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INVITED REVIEW

Ultraviolet radiation thin film dosimetry: A review of properties and applications

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Abstract

Spectroradiometry, radiometry, and dosimetry are employed for the measurement of ultraviolet radiation (UVR) irradiance and non-ionizing exposure. Different types of UVR dosimeter have been developed for measuring personal and environmental UVR exposures since film dosimetry was pioneered in the 1970s. An important type of dosimeter is the thin film variant, which contains materials that undergo changes in optical absorbance when exposed to UVR. These changes can be measured at a specific wavelength using a spectrophotometer. Thin film dosimeters allow UVR exposure measurements on humans at various body sites during daily activities, as well as on plants, animals, and any sites of interest when utilized in a field environment. This review examines the properties and applications of five types of thin film UVR dosimeter that have different dynamic exposure limits and spectral responses. Polysulphone, with a spectral response approximating the human erythema action spectrum, was one of the first materials employed in thin film form for the measurement of UVR exposures up to 1 day, and up to 6 days with an extended dynamic range filter. Polyphenylene oxide has been characterized and employed for personal UVR exposure measurements up to approximately four summer days and has also been used for long-term underwater UVR exposures. Phenothiazine and 8-methoxypsoralen have been reported as suitable for the measurement of longer wavelength UVA exposures. Finally, polyvinyl chloride with an extended dynamic exposure range of over 3 weeks has been shown to have predominantly a spectral response in the UVB and extending up to 340 nm.

KEYWORDS

8-methoxypsoralen, dosimeter, erythema, phenothiazine, polyphenylene oxide, polysulphone, polyvinyl chloride, UV, UVA, UVB

Abbreviations: 280–320 nm, UVB; 320–400 nm, UVA; 8MOP, 8-methoxypsoralen; AEST, Australian Eastern Standard Time; DOM, dissolved organic matter; K_d, attenuation coefficient; MED, minimum erythemal dose; NDF, neutral density filter; PPO, polyphenylene oxide; PVC, polyvinyl chloride; SED, Standard Erythema Dose; SZA, solar zenith angle; UPF, ultraviolet protection factor; UVR, ultraviolet radiation; ΔA, change in optical absorbance.

INTRODUCTION

The measurement of ultraviolet radiation (UVR) irradiance and exposure can be conducted using spectroradiometry, radiometry, or dosimetry.[1] Dosimetry is an essential tool for the characterization of UVR exposures in situ and when calibrated locally to a radiometer or spectroradiometer and is applicable across a range of environments. The small size and light weight of thin film dosimeters allow for the measurement of UVR exposure on humans across various anatomical locations during daily activities, to leaves on plants, on animals and on any sites of interest when applied to field studies.[2] The types of UVR dosimeters for use in human exposure studies can be categorized as chemical,[3] biological,[4] electronic,[5,6] and with related smart phone applications.[3] The dosimeters considered in this review are thin film chemical dosimeters, which undergo photodegradation upon exposure to UVR and measure cumulative UVR exposure across a desired wavelength range.[7] Quantification of the photodegradation for each type of dosimeter is by measuring the pre- and post-exposure optical absorbance using a spectrophotometer at the wavelength where there is the largest change in optical absorbance (ΔA).[8]

A photodegrading material is suitable for use as a UVR dosimeter, if it can be produced in a consistent manner with a reproducible thickness, followed by standardized measurement of the optical absorbance pre- and post-exposure. A commonly used technique for producing a thin film of photodegrading material involves casting a thin polymer sheet of film by spreading the relevant solution of photo-active material, mixed within a solvent, on a uniformly flat A4 glass block or blank. The solution is spread using a motor driven blade set at the appropriate height above the glass to produce a thin film of the required thickness once the solvent evaporates.[9] The optical absorbance measurement when the film is dry and assembled into a dosimeter frame is standardized by placing each dosimeter in a fixed holder so that the spectrophotometer beam measures the optical absorbances at the same location on the dosimeter. Errors in the measurement can be reduced by measuring and averaging the optical absorbance at four locations over the surface of the dosimeter.[2,10]

UVR dosimeters need to be characterized for their dark reaction, cosine response, reproducibility, temperature independence, dose response, and spectral response.[11,12] The dose response requires exposing a set of dosimeters on a horizontal plane while measuring the respective UVR exposures with a calibrated radiometer or spectroradiometer.[12] Calibrating the ΔA response of each film batch for the local conditions and season ensures the accuracy of the dosimeters.[13] Consequently, calibration is an essential component of thin film dosimetry to measure UVR exposure.

The history of the development and characterization of polysulphone UVR dosimetry has been detailed.[11] The use of film dosimeters for the measurement of personal UVR exposures during nonoccupational settings[14] and recent comparisons between different types of wearable UVR sensors including film dosimeters have been reviewed.[3,15] Studies have demonstrated the versatility of UV dosimeters to research that looks at spatial and orientation variations.[16–18]

This article extends previous work to review the properties and applications of five types of thin film UVR dosimeter. These dosimeters offer a range of dynamic responses and spectral responses for UVR exposure measurements to individuals, as well as to plants and various sites of interest in a field environment. The thin film dosimeters reviewed in the next five sections are polysulphone, polyphenylene oxide (PPO), phenothiazine, 8-methoxypsoralen (8MOP), and polyvinyl chloride (PVC). These five types have commonalities in their fabrication, calibration, and processing. The first section on polysulphone is lengthier than the next four as polysulphone dosimeters have been more widely employed than the other types.

POLYSULPHONE

Polysulphone has a spectral response up to 340 nm that approximates the human erythema action spectrum[19] (Figure 1). The application of polysulphone to measure UVR exposure was first reported in 1976.[20] It has been used in numerous studies to quantify personal UVR exposures, calibrated to the human erythema action spectrum for various human anatomical sites measured across

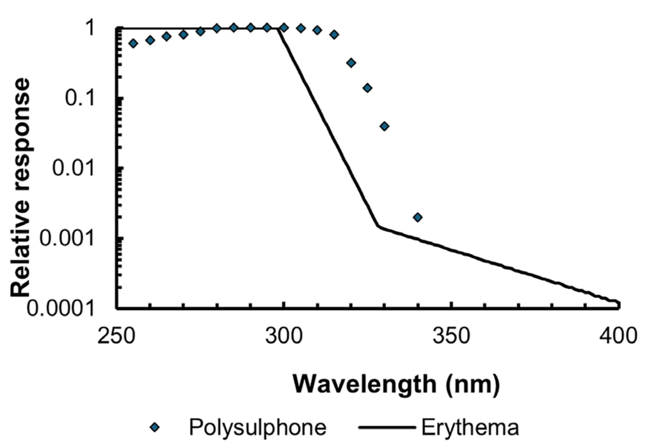

FIGURE 1 Comparison of the erythema action spectrum[19] and the polysulphone spectral response.[12]

a range of activities.[2,21] Additionally, polysulphone has been employed on manikins to quantify the anatomical distribution of UVR exposure[22] and has also been calibrated to different biologically effective responses. The action spectrum for pre-vitamin D_3 is predominantly at wavelengths shorter than 330 nm.[23] This has allowed calibration of polysulphone to measure pre-vitamin D_3 effective UVR exposures in addition to the human erythema response.[24] Additionally, a thin film of polysulphone has been layered on a thin film of nalidixic acid[25] to produce a combined spectral response[26] that approximates the action spectrum for the plant growth inhibition in higher plants.[27] An advantage of using polysulphone dosimeters for UVR exposure measurements compared to biological-based or electronic dosimeters is that the low cost and unobtrusiveness of the dosimeter allows for multiple measurements to be made, providing a comprehensive analysis of different exposure sites and for multiple occupational observations.[11]

Polysulphone dosimeters are typically calibrated on a horizontal surface to measure the UVR at various orientations. Research has shown that calibrations conducted on a horizontal plane are applicable for measurements taken at incident angles between the sun and the dosimeter surface of up to 70°,[18] particularly for surfaces without very high albedo. The steps involved in the calibration and determination of UVR exposures with polysulphone dosimeters are shown in Figure 2. The coefficient of variation in the evaluation of the UVR exposure is reported as 10% for a ΔA up to 0.3 and increases for a ΔA above 0.3.[8] The following in this section outlines 11 application areas.

