

INVITED REVIEW

Current status of photoprotection by window glass, automobile glass, window films, and sunglasses

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SUMMARY

Ultraviolet radiation (UVR) has known adverse effects on the skin and eyes. Practitioners are becoming more aware of the importance of outdoor photoprotection. However, little attention is directed to the exposure of the skin and eyes to UVR through the window glass or sunglasses. The amount of ultraviolet transmission through glass depends mainly on the type of the glass. All types of commercial and automobile glass block the majority of ultraviolet-B; however, the degree of ultraviolet-A transmission depends on the type of glass. Laminated glass offers better UVA protection than tempered glass; new safety regulations for automobiles may result in increased use of laminated glass for side windows. Window films can be applied to glass to increase UVR protection. Sunglasses need to be compliant with one of the national standards; a wraparound style or side shields offer the best protection. Increased understanding by practitioners on the transmission of UVR through glass, window films, and sunglasses would allow them to better educate the public and to better manage photosensitive patients.

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Solar radiation is composed of ultraviolet radiation (UVR), visible light, and infrared radiation. UVR, which constitutes approximately 5% of the solar radiation, is divided into UVA (320–400 nm), UVB (290–320 nm), and UVC (200–290 nm). The ozone layer absorbs UVR that is shorter than 290 nm (UVC). UVB constitutes approximately 3.5% of UVR, reaching the earth on a summer day, while UVA constitutes approximately 96.5% (1).

UVR has acute and chronic effects on the skin and eyes. On the skin, the acute effects include erythema, edema, immediate and persistent pigment darkening, and delayed pigmentation/tanning; chronic effects include immunosuppression, photoaging, and photocarcinogenesis (2).

Skin cancers have been shown to be associated with UV exposure in multiple studies (3). Both basal cell carcinomas and melanomas are associated with intermittent exposure, whereas squamous cell carcinomas (SCCs) are associated with chronic exposure (4). Animal studies showed that exposure to wavelengths within the UVB and UVA spectra was associated with the development of SCCs and melanomas (3). Exposure to artificial UV emitted from sunbeds has also been shown to be associated with increased risk of squamous cell carcinoma, basal cell carcinoma, and melanoma (5–8).

UV and visible light can also have adverse effects on the conjunctive, cornea, lens, and retina. The effect on the cornea can be acute, which is self-limited photokeratoconjunctivitis, or chronic, which is climatic droplet keratopathy (9, 10). Chronic exposure of UVR to the conjunctiva is associated with the formation of pterygium (11) and pinguecula (9). Chronic UV exposure to the lens is associated with cortical cataract formation. These associations were supported by many epidemiologic studies with an estimated odds ratio of 1.4 (12, 13). It should be noted that UVR cannot reach the retina except in young children and individuals with aphakia (absence of lens). However, blue visible light can increase the risk of developing macular degeneration (14). Solar retinitis, which is a photochemical injury, results from exposure to blue and violet light in either a high dose over a short period or low dose over a longer period of time to reach the injury threshold (15).

Public education on photoprotection includes seeking shade during peak UV hours of 10 am–2 pm, using photoprotective clothing, wearing a wide brimmed hat and sunglasses, and proper application of broad spectrum sunscreens with SPF30 or above (16). This is an important step in maintaining cutaneous and ocular health.

The above photoprotection message is aimed for outdoor activities. It has been estimated that the average American spends 90% of their time indoors and in their cars (17). Therefore, another potential source of UV exposure is the exposure through window or automobile glass. In fact, a study evaluating the exposure to UVR in cars with open and closed windows reported that exposure is high enough that it needs to be considered in calculating lifetime UV exposure (18). In Australia, studies found actinic keratosis and lentigo maligna to be more common on the right side (outboard glass side for a driver in Australia) than the left side of sun-exposed areas (19, 20). A blinded study done in Michigan evaluating asymmetrical facial photodamage showed a correlation between subjects with more photodamage on their left side (driver side) and the time they spent driving (21). Also, a case report of unilateral Favre–Racouchet syndrome, which is one of the manifestations of chronic sun exposure, occurred in a 65-year-old woman who was exposed to UVR through windows by working in the same location for 15 years (22). In the United States, two recent retrospective studies looked at the distribution of different types of skin cancers. The first study found basal cell carcinomas, squamous cell carcinomas, and melanomas to be slightly more common on the left side than the right side (52.6% vs. 47.4%) (23). The second study looked at melanomas and Merkel cell carcinomas between 1986 and 2006; it found these cancers to be slightly more common on the left side (24). These

data indicate the biologic significance of UV exposure through glass-filtered sunlight.

