Spectral changes in plastic ophthalmic lenses following ultraviolet exposure

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Abstract
INTRODUCTION. Several patients returned spectacles to our dispensary, indicating that the clear lenses had yellowed after less than 2 years of continuous wear. The lenses were made of Trivex (PPG), a proprietary monomer introduced in 2001. We hypothesized that exposure to ultraviolet radiation (UV) caused the lenses to yellow.

METHODS. We purchased 3 pairs of single vision lenses of each of Trivex, CR-39, and polycarbonate in +3.00 D, -3.00 D, and plano with scratch-resistant coating only; and a fourth pair of each material in -3.00 D with anti-reflective coating. One lens of each pair was the test lens, the other was the control. We used a UV curing oven (Dymax), whose output at 365 nm is about 2.34 times greater than the maximum solar irradiance at midday. Assuming peak UV of 4 hrs per day, test lenses were exposed for periods totaling 48 weeks of simulated environmental exposure. Spectral transmission was measured at the center of each lens with a Lambda 20 UV/VIS Spectrometer (Perkin Elmer). Data were analyzed for visible, UV, and infrared (IR) using algorithms described in US and international standards.

RESULTS. All test lenses increased in optical density with increased UV exposure; thicker lenses and ARC lenses increased less. Trivex initially changed sooner than the other materials (at least 1% change in all lenses by 12 weeks of simulated exposure), but CR-39 increased the most (up to 9.3%) after 48 weeks of simulated exposure. Shift in color for all lenses was consistently toward 568-570 nm (“yellow”), and saturation increased most quickly and greatest for Trivex (up to 12.8%), followed closely by polycarbonate. All CR-39 increased in UV-A transmittance, while Trivex remained constant, and polycarbonate actually decreased. All CR-39 also increased in UV-B transmittance and decreased in IR transmittance, while the other materials remained constant.

DISCUSSION. Short-term, high-intensity UV exposure can simulate environmental conditions. Clear plastic lenses are susceptible to yellowing, darkening, and reduction of UV absorption, based on material and lens thickness. These changes are reduced, but not eliminated with antireflective coating.

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SPECTRAL CHANGES IN PLASTIC OPHTHALMIC LENSES
FOLLOWING ULTRAVIOLET EXPOSURE

By

MELISSA KUNTZ

MONICA STOTLER

A thesis submitted to the faculty of the
College of Optometry
Pacific University
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for the degree of
Doctor of Optometry
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Advisor:

KARL CITEK, O.D., Ph. D., FAAO
BIOGRAPHIES

Melissa Kuntz is from Moorhead, Minnesota, and graduated with honors from the University of Minnesota with a BS in Biology. She will complete her studies at Pacific University College of Optometry in May of 2006. During her time at Pacific University, she was the National Student Liaison for the American Public Health Association and was also active in the National Optometric Student Association. She plans to work in a small town private practice following graduation.

Monica Stotler was born and raised in Prescott, Arizona. She earned an Associates of Arts and an Associates of Science graduating with honors from Yavapai College in Prescott. She then attended The University of Arizona where she earned her Bachelor of Science in 2002, with a Major in Biology and a Minor in Chemistry. She will graduate in May 2007 with a Doctor of Optometry degree from Pacific University College of Optometry. Monica is currently a member of the Beta Sigma Kappa Honor Society, COVD, SOA, AOSA, and Amigos Eye Care which provides eye care worldwide to the underprivileged. She plans to apply for an optometric residency during her fourth year to further increase her level of expertise and would like to practice in Arizona or Oregon after she graduates.
ABSTRACT

INTRODUCTION. Several patients returned spectacles to our dispensary, indicating that the clear lenses had yellowed after less than 2 years of continuous wear. The lenses were made of Trivex (PPG), a proprietary monomer introduced in 2001. We hypothesized that exposure to ultraviolet radiation (UV) caused the lenses to yellow.

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DISCUSSION. Short-term, high-intensity UV exposure can simulate environmental conditions. Clear plastic lenses are susceptible to yellowing, darkening, and reduction of UV absorption, based on material and lens thickness. These changes are reduced, but not eliminated with anti-reflective coating.
INTRODUCTION

Plastic materials have been used for ophthalmic lenses for over half a century. Allyl diglycol carbonate, provided by several manufacturers under the name CR-39, has been available since 1947, and polycarbonate was introduced by Gentex Corp. in 1978. Together, these materials currently account for most ophthalmic lenses. Other available ophthalmic plastics are less common, ranging from inexpensive materials with relatively poor optical characteristics, such as acrylic, to expensive proprietary compounds with limited availability supplied by individual manufacturers.