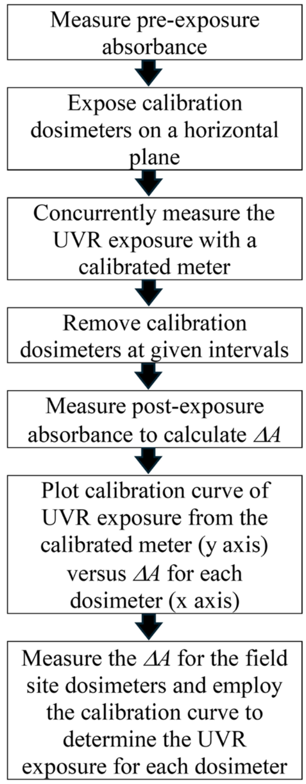

FIGURE 2 The steps involved in the determination of UVR exposures with polysulphone dosimeters. The same principle applies to the use of other thin film dosimeters.

Applications—Outdoor activities

Exposure to UVR may occur during sporting or leisure activities as well as outdoor occupational activities. Early studies utilizing polysulphone dosimeters include exposures received by:

1. Participants engaged in outdoor leisure activities[28,29];
2. Cyclists[30];
3. Sunbathers[31];
4. Individuals in urban canyons[32];
5. Australian adults undertaking normal daily activities[33–35];
6. Ski instructors and skiers.[16,36]

Polysulphone dosimeters have also been deployed for determination of exposure to the eyes[37–39] and on a manikin head to determine facial UVR exposure for a range of solar positions and elevations.[40,41] One advantage of using a thin film dosimeter is that they can readily be adhered to exposed skin surfaces using tape. They are often used to determine exposure ratios expressing relative body site exposure with respect to the maximum available ambient UVR. These measures are used to differentiate between different body sites, different activities, and exposures received during different times of the day or season[42] and are useful for expressing comparative exposure risks.

Applications—Miniaturized dosimeters

The flexibility of polysulphone film allows manufacture of dosimeters small enough to adhere to the fine scale topography of the human face. Polysulphone film attached to lightweight flexible frames measuring 10 mm × 15 mm with the polysulphone covering a 6 mm diameter aperture was utilized.[43] This miniaturization allowed for the placement of up to 709 dosimeters on individual facial locations on a human size manikin head form. When calibrated, exposures of the miniaturized polysulphone dosimeters were evaluated relative to the local ambient UVR in three solar zenith angle (SZA) ranges from zero to eighty degrees. Evaluation of the UVR exposure received over a full day, a week, or longer periods was derived by multiplying individual facial site exposure ratios (for a respective SZA) by the ambient exposure received on a horizontal plane. This enabled the evaluation of detailed facial exposures by utilizing calibrated UVR radiometers deployed for ongoing measurement at an existing monitoring site or modeled directly using ambient UVR exposure algorithms.

Miniaturized polysulphone dosimeters have been utilized for the evaluation of UVB (280–320 nm) exposures to plants.[44] The small size and light weight (0.03 g) ensure that there is minimal disruption to the plant leaves enabling determination of the cumulative UVB exposures to the plant accounting for cloud cover, shading, leaf inclination, and orientation and atmospheric conditions.

Applications—Workers

In addition to environmental and individual factors, occupational factors are an important and relevant factor for determining an individual's UVR exposure.[45] Researchers have utilized polysulphone dosimeters to evaluate the UVR exposures to outdoor workers such as those in building and construction,[46,47] lifeguards and farm workers,[48] swimming pool staff,[49] and workers in agriculture,[50–53] due to the risks of cumulative UVR exposure.[50,54–58] Artificial sources such as arc welders[59] and phototherapy cabins[60] also contribute to UVR exposure. Researchers have used polysulphone dosimeters to measure the cumulative UVR exposure of indoor workers such as schoolteachers,[57,61,62] office workers,[63] indoor home workers,[64] pregnant women,[65] and pilots on flight decks.[66] Further studies have included investigations on the influence of vitamin D supplementation and sunlight on women in Brazil and England,[67] on seasonal variations of 25(OH)D in women,[68] on UVR exposures and 25(OH)D concentration in south Asian adults compared to white adults in England,[69] on serum 25(OH)D concentrations of office workers and environmental UVR exposure,[70] and the UVR from office lighting.[71]

UVR exposure measurements to workers have shown that the daily occupational limit of 30 J/m^2, based on the International Commission on Non-Ionizing Radiation Protection action spectrum,[72,73] or approximately 1.0–1.3 Standard Erythema Dose (SED),[19] is frequently exceeded.[45,47,50,54–58,62,74] Examples include Antarctic resupply personnel receiving up to 18 SED,[58] Antarctic expedition workers receiving daily exposures ranging from 3 SED to 43 SED,[75] and utility workers in Canada receiving up to 6.1 SED[56] during their normal occupational duties. Some jobs classified as traditionally indoors, such as school teaching[62] can experience UVR exposures comparable to outdoor occupations such as gardeners.[57] Measurements with polysulphone dosimeters[61–63,76] showed that schoolteachers often approach or exceed the UVR exposure limits due to intermittent exposures during their normal duties which include outdoor yard and activity supervision duties.

Applications—Children

The UVR exposures received during childhood are an important component of the cumulative UVR exposure received during a lifetime. Polysulphone dosimeters have been employed in several investigations focusing on UVR exposures to children and adolescents, along with the influencing factors. Examples include measurement of UVR exposure to primary school children in Sweden,[77] early childhood centers,[78] preschools,[79,80] and a childcare center.[81] Others are a total of 180 children from a primary school and secondary school in three areas in England,[82] children in three age groups in South Africa,[83] children from primary schools in Queensland, Australia,[84] UVR exposures and the use of shade by children in Perth primary schools,[85,86] UVR exposures to facial sites of 45 high school children playing sport,[87] children at a day camp in Massachusetts,[88,89] 93 adolescent child and mother pairs at two locations in China,[90] and 1 and 2 1/2-year-old children.[91,92] UVR exposures quantified with polysulphone dosimeters have been compared to data collected through questionnaires on 125 adolescent schoolchildren, with reasonable agreement between the two datasets.[93] Further research evaluated the cumulative UVR exposure to individuals up to 20 years of age using a model and measured UVR exposures.[94]

Applications—Hair and beards

The protection from UVR by head hair and beards and mustaches has been investigated with polysulphone dosimeters.[95,96] The dosimeters were deployed on life-size manikin heads at multiple sites under wigs and beards and mustaches made from human hair. Dosimeters were also deployed on a manikin head with no head hair or facial hair to calculate the protection provided.

Applications—Clothing

The standard for the evaluation and classification of the ultraviolet protection factor (UPF) of clothing employs laboratory measurement.[97] This provides consistent evaluation and classification and is the most practicable and efficient technique for large numbers of measurements.[98] The in vivo measurements of the UPF are useful in practical life-like cases.[98] The in vivo methodology employs either the determination of the minimum erythemal dose (MED) through clothing on human skin or the use of dosimeters.[99]

Life-size manikins have been used in a phototherapy cabinet for in vivo research of the UPF with polysulphone dosimeters under various T-shirts at 10 sites on a manikin and another set adjacent to these, on the surface of the T-shirts.[100] In sunlight, dosimeters have been placed under clothing on both life-sized manikins and on humans. A wet and a dry, black and white, summer garment was tested with polysulphone dosimeters on human volunteers while swimming and jogging. Manikins have been used to test the reduction of UVR exposures by stockings.[101] Simulated wear in the field with two commonly available black and white dry knit fabrics, both wet and dry, provided results indicating that the main influences on erythemal UVR transmission[102] and pre-vitamin D_3 UVR[103] were fabric type and fit. Color and wetness were found to have a lesser influence compared to fabric type and fit. These simulated wear measurements have the advantage of accounting for the stretch and wetness of the garment while it is being worn.

