The yellow pigments in the human eye lens result in yellowing of the lens that can be observed subjectively with slit lamp examination. In principle, a straightforward relationship could exist between slit lamp lens color and yellow pigment content. This relationship is the subject of the present study. The results might be of practical interest if slit lamp examination could be used to allow conclusions of a more physical nature.

Most interest in lens pigments concerns the chemical characteristics of the lens, especially in relation to light damage mechanisms. However, the incentive of the present study was a problem in visual psychophysics. The retinal stimulus strongly depends on the pigments in the lens, particularly when short wavelength stimuli are used. For instance, this problem was recognized when blue-on-yellow perimetry was introduced. An elegant but time-consuming technique was designed to correct for the spectrally selective light losses in the lens, involving psychophysical threshold measurements after dark adaptation of the patient. Would it be possible to obtain a good estimate of spectral transmittance from a slit lamp observation of lens color?

Two important prerequisites for such an approach must be met. First, slit lamp lens color is a subjective observation that must be transformed to a quantitative scale. Second, subjective color and its objective counterpart (spectral transmittance) are basically multidimensional with unequal numbers of dimensions. A one-dimensional system for both would be preferable. There are reports in the literature to fulfill both prerequisites. As part of a lens opacity classification system (LOCS), Chylack et al. defined a method to classify the color of lenses on the basis of slit lamp information (nuclear color or NC score). The latest (1993) refined version is LOCS III. The NC score summarizes the color of the lens in one numeric dimension (0.1 to 6.9). Validation studies have shown good interobserver and intraobserver reproducibility.

A one-dimensional approach obviously is a simpli-
Spectral Transmittance and Slit Lamp Lens Color

Within the visual region two important classes of chromophores have been identified, kynurenines and aged proteins. The spectral absorbance within these classes varies. So, the overall spectral transmittance of the lens might vary in a rather complex way. Conversely, the amount of kynurenines might be more or less constant during adulthood. The amount of yellow proteins varies largely and increases with age. But the variation in spectral absorbance of the yellow proteins might be limited.

Physical studies support these findings. Pokorny, Smith and Lutze derived a transmittance spectrum (TL1) that could account for most of the differences in visual sensitivity among persons of different ages. These authors concluded that the photographic pigments in the transparencies did not faithfully mimic the transmission characteristics of human lens pigments, so, we did not use this technique. It might be an alternative to the subjective LOCS scoring technique, though.

METHODS

Details on the methods for donor lenses are published elsewhere. In short, eyes (N = 29, donor age = 59 ± 20 years [± standard deviation, SD]; of 5 more lenses no photographs were made) with short postmortem enucleation times (7 ± 4 hours) and no potential damage to the lens (for example, trauma to the head) were obtained from the Cornea Bank in Amsterdam. The lenses were carefully isolated and mounted in a special holder with a free diameter of 8 mm. As immersion medium an isotonic solution was chosen (mostly Na+ 150, K+ 4, Ca2+ 2.2, Cl− 160 and Glucose 6 mmol/l). The lenses were normal for their age, but occasional postmortem changes (superficial irregularity, spokelike structures) were observed. Measurements were performed within the first few hours of isolating the lens. A first measurement was repeated at the end of the measurements to check that no change had taken place during the experiment.

Spectral transmittance was measured with a slightly modified version of the setup described earlier. In short, a pencil beam of light was derived from a high-pressure mercury lamp and centered on the donor lens. At the donor lens it had a maximal diameter of 4 mm. A 9 mm radius (0.98°) diaphragm was positioned at 550 mm behind the donor lens. This diaphragm could rotate with the donor lens as the center of rotation. Light collected by this diaphragm was fed into a calibrated photomultiplier with a calibrated interference filter in front (wavelengths 400, 420, 440, 460, 480, 500, 520, 540, 560, 600, and 700 nm, half band widths about 10 nm). Measurements were made using the full series of wavelengths for six lenses to study in detail the correspondence with the slit lamp color score. The TL1 spectrum corresponds more or less to that of kynurenine and the TL2 spectrum to aged protein.

