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Protection of skin
against full solar, visible and infrared radiation by fabrics: new testing methodology and perspective

KEYWORDS: sun, skin, UV, VIS, IR, UPF, fabric, protection, evaluation, in vitro methods

Abstract The developed testing methodology is capable to measure fabrics protection potential against full solar spectrum irradiation and its VIS+ IR portion; it could be applied, in addition to UPF, to comprehensively evaluate sun protective fabrics. This methodology was utilized in comparative evaluation of various sun protective fabrics to determine their ability to provide protection beyond UV. It was demonstrated that fabrics are capable to effectively protect skin from full solar radiation and its VIS + IR portion and could contribute to novel strategies to help prevent skin photoaging.

INTRODUCTION

According to CIE (Commission Internationale de l'Eclairage) the spectral distribution of natural solar radiation at earth surface contains ~ 7 percent of Ultraviolet light (UV) consisting of UVB (290-320 nm) and UVA (320-400 nm), ~ 55 percent of Visible light (VIS) from 400 to 780 nm, and ~ 40 percent Infrared light (IR) from 780 nm to 1 mm. (1-3). The damaging effects of UV radiation on skin are well-known. However, more than 90 percent of full solar radiation spectrum is in the VIS - IR range, and its potential contribution to skin damage is being increasingly recognized and actively evaluated. For example, Cho *et al.* indicated that in addition to UV radiation, VIS, IR plus heat energy generated by sunlight exposure induce MMP-1 expression in human skin. (4) Zastrow *et al.* demonstrated that the free radical formation is occurring in epidermis and dermis at UV, VIS and near-IR wavelengths; with fifty percent of the total skin oxidative burden being induced by VIS light. (5-6) The contribution of VIS to solar urticarial and porphyria cases, and the predominance of UVA and/or VIS in elicitation of photosensitivity conditions was noted by Menter and Hatch. (7) Cho *et al.* emphasized that in addition to sunscreens that block the effects of UV radiation, novel strategies to prevent VIS, IR- and heat induced skin aging need to be developed. (8) Grether- Beck *et al.* indicated that VIS and IR-A contribute to skin damage in general and photoaging of human skin in particular; as a consequence, attempts have been made to develop skin care/sunscreen products that not only protect against UVB or UVA radiation but provide photoprotection against VIS light and IR radiation as well. (9) Recently Dueva-Koganov *et al.* developed the *in vitro* testing methodologies to qualitatively and semi-quantitatively rank protective properties of various finished goods products against full solar, VIS+IR radiation. These methodologies utilize PMMA HD6 plates; simulated sunlight source with mirrors and cut-off filters producing full solar or VIS+IR irradiation - in conjunction with pyranometer; and monochromator-based spectrophotometer with wavelength range extending to 1100 nm. An expanded protection wavelength (EPW) definition and metric were also proposed to measure the breadth of the protection of topical products beyond UV; and selected topical products demonstrated protection potential against VIS+IR. (10) Term fabric refers to woven or knitted material (11) and sometimes fabric is used interchangeably with cloth or textile. (11-13) Fabrics represent simple and effective wide-spectrum protection against UV radiation (14-18); and the vast majority of studies were related primarily to fabric protection against UV-induced sunburn. (7) The UPF (ultraviolet protection factor) testing concept was first standardized in Australia in 1996 (Standard AS/NZS 4399); it quantifies how effectively a piece of clothing (fabric) shields against the sun. (15) UPF is determined by instrumental *in vitro* test methods based on the fabric transmission in UV range in conjunction with solar UV spectrum and erythemal action spectrum; basically UPF is the ratio of the erythemally weighted UV irradiance at the detector without test fabric to the erythemally weighted UV irradiance at the detector with the test fabric. The systems for determining UPFs are similar around the world. (16) In general, UPF metric used for fabrics is somewhat similar to sun protection factor (SPF) of sunscreen products applied topically.