Polysulphone dosimeters attached to head forms fitted with different hat styles provided the UVR protection due to hat type. The hat styles studied included small and broad brimmed hats, baseball caps, broad brimmed "bucket hats," and legionnaires hats.[104–106]

Applications—Aquatic environments

The polysulphone thin film does not undergo a chemical reaction when immersed in water and is less expensive than any electronic meter or electronic dosimeter that can be submerged in water. The dosimeter was successfully employed underwater at a tropical latitude.[107] Subsequently, polysulphone has been used to study UVR exposures of swimmers,[108] triathletes[109] and snorkelers.[110] The film is calibrated either underwater or on the waterline and simultaneously, a radiometer measures the cumulative UVR exposure to generate an underwater dose response calibration curve.[110]

Applications—Trees

The use of tree shade is an important component of UVR minimization strategies. Polysulphone dosimeters have been employed to quantify the UVR protection of tree shade by deployment on a horizontal plane in full sun and on eight upright manikin body sites in the shade of a gum tree (*Eucalyptus* sp.) and a she-oak (*Casuarina* sp.).[111] Protection factors of 2–6 and 3–20 compared to a horizontal plane in full sun for the gum tree and the she-oak, respectively, were determined for cumulative exposures between 9:00 and 15:00 Australian Eastern Standard Time (AEST). Follow-up research employed polysulphone dosimeters to measure the erythema UVR exposure distribution to body sites of an upright manikin in the shade of Australian gum trees,[112,113] enabling the determination of the UVR exposures in the shade of these trees over summer[112] and over an entire year.[113] Research employing polysulphone dosimeters exposed for 1 hour either side of solar noon on a horizontal and a vertical plane in the shade of six common trees planted in Australian urban environments found protection factors of 5–10 compared to full sun on a horizontal plane.[114]

Applications—Albedo effects

UVR reflected from natural and constructed surfaces can have a significant impact on an individual's UVR exposure. Albedo is the reflectance of isotropic irradiance from predominantly natural surfaces and is typically considered in most ambient UVR measurements. Reflectance from built environment materials tends to be anisotropic reflected irradiance and can enhance or decrease the total irradiance to a localized area. UVR dosimeters provide a means of measuring the impact of localized reflective surfaces on the UVR exposure an individual experiences near built surfaces.

Previous research[115,116] employed manikins with 14 mm × 20 mm polysulphone dosimeters attached to specific body sites on manikins and placed in the set positions of proximity to a reflective surface and a non-reflective surface and an open area unobstructed by a nearby surface. These studies demonstrated that anatomical sites normally considered to be shaded from ambient UVR exposure were significantly influenced by added reflected UVR irradiance. For example, a polysulphone dosimeter attached to a manikin's chin close to zinc aluminum coated steel sheeting underwent significant increases in UVR exposure in certain seasons.[116] In autumn, characterized by a high SZA (but not necessarily high ambient UVR irradiance), the increase in the expected exposure on the chin was 150% higher to that on a manikin not located near a structure. A repeat of the research during spring (smaller SZA but higher ambient UVR irradiance) indicated only a 20% higher UVR exposure.

The addition of a second reflective surface normal to the first surface (creating a corner) can reduce the effect of reflectance on ambient UVR exposure,[117] despite the original increase in UVR exposure measured from a single wall.[116] The inclination of the surface relative to the sun-normal plane[118] and the surface smoothness of the material[119] both influence the effect of reflectivity on the UVR exposure in localized environments.

Similar techniques using polysulphone dosimeters have been utilized to evaluate the influence of solar UVR reflectivity from solar photovoltaic panels on UVR exposure to the technicians maintaining and installing these panels.[120] The photovoltaic cells generally absorb dispersed radiation in the UVR waveband; however, direct UVR reflectance from these surfaces may increase an individual's exposure by as much as 50% under specific conditions.

Applications—Shade structures

The use of shade is an important strategy in the minimization of UVR exposures. Polysulphone dosimeters were employed to evaluate the protection provided by various shade structures with dosimeters placed in the shade of the structure and in full sun, either on a horizontal plane or on a manikin. The UVR protection has been evaluated for a shade cloth structure to 10 anatomical sites,[121] for five types of umbrellas,[122] for 29 shade structures in 10 New Zealand schools in the school lunch break[123] and for a manikin head form under a shade structure in the form of a gazebo with a metal roof in a public park.[124] At swimming pools, the protection provided by the shade structures has been evaluated between 1.00 and 2.00 pm local time with polysulphone dosimeters placed both horizontally on a kickboard floating in the approximate center of the pool and on a child sized manikin approximately in the pool center.[125]

Applications—Extension of dynamic range

Polysulphone has a dynamic range approximately equivalent to a single day of UVR exposure in temperate environments, requiring the dosimeters to be replaced each day. A thin mesh over the dosimeter material has extended the dynamic range of polysulphone to allow measurements over a longer period.[12] Additionally, a neutral density filter fabricated from exposed black and white photographic film has extended the dynamic range to 3 to 6 days in subtropical Australia.[126]

PHENOTHIAZINE

The UVA (320–400 nm) wavelengths have been reported as a potential carcinogen in human skin[127] and also contribute to premature photoaging.[128] Typically, the UVA irradiance is higher by a factor of approximately 20 for clear skies and SZA below 50°, and higher by a factor of over 60 for SZA exceeding 80°.[129] Additionally, UVA penetrates deeper into human skin[130] and is transmitted through untinted window glass.[131] Population studies aiming to characterize UVA exposures during normal daily activities require a UVA waveband sensitive dosimeter.

A dosimeter based on the chemical phenothiazine that reacts to both UVA and UVB wavelengths was developed and used for measurements of personal exposures,[132] exposures in two photochemotherapy units,[133] and indoor exposures in museums.[134] Application of Mylar film (Cadillac Plastics, Australia) approximately 0.13 mm thick, which has a transmission predominantly in the UVA on top of a 30 to 40 micron film of phenothiazine,[135,136] results in a dosimeter sensitive to the UVA with a dynamic range of 3–4 h at a subtropical latitude. The ΔA of this UVA dosimeter is measured at 370 nm, with calibration under the same conditions in which it will be utilized. The phenothiazine dosimeter does not undergo a dark reaction. Additionally, its cosine response is within 10% up to 70°, and its operational temperature range extends up to 50°C while maintaining a 12% error tolerance associated with the dosimeter.[136]

POLYPHENYLENE OXIDE (PPO)

Initial research described how polyphenylene oxide film can be employed in air to evaluate UVR exposures over prolonged time intervals,[137–139] followed by quantification of the dosimeter properties.[140] This research reported a dynamic range up to 4 days in summer at a subtropical site.

Testing conducted on the characteristics of the PPO UVR dosimeters underwater[141] indicated that the uncertainty of PPO film underwater measurements could vary from ±15% to an upper limit of ±20%. Further research[142–144] detailed a series of underwater calibrations in stagnant water, free-flowing water, and sea water using PPO dosimeters exposed over a year. The calibrations performed in air were not suitable for underwater measurements, and the SZA had a pronounced influence on the shape and distribution of underwater calibration data. Calibrations conducted in one type of water at various depths could be applicable to another type of water and provided that the different water types have similar levels of turbidity and dissolved organic matter (DOM) content. The PPO dosimeter was applied for long-term measurements in three aquatic environments (a dam, creek and an ocean simulator).[142–144] The data enabled calculation of an underwater UVR attenuation coefficient (K_d) of sea water in each season. These values were comparable to K_d values calculated from calibrated spectrometer data; however, caution is required when the PPO dosimeter is deployed in water bodies with high turbidity and high DOM levels, as significant deposits of inorganic/organic matter on the PPO film may negatively interfere with its structural integrity and post-exposure optical properties.

In-air measurements made with the PPO dosimeter over an entire year at a subtropical Australian location[145] reported that the in-air PPO dose response is sensitive to variations in SZA and atmospheric ozone levels. Additionally, PPO dosimeters have been employed to evaluate the UVB exposures to both sides of plant leaves.[44] An inexpensive polyethylene neutral density filter (NDF) applied to the top of a PPO dosimeter can extend the dynamic range by up to 5 days before reaching saturation.[143] The usefulness and versatility of PPO dosimeters have been extended by producing miniaturized dosimeters with similar properties compared to larger PPO dosimeters.[146] Miniaturized PPO dosimeters have been used to measure ICNIRP[73] weighted UVR exposures to teachers over a 5-week time interval. Further research[147] conducted simultaneous calibrations of the PPO dosimeter to the erythema and vitamin D_3 effective UVR, enabling its use as a dual-application dosimeter.