While it must be realized that the TL model is an approximation, it is worthwhile to study the possibility of translating slit lamp color score into the parameter of this model. Also the original single template models were tested. To measure spectral transmittance directly, donor lenses were used. They were photographed and the photographs were scored according to the LOCS standard. The TL model was fitted to the measured spectral transmittance functions and the relationship between model parameter and LOCS NC score was studied. Also, from the closeness of the fit, correspondence between psychophysically derived TL model and physical lens transmittance could be studied. One of the two alternatives to the TL model could be chosen. To test application of this study, the usual correction in blue-on-yellow perimetry was measured for some subjects, and compared to the correction predicted on the basis of the LOCS NC score for photographs of their lenses.

As a potential alternative to direct measurement of lens transmittance, transmittance of photoimages (color transparencies) of lenses has been measured. These authors concluded that the photographic pigments in the transparencies did not faithfully mimic the transmission characteristics of human lens pigments, so, we did not use this technique. It might be an alternative to the subjective LOCS scoring technique, though.
RESULTS

Direct transmittance was as a rule slightly less than total transmittance. Average \( \pm SD \) of the differences were 0.10 \( \pm 0.12 \), 0.09 \( \pm 0.09 \), 0.06 \( \pm 0.07 \), and 0.06 \( \pm 0.06 \) log units, respectively for 400, 500, 602, and 700 nm. As noted already by Boettner and Wolter, 25 the difference between direct and total transmittance can be assumed to be caused by (forward) light scattering. Absorption (reflection) and backward scattering processes can be assumed to affect direct and total transmittance about equally. Also psychophysical studies suggest the difference between direct and total transmittance to be small, 26 maximally about 10% (0.05 log units) for young eyes and 20% (0.10 log units) at age 70 years. Because the differences were unimportant for this analysis, presentation will be limited to total transmittance.

At 700 nm average log transmittance \( \pm SD \) was \(-0.04 \pm 0.04\). Because only differences in spectral transmittance are important for subjective color and the TL model, all data processing was performed relative to the 700 nm value. In the fits of the individual spectral transmittance curves, absolute transmittance was a free parameter. The results are summarized in Table 1.

First, the correspondence between the present data and the TL models for spectral transmittance was studied. The model reads: log transmittance \( = TL = (\text{individual TL1 multiplier}) \times TL1 + TL2 \). We decided to use the TL2 version based on Van Norren and Vos 5 because it gave the closest fits for all the data (Figs. 1, 2, 3). In five lenses transmittance was higher than that of TL2 alone (TL1 multiplier = 0). For these lenses, we used \( TL = (\text{TL2 multiplier}) \times TL2 \). Using abbreviated notation for the TL multipliers (tl1, tl2), this is equivalent to estimating in all cases one parameter only, that can be defined as tl \( = tl1 + tl2 \). The multipliers follow from tl as tl1 \( = \max (1,tl)-1 \) and tl2 \( = \min (1,tl) \). Figure 1 shows the results for three lenses. (tl1, tl2) was (3.4, 1), (2.0, 1) and (0, 0.53), and residual SDs were 0.07, 0.05, and 0.05 log units, respectively, for the lenses from persons aged 86, 68, and 21 years. Figure 2 shows spectral transmittance for three other lenses. Residual SDs were 0.04, 0.04, and 0.18 log units, respectively for the lenses of persons aged 28, 69, and 22 years. (These spectra are from Fig. 3 in another paper. 27 They were estimated with a different technique, using the autofluorescence of the lens as [internal] light source.)

Figure 3 gives log transmittance as function of age. Table 1 summarizes all data. Corresponding to other studies, 5, 7, 20, 21 the data show considerable differences within age groups. To ensure that extreme values were not caused by experimental errors, some of the data were checked by an independent technique. This involved comparison of the difference in observed back scattered light between the anterior and posterior parts of the lens (manuscript in preparation). Consistent results were obtained.

Figure 4 gives the parameters (TL1, TL2) resulting from fitting the model to the four data points of each lens. Residual SDs (degrees of freedom 4 \( -2 = 2 \)) ranged from 0.00 to 0.10 with one outlier of 0.16 log units (average \( \pm SD \): 0.05 \( \pm 0.05 \) log units. For the model version based on Wyszecki and Stiles 21 average residual SD was 0.08 \( \pm 0.05 \). As a side step, fits were also performed with both TL parameters free. Average residual SD became 0.03 log units (4 \( -1 = 3 \) degree of freedom). This residual SD can be considered as an upper limit to experimental error. Also, fits were performed with optimized spectral shapes of TL1 and TL2. Only the four non-zero values of TL1
TABLE 1. Summary Results