Standard AS/NZS 4399 provides following UPF rating scheme: fabrics with UPFs in the range 15-24 are rated as UPF 15 or 20 (Good Protection Category); for UPF range of 25-39 rating would be UPF 25, 30 or 35 (Very Good Protection Category); for UPF range 40-50, and 50+ ratings are UPF 40, 45, 50 or 50+, respectively (Excellent Protection Category). (15) AS/NZS 4399 lists a maximum limit of UPF 50+, even though many of the sun protective fabrics have measured UPFs well in excess of this. In 2007 Gies published the overview of photoprotection by clothing and included the measured UPF values of over 22,000 various fabrics tested by Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) according to AS/NZS 4399. These data included median measured UPF values with inter quartile ranges (IQR) for major fabric types: cotton, nylon, polyester, polyester/cotton and nylon/elastane. For example, 6694 samples of nylon/elastane demonstrated median measured UPF value of 161 with IQR range of 96-270. (17) It was also observed that "the right everyday clothing can be highly sun-protective; jeans, for example have a UPF of 1700, and you can't do much better than that". (18) However, when fabric samples are found to have a measured UPF values over 50, AS/NZS 4399 allows rating them only as UPF 50+. (15) An upper limit of UPF 50+ was set to prevent escalating claims from clothing manufacturers. (17) Additionally, Gies emphasized that for photosensitive people it would be desirable to develop protective clothing with extremely low transmittances across not only UVB, but also the UVA and VIS; however, the testing of very high protection garments would require specialized equipment as most commercially manufactured UPF testing equipment does not have the adequate dynamic ranges. (17)

Presently the available information regarding fabric's protection potential against full solar irradiation spectrum, and its VIS+IR portion are very limited.

Thus, the goal of this study was to develop a new testing methodology capable to measure protection provided by fabrics against full solar irradiation spectrum, and its VIS+IR portion; and to apply this methodology in comprehensive evaluation of various sun protective fabrics.

TEST ARTICLES

Seventy five (75) samples of sun protective fabrics having different composition, colour, thickness, weave densities; surface treatments and construction (e.g. woven or knit) were purchased from a well-known industry supplier. (19) Fabrics were divided into seven test groups* based on the description of fabric composition provided on the supplier's website (19): Polyester (I), Polyester/Elastane (II), Nylon (III), Supplex Nylon (IV), Cotton/Nylon (V), Cotton/Elastane (VI) and Cotton (VII).

*Test Groups: Polyester (I) - 8 samples: Barn Red, Tan Plaid, Dark Olive, Dark Grey, Blue Plaid, Pink Plaid, Dark Grey and Wisteria; Polyester/ Elastane (II) - 27 samples: Red, Pink, Neon Green, Purple, Hot Pink, Melon, White, Neon Orange, Black, Charcoal Grey, Forest Green (84 percent Polyester and 16 percent Spandex); Pine, White, Graphite, Black, Royal and Red (95 percent Polyester and 5 percent Elastane); Turquoise, Grey, Royal and Fuchsia (89 percent Polyester and 11 percent Spandex); Lavender, Tan, Light Pink, Black, Columbia Blue and Neon Yellow (90 percent Micropolyeser and 10 percent Lycra); Nylon (III) - 19 samples: Eggplant and Slate Grey (lightweight nylon); Desert Rose, White, Black, Pastel Blue, Vanilla, Warm Taupe, Green Milieu and Apricot Ice (Woven Nylon Wickaway); White, Vanilla, Sage Green, Pastel blue, Royal Blue, Black, Pink Carnation, Cream and Desert Rose (Woven Nylon Water Repellent); Supplex Nylon (IV) - 9 samples: Navy Blue, Stone Beige, Blackberry Cordial, Sage Green, Yellow, White and Mojave Desert (Supplex Nylon); Black and Vegas Gold (Supplex Nylon Water Repellent). Cotton/ Nylon (V) - 2 samples: Woven Olive and Woven Black; Cotton/ Elastane (VI) - 5 samples: Fuchsia, Heather Grey, Black, White, Baby Blue (94 percent Cotton and 6 percent Lycra); Cotton (VII) - 5 samples: Khaki, Natural, Navy, White (Cotton Canvas Duck); White (Cotton).It should be noted that term elastane is often used interchangeably with spandex or lycra. Wool-containing sun protective fabrics were not available from the supplier we used (19) and therefore were not tested in this study.