8-METHOXYPSORALEN (8MOP)

Diffey & Davis[148] identified 8-methoxypsoralen as a potential UVA dosimeter. Subsequently, a miniaturized UVA dosimeter using 8MOP with a 0.13 mm thick Mylar sheet to filter out UVB has been fully characterized and calibrated to quantify seasonal UVA exposure, with measurement of the ΔA at 305 nm.[149]

A combined dosimeter badge, consisting of a miniaturized PPO dosimeter and a miniaturized 8MOP UVA dosimeter,[150] was worn by volunteers to record simultaneously personal UVA, erythemal UVR, and vitamin D_3 effective UVR exposures of indoor workers. The measurements were conducted over a minimum of 1 week during each season over a period of 1 year showing that there are changes with season in the relative proportions of each waveband.[150]

POLYVINYL CHLORIDE (PVC)

The potential application of unstabilized PVC as a UVR dosimeter with sensitivity in the UVR and a linear increase in the infrared absorbance at 1730 cm^{-1} resulting from up to approximately 14 MJ/m^2 total solar radiation was reported.[151,152] A long-term UVR dosimeter with solvent cast PVC has been introduced,[153] with its properties fully characterized[154] employing the UVR induced change in the 1064 cm^{-1} peak intensity. The dosimeter exhibits its highest response at 290 nm, declining exponentially across the UVB band, independently of temperature and exposure dose.[155] The dosimeter can measure up to 900 SED, equivalent to around 3 weeks of exposure in summer at subtropical locations.[154]

The PVC dosimeter was used to assess erythemal UVR exposure at specific anatomical sites on rotating upper-body manikins over a 12-day period. The exposures closely matched those obtained concurrently with three sets of PPO dosimeters.[154] The PVC dosimeter, calibrated to the plant damage action spectra, measured UVR exposures on plant canopies for over a month.[156] The extended dynamic range of the PVC dosimeter is an advantage, making dosimeter replacement unnecessary for extended exposures of up to 3 weeks. Studies of long-term personal exposure behavior may be well suited to thin film dosimeters with long dynamic ranges such as PVC. This remains an avenue for future research, with the main features of PVC and the other four types of thin film dosimeters in this review summarized in Table 1 to assist researchers contemplating their use.

CONCLUSION

Thin film dosimeters provide a means of measuring cumulative UVR exposures at sites that are inaccessible to bulkier and heavier radiometers or spectroradiometers. Calibrating them in the local environment where they will be employed allows for accurate exposure measurements. Additionally, the exposure can be assessed relative to ambient exposure by comparing the dosimeter's absorbance change to that of a dosimeter placed on a horizontal plane in full sun. Thin film UVR dosimetry has the advantages over electronic dosimeters of low cost and the unobtrusiveness of the film badges, allowing for high volume of measurements over multiple sites across various environments and research applications. The disadvantage is the lack of time resolution that electronic dosimeters provide. They also require access to a spectrophotometer for measurement of the absorbances and to a radiometer or spectroradiometer for calibration. Nevertheless, they provide site measurements of cumulative exposure which are required in numerous applications. The research applications reviewed in this paper were possible due to the specific characteristics of chemical film dosimeters.

Polysulphone dosimeters have been extensively used across diverse environments. They can be seasonally calibrated and employed for use at all latitudes and altitudes. Other thin film UVR dosimeters that have been employed are polyphenylene oxide, phenothiazine,

TABLE 1 Summary of the main features of polysulphone, phenothiazine, polyphenylene oxide, 8-methoxypsoralen, and polyvinyl chloride as thin film dosimeters.

Dosimeter type	Dynamic range	Wavelength for measurement of ΔA (nm)	UVR wavebands measured
Polysulphone[8,24]	One day	330	Pre-vitamin D_3, UVB and erythema exposures
Phenothiazine with Mylar film filter[135,136]	3–4 h	370	UVA exposures
Polyphenylene oxide (PPO)[140,143,147]	Four days with extension by up to 5 days with a neutral density filter	320	UVB, erythema and vitamin D_3 exposures
8-methoxypsoralen (8MOP) with Mylar film filter[149]	One week	305	UVA exposures
Polyvinyl chloride (PVC)[153–156]	Three weeks	1064 cm^{-1}	Erythema exposures and plant damage effective UVR

8-methoxypsoralen, and polyvinyl chloride. These five types of dosimeters have been fabricated at the University of Southern Queensland, Australia. These respond to various wavebands and have different dynamic ranges. The versatility of these films has yet to be fully realized, given the relatively low number of studies conducted using them compared to polysulphone. Thin film dosimeters with appropriate spectral responses and dynamic ranges are versatile tools that can be employed in further research investigating cumulative UVR exposure, as well as UVR exposures relative to a horizontal plane to multiple anatomical sites during daily activities of population groups. Furthermore, they are valuable tools for environmental studies involving plants, underwater studies, and further examination of the UVR environment.

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REFERENCES

1. Diffey BL. Sources and measurement of ultraviolet radiation. *Methods*. 2002;28:4-13.
2. Diffey BL. Personal ultraviolet radiation dosimetry with polysulphone film badges. *Photo-Dermatology*. 1984;1:151-157.
3. Huang X, Chalmers AN. Review of wearable and portable sensors for monitoring personal solar UV exposure. *Ann Biomed Eng*. 2021;49:964-978. doi:10.1007/s10439-020-02710-x
4. Furusawa Y, Quintern LE, Holtschmidt H, Koepke P, Saito M. Determination of erythema-effective solar radiation in Japan and Germany with a spore monolayer film optimized for the detection of UVB and UVA – results of a field campaign. *Appl Microbiol Biotechnol*. 1998;50:597-603.
5. Allen M, Swift N, Nield K, Liley B, McKenzie R. Use of electronic UV dosimeters in measuring personal UV exposures and public health education. *Atmos*. 2020;11:744. doi:10.3390/atmos11070744
6. Thieden E, Philipsen PA, Wulf HC. Ultraviolet radiation exposure pattern in winter compared with summer based on time-stamped personal dosimeter readings. *Br J Dermatol*. 2006;154:133-138.
7. Driscoll CMH. Dosimetry methods for UV radiation. *Radiat Prot Dosim*. 1997;72:217-222.
8. Diffey BL. Ultraviolet radiation dosimetry with polysulphone film. In: Diffey BL, ed. *Radiation Measurement in Photobiology*. Academic Press; 1989:136-159.
9. Davis A, Diffey BL, Tate TK. A personal dosimeter for biologically effective solar UV-B radiation. *Photochem Photobiol*. 1981;34:283-286.
10. Gibbs NK, Young AR, Corbett MF. Personal solar UVR exposure: a method of increasing the reliability of measurements made with film badge dosimeters. *Photo-Dermatology*. 1984;1:133-136.
11. Diffey BL. The early days of personal solar ultraviolet dosimetry. *Atmos*. 2020;11:125. doi:10.3390/atmos11020125
12. CIE (International Commission on Illumination). Personal dosimetry of UV radiation. *Publication No CIE*. 1992;98:6-11.
13. Casale GR, Borra M, Colosimo A, et al. Variability among polysulphone calibration curves. *Phys Med Biol*. 2006;51:4413-4427.
14. Schmalwieser AW, Siani AM. Review on nonoccupational personal solar UV exposure measurements. *Photochem Photobiol*. 2018;94:900-915. doi:10.1111/php.12946
15. Henning A, Downs NJ, Vanos JK. Wearable ultraviolet radiation sensors for research and personal use. *Int J Biometeorol*. 2022;66:627-640.
16. Siani AM, Casale GR, Diemoz H, et al. Personal UV exposure in high albedo alpine sites. *Atmos Chem Phys*. 2008;8:3749-3760.
17. Seckmeyer G, Klingebiel M, Riechelmann S, et al. A critical assessment of two types of personal UV dosimeters. *Photochem Photobiol*. 2012;88:215-222.
18. Casale GR, Siani AM, Diemoz H, Kimlin MG, Colosimo A. Applicability of the polysulphone horizontal calibration to differently inclined dosimeters. *Photochem Photobiol*. 2012;88:207-214.