<table>
<thead>
<tr>
<th></th>
<th>Full Sample</th>
<th>Lenses From Figure 1</th>
<th>Lenses From Figure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>59 ± 20</td>
<td>86</td>
<td>68</td>
</tr>
<tr>
<td>Number</td>
<td>29</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LOCS NC score</td>
<td>3.1 ± 1.4</td>
<td>5.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Results With the Four-Wavelengths Set (400, 500, 602 nm relative to 700 nm)

<table>
<thead>
<tr>
<th></th>
<th>Log transmittance (400 nm)</th>
<th>Log transmittance (500 nm)</th>
<th>Log transmittance (602 nm)</th>
<th>TL1 multiplier</th>
<th>TL2 multiplier</th>
<th>Residual standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.96 ± 0.84</td>
<td>-0.15 ± 0.16</td>
<td>-0.02 ± 0.04</td>
<td>1.17 ± 1.29</td>
<td>0.95 ± 0.16</td>
<td>0.05 ± 0.03</td>
</tr>
</tbody>
</table>

Results With the Extended Wavelength Set and (Figure 2) Using Fluorescence

<table>
<thead>
<tr>
<th></th>
<th>TL1 multiplier</th>
<th>TL2 multiplier</th>
<th>Residual standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.40</td>
<td>1.00</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>0.53</td>
<td>2.43</td>
<td>0.06</td>
</tr>
</tbody>
</table>

and TL2 were optimized. Most improvement was seen with a change of the 400 nm value of TL1 from (now) 0.600 to 0.9 log units. With optimal TL1 and TL2 spectra a residual SD of 0.03 log units was obtained. In both cases the effects were statistically significant. The single template models were also tried. As observed earlier, the residual SDs were much larger.

In Figure 4 the LOCS NC score is plotted horizontally. The plotted values for LOCS NC are the averages of four scores, two for each of two observers. The average SD of these four observations was 0.26. An additional check on the consistency of the scores was performed as follows. For each observer all slides were placed randomly on the luminous screen without the large LOCS transparency. Each observer had to put all slides in order of increasing yellowness. This order was compared to that dictated by the LOCS scores. The consistency was remarkable, with only a few reversals of order. The human eye is very capable of making simultaneous comparisons (as opposed to sequential comparison).

The drawn lines in Figure 4 present a model for a mathematical relationship between TL1 and TL2 and LOCS NC score. Model assumptions were: 1) For
high LOCS scores, TL1 is a linear function of LOCS score, with TL2 = 1; 2) For low LOCS scores, TL2 is a linear function of LOCS score, with TL1 = 0; 3) At precisely one LOCS score, (TL1, TL2) = (0, 1). This model contains four parameters that need to be established, but only three are independent. These parameters were estimated by a simultaneous fit of the 29 spectra. The result is given in Figure 4 (upper left corner). Note that this model could also be fitted to the 29 estimated values of TL1 and TL2 themselves. However, virtually the same model parameters were obtained.

Figure 5 gives log transmittance as function of the LOCS NC score. Linear regression analysis of the 400 nm data on the LOCS data gave y = -0.29 -0.53x (r = -0.90, P < 0.0001), for 500 nm y = 0.13 -0.088x (r = -0.77, P < 0.0001), and for 602 nm y = 0.034 -0.016x (r = -0.55, P < 0.001). The regression lines are not plotted. Using the mathematical relationship presented in Figure 5, transmittance spectra can be

![Figure 2](Image)

** FIGURE 2.** Same as Figure 1, except that the spectral transmittance data were obtained using the autofluorescence of the lens as (internal) light source (Fig. 3 from van den Berg[1]).
predicted from LOCS scores. Predicted transmittances are given as continuous lines for the three wavelengths of Figure 5. To judge expected accuracy of such prediction, residual SDs were calculated. They were 0.38, 0.12, and 0.04 log units for 400, 500, and 602 nm, respectively. However, these figures might depend on (or increase with) LOCS score.

We could now try to predict a variety of other data on the basis of the LOCS NC score, such as the correction needed in blue-on-yellow perimetry. The steps involved are given for the LOCS NC score = 3.5 as an example: (1) From Figure 4 can be read (TL1, TL2) = (1.4, 1); (2) For the blue and yellow stimuli retinal spectral distributions were calculated, and multiplied by the rod spectral sensitivity function; (3) The integral for the blue test light spectrum was 0.48 relative to 1.00 for the yellow test light spectrum, so the predicted dB difference (ΔdB) was 3.2. Figure 6 shows ΔdB as a function of (TL1, TL2); 4) The continuous line in Figure 7 shows ΔdB as a function.