Experimental Data

Fabrics were evaluated in new, un-stretched, dry, un-washed state.

Microscopy

Brightfield images of fabrics were taken on Nikon Eclipse Ti-S inverted microscope with Nikon Plan Fluor 4x objective and QIClick monochrome camera, with light source illuminating the face side, and objective viewing the back side. Images of selected fabric samples from each test group are presented below. Scale bar is 200 μm in length.

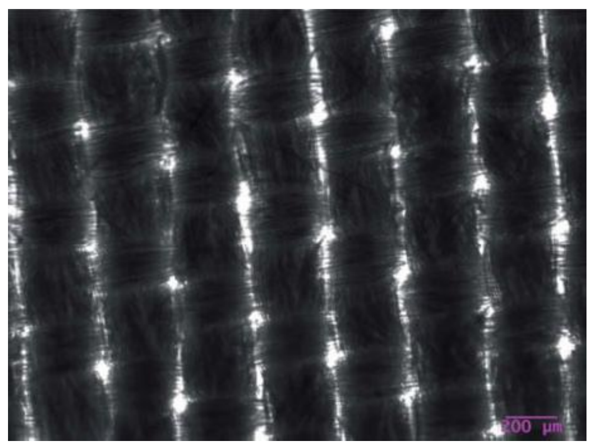


Figure 1. Group I

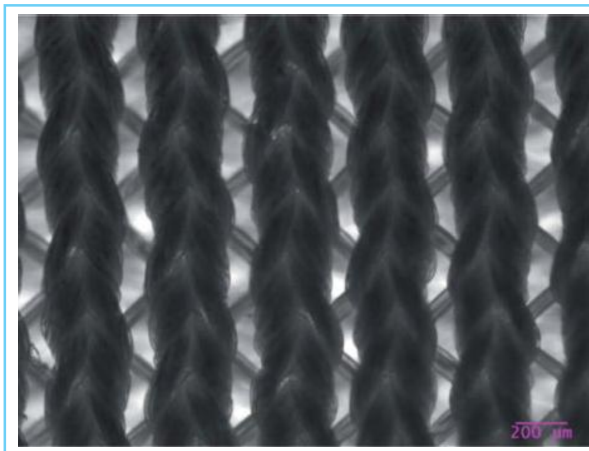


Figure 2. Group II

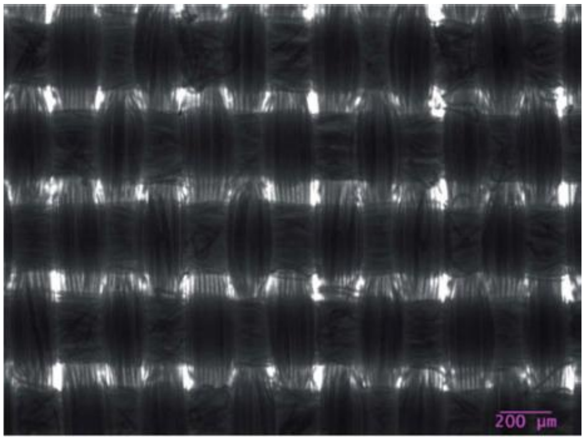


Figure 3. Group III

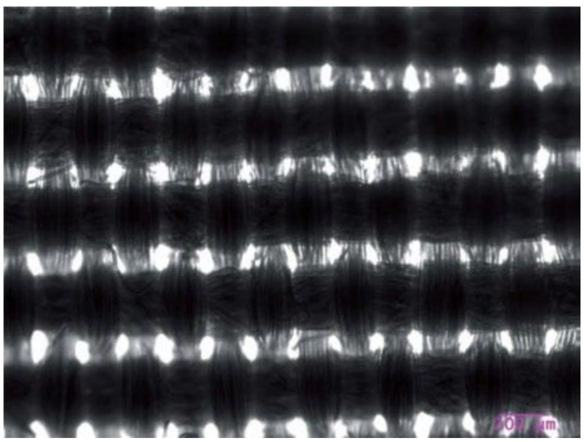


Figure 4. Group IV