19. CIE (International Commission on Illumination). *Erythema Reference Action Spectrum and Standard Erythema Dose, CIE S007E-1998*. CIE Central Bureau; 1998.
20. Davis A, Deane GHW, Diffey BL. Possible dosimeter for ultraviolet radiation. *Nature*. 1976;261:169-170.
21. Neale RE, Hamilton AR, Janda M, Gies P, Green AC. Seasonal variation in measured solar ultraviolet radiation exposure of adults in subtropical Australia. *Photochem Photobiol*. 2010;86:445-448.
22. Wright C, Diab R, Martincigh B. Anatomical distribution of ultraviolet solar radiation. *S Afr J Sci*. 2004;100:498-500.
23. CIE (International Commission on Illumination). Action spectrum for the production of previtamin D_3 in human skin. *CIE*. 2006;174:2006.
24. Siani AM, Casale GR, Modesti S, Parisi AV, Colosimo A. Investigation on the capability of polysulphone for measuring biologically effective solar UV exposures. *Photochem Photobiol Sci*. 2014;13:521-530.
25. Tate TJ, Diffey BL, Davis A. An ultraviolet radiation dosimeter based on the photosensitising drug, Nalidixic acid. *Photochem Photobiol*. 1980;31:27-30.
26. Turner J, Parisi AV, Turnbull D. Dosimeter for the measurement of plant damaging solar UV exposures. *Agric For Meteorol*. 2009;149:1301-1306.
27. Flint SD, Caldwell MM. Field testing of UV biological spectral weighting functions for higher plants. *Physiol Plant*. 2003;117:145-153.
28. Holman CDJ, Gibson IM, Stephenson M, Armstrong BK. Ultraviolet irradiation of human body sites in relation to occupation and outdoor activity: field studies using personal UVR dosimeters. *Clin Exp Dermatol*. 1983;8:269-277.
29. Herlihy E, Gies PH, Roy CR, Jones M. Personal dosimetry of solar UV radiation for different outdoor activities. *Photochem Photobiol*. 1994;60:288-294.
30. Kimlin MG, Martinez N, Green AC, Whiteman DC. Anatomical distribution of solar ultraviolet exposures among cyclists. *J Photochem Photobiol B Biol*. 2006;85:23-27.
31. Siani AM, Casale GR, Sisto R, et al. Short-term UV exposure of sunbathers at a Mediterranean Sea site. *Photochem Photobiol*. 2009;85:171-177.
32. Wright CY, Du Preez DJ, Martincigh BS, et al. A comparison of solar ultraviolet radiation exposure in urban canyons in Venice, Italy and Johannesburg, South Africa. *Photochem Photobiol*. 2020;96:1148-1153.
33. Sun J, Lucas RM, Harrison SL, et al. Measuring exposure to solar ultraviolet radiation using a dosimetric technique: understanding participant compliance issues. *Photochem Photobiol*. 2014;90:919-924.
34. Xiang F, Harrison S, Nowak M, et al. Weekend personal ultraviolet radiation exposure in four cities in Australia: influence of temperature, humidity and ambient ultraviolet radiation. *J Photochem Photobiol B Biol*. 2015;143:74-81.
35. King L, Dear K, Harrison SL, et al. Investigating the patterns and determinants of seasonal variation in vitamin D status in Australian adults: the seasonal D cohort study. *BMC Public Health*. 2016;16:1-6.
36. Casale GR, Siani AM, Diémoz H, Agnesod G, Parisi AV, Colosimo A. Extreme UV index and solar exposures at plateau Rosa (3500 m a.s.l) in Valle D'Aosta region. *Italy Sci Total Environ*. 2015;512-513:622-630.
37. Duncan DD, Schneider W, West KJ, Kirkpatrick SJ, West SK. The development of personal dosimeters for use in the visible and ultraviolet wavelength regions. *Photochem Photobiol*. 1995;62:94-100.
38. Lindgren G, Diffey BL, Larkö O. Basal cell carcinoma of the eyelids and solar ultraviolet radiation exposure. *Br J Ophthalmol*. 1998;82:1412-1415.
39. Rosenthal FS, Phoon C, Bakalian AE, Taylor HR. The ocular dose of ultraviolet radiation to outdoor workers. *Invest Ophthalmol Vis Sci*. 1988;29:649-656.
40. Kimlin MG, Parisi AV, Wong JCF. The facial distribution of erythemal ultraviolet exposure in south east Queensland. *Phys Med Biol*. 1998;43:231-240.
41. Kimlin MG, Downs NJ, Parisi AV. Comparison of human facial UV exposure at high and low latitudes and the potential impact on dermal vitamin D production. *Photochem Photobiol Sci*. 2003;2:370-375.
42. Downs N, Parisi AV. Mean exposure fractions of human body solar UV exposure patterns for application in different ambient climates. *Photochem Photobiol*. 2012;88:223-226.
43. Downs N, Parisi AV. Three dimensional visualisation of solar UV exposure to the human face. *Photochem Photobiol Sci*. 2007;6:90-98.
44. Parisi AV, Schouten P, Downs N, Turner J. Solar UV exposures measured simultaneously to all arbitrarily oriented leaves on a plant. *J Photochem Photobiol B Biol*. 2010;99:87-92.
45. Modenese A, Korpinen L, Gobbo F. Solar radiation exposure and outdoor work: an underestimated occupational risk. *Environ Res Public Health*. 2018;15:2063. doi:10.3390/ijerph15102063
46. Gies HP, Roy CR, Toomey S, Maclennan R, Watson M. Solar UVR exposures of three groups of outdoor workers on the sunshine coast. *Queensland Photochem Photobiol*. 1995;62:1015-1021.
47. Gies P, Wright J. Measured solar ultraviolet radiation exposures of outdoor workers in Queensland in the building and construction industry. *Photochem Photobiol*. 2003;78:342-348.
48. Liljendahl TS, Blomqvist A, Andersson EM, Barregard L, Segerbäck D. Urinary levels of thymine dimer as a biomarker of exposure to ultraviolet radiation in humans during outdoor activities in the summer. *Mutagenesis*. 2013;28:249-256.
49. O'Riordan DL, Glanz K, Gies P, Elliott T. A pilot study of the validity of self-reported ultraviolet radiation exposure and sun protection practices among lifeguards, parents and children. *Photochem Photobiol*. 2008;84:774-778.
50. Siani AM, Casale GR, Sisto R, Colosimo A, Lang CA, Kimlin MG. Occupational exposures to solar ultraviolet radiation of vineyard workers in Tuscany (Italy). *Photochem Photobiol*. 2011;87:925-934.
51. Linde K, Wright C, du Plessis JL. Personal solar ultraviolet radiation exposure of farmworkers: seasonal and anatomical differences suggest prevention measures are required. *Annals Work Exp Health*. 2022;66:41-51. doi:10.1093/annweh/wxab049
52. Sisto R, Borra M, Casale GR, Militello A, Siani AM. Quantitative evaluation of personal exposure to UV radiation of workers and general public. *Radiat Prot Dosim*. 2009;137:193-196.
53. Airey DK, Wong JCF, Fleming RA, Meldrum LR. An estimate of the total UV-B exposure for outdoor workers during a south-east Queensland summer. *Health Phys*. 1997;72:544-549.
54. Schmalwieser AW, Casale GR, Colosimo A, Schmalwieser SS, Siani AM. Review of occupational personal solar UV exposure measurements. *Atmos*. 2021;12:142.