In this review, we will focus on UV transmission through, and photoprotection offered by, window glass, automobile glass, window films, and sunglasses. We will also bring to light a new automobile regulation, which can indirectly result in greatly decreasing the UVR transmission through automobile windows.

GLASS

Glass is a material with a random, disorganized, noncrystalline structure, resembling the definition of a liquid that allows transmission of a variety of types of electromagnetic radiation. The vast majority of commercially used glass is soda lime glass. It is made up of a mixture of silica (approximately 75%), salt cake, limestone, dolomite, feldspar, soda ash, and typically recycled broken glass called cullet. The mixture, which is called a batch, is melted and poured onto a bed of molten tin metal where it floats and gains its flatness and optical properties as it is drawn downstream and cooled in a long continuous section called a ribbon. The ribbon is ultimately cooled slowly to relieve stresses; this results in annealed glass that can then be freely cut into a variety of sizes for commercial use or further fabrication (25–27).

TYPES OF TYPICAL COMMERCIAL GLASS

A summary of different types of glass is listed in Table 1.

Annealed glass is glass that has been slowly cooled to achieve very low levels of residual stress. It breaks into large sections when fractured and is used in many window applications and layers of laminated automotive windshields (26).

Heat-strengthened glass is made up by uniform heating of regular glass then cooling it at a specific rate resulting in a glass with approximately twice the bending strength of the regular glass despite having the same thickness. This glass fractures in large pieces similar to annealed glass (26).

Tempered glass is made up by uniform heating of annealed glass followed by rapid cooling with air. Tempered glass has the same color and light transmission of annealed glass. The advantage of this type of glass is that it is approximately four times stronger than annealed glass in bending. When it breaks, it results in small pieces with less risk for injury. Tempered glass has commonly been used in areas like furniture tops and on the back and side windows of automobiles (26, 27).

Laminated glass is made by adding a polyvinyl butyral (PVB) layer between two or more layers of glass. Any type

Table 1. Common types of glass

Types of glass	Comments
Annealed glass	Low level of residual stress Breaks into large pieces
Heat-strengthened glass	Twice the strength of annealed glass in bending Breaks into large pieces
Tempered glass	Four time stronger than annealed glass in bending Breaks into small pieces resulting in less risk for injury
Reflective glass	Has mirror-like appearance Reflects both infrared and visible light
Low-emissivity glass	Reflects infrared while selectively transmitting visible light
Laminated glass	Made up of two or more layers of any type of glass with polyvinyl butyral (PVB) layer in between Blocks majority of ultraviolet radiation, decreases sound transmission, and improves security Breakage particle size depends on type of glass layers but pieces adhere to the PVB layer
Insulating glass	Made up of two or more layers of any type of glass with air- or gas-filled space in between Decreases heat transfer

of glass can be used, such as clear, tinted, reflective, annealed, heat-strengthened, or tempered glass. This type of glass is used in automobile windshields and skylight glazing, and is growing in popularity in other glass areas of vehicles. It has been required by regulation for many decades in windshields and is now required for buildings in hurricane zones. Laminated glass has many advantages including decrease in UVR transmission, decrease in sound transmission, better retention in impacts, improved security as it is difficult to penetrate, and low risk of injury when broken because glass pieces stay attached to the PVB layer (26, 27).

Reflective glass is made by adding a thin layer of metal such as silver, gold, copper, or metallic oxide to the surface of glass. This results in reflection of visible light and heat-producing infrared rays (26).

Low-emissivity (low-E) glass is made by adding a stack of very thin (microscopic) metallic and oxide layers to the surface of the glass. These layers may be designed to reflect infrared energy while selectively transmitting visible light in order to reduce solar heat load. When low-E (or infrared reflective) coated glass is combined with lamination, the resulting assembly has all of the benefits of laminated glass, with very low UV and infrared transmission, hence, providing the best performance in terms of comfort, security, safety, and health (26).

Insulating glass units are made by two or more layers of glass separated by a space filled with air or another gas. Similar to laminated glass, any type of glass can be used for the layers (26).

ARCHITECTURAL GLASS FOR BUILDINGS

Architectural glass used for buildings has not changed significantly since this topic was comprehensively reviewed (28). All types of glass summarized in Table 1 can be used as architectural glass.