A problem with early incarnations of polycarbonate was that the material had a yellowish tinge, and that it became more yellow and dark with age. This was not cosmetically acceptable to many patients, who were expecting a “clear” lens. However, the ophthalmic lens industry benefited directly from the advent and economic explosion of optical storage media, such as CDs and DVDs. Dyes were added to polycarbonate to make the material more clear, referred to as “water white,” and less susceptible to yellowing with age. Some suppliers of non-ophthalmic polycarbonate will now even provide multi-year warranties against yellowing of the material.

In 2001, PPG Industries introduced Trivex, a proprietary monomer with relatively low chromatic aberration, low specific gravity, and high impact resistance. As such, it competes directly with the excellent optics provided by crown glass and CR-39, and the light weight and superior safety provided by polycarbonate. Trivex is available from various manufacturers in a wide range of powers and lens designs, such as Phoenix lenses from Hoya Vision Care, Trilogy lenses from Younger Optics, Trinity lenses from Augen, and Genesis lenses from Shamir.

In spite of the optical and physical benefits of Trivex, several of our patients and colleagues have observed that their clear lenses yellowed and darkened after less than two years of continuous wear. We were interested in determining if this change in spectral characteristics was due to exposure to ultraviolet (UV) radiation, and if there were any public safety consequences to the wearer, either via decreased absorption of non-visible radiation or altered visual perception due to the changes in optical density and hue.
METHODS

LENSES

We purchased four pairs of single vision lenses of each of CR-39, polycarbonate, and Trivex in various spherical powers through the Pacific University Family Vision Center. One lens of each pair was used as the test lens, and the other was the control. Three pairs of lenses of each material were ordered with a scratch-resistant hard coating only, and the fourth pair of each material was ordered with anti-reflective coating. Table 1 lists the physical parameters of the lenses received. Back vertex power was measured to the nearest 0.12 D with a standard lensmeter (Marco, Jacksonville, FL), base curve was measured to the nearest 0.12 D with a lens measure with calibration index 1.53 (Vigor), and center thickness was measured to the nearest 0.01 mm with a precision thickness gauge (L.S. Starrett Co., Athol, MA).

Even though the lenses were not ordered with a UV400 coating, one of the two CR-39 Plus Power lenses was supplied with such a coating; this was designated the test lens of that pair. All standard polycarbonate lenses include a dye to absorb UV up to about 380 nm, and all standard Trivex lenses include a dye to absorb UV up to 400 nm.

All lenses except the Trivex Plus Power lenses were available in stock 70-mm finished blanks. All coatings were applied by the lens manufacturers, and were presumed to be the proper coatings for the lens materials. Lenses were edged to a 50-mm diameter to fit in the spectrophotometer and the UV curing oven (see below). Each lens was marked using a grease pencil with an identifying code along the edge of the lens.

Test and control lenses were maintained in a room with a combination of standard fluorescent and incandescent lighting, ambient temperature about 23-25 degC, and relative humidity about 30-40%. All lenses were kept in individual opaque protective sleeves when not being measured or exposed to test conditions. Lenses were never exposed to direct or indirect sunlight, nor to any high-intensity sources other than those used in the test conditions.

SPECTRAL ANALYSIS

Spectral transmission, from 200 to 1100 nm, was measured with a Lambda 20 UV/VIS Spectrometer (Perkin Elmer, Norwalk, CT). Each lens was measured at its center three times after each exposure period, and the results were averaged to provide a single transmission curve for the lens for that period.
Spectral data were analyzed for visible, UV, and infrared (IR) transmission using algorithms described in US and international standards.\textsuperscript{5,6}

Table 1. Baseline physical parameters of study lenses. SRC=scratch-resistant hard coating; ARC=anti-reflective hard coating. *Includes UV400 coating.

<table>
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<th>Material</th>
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<th>Coating</th>
<th>Lens</th>
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<th>Center Thickness, mm</th>
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UV EXPOSURE

Test lenses were exposed for specified time periods in a UV curing oven (Dymax, Torrington, CT). The UV curing oven contains a xenon arc source with overall output from about 200 nm (UV) to the IR spectrum, with discrete peaks at particular wavelengths throughout. A heat-absorbing filter reduced IR irradiance of the lenses. Most of the remaining non-visible output occurs in the near UV zone (UV-A). At 365 nm, the output is about 2.34 times the
maximum solar irradiance at midday. Assuming peak UV of 4 hrs per day, test lenses were exposed for periods totaling 48 weeks, or 4 peak seasons, of simulated environmental exposure.

All 12 test lenses were placed together in the UV curing oven. To avoid any potential asymmetric exposure effects, lenses were regularly and repeatedly rotated in position from the center to the edge of the tray throughout each exposure period. (See Figure 1)

Figure 1. Test lenses placed on tray being returned to UV curing oven following lens position rotation.
RESULTS

All test lenses increased in optical density with increased UV exposure. However, thicker lenses and anti-reflective coated lenses increased less. Trivex initially changed sooner than the other materials (at least 1% change in all lenses by 12 weeks of simulated exposure), but CR-39 increased the most (up to 9.3%) by the end of the study. Shift in color for all lenses was consistently toward 568-570 nm ("yellow"), and saturation increased most quickly and greatest for Trivex (up to 12.8%), followed closely by polycarbonate.

Figures 2-4 show the lenses and data at the conclusion of the study. Figure 2 shows the test and control lenses side by side. Figure 3 shows the spectral transmission curves of the lenses. Figure 4 shows the plot of the chromaticity coordinates on the CIE (1931) standard chromaticity diagram.

Figure 2. Appearance of test and control lenses following 48 weeks of simulated UV exposure. PC=polycarbonate. +3=+3.00 D; -3=-3.00 D. SRC=scratch-resistant coating; ARC=anti-reflective coating.
Figure 3. Spectral transmission curves of (a) test lenses following 48 weeks of simulated exposure and (b) control lenses. Lens code: C=CR-39; T=Trivex; P=polycarbonate. P=+3.00 D; O=plano; M=-3.00 D. U=scratch-resistant coating only; C=anti-reflective coating.
Figure 4. Plots of chromaticity coordinates on CIE (1931) standard chromaticity diagram: (a) Plots on overall diagram, including yellow and green traffic signal transmissibility and average daylight (D65) appearance; (b) close-up of plots. Lens code as in Figure 4.
Figures 5-12 show composite data throughout the study. Figure 5 shows the change in overall daylight (D65) transmission. Figure 6 shows the change in saturation, based on the CIE chromaticity coordinate plots. Figures 7 and 8 show the changes in spectral transmission based on the proper identification of traffic signals. Figure 7 shows overall transmission in the green-yellow portion of the spectrum, as defined by ANSI Z80.3, while Figure 8 shows overall transmission in the blue-yellow portion of the spectrum, as defined by AS/NZS 1067.

All CR-39 increased in UV-A transmittance, while Trivex remained constant, and polycarbonate actually decreased. Figures 9 and 10 show the changes in UV-A transmission, as calculated using algorithms provided in ANSI Z80.3 and AS/NZS 1067, respectively. All CR-39 increased in UV-B transmittance and decreased in IR-A transmittance, while the other materials remained constant. Figure 11 shows the change in UV-B transmission, as defined by ANSI Z80.3. Figure 12 shows the change in near infrared (IR-A) transmission. While ANSI Z80.3 defines IR-A as extending to 1400 nm, the data in Figure 12 are an approximation of the actual transmission, since the spectrophotometer was only capable of measuring to 1100 nm.
Figure 5. Change in D65 transmission over study period. Blue=CR-39, red=polycarbonate, green=Trivex; ▲=-3.00 D with anti-reflective coating; scratch-resistant coating only: ♦=+3.00 D, ■=plano, ◆=-3.00 D.

![Figure 5](image_url)

Figure 6. Change in saturation over study period. Symbols as in Figure 5.

![Figure 6](image_url)
Figure 7. Change in green-yellow (G-Y) transmission, as defined by ANSI Z80.3, over study period. Symbols as in Figure 5.

Figure 8. Change in blue-yellow (B-Y) transmission, as defined by AS/NZS 1067, over study period. Symbols as in Figure 5.
Figure 9. Change in UV-A transmission, as defined by ANSI Z80.3, over study period for (a) CR-39 and (b) polycarbonate and Trivex lenses. Symbols as in Figure 5.
Figure 10. Change in UV-A transmission, as defined by AS/NZS 1067, over study period for (a) CR-39 and (b) polycarbonate and Trivex lenses. Symbols as in Figure 5.
Figure 11. Change in UV-B transmission, as defined by ANSI Z80.3, over study period. Symbols as in Figure 5.

Figure 12. Change in IR-A transmission, as defined by ANSI Z80.3, over study period. Symbols as in Figure 5.
DISCUSSION

Short-term, high-intensity UV exposure can simulate environmental conditions. Clear plastic lenses are susceptible to yellowing, darkening, and reduction of UV absorption, based on material and lens thickness. These changes are reduced, but not eliminated, with anti-reflective coatings.

Patients should be advised of the possible lens changes if spectacles are exposed to environmental UV for extended periods. Certain clear lens materials, such as CR-39, should be avoided, or used in conjunction with additional filters, for occupational UV hazards.

ACKNOWLEDGMENTS

This study was generously supported by Beta Sigma Kappa for purchase of the lenses, Pacific University Sports Vision Fund for the purchase of the UV curing oven, and Pacific University Corporate Research Fund for use of the spectrophotometer. Lens edging was provided by Opticraft, Portland, OR. We thank Dr. Alan Reichow and Mr. Lowell Galambos for helpful discussions and insights.
REFERENCES