55. Moldovan HR, Wittlich M, John SM, et al. Exposure to solar UV radiation in outdoor construction workers using personal dosimetry. *Environ Res*. 2020;181:108967.
56. Peters CE, Pasko E, Strahledorf P, Holness DL, Tenkate T. Solar ultraviolet radiation exposure among outdoor workers in three Canadian provinces. *Annals Work Exp Health*. 2019;63:679-688.
57. Casale GR, Siani AM, Colosimo A. Occupational exposure to solar UV radiation, a short review of relevant papers on the quantification of exposure to solar ultraviolet (UV) radiation of outdoor workers. *Household Personal Care Today*. 2011;6:14-17.
58. Gies P, Watz R, Javorniczky J, Henderson C, Ayton J, Kingston M. Measurement of the UVR exposures of expeditioners on Antarctic resupply voyages. *Photochem Photobiol*. 2009;85:1485-1490.
59. Tenkate TD, Collins MJ. Personal ultraviolet radiation exposure of workers in a welding environment. *Am Ind Hyg Assoc J*. 1997;58:33-38.
60. Hamilton D, Diffey BL. How effective are UV opaque face shields in UVB phototherapy cabins? *Photodermatol Photoimmunol Photomed*. 1998;14:134-135.
61. Downs N, Harrison S, Chavez D, Parisi AV. Solar ultraviolet and the occupational radiant exposure of Queensland school teachers: a comparative study between teaching classifications and behavior patterns. *J Photochem Photobiol B Biol*. 2016;158:105-112.
62. Downs NJ, Igoe D, Parisi AV, et al. Seasonal minimum and maximum solar ultraviolet exposure measurements of classroom teachers residing in tropical North Queensland. *Australia Photochem Photobiol*. 2019;95:1083-1093. doi:10.1111/php.13081
63. Downs N, Parisi AV, Igoe D, Wainwright L, Butler H. Actinic exposure film dosimetry: indicators of occupational exposure risk for office workers and school teachers. In: Byrne S, Chen M, eds. *6th Asia & Oceania Conference on Photobiology (AOCP 2013): Life on a Sun-Drenched Planet, Sydney, Australia 10–13 Nov 2013*. University of Southern Queensland. 2013.
64. Kimlin MG, Parisi AV, Wong JCF. Quantification of the personal solar UV exposure of outdoor workers, indoor workers and adolescents at two locations in southeast Queensland. *Photodermatol Photoimmunol Photomed*. 1998;14:7-11.
65. Kaur S, Kok EY, Jamil NA, Sebayang SK. Exploring the relationship between sunlight exposure, psychological health, and gestational weight gain: a prospective observational study. *BMC Public Health*. 2024;24:122. doi:10.1186/s12889-024-17677-w
66. Diffey BL, Roscoe AH. Exposure to solar UV radiation in flight. Aviation, space. *Env med*. 1990;61:1032-1035.
67. Mendes MM, Hart KH, Williams EL, Mendis J, Lanham-New SA, Botelho PB. Vitamin D supplementation and sunlight exposure on serum vitamin D concentrations in 2 parallel, double-blind, randomized, placebo-controlled trials. *J Nutr*. 2021;151:3137-3150.
68. Mavroeidi A, Aucott L, Black AJ, Fraser WD, Reid DM, Macdonald HM. Seasonal variation in 25 (OH) D at Aberdeen (57° N) and bone health indicators–could holidays in the sun and cod liver oil supplements alleviate deficiency? *PLoS One*. 2013;8:e53381. doi:10.1371/journal.pone.0053381
69. Kift R, Berry JL, Vail A, Durkin MT, Rhodes LE, Webb AR. Lifestyle factors including less cutaneous sun exposure contribute to starkly lower vitamin D levels in U.K. south Asians compared with the white population. *Br J Dermatol*. 2013;169:1272-1278.
70. Khan SR, Whiteman DC, Kimlin MG, et al. Effect of solar ultraviolet radiation exposure on serum 25 (OH) D concentration: a pilot randomised controlled trial. *Photochem Photobiol Sci*. 2018;17:570-577.
71. Webb AR, Van Der Zande BM, Kift RC, O'Neil H, Lin NX, Wright D. Ultra-low ultraviolet radiation in office lighting can moderate seasonal vitamin D cycle: a pilot study. *Anticancer Res*. 2022;42:5101-5106.
72. ARPANSA (Australian Radiation Protection and Nuclear Safety Agency). Occupational Exposure to Ultraviolet Radiation. Radiation Protection Series No 12. 2006.
73. International Commission on Non-Ionising Radiation Protection (ICNIRP). ICNIRP statement on protection of workers against ultraviolet radiation. *Health Phys*. 2010;99:66-87.
74. Vishvakarman D, Wong JCF, Boreham BW. Annual occupational exposure to ultraviolet radiation in central Queensland. *Health Phys*. 2001;81:536-544.
75. Russell A, Gohlan M, Smedley A, Densham M. The ultraviolet radiation environment during an expedition across the Drake Passage and on the Antarctic peninsula. *Antarct Sci*. 2015;27:307-316.
76. Downs N, Parisi AV, Igoe D. Measurements of occupational ultraviolet exposure and the implications of timetabled yard duty for school teachers in Queensland, Australia: preliminary results. *J Photochem Photobiol B Biol*. 2014;131:84-89.
77. Pagels P, Wester U, Mårtensson F, et al. Pupils' use of school outdoor play settings across seasons and its relation to sun exposure and physical activity. *Photodermatol Photoimmunol Photomed*. 2020;36:365-372. doi:10.1111/phpp.12558
78. Christian H, Lester L, Trost SG, et al. Shade coverage, ultraviolet radiation and children's physical activity in early childhood education and care. *Int J Public Health*. 2019;64:1325-1333.
79. Boldemann C, Blennow M, Dal H, et al. Impact of pre-school environment upon children's physical activity and sun exposure. *Prev Med*. 2006;42:301-308.
80. Boldemann C, Dal H, Mårtensson NC, et al. Preschool outdoor play environment may combine promotion of children's physical activity and sun protection. Further evidence from southern Sweden and North Carolina. *Science & Sports*. 2011;26:72-82.
81. Stanton WR, Saleheen HN, O'Riordan D, Roy CR. Environmental conditions and variation in levels of sun exposure among children in child care. *Int J Behav Med*. 2003;10:285-298.
82. Diffey BL, Gibson CJ, Haylock R, McKinlay AF. Outdoor ultraviolet exposure of children and adolescents. *Br J Dermatol*. 1996;134:1030-1034.
83. Guy C, Diab R, Martincigh B. Ultraviolet radiation exposure of children and adolescents in Durban, South Africa. *Photochem Photobiol*. 2003;77:265-270.
84. Gies P, Roy C, Toomey S, MacLennan R, Watson M. Solar UVR exposures of primary school children at three locations in Queensland. *Photochem Photobiol*. 1998;68:78-83.
85. Milne E, Corti B, English DR, Cross D, Costa C, Johnston R. The use of observational methods for monitoring sun-protection activities in schools. *Health Educ Res*. 1999;14:167-175.
86. Milne E, English B, Cross D, et al. Direct measurement of sun protection on primary schools. *Prev Med*. 1999;29:45-52.

87. Downs N, Parisi AV. Patterns in the received facial ultraviolet exposure of school children measured at a sub-tropical latitude. *Photochem Photobiol*. 2008;84:90-100.
88. Rosenthal FS, Lew RA, Rowleau LJ, Thomson M. Ultraviolet exposure to children from sunlight: a study using personal dosimetry. *Photodermatol Photoimmunol Photomed*. 1990;7:77-81.
89. Melville SK, Rosenthal FS, Luckmann R, Lew RA. Quantitative ultraviolet skin exposure in children during selected outdoor activities. *Photodermatol Photoimmunol Photomed*. 1991;8:99-104.
90. Kimlin MG, Fang L, Feng Y, et al. Personal ultraviolet radiation exposure in a cohort of Chinese mother and child pairs: the Chinese families and children study. *BMC Public Health*. 2019;19:281. doi:10.1186/s12889-019-6610-y
91. Moise AF, Harrison SL, Gies HP. Solar ultraviolet radiation exposure of infants and small children. *Photodermatol Photoimmunol Photomed*. 1999;15:109-114.
92. Moise AF, Gies HP, Harrison SL. Estimation of the annual solar UVR exposure dose of infants and small children in tropical Queensland. Australia. *Photochem Photobiol*. 1999;69:457-463.
93. Dwyer T, Blizzard L, Gies PH, Ashbolt R, Roy C. Assessment of habitual sun exposure in adolescents via questionnaire—a comparison with objective measurement using polysulphone badges. *Melanoma Res*. 1996;6:231-239.
94. Parisi AV, Meldrum LR, Wong JCF, Aitken J, Fleming RA. Effect of childhood and adolescent ultraviolet exposures on cumulative exposure in south East Queensland schools. *Photodermatol Photoimmunol Photomed*. 2000;16:19-24.
95. Parisi AV, Smith D, Schouten P, Turnbull DJ. Solar ultraviolet protection provided by human head hair. *Photochem Photobiol*. 2009;85:250-254.
96. Parisi AV, Turnbull DJ, Downs N, Smith D. Dosimetric investigation of the solar erythemal UV protection provided by beards and moustaches. *Radiat Prot Dosim*. 2012;150:278-282.
97. Australian Standard AS 4399:2020, Sun Protective Clothing – Evaluation and Classification.
98. Gambichler T, Altmeyer P, Hoffmann K. Comparison of methods: determination of UV protection of clothing. *Recent Results Cancer Res*. 2002a;160:55-61. doi:10.1007/978-3-642-59410-6_8
99. Gambichler T, Hatch KL, Avermaete A, Altmeyer P, Hoffmann K. Influence of wetness on the ultraviolet protection factor (UPF) of textiles: in vitro and in vivo measurements. *Photodermatol Photoimmunol Photomed*. 2002b;18:29-35. doi:10.1034/j.1600-0781.2002.180105.x
100. Ravishankar J, Diffey B. Laboratory testing of UV transmission through fabrics may underestimate protection. *Photodermatol Photoimmunol Photomed*. 1997;13:202-203.
101. Parisi AV, Kimlin MG, Meldrum LR, Relf CM. Field measurements on protection by stockings from solar erythemal ultraviolet radiation. *Radiat Prot Dosim*. 1999;86:69-72.
102. Wilson CA, Parisi AV. Protection from solar erythemal ultraviolet radiation -simulated wear and laboratory testing. *Text Res J*. 2006;76:216-225.
103. Parisi AV, Wilson CA. Pre-vitamin D_3 effective UV transmission through clothing during simulated wear. *Photodermatol Photoimmunol Photomed*. 2005;21:303-310.
104. Diffey BL, Cheeseman J. Sun protection with hats. *Br J Dermatol*. 1992;127:10-12.
105. Wong CF, Airey DK, Fleming R. Annual reduction of solar UV exposure to the facial area of outdoor workers in Southeast Queensland by wearing a hat. *Photodermatol Photoimmunol Photomed*. 1996;12:131-135.
106. Gies P, Javorniczky J, Roy CR, Henderson S. Measurements of the UVR protection provided by hats used at school. *Photochem Photobiol*. 2006;82:750-754.
107. Dunne RP. Polysulphone film as an underwater dosimeter for solar ultraviolet-B radiation in tropical latitudes. *Mar Ecol Prog Ser*. 1999;189:53-63.
108. Parisi AV, Kimlin MG, Mulheran L, Meldrum LR, Randall C. Field based measurements of personal erythemal ultraviolet exposure through a common summer garment. *Photodermatol Photoimmunol Photomed*. 2000;16:134-138.
109. Downs NJ, Axelsen T, Parisi AV, Schouten PW, Dexter BR. Measured UV exposures of Ironman, Sprint, and Olympic-distance triathlon competitors. *Atmos*. 2020;11:440. doi:10.3390/atmos11050440
110. Downs N, Parisi AV, Schouten P. Solar ultraviolet radiation incident upon reef snorkelers determined by consideration of the partial immersion of dosimeters in the natural ocean environment. *Meas Sci Technol*. 2010;22:015801. doi:10.1088/0957-0233/22/1/015801
111. Parisi AV, Willey A, Kimlin MG, Wong JCF. Penetration of solar erythemal UV radiation in the shade of two common Australian trees. *Health Phys*. 1999;76:682-686.
112. Parisi AV, Kimlin MG, Wong JCF, Wilson M. Personal exposure distribution of solar erythemal ultraviolet radiation in tree shade over summer. *Phys Med Biol*. 2000;45:349-356.
113. Parisi AV, Kimlin MG, Wong JCF, Lester R, Turnbull D. Reduction in the personal annual solar erythemal ultraviolet exposure provided by Australian gum trees. *Radiat Prot Dosim*. 2000;92:307-312.
114. Gies P, Elix R, Lawry D, et al. Assessment of the UVR protection provided by different tree species. *Photochem Photobiol*. 2007;83:1465-1470.
115. Turner J, Parisi AV. Measuring the influence of UV reflection from vertical metal surfaces on humans. *Photochem Photobiol Sci*. 2009;1:62-69.
116. Turner J, Parisi AV. Ultraviolet reflection irradiances and exposures in the constructed environment for horizontal, vertical and inclined surfaces. *Photochem Photobiol*. 2013;89:730-736.
117. Turner J, Parisi AV. Influence of reflected UV irradiance on occupational exposure from combinations of reflective wall surfaces. *Photochem Photobiol Sci*. 2013;12:1589-1595.
118. Turner J, Parisi AV. Improved method of ultraviolet radiation reflection measurement for non-horizontal urban surfaces. *Meas Sci Technol*. 2012;23:045701. doi:10.1088/0957-0233/23/4/045701
119. Turner J. Ultraviolet Radiation Reflection from Building Materials: Characterisation, Quantification and the Resulting Effects (Doctoral thesis, University of Southern Queensland, Australia). 2011.
120. Dawes A. A Case Study into the Effect on Ambient Ultraviolet Exposure Levels and Subsequent Health Risks Associated with Close Proximity to a Commercially Available Photovoltaic Array. SCI3301 Science Project, University of Southern Queensland. 2016.