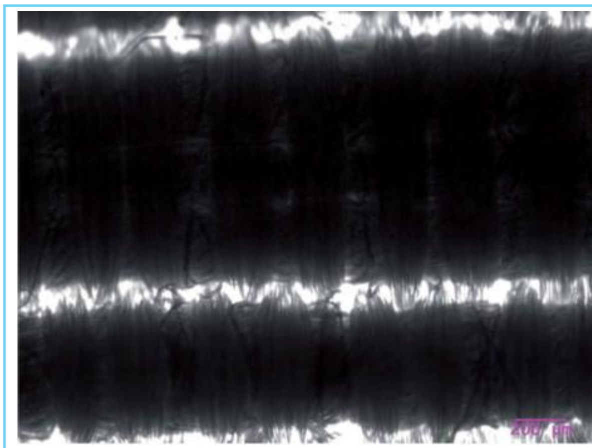


Figure 5. Group V

Images of selected fabric samples from each test group indicate their differences in weave density, space between fibres, the geometrical arrangement of fibres and the open area portions.
It is known that these factors, in addition to fabric composition, colour and mass of fabric per cm^2, can significantly impact UPF values. (14, 16-18)

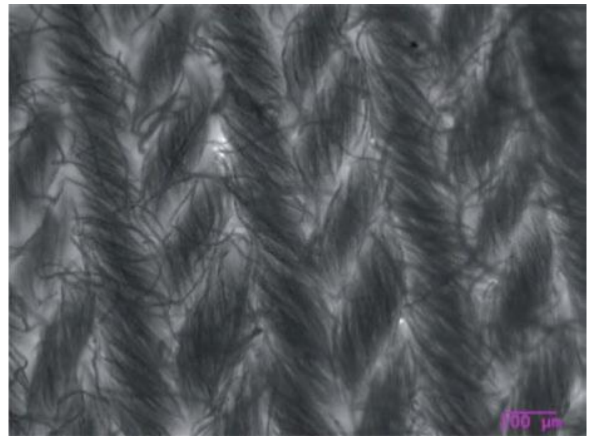


Figure 6. Group VI

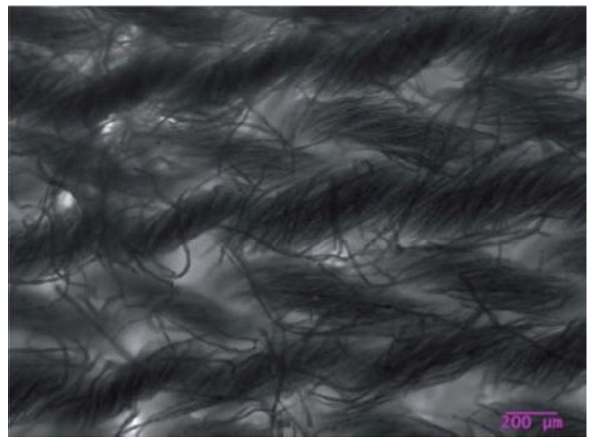


Figure 7. Group VII

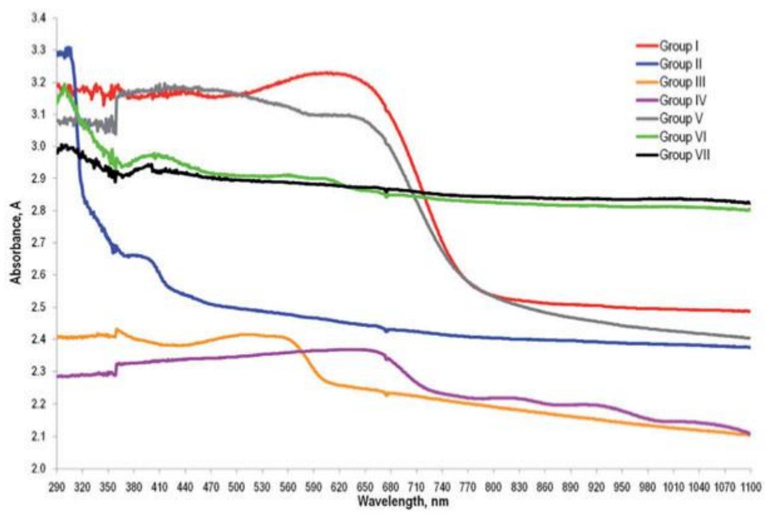
For example, the tighter the knit or weave, the smaller the holes, the less UV irradiation can get through. (14, 16-17)