A recent study looked at UVA transmission through different types of building glass measured by a photometer at 0-cm distance from the source, using a light source that emitted UVA from 315 to 400 nm (29). The highest transmission was through smooth annealed glass (74.3%), followed by tempered glass (71.6%), followed by imprinted (textured) annealed glass (44.6), and finally laminated glass (0%). For smooth annealed glass, the amount of UVA transmission varied from 51.4% to 75.7% according to the thickness of the glass tested, which ranged from 0.2 to 1.0 cm. Using colored imprinted annealed glass, the UVA transmission from the highest to the lowest were blue, colorless, wine, yellow, and green (29).

GLASS USED IN AUTOMOBILES

People are exposed to considerable amount of UVR in their automobiles. An epidemiological study looked at a sample of 169 individuals in different parts of the United States and found that people spent approximately 20 h a day indoors, 2.5 h outdoors, and 1–2 h in their automobiles (17). Edlich *et al.* estimated the average exposure to UVR in automobiles to be 80–96 min/day, based on the US Federal Highway Administration National Statistics (30).

Kimlin *et al.* evaluated UV exposure in cars; they suggested that UV exposure inside cars is high enough that it should be taken into account in estimating total lifetime UV exposure (18).

Characteristics of automobile glass that affect UVR transmission

Transmission of UVR through car windows depends on many characteristics of the glass, which include types, color, and thickness.

The most important factor is the type of glass. All windshields are laminated glass as a result of safety regulations, which have existed for decades to mitigate ejections through the windshield in frontal impacts, whereas side and rear windows are usually tempered glass. Both types of window glass block UVB radiation. On the other hand, UVA transmission varied greatly according to the type of glass. Windshields (laminated glass) block the majority of UVA radiation. Bernstein *et al.* found that windshields block 98% of the UVA radiation as measured by ELSEC® UV Monitor (Littlemore Scientific Engineering, Dorset, UK) (which measured 300- to 400-nm UV wavelength range) (31). Moehrle *et al.* looked at transmission of solar radiation through three different types of windshield glass, which were blue, green, and infrared reflective glass on a sunny day, in Germany during the month of July. For all types, only UV longer than 380 nm was transmitted as measured by spectrophotometry (280–390 nm) (32). Hampton *et al.* looked at a sample of vehicle glass that represented the type of glass used in vehicles in the UK; they found that the total amount of UVA transmission through laminated glass ranged from 0.6% to 9.7% depending on the color of the glass (33).

Side and back windows, which for most automobiles are made up of tempered glass, blocked almost all of the UVB radiation but only 21% of UVA radiation (31). One study found that only wavelengths longer than 315, 330, and 340 nm could be transmitted through clear, light green, and dark green tempered glass, respectively (33). Another study found that only wavelengths longer than 335 nm could be transmitted through blue- and green-insulated tempered glass (32). In conclusion, tempered glass transmits a large amount of UVA radiation and the amount of transmission depends on the color of the glass.

An important clinical consequence of this fact is the possibility of inducing eruptions in patients with severe photosensitive disorders through nonlaminated window glass-filtered UVA exposure. It has been demonstrated that 30–60 min of exposure to solar radiation through nonlaminated window glass, based on the calculation of

midday summer sunlight in the UK, can reach a UVA dose of 5 J/cm², which is sufficient to induce eruption in patients with severe photosensitivity (33).

The other characteristics that affect glass transmissions of UVR are the color and the thickness. The thickness of the glass was shown to have a limited effect on the protection against UVR compared with the other factors (29). On the other hand, the color of the glass plays an important role in UVR protection. Hampton *et al.* studied UVR transmission (300–400 nm) through gray, green, and clear glasses from a sample that represent the different colors of vehicle glass used in the UK; they reported that a gray color offered the highest protection (33). However, dark gray, light gray, and dark green cannot be used in windshields or front side windows of cars because they decrease visible light transmission below the regulatory threshold, which is at least 70% for windshields and front side windows according the European regulation. In the United States, passenger cars are required to maintain at least 70% visible transmission all around. Vehicles classified as trucks are exempt and require 70% only in the windshield and front door windows (34). In a study, Moehrle *et al.* looked at a sample of glass used by Mercedes-Benz; they found that for tempered glass, blue-colored glass transmitted more UVA radiation than did green (32).

New automobile regulation

In the United States, between 1995 and 2003, there were more than 52 000 passenger ejections from automobiles per year with more than 10 000 resulting in fatalities (35). As a result, in January 2011, the National Highway Traffic Safety Administration (NHTSA) issued a new rule, FMVSS 226, for ejection mitigation. This rule states that by September 1, 2017, all automobiles shall pass a special impact test to decrease the risk of ejection from all side windows adjacent to seating positions in passenger vehicles. In testing done by NHTSA, both laminated window glass and side curtain airbags were needed to achieve passing results. However, in some instances, it may be possible to achieve compliance without laminated glass by using augmented airbags. If laminated glass were to be widely used on side, back, and roof windows in addition to windshields, it could have a great impact in decreasing the UV exposure in cars.

