FINAL REPORT

BENEFICIAL VITAMIN D3 PRODUCING UV COMPARED TO DAMAGING OVEREXPOSURE

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Executive Summary

The measured UV radiation in full sun and in shade and how this relates to vitamin D_3 exposures for various latitudes throughout Australia is reported. Calibrated spectral and dosimetric measurements were employed to measure the UV radiation in the shade of numerous shade environments for varying solar zenith angles and seasons. This was for exposures to the horizontal, 45° and vertical planes; as well as to specific anatomical sites for the solar zenith angle range of approximately 5° to 80° and provides a comprehensive data set of the vitamin D_3 exposures and the damaging UV exposures. The results and findings are summarised as follows:

- Shade environments were divided into two groups: shade with sky view of greater than 40%; and shade with sky view of less than 40%;
- The highest UV_{D3} irradiances for both global and diffuse were found to occur in the middle of the day;
- There is a significant variation in the relative proportions of the UV wavelengths when comparing diffuse UV to global UV;
- The average difference (15% to 20%) between the proportions of the diffuse UV in the global UV were at a maximum for SZA's smaller than approximately 55°;
- For a SZA of approximately 5°, average UV_{D3} irradiances were 0.67 W/m² and 0.20 W/m² for global and for shade with a sky view of greater than 40% respectively;
- Variations in cloud cover (below 8 okta) are far less likely to cause an obvious change in UV_{D3} exposure times in the shade; whereas global UV_{D3} exposure times will vary significantly depending on cloud cover and solar disc cover.;
- Shade with a sky view of greater than 40% can be found very easily and this makes it very useful for the general public as the damaging UVA wavelengths are reduced more on a relative basis compared to the beneficial vitamin D_3 wavelengths;
- Utilising shade for UV_{D3} exposures can reduce total UV exposure by 37% to 58% compared to full sun UV_{D3} exposures;
- The best time to expose the human body to UV radiation while utilising shaded environments with a sky view of greater than 40% for vitamin D_3 synthesis is for SZAs less than approximately 45°
- The largest variation in exposure ratios to the anatomical sites between the seasons was for the nose compared to full sun UV_{D3} exposure. The shade reduced exposures to the nose to approximately 38% and 63% of full sun exposures in summer and winter respectively.;
- Shade can be used throughout Australia during summer and winter; However, winter exposure times will vