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Description
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Anti-Reflective Coatings Reflect Ultraviolet Radiation

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Abstract

Anti-reflective (AR) coatings provide numerous visual benefits to spectacle wearers. However, coating designers and manufacturers seem to have placed little or no emphasis on reflectance of wavelengths outside the visible spectrum. Ultraviolet (UV) radiation, from sources behind the wearer, can reflect from the back lens surface toward the wearer's eye. Various clear lens materials, with and without AR coatings, were tested for their transmittance and reflectance properties. While the transmittance benefits of AR coatings were confirmed, most coatings were found to reflect UV radiation at unacceptably high levels. Tinted sun lenses also were tested with similar results. Frame and lens parameters were evaluated, confirming that eyewear that incorporates a high wrap frame and high base curve lenses can prevent UV radiation from reaching the eye. The findings strongly suggest that clear flat lenses should not be dispensed for long-term use in sunny environments, even if clip-on tints are provided.

Keywords: anti-reflective coating, ultraviolet radiation, UV, lens reflections, transmittance, reflectance

Introduction

Anti-reflective (AR) coatings have long been known to provide numerous visual benefits to spectacle wearers, including increased transmissibility, reduced surface reflections and ghost images, and decreased glare. While AR coating is essential for high index materials, such as polycarbonate and many proprietary plastics and glasses, it also is beneficial for lower index materials such as crown glass, CR-39™, and Trivex™. For maximum advantage, both surfaces of the spectacle lens should be coated, as has been demonstrated for both dress1-4 and occupational/safety5-6 eyewear.

Nonetheless, coating designers and manufacturers seem to have placed little or no emphasis on reflectance of wavelengths outside the visible spectrum. To wit, a colleague who conducts eye movement research with an infrared eye monitor noted that subjects cannot wear spectacles during his projects, since the increased reflectance of infrared caused by AR coatings typically interferes with the reflected ocular images. Likewise, from the characteristic reflectance increase that most AR coatings demonstrate in the violet region of the visible spectrum, it seems likely that the reflectance of ultraviolet (UV) radiation is not negligible.

With this latter point in mind, the public is increasingly being made aware of the dangers of ocular exposure to UV radiation. For example, advertisements from manufacturers of photochromic lenses tout the fact that their...
lenses absorb UV, which is an initiating factor of the photochromic process.\textsuperscript{8-9} Likewise, a contact lens manufacturer has received the World Council of Optometry’s Seal of Acceptance for the UV protection provided by its products.\textsuperscript{10} Ocular health effects of short- and long-term environmental UV exposure are well known, including increased risk of photokeratitis, pterygium, cataract, and melanoma of the adnexa.\textsuperscript{11-13} Exposure to UV-C (far or germicidal UV, 200-290 nm), or high-intensity UV-B (middle or erythemal UV, 290-315 nm) or UV-A (near UV, 315-380 nm), in industrial settings causes similar acute damage to the superficial structures of the eye and orbit.\textsuperscript{6}

Previous studies have demonstrated that spectacles that are not fit properly to the wearer’s head can expose the eye to UV radiation from the side and even from reflection off the back surface of the spectacle lens.\textsuperscript{14-16} This paper confirms the transmittance properties, and demonstrates the reflectance properties, of common lens materials and coatings for sources located behind the spectacle wearer. In addition, it provides lens parameter options for the ophthalmic dispenser to minimize the patient’s ocular exposure to UV.

**Methods**

*Test Lenses*

Clear lenses of several common ophthalmic materials with popular coatings, identified in Table 1, were provided by the Pacific University Family Vision Center. Most were actual prescription lenses, with two exceptions: CR-39\textsuperscript{TM} with Teflon\textsuperscript{®} AR coating was a demonstration lens provided by the manufacturer to the dispensary; and acrylic was a display lens for a frame. This latter lens material was included because, even though it is not dispensed by practitioners, it is encountered in “toy” and counterfeit eyewear. In addition, Zeiss 1.9-index glass with Gold ET AR coating was provided by a patient from Canada; because of its low center thickness, this lens is not legal for dispensing in the US. All but one of the lens coatings were applied by the lens manufacturers; the UV400 coating on a CR-39\textsuperscript{TM} lens was applied by the local optical laboratory.