Evaluation of UPF values

The measured UPF values of selected test fabrics and their UPF ratings were determined according to AS/NZS 4399. (15) Majority of test fabrics were evaluated using the UV-2000S UV Transmittance Analyser with integrating sphere (manufactured by Labsphere, Inc. North Sutton, NH, USA) to measure the diffuse absorbance of fabric samples in the UV region.
The UV-2000S Transmittance Analyser provides a minimum absorbance sensitivity of 2.7A at all wavelengths between 290 and 400nm. Absorbance spectra of 58 out of 75 test fabrics were within the dynamic range for Labsphere UV 2000S and therefore their UPFs were measured.
It should be noted that the wavelength incident on the fabric during the UPF test are limited to UV range and there is no VIS or IR present; and knowledge about UPF is not a good indicator of the ability of fabric to protect skin that is photosensitive to wavelengths outside of UV range. (7)
Test results are presented in summary Table 1.

The absorbance spectra of fabrics in 290 - 1100 nm wavelength range (UV, VIS and part of IR-A range)

Absorbance (attenuation) of specific wavelengths by the



Graph 1. The absorbance spectra of selected fabrics from each test group (I-VII).

fabrics in the 290-1100 nm wavelength range covering UV, VIS and part of IR-A was determined using a dual-beam UV-Visible Spectrophotometer Ultrospec 9000 equipped with tungsten and deuterium light sources (manufactured by General Electric Healthcare Pittsburgh, PA, USA).
Empty reference channel was used as blank. Fabrics were placed in slides and positioned in a sample light path, at a distance of about 2 mm from the lamp aperture.
Absorbance readings of the fabrics were taken at wavelengths from 290 nm to 1100 nm, with 1nm bandwidth. These absorbance readings combine absorption of light by the fabric and the scattering of light at angles sufficient to miss the detector and are believed to be a practical measure of attenuation.
The absorbance spectra of the selected fabrics from each test group (I-VII) are presented in Graph 1.

These absorbance data confirm fabrics' protection potential against irradiation from the 290 to 1100 nm representing the UV, VIS, and partial IR-A range of full solar spectrum. The absorbance values below 400 nm contribute to UPF values and values above 400 nm indicate fabrics protection potential against VIS, and partial IR-A range of full solar spectrum. These data also allow discriminating fabrics' protection qualitatively in these irradiation ranges.
Specifications for the UV-Visible Spectrophotometer Ultrospec 9000 suggest that instrument can provide readings up to 4 A (Absorbance Units) for samples in the signal path for stand-alone systems without PC control. However, Ultrospec 9000 used with PC and Datrys software control enables reliable readings to be made above 4 A. During the testing of few stronger-absorbing fabrics (not shown in the Graph), absorbance readings above 4 were obtained; and according to manufacturer of Ultrospec 9000, the readings for very highly absorbing fabrics could still be useful for qualitative judgment if they fall below absorbance readings generated with a completely blocked sample light path, while any readings above would represent attenuation beyond instrument's measurement capacity. The suitability of Ultrospec 9000 (with excellent dynamic range) for measuring UPFs of highly UV absorbing fabrics will be investigated in a follow-up study.

