Chronological age	0.92	−0.69*	0.015	−0.71*

*Significant nonzero slope of the regression line from one parameter to another.

p_1, lens-density parameter; p_2, hemoglobin-density parameter; p_3, optical disk reflectance parameter; p_4, superficial stray light parameter.

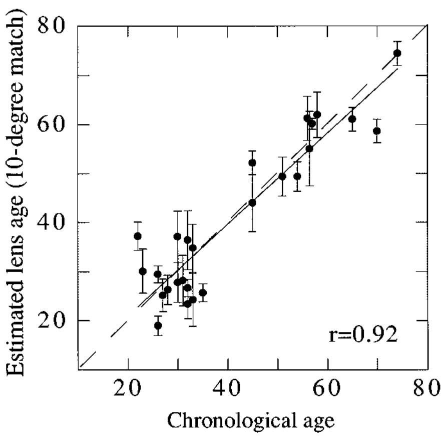

Fig. 6. Lens age estimated from the psychophysical match as a function of the observer's chronological age. The solid line shows the linear regression.

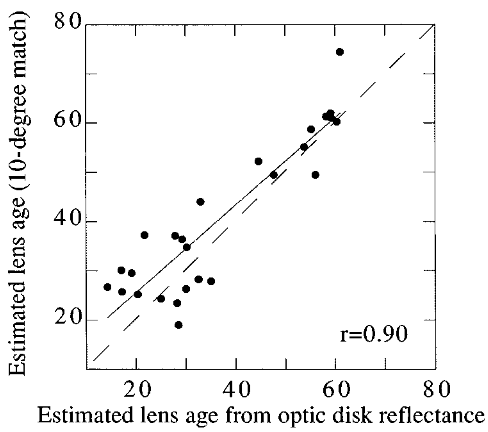

Fig. 7. Comparison of lens age estimated from psychophysical and from reflectance data.

tion between some model parameters was found in the study by Delori and Pflibsen.[38] By including in their model an unknown light loss, they were able to improve the fits to their reflectance data and reduce the interdependence of the different model parameters. The lens parameter (p_1) correlated with the chronological age ($r = 0.92$). This was expected, since we used p_1 to compute the estimated lens age.

B. Psychophysical Data of Normal Observers

The estimated lens age from the heterochromatic flicker match is plotted against the chronological age in Fig. 6. Error bars show ± 1 standard deviation of the mean. The linear regression lines (solid) and the diagnosis (dashed) are also shown. The correlation coefficient between estimated lens age and the chronological age is 0.92. Figure 7 compares the estimated lens ages for the psychophysical data with the reflectance data. The correlation coefficient was 0.90.

C. Reflectometric Data of Pseudophakic Patients

Figure 8 shows optic disk reflectance data expressed in density units for the pseudophakic patients. The solid curves passing through the data points were the fits from a model incorporating corneal density [Eq. (1a)]. There were minor deviations at long wavelengths, which likely indicated that the reflectance of the optic disk was not completely flat.

5. DISCUSSION

The model of Eq. (1) assumes that the optic disk reflectance is spectrally neutral. The parameter p_3 represents overall optic disk reflectance. The fits of the pseudophakic data when corneal absorption was used prompted us to infer that the reflectance spectrum of the optic disk is close to spectrally neutral. So far, to our knowledge, there have been no quantitative measurements of the reflectance spectrum of the optic disk. In several studies[38,41] the reflection of the fundus has been assumed to be perfectly diffusing.

For the heterochromatic photometric match developed in the psychophysical part of this study, a wavelength pair (430 and 495 nm) was adopted after a search that was more stringent than in previous studies.[24,26] The two wavelengths are sufficiently separated that the lens-density difference is large.

We examined three lens-density models by fitting the models separately to the reflectance data. The results showed that the two-factor model by Pokorny *et al.*[21] fitted the data better than either Weale's exponential model[19] or the linear model of Savage *et al.*[15]: reflectance data from 22 of 26 observers had smaller residuals when fitted with the model of Pokorny *et al.* than had the data fitted with Weale's model, with a 0.000534 probability that smaller residuals occurred only by chance. No residuals from the fit of the model of Pokorny *et al.* were larger than the residuals from the fit of the model of Savage *et al.* The fits of the exponential model showed in-

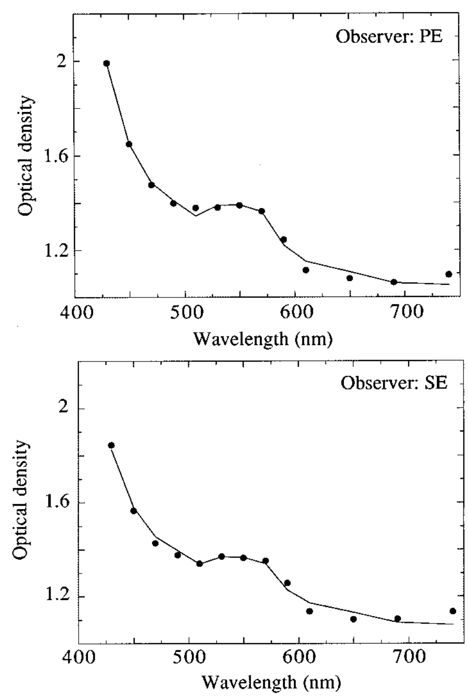

Fig. 8. Data (solid circles) from two pseudophakic patients and fits (solid curves) obtained with a model incorporating the corneal spectral density and the spectral density of the IOL [Eq. (1a)].

creasing residuals with age. The correlation between the residual and the age was significant ($\alpha < 0.05$). The two-factor model and the linear model did not have such a problem: neither of the correlations was significant, $\alpha > 0.1$ for the two-factor model and $0.05 < \alpha < 0.1$ for the linear model. Delori and Burns[26] estimated the lens density from the reflectance at a fundus site 7 deg temporal to the fovea. They found that the lens extinction spectrum of Savage *et al.* underestimated the lens density for wavelengths between 450 and 600 nm.

Although the two-factor model provides a satisfactory description of the spectral density of human lenses of varying ages, there may also be individual variation in the density of T_{L2}. van den Berg and Felius[23] measured spectral density of donor lenses and found 1 of 29 lenses to have a lower density than T_{L2} at short wavelengths.

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