WINDOW FILMS

Window films are used mainly as aftermarket products that can be applied to residential or car windows. However, they can also be used between two panes of glass in insulating glass units.

Table 2 Summary of the Australian standard (AS/NZS 1067:2003) and the European standard (EN 1836:2005)

Lens category	Luminous transmittance (LT)	UVB (280–315 nm)		UVA	
		EN (280–315 nm)	AS (280–315 nm)	EN (315–380 nm)	AS (315–400 nm)
AS/NZS 1067 and EN 1836	AS/NZS 1067 and EN 1836				
0 (very light tint)	80%–100%	10% LT	5% LT	LT	LT
1 (light tint)	43%–80%	10% LT	5% LT	LT	LT
2 (medium tint)	18%–43%	10% LT	5% LT	LT	LT
3 (dark tint)	8%–18%	10% LT	5% LT	50% LT	50% LT
4 (very dark tint)	3%–8%	10% LT	5% LT	50% LT	50% LT

UVA, ultraviolet A; UVB, ultraviolet B.

Almost all films are made of multiple layers of polyethylene terephthalate (PET), a polyester resin. Adding color to the films can be done either by passing the film through a solvent bath containing the dyes or alternately dyes can be incorporated within the resin before the film is extruded (Carl Kernander, Madico, Inc., personal communication, 2012).

The UV blocking ability of films is acquired by multiple processes. The addition of a thin layer of aluminum to the PET can result in reflection of the solar radiation; however, it is less desirable because of the mirror-like appearance of the films. Recently, aluminum and other metal particles are sprayed onto the PET, resulting in films that reflect a high percentage of solar radiation while transmitting a high percentage of the visible light. These measures decrease some level of UV transmission by either reflectance or absorbance. However, the primary measure of UV blocking is by adding UV absorbers to the adhesives or directly into the films (Carl Kernander, Madico, Inc., personal communication, 2012).

Two studies have confirmed that the addition of window films to tempered glass usually used in side and back windows resulted in more 99% reduction in the transmission of UVR as measured by UV monitors (29, 31). Bernstein *et al.* evaluated the survival of *in vitro* cultured fibroblasts after exposure to a xenon arc solar simulator through tempered glass, commonly used in side and back windows, and through UV-absorbing window film (Formula One®, Solutia, St. Louis, MO, USA) (31). The study found that 11.1% of cells survived following exposure to unfiltered solar simulator, 36.9% through autowindow glass alone, 90.9% through window films alone, and 93.5% through the combination of autowindow glass and window films. The same study measured the transmission of UVR from solar radiation in Marlton, NJ, in September through a windshield, side widow, and side window plus

UV-absorbing window film. It was found that the windshield blocked 98% of the total UVR as measured by a UV monitor (ELSEC UV monitor). On the other hand, side widows blocked only 21% of the total UVR, and the combined side widow and film blocked 99.6% of the total UVR (31).

Based on current evidence, the addition of window films to tempered glass, which is commonly used in car side and back windows, is an excellent way to increase UVA protection. This is especially useful for patients with severe photodermatoses because the action spectrum for the vast majority of photodermatoses is in the UVA range. On the other hand, laminated glass used in windshields has excellent UVA protection; as such, adding window films is not necessary. Furthermore, adding window films to laminated glass on windshields may reduce the transmission of visible light to below the 70% that is mandated by the United States and European Motor Vehicle Safety Standards. However, if the new automobile regulations make it necessary for automobile manufacturers to use laminated glass for all windows, obviously, the use of window films would then be unnecessary.

For UV protection and energy conservation purposes, the use of window films might be helpful in houses and buildings where older, less UV-protective glass is used for their windows (Table 1).