***In vitro* determination of fabrics protective properties against simulated full solar and its VIS + IR portion**

Tests were conducted under controlled irradiation to quantitatively evaluate potential protective properties of various fabrics against simulated full spectrum sunlight and its VIS+IR portion. The experimental set-up included: Solar Simulator LS 1000-6R-002 Rev.3 with Xenon Arc Lamp and XPS 1000 precision current source; PMA2144 Pyranometer providing uniform spectral response - with PMA2101 Detector to measure the total radiant power of incident radiation from 310 nm to 2800 nm.
Simulated full spectrum sun irradiance at Earth surface was produced with the use of plain mirror, AM0 (SL04486) and AM1.5 (SL04204) filters; the VIS+IR portion of sun irradiance at Earth surface was achieved with plain mirror, M0 (SL04486) , AM1.5 (SL04204) and UV cut-off (SL07876) filters (all from SolarLight Company, Glenside, PA, USA).
PMA2144 Pyranometer (cosine-corrected) and PMA2101 Detector were used to measure the total radiant power of incident radiation. An opaque housing was made for the PMA2144 Pyranometer to ensure accurate positioning of the fabrics over the detector.
Distance from the bottom lip of solar simulator aperture to the top of fabric was about 250 mm, with a distance of about 5 mm from the fabric to the top of the Pyranometer protective dome. This set-up is presented in Figure 8.

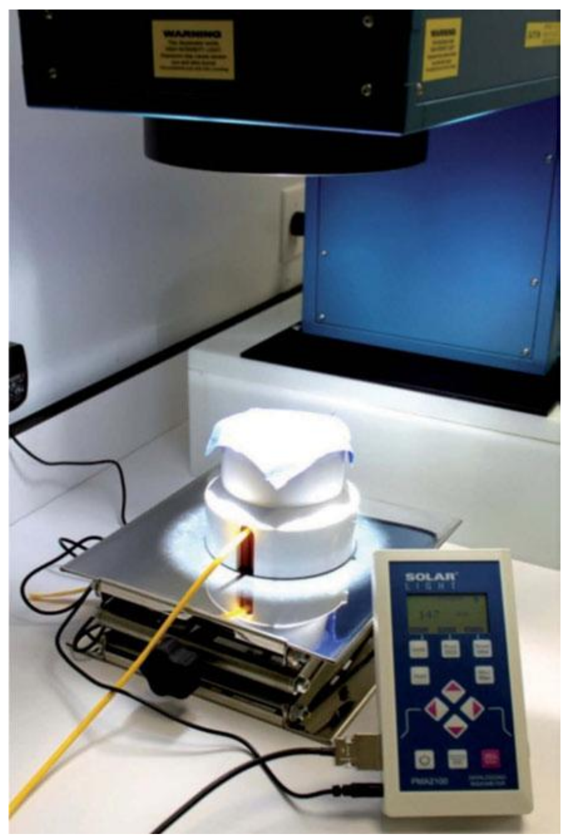


Figure 8. The set-up to determine protective properties of fabrics against full solar and VIS + IR radiation.

Fabric Type	Test Group	Number of Fabrics	Measured UPF*	AS/NZS 4399 UPF Rating	**Full Solar percent Attenuation Median (Range)	**VIS+IR percent Attenuation Median (Range)
Polyester	I	8	31-707	30-50+	**78** (73-83)	**75** (74-81)
Polyester/Elastane	II	27	39-743	35-50+	**80** (63-87)	**79** (58-88)
Nylon	III	19	77-559	50+	**75** (64-87)	**71** (61-86)
Supplex Nylon	IV	9	15-424	15-50+	**73** (63-86)	**70** (62-86)
Cotton/Nylon	V	2	291	50+	**88** (87-89)	**87** (86-87)
Cotton/Elastane	VI	5	278	50+	**84** (74-92)	**83** (72-89)
Cotton	VII	5	201-447	50+	**81** (78-90)	**79** (75-88)

Table 1. Summary of Test Results.
*UPFs of 58 out of 75 test fabrics were measured; 17 of test fabrics exceeded the dynamic range for Labsphere UV 2000S and were not measured; **Irradiance recorded for the empty light path was considered as 100 percent Transmittance and 0 percent Attenuation for: *Full Solar - 1149 W/ m^2; ** VIS+IR - 1038 W/ m^2.