Several common tinted non-prescription sun lenses from the author’s collection also were tested. Many of these lenses have high base curves (8 D or greater), are intended for use in high wrap frames, and do not have AR coating. One of the lenses, purchased at a roadside stand, was marked “UV500” and made of acrylic with a silver flash front surface coating. It is important to determine the reflectance properties of such lenses in the event that the eyewear is worn incorrectly. For example, light can reflect easily from the rear lens surface if the frame size, frame contour, and/or vertex distance are inappropriate for the wearer, such as a small child wearing an adult frame.

*Measurements*

Back vertex power was measured with a standard manual lensmeter (Marco, Jacksonville, FL), surface curvature was measured with a lens clock calibrated for index 1.53 (Vigor Optical, Carlstadt, NJ), and thickness at the distance reference point of the lens was measured with a precision depth gauge (Starrett, Athol, MA). Parameters of the clear and tinted lenses are listed in Tables 1 and 2, respectively.
Table 1. Physical parameters and transmittance and reflectance properties of clear lenses of various materials with various coatings. Green cells: increased transmissibility resulting from AR coating; negligible UV transmittance. Orange cells: non-negligible but acceptable UV transmittance; low but non-negligible (<10%) UV reflectance. Red cells: significant UV transmittance or reflectance. Standards requirements: P, pass; F, fail; N/A, lens is exempt.
Table 2. Physical parameters and transmittance and reflectance properties of various tinted lenses. Green cells: increased transmissibility resulting from AR coating; negligible UV transmittance. Orange cells: non-negligible but acceptable UV transmittance; low but non-negligible (<10%) UV reflectance. Red cells: significant UV transmittance. Standards requirements: P, pass; F, fail; N/A, lens is exempt.

Spectrophotometry was conducted over the wavelengths of 200-800 nm in 5-nm increments with a Perkin-Elmer Lambda 20 UV/VIS Spectrometer (Norwalk, CT). Lenses were assessed for total transmittance and back surface specular reflectance at their distance reference points.

Transmittance and Reflectance Calculations

All transmittance properties for visible, UV-A, and UV-B were analyzed according to the US non-prescription sun eyewear standard, ANSI Z80.3-2001,17 since the prescription lens standard, ANSI Z80.1-2005,18 describes only how to calculate mean UV transmittances but makes no recommendations regarding visible UV transmittance.

Transmittance requirements for UV-C are not explicitly included within any standard. However, the occupational safety eyewear standard, ANSI Z87.1-2003,19 does define “effective far ultraviolet,” which extends from UV-C to UV-B (200-315 nm), but clear safety lenses (i.e., visible light transmittance above 85%) are exempt from this requirement. Nonetheless, UV-C transmittance was calculated using an equation similar to those for UV-A and UV-B transmittances, as described in ANSI Z80.3.

Reflectance characteristics also are not included in any standard, but were analyzed for visible and UV regions using procedures similar to those defined above for transmittances. Reflectance
was calculated only with regard to the specular performance of the lens. An integrative procedure to determine the overall amount of radiation to strike the eye and adnexa, along the lines used by other researchers, is not relevant here, since the only interest of the current study was to determine if, and how much, a particular lens could reflect UV radiation.

Frame and Lens Parameters

With regard to the actual performance of the eyewear when worn, several parameters of the frame, lens, and wearer contribute simultaneously to the ability of the eyewear to reduce ocular exposure to either direct or reflected UV. These parameters include rear surface curvature of the lens, lens size, vertex distance, structure of the wearer’s facial features, frame wrap, and frame temple or sideshield properties. A mathematical analysis was conducted to assist the dispenser in the judicious selection of eyewear for a given patient.