SUNGLASSES

There are three available national standards for sunglasses: the American standard, ANSI Z80.3, last updated in 2010; the European standard, EN 1836:2005; and the Australia/New Zealand standard, AS/NZS 1067:2003. With regard to UV protection, the Australian and European standards are very similar (Table 2) (36, 38). The two standards differ in the maximum amount of UVB transmission allowed and

Table 3. Summary of the United States standard (ANSI Z80.3)

Lens color	Purpose	Luminous transmittance (LT)	UVB (280–315 nm)		UVA (315–380 nm)	
			Normal use	Prolonged use	Normal use	Prolonged use
Light	Cosmetic	> 40%	12.5% LT	1% LT	LT	50% LT
Medium to dark	General purpose	8%–40%	12.5% LT	1% LT	LT	50% LT
Very dark	Special purpose	3%–8%	1% LT	1% LT	50% LT	50% LT
Strongly colored	Special purpose	> 8%	1% LT	1% LT	50% LT	50% LT

UVA, ultraviolet A; UVB, ultraviolet B.

the definition of UVA (315–380 nm in the European and 315–400 nm in the Australian standard). Based on the American standard (ANSI Z80.3), lenses used in sunglasses are classified into cosmetic, general purpose, special purpose very dark, and special purpose strongly colored (Table 3). The mean UV transmittance allowed depends on whether the lens is to be used for normal (for example, in car and from car to office or home) or prolonged use (38).

In the United States, compliance with ANSI standard is voluntary, whereas in Australia and the European Union, compliance with the respective standard is mandatory. However, only the Australian standard is mandated by the law to be assessed by an independent party. In Europe, products that comply with the European standard can carry a 'CE' mark. Compliance with the European standard can be certified by the manufacturer and does not need to be tested by an independent party. A recent study testing 646 pairs of eyeglasses that carry the CE label to evaluate their compliance with the European standard found that 17% fail to meet the standard requirements. However, only 1.8% failed to meet the UV transmittance requirements. The investigators concluded that manufacturers are becoming more aware of the importance of UVR and the need to protect the eyes from these radiations (37).

The size and the geometry of the sunglasses are other very important factors in the protection against UVR. The Australian standard is the only one that has a minimal requirement for the vertical lens diameter, which is 28 mm for adults and 24 mm for children. A study looked at the amount of UVR reaching the eye in manikins wearing sunglasses; it found that a slight movement (6 mm) of the sunglasses away from the forehead results in a large increase in the amount of UVR reaching the eye. In some sunglasses, especially those with small size, the amount of UVR transmittance can be up to 44% of the amount that reaches the eye without sunglasses

(39). Sakamoto *et al.* measured UVR that reached the eye using sunglasses of varying sizes, sunglasses with side covers, and sunglasses combined with wide brimmed hats. The study concluded that UV protection by sunglasses depends on the size of the sunglasses, regular sunglasses offer poor protection from the sides, and UVR from the back can reflect from the inner surface of the lens on to the eyes (40). These two studies confirm the importance of the size of the lens and indicate that ideal protection from UVR is best achieved by the wraparound style or sunglasses with side shields.

The color of the lens differs according to the purpose and the fashion. The commonly used colors are brown, gray, green, yellow, and rose. For normal use, gray, brown, and green are commonly used because they create minimal or no color distortion, which make them safe in driving (41). Brown has an added advantage of absorbing the blue visible light, which, as we discussed earlier, increases the risk of macular degeneration. Dark-colored lenses can greatly decrease the amount of visible light transmission resulting in dilation of pupils. This can be harmful if the lens does not offer good UV protection or if UV radiation reaches the eye from the sides of the lens. Expensive sunglasses do not guarantee better UV protection; this was confirmed by a study done in 1995 that looked at UVA transmission through a sample of sunglasses (42). Finally, the time of maximum risk of UVR to the eye is different from that of the skin. A recent study found that the time of maximum UVR exposure to the eye is not from 10 am–2 pm as in the case of the skin, but it is between 8–10 am and 2–4 pm where the solar radiation is parallel to the eye (43).

SUMMARY

UVR is a well-known risk factor for skin cancers and photodamage. The general public and physicians are becoming more aware of UVR and the importance of

photoprotection. However, little attention has been paid toward UV exposure in indoor settings, where people spend the majority of their time.

The amount of UV transmission through glass depends mainly on the type of the glass. All types of glass block the majority of UVB, while they transmit a variable amount of UVA. Laminated glass, which is used in automobile windshields, provides the best protection against UVA, while tempered glass used for side and back car windows in the majority of cars is a poor filter of UVA. A new automobile regulation that aims to mitigate passenger ejection might result in more automobile manufacturers using laminated glass instead of tempered glass for side windows, which will indirectly result in a great decrease in the transmission of UVR through automobile windows. Films can be added

to either residential or automobile glass to increase their UVR protection while still allowing variable amount of visible light transmission.

Choosing a sunglass is an important task. The importance of compliance with national standards and wrap-around style or side shields are among the important factors that need to be considered by the public and physicians.

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