The irradiance received by the Pyranometer was recorded 1 minute after opening of the lamp shutter - to ensure stable readings. Under these test conditions the full solar simulated sun irradiance closely resembles typical solar radiation at clear sky - 1100 W/m^2.
The attenuation of simulated full spectrum sunlight and its VIS-IR portion by test fabric was calculated as a percentage of irradiance attenuated (blocked) assuming that the irradiance data for recorded for the empty light path is 100 percent.
Measured absorbance values represent the "worst case" scenario due to the fact that they were obtained by passing irradiation in a direction perpendicular to the fabric, which minimizes the scattering.
Test results are summarized in the Table 1.

DISCUSSION

The measured UPF median values and ranges vary significantly within each group and among different groups. In general, higher UPF measured values could indicate greater UV protection. Fabrics made from cotton/elastane, cotton/nylon and polyester/elastane demonstrated higher UPFs. It was also found that fabrics from the same group with darker colors tend to have higher UPFs than ones with lighter colours and whites, but fabrics with bright colours such as red can also substantially absorb UV rays, which is consistent with findings reported by Gies. (17) Fabric samples with measured UPF values over 50 could be rated as UPF 50+ according to AS/NZS 4399. (15) Based on their absorbance (attenuation), fabrics demonstrated about 63 percent to 90 percent protection against simulated full solar sun irradiation (in the 310 nm - 2800 nm range) and 58 percent to 89 percent protection against its VIS + IR portion (from about 400 nm to 2800 nm). The higher percent absorption indicates higher protection potential of fabrics in the respective wavelengths ranges. Our findings indicate that fabric type; weave and colour significantly contribute to its protection potential against simulated full solar irradiation and its VIS + IR portion. In the fabric samples tested, we found that attenuation of full spectrum sunlight correlates well with attenuation of its VIS+IR portion (linear, R^2 = 0.97). Interestingly, fabrics with the highest percent absorption of simulated full solar and its VIS + IR portion not always showed highest UPF value, which indicates that there is no direct correlation among these protective properties. A notably weak (exponential, R^2 = 0.41) correlation exists between attenuation of full spectrum sunlight and UPF properties of the fabric. The developed testing methodology described above is capable to measure protection provided by various fabrics against full solar spectrum and VIS+ IR. It could be used, in addition to UPF, to comprehensively evaluate sun protective fabrics. This methodology was successfully utilized to comparatively evaluate sun protective fabrics ability to provide protection beyond UV. It was demonstrated that fabrics are capable to effectively protect skin from full solar radiation and its VIS + IR portion. Fabrics can contribute to the novel strategies to protect against skin photo ageing induced by full solar radiation and its VIS+ IR portion. Fabrics can be used in conjunction with topical sunscreen and anti-aging products in order to achieve expanded photoprotection of skin. The possible extension to this study could provide more fundamental understanding of the absorption processes occurring and the base properties of various fabrics. For example, "normalization" for the void area in the fabric weaves, fabric thickness, and mass of fabric/cm^2 could be applied in order to determine which fabric has the highest protection potential against simulated full solar irradiation and its VIS + IR portion.

CONCLUSION

The developed testing methodology is capable to measure fabrics protection potential against full solar spectrum and its VIS+ IR portion. It could be applied, in addition to the UPF, to comprehensively evaluate sun protective fabrics and used as screening tool for the development of new photoprotective fabrics. This methodology was utilized in comparative evaluation of various fabrics to determine their ability to provide protection beyond UV. It was demonstrated that fabrics are capable to effectively protect skin from full solar radiation and its VIS + IR portion. Therefore, fabrics can contribute to the novel strategies to protect against skin photoageing and can be used in conjunction with topical sunscreen and anti-aging products in order to achieve expanded photoprotection of skin.

ACKNOWLEDGEMENTS

The authors wish to thank Staffan Asplund, Bruce Beard, Ralph Mancini, Robert Turner and Katherine Figueroa.

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