Results

Reflectance characteristics of the back surfaces of the test lenses are listed in Tables 1 and 2, and spectral reflectance curves are shown in Figures 1-4. Note that the luminous reflectances, even of uncoated crown glass and acrylic, are slightly different than what is expected based on the Fresnel equation. This occurs for several reasons:

- internal reflection from the inside of the front lens surface contributes to the result;
- luminous reflectance is calculated across the entire visible spectrum, in which refractive index of the reflecting material varies with wavelength;
- luminous reflectance takes into account the spectral sensitivity of the eye, such that the result is weighted toward the green-yellow portion of the spectrum (around 555 nm), while the nominal refractive index is based on a yellow wavelength (about 587 nm); and
- for coated lenses, the exact refractive properties of the coatings are not accounted for.

Nonetheless, this is an accurate representation of how the lens performs, since exactly the same phenomena occur when the lens is worn by the patient.
Figure 1. Spectral reflectance curves for clear CR-39™ lenses with various coatings. UV bands: A (near); B (middle or erythemal); C (far or germicidal).

Figure 2. Spectral reflectance curves for clear polycarbonate (PC) and Trivex™ lenses with various coatings. UV bands: A (near); B (middle or erythemal); C (far or germicidal).
Figure 3. Spectral reflectance curves for various clear high-index materials with AR coatings and uncoated crown glass and acrylic. Peak reflectances (not shown) of 1.67-index plastic (purple curve) of about 77% at 235 nm, and of 1.7-index plastic (green curve) of about 88.5% at 325 nm. UV bands: A (near); B (middle or erythemal); C (far or germicidal).

Figure 4. Spectral reflectance curves for various non-prescription tinted sun lenses. UV bands: A (near); B (middle or erythemal); C (far or germicidal).
For comparison purposes, transmittance characteristics also are listed in Tables 1 and 2. Note that all clear lenses except uncoated crown glass and acrylic pass, or are exempt from, all applicable transmittance requirements. Likewise, all tinted lenses except UV500 acrylic brown pass ANSI Z80.3 transmittance requirements. However, all CR-39™ lenses, except the one with UV400 coating, and Zeiss 1.9-index glass with Gold ET AR coating transmit non-negligible (but acceptable) amounts of UV-A, based on ANSI Z80.3. The results for the UV500 lens reiterate the concern that discounted sun eyewear may not perform as advertised and may actually present a significant risk to ocular health.

If the transmittance standards were applied to the reflectance properties, NONE of the lenses tested would pass all requirements. As a matter of fact, as hypothesized, lenses with AR coating actually demonstrate increased reflectance of UV from sources behind the wearer compared to non-AR-coated lenses. Some of the AR-coated lenses even reflect more than 40% of one or more UV bands, and up to almost 90% of individual UV wavelengths (see Figure 3). At these levels, the wearer must be concerned not only with lens reflections of directly-incident solar UV, but also with lens reflections of indirect (reflected) solar UV from common surfaces that readily reflect UV, such as fresh snow, white beach sand, water, and concrete.22

Frames with large horizontal eyesizes and lenses with relatively flat back surfaces do not prevent the incidence of UV from the side or behind the wearer. For example, Figure 5 shows the range of incident angles, with respect to straight ahead on an adult Canadian standard headform, for which rays that reflect from the back lens surface potentially can strike either the temporal limbus or the central cornea. Note that specular reflection is independent of wavelength, such that this analysis is valid for all wavelengths, both visible and non-visible. Rays that are incident from the side and bypass the lens, striking the eye directly, also are possible but are not shown.
Figure 5. Range of incident angles, with respect to straight ahead on an adult Canadian standard headform, for which reflected rays potentially can strike either the temporal limbus (yellow lines) or the central cornea (red lines). Monocular interpupillary distance of 32 mm. Lens parameters: horizontal dimension of 62 mm, vertex distance of 13 mm, wrap angle of 0 deg, and back surface curvature (measured with a lens clock calibrated for index 1.53) of -4.00 D (i.e., radius of -132.5 mm). Red lines: range of rays that reflect towards the central cornea; yellow lines: range of rays that reflect toward the temporal limbus.