121. Wong CF. Scattered ultraviolet radiation underneath a shade-cloth. *Photodermatol Photoimmunol Photomed*. 1994;10:221-224.
122. Vejakupta K, Udompataikul M. Umbrella with ultraviolet radiation protection. *J Cosmetics, Dermatol Sci Applic*. 2014;4:228-233. doi:10.4236/jcdsa.2014.44031
123. Gies P, Mackay C. Measurements of the solar UVR protection provided by shade structures in New Zealand primary schools. *Photochem Photobiol*. 2004;80:334-339.
124. Turnbull D, Parisi AV. Increasing the ultraviolet protection provided by shade structures. *J Photochem Photobiol B Biol*. 2005;78:62-67.
125. Gies P, Makin J, Dobbinson S, et al. Shade provision for toddlers at swimming pools in Melbourne. *Photochem Photobiol*. 2013;89:968-973.
126. Parisi AV, Kimlin MG. Personal solar UV exposure measurements employing polysulphone with an extended dynamic range. *Photochem Photobiol*. 2004;79:411-416.
127. Agar NS, Halliday GM, Barnetson RS, Ananthaswamy HN, Wheeler M, Jones AM. The basal layer in human squamous tumors harbours more UVA than UVB fingerprint mutations: a role for UVA in human skin carcinogenesis. *Proc Natl Acad Sci*. 2004;101:4954-4959.
128. Battie C, Jitsukawa S, Bernerd F, Del Bino S, Marionnet C, Verschoore M. New insights in photoaging, UVA induced damage and skin types. *Exp Dermatol Suppl*. 2014;1:7-12. doi:10.1111/exd.12388
129. Kollias N, Ruvolo E, Sayre RM. The value of the ratio of UVA to UVB in sunlight. *Photochem Photobiol*. 2011;87:1474-1475.
130. WHO (World Health Organization). *Environmental Health Criteria 160: Ultraviolet Radiation*. WHO; 1994.
131. Duarte I, Rotter A, Malvestiti A, Silva M. The role of glass as a barrier against the transmission of ultraviolet radiation: an experimental study. *Photodermatol Photoimmunol Photomed*. 2009;25:181-184.
132. Diffey BL, Davis A, Johnson M, Harrington TR. A dosimeter for long wave ultraviolet radiation. *Br J Dermatol*. 1977;97:127-130.
133. Diffey BL, Harrington TR, Challoner AV. A comparison of the anatomical uniformity of irradiation in two different photochemotherapy units. *Br J Dermatol*. 1978;99:361-363. doi:10.1111/j.1365-2133.1978.tb06170.x
134. Tennent NH, Townsend JH, Davis A. A simple integrating dosimeter for ultraviolet light. *Stud Conserv*. 1982;27(sup1):32-38. doi:10.1179/sic.1982.27.Supplement-1.32
135. Parisi AV, Kimlin MG, Turnbull DJ, Macaranas J. Potential of phenothiazine as a thin film dosimeter for UVA exposures. *Photochem Photobiol Sci*. 2005;4:907-910.
136. Jia K, Parisi AV, Kimlin MG. Phenothiazine UVA dosimeter: characteristics and performance. *Photochem Photobiol Sci*. 2010;9:1224-1227.
137. Davis A, Deane GHW, Gordon D, Howel GV, Ledbury AK. A world-wide programme for the continuous monitoring of solar ultraviolet radiation using poly (phenylene oxide) films and a consideration of results. *J Appl Polym Sci*. 1976;20:1165-1174.
138. Lala, D. (1984) Photochemical measurement of ultraviolet solar radiation. Symp. Procs: Recent Advances in Pyranometry, IEA Solar R&D SMHI, Norrkoping, Sweden, pp. 269–283.
139. Berre B, Lala D. Investigation on photochemical dosimeters for ultraviolet radiation. *Sol Energy*. 1989;42:405-416.
140. Lester RA, Parisi AV, Kimlin MG, Sabburg J. Optical properties of poly(2,6-Dimethyl-1,4-Phenylene oxide) and its potential for a long-term solar ultraviolet dosimeter. *Phys Med Biol*. 2003;48:3685-3698.
141. Schouten P, Parisi AV, Turnbull DJ. Evaluation of a high exposure solar UV dosimeter for underwater use. *Photochem Photobiol*. 2007;83:931-937.
142. Schouten P, Parisi AV, Turnbull DJ. Applicability of the polyphenylene oxide film dosimeter to high UV exposures in aquatic environments. *J Photochem Photobiol B Biol*. 2009;96:184-192.
143. Schouten P, Parisi AV. Underwater deployment of the Polyphenylene oxide dosimeter combined with a neutral density filter to measure long-term solar UVB exposures. *J Photochem Photobiol B Biol*. 2012;112:31-36.
144. Schouten P, Parisi AV, Turnbull DJ. Field calibrations of a long–term UV dosimeter for aquatic UVB exposures. *J Photochem Photobiol B Biol*. 2008;91:108-116.
145. Schouten P, Parisi AV, Turnbull DJ. Usage of the polyphenylene oxide dosemeter to measure annual solar erythemal exposures. *Photochem Photobiol*. 2010;86:706-710.
146. Wainwright L, Parisi AV, Schouten P. Characterisation and evaluation of a miniaturised polyphenylene oxide dosimeter for ultraviolet exposures. *J Photochem Photobiol B Biol*. 2013;120:98-103.
147. Wainwright L, Parisi AV, Downs N. Dual calibrated dosimeter for simultaneous measurements of erythemal and vitamin D effective solar ultraviolet radiation. *J Photochem Photobiol B Biol*. 2016;157:15-21.
148. Diffey BL, Davis A. A new dosemeter for the measurement of natural ultraviolet radiation in the study of photodermatoses and drug photosensitivity. *Phys Med Biol*. 1978;23:318-323.
149. Wainwright L, Parisi AV, Downs N. Dosimeter based on 8-methoxypsoralen for UVA exposures over extended periods. *J Photochem Photobiol B Biol*. 2015;148:246-251.
150. Wainwright L, Parisi AV, Downs N. Concurrent evaluation of personal damaging and beneficial UV exposures over an extended period. *J Photochem Photobiol B Biol*. 2017;170:188-196.
151. Martin KE. Monitoring ultraviolet radiation with polyvinylchloride. *Br Polymer J*. 1973;5:443-450.
152. Martin KE, Tilley RI. Influence of radiation intensity on photooxidation of unstabilised PVC. *Br Polymer J*. 1969;1:213-216. doi:10.1002/pi.4980010505
153. Amar A, Parisi AV. Investigation of unstabilized polyvinyl chloride (PVC) for use as a long-term UV dosimeter: preliminary results. *Meas Sci Technol*. 2012;23:085703. doi:10.1088/0957-0233/23/8/085703
154. Amar A, Parisi AV. Optical properties of a long dynamic range chemical UV dosimeter based on solvent cast polyvinyl chloride (PVC). *J Photochem Photobiol B Biol*. 2013;128:92-99.
155. Amar A, Parisi AV. Spectral response of solvent-cast polyvinyl chloride (PVC) thin film used as a long-term UV dosimeter. *J Photochem Photobiol B Biol*. 2013;125:115-120.
156. Parisi AV, Amar A, Igoe D. Long-term UV dosimeter based on polyvinyl chloride for plant damage effective UV exposure measurements. *Agric For Meteorol*. 2017;243:68-73.

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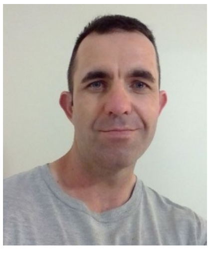

Peter Schouten has been teaching secondary and undergraduate level Mathematics and Physics since 2005. Alongside this, Peter has obtained a PhD in atmospheric Physics and has worked for over 5 years as a research fellow in the tertiary education and government sectors. During this time, Peter has published numerous journal articles and book chapters investigating a wide variety of topics in environmental Physics such as the terrestrial and underwater measurement of UV radiation, wave action and the influence of chemical monolayers on evaporation, and greenhouse gas emissions from natural and man-made sources.

Damien P. Igoe is an Adjunct Lecturer with the University of Southern Queensland. His research interests include solar UV radiation and urban shade measurement using accessible and low-cost devices, also the related fields of sun safety and shade provision. His research portfolio includes practical education techniques and Python programming for scientific analysis. Damien currently works as a teacher. His interests include hiking, photography, and history—it is common for Damien to be hiking the trails near his north Queensland home.

Joanna Turner is a Senior Lecturer (Physics) at the University of Southern Queensland and a Lead Scientist with the Kennaook Cape Grim Baseline Air Pollution Station. Her research area focuses on improving measurement and monitoring of ultraviolet (UV) radiation, with special interest in the impact of reflectance of UV radiation from the built environment, using smartphones in the measurement of UV radiation, and educating students and the public on understanding UV radiation. Her outreach includes promoting STEM fields to students using cyanotype media to explain how UV radiation influences our everyday lives.

Abdurazaq Amar, a Lecturer at the University of Southern Queensland College, focuses his research on solar ultraviolet (UV) radiation. His work encompasses the effects of atmospheric conditions on UV levels, UV dosimetry, innovative methods for monitoring UV exposure, measures to enhance UV protection, and strategies to improve public awareness of the risks associated with UV exposure.

Lisa Wainwright completed both a BSc. (Hons) in Physics and Mathematics and a PhD in Physics at the University of Southern Queensland. Utilizing skills honed during these studies Lisa is now employed in the Research and Innovation Division of the University as a Research Data Analyst. Her research interests continue in UV radiation and UV related vitamin D production.

Adrian Dawes, BSc. (Hons) is a research student attached to the Faculty of Health, Engineering and Sciences within the School of Mathematics, Physics and Computing at the University of Southern Queensland. His research studies include examinations into mitigating the physiological impacts of overexposure to solar irradiance and monitoring atmospheric conditions.

Harry Butler completed his BSc. (Hons) degree in Applied Mathematics and Physics at the University of New England, Armidale Australia before completing a PhD at Griffith University, Brisbane, Australia, with a focus on Environment Modelling. Currently, he holds the position of Senior Lecturer in Mathematics and Computing in the School of Mathematics, Physics and Computing at the University of Southern Queensland, Toowoomba Australia. He has research interests in the areas: Aerosols, Dust transport, Atmospheric transport systems, Sediment transport, and UV.

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