**FIGURE 4.** For each lens, the model parameters (TL1, TL2) (one independent) were estimated by fitting the model to the transmittance spectrum. The continuous lines (formulas in upper left corner) have their knee-points at the same LOCS score.

**FIGURE 5.** Log relative transmittance as function of LOCS III NC score. The continuous lines are predictions based on the model lines in Figure 4.
of LOCS NC score. In the same figure data for 18 subjects are given as well as the linear regression line (broken) through these data. Note that the continuous lines in Figures 6 and 7 depend on the spectral characteristics of the lights and filters used. So, the specific relationships presented in these figures have no general applicability. The correspondence between prediction and data in Figure 7 is as close as one might hope for in view of the scatter inherent in perimetric threshold estimation.

The error in AdB associated with using LOCS rather than the psychophysical technique could be estimated speculatively as follows: On the basis of the residual errors, the dominant source of error is estimating TL from LOCS (Fig. 4). For each data point in Figure 4 two estimates of AdB were calculated, one using the actual TL parameters, and one using the model TL parameters. The root mean square value of the differences between these two AdBs (=0.9 dB) could be used for the error in LOCS based AdB.

DISCUSSION

Some lenses had higher transmittance than could be accommodated in the original model of Pokorny et al. The lenses of the 21- and 43-year-old donors had exceptionally high transmittance. Other reports indicate transmittance to be occasionally as high. In their review, Van Norren and Vos concluded that important differences exist among young persons. All of this seems to justify a modification of the TL model as introduced in the Results section.

Although the (adapted) TL model of Pokorny et al. is based on a different type (psychophysical) of data and contains only one free parameter, the correspondence with the present data is close. The improvement (to a residual error of 0.05 log units) obtained with more free parameters or differently shaped TL1 or TL2 spectra is significant. But the original residual error (0.05 log units) was so small, that no such change to the model seems warranted. This may depend however on the field of application.

The key issue was the correspondence between slit lamp lens color (LOCS NC score) and log transmittance. The correlation was high (Fig. 5) and a model was formulated to predict log transmittance from the LOCS NC score (Fig. 4). The residual errors in predicted log transmittance might be acceptable for many applications. For example, in our sample of donor lenses, log transmittance (400 nm) was on average $-1.96 \pm 0.84$, and the residual error of the prediction was 0.38 log units. This might be acceptable for estimating the amount of pigment in the lens, or estimating transmittance for psychophysical purposes, but is this correspondence also acceptable in view of the uncertainties inherent in the present experiments? Experimental log transmittance and the TL model were accurate with errors of 0.03 and 0.05 log units. For the LOCS NC score interindividual variation was about 0.26. These errors are too small to explain the scatter of data points in Figure 4, but many other errors might enter into this relationship. Subjective lens color might depend in a more complicated way on lens characteristics.

For instance, we must realize that observed lens color depends on at least two phenomena: absorption and backscatter. The analysis presented here only holds true if backscatter complies with certain rules such as: if backscatter would be spectrally unselective, or if the spectral dependence of backscatter would be the same for all lenses. Many studies devoted to scattering in eye lenses showed short wavelength light to be scattered more strongly. With age, the scatterers in the eye lens increase in size, therefore the wavelength dependence of scattering might change.

![Figure 6. Theoretical relationship between the model parameters (TL1, TL2) (one independent) representing lens spectral transmittance, and the dB difference between the thresholds for a blue and a yellow stimulus.](http://iovs.arvojournals.org/pdfaccess.ashx?url=data/journals/iovs/933410/)
Spectral Transmittance and Slit Lamp Lens Color

Many other complications could be considered, such as: influences of light distribution within the slit lamp image on subjective color estimation, or inhomogeneities of pigment distribution within the lens, or variations in the photographic quality, etc. In view of the number of potential sources of error, we were satisfied with the results obtained.

Key Words
LOCS, lens pigments, spectral sensitivity, human lens, spectral transmittance

Acknowledgments
The authors thank the staff of the Hoornwica bank in Amsterdam for their cooperation, R. Boellaard, J. van Bracht, J. Gieremans, J.K. Ijspeert, J. Kwa, F. Terheggen, W. Verkruijse, for collection of data, and S. Brazel assistance with English.

References