Reducing the vertex distance can prevent some rays from directly striking the eye, but it has little effect on decreasing the range of incident angles that can reflect from the back lens surface toward the cornea. Likewise, simply decreasing the horizontal lens dimension, even by as much as 10 mm on the temporal side for the lens shown in Figure 5, has no effect on the reflected rays that can strike the central cornea, and actually increases the likelihood of rays striking the eye directly from the side. Consequently, the range of incident angles varies primarily with the back surface curvature: decreasing the curvature to -2.00 D increases the respective ranges to about 20 deg, while increasing the curvature to -6.00 D decreases them to about 5 deg. In any case, both direct and reflected rays can be eliminated if sufficient wrap is introduced, regardless of the lens curvature. However, the lens designer must then adjust the prescription to compensate for the induced astigmatism and prism, even in zero-power lenses. Several currently available premium prescription and non-prescription lens designs incorporate these design principles. Alternately, some manufacturers still offer prescription lens inserts in non-prescription high wrap eyewear and goggles, but these are optically inferior because of the decreased field of view and multiple optical surfaces, allowing for internal reflections, fogging, and debris accumulation to occur between the lenses.
Discussion

The results confirm the beneficial transmittance properties of AR coatings, achieving transmittances of 95% or better, even for very high index lens materials. However, the results also demonstrate that certain clear lenses – CR-39™ with any coating other than UV400; Zeiss 1.9-index glass with Gold ET AR coating; uncoated crown glass; and acrylic – transmit non-negligible amounts of UV-A. These types of clear lenses probably should not be dispensed to patients who spend much of their time in sunny environments. Of course, tinted lenses are intended for outdoor use, and the results confirm that nearly all UV transmittance can be eliminated, but also that “discount” sun eyewear may not perform to the same standards. Keep in mind that clip-on sun lenses only attenuate frontally-incident visible light and UV radiation; sources located behind the patient will still reflect from the back surface of the clear base eyewear.

With regard to reflectance characteristics, clear non-AR-coated lenses and tinted lenses reflect about 4-6% UV-A and UV-B and less than about 8% UV-C. With exceptions, most AR-coated lenses reflect on average about 25% of any UV band. Notably, CR-39™ with Hoya HiVision™ AR coating, Polycore polycarbonate with Mxplus™ AR coating, and Zeiss 1.9-index glass with Gold ET AR coating offer low UV reflectances similar to non-AR-coated lenses. On the opposite extreme, Hoya Aspheric 1.7-index plastic with Super HiVision™ AR coating reflects over 62% UV-A and almost 77% UV-B, with reflectances of individual wavelengths approaching 90%. Based solely on the reflectance characteristics, none of the lenses tested would be suitable for use in safety eyewear around industrial UV sources (e.g., lasers, curing ovens, certain welding operations) unless sideshields, high wrap, or goggle-style frames are provided.19

Ultimately, it is practitioner’s responsibility to provide patients with the best optical products that also offer superior protection for the health of the eyes and adnexa. It is the author’s opinion that large, flat lenses without wrap or sideshields are not appropriate for long-term use outdoors, regardless of the lens tint or the use of clip-on sun lenses. Enough quality high wrap frames and high base curve lenses, with non-prescription, single vision, and even progressive addition lens powers, are available in a variety of tints to allow the practitioner to properly meet the patient’s visual and health needs. Alternately, the patient can be fit with single vision or multifocal contact lenses, as appropriate, and quality non-prescription spectacles.

Conclusion

This study evaluated the transmittance and reflectance characteristics of a limited number of popular lens materials and coatings. Future evaluations of additional materials and coatings are recommended as new products are introduced by lens manufacturers.
Acknowledgments and Conflict of Interest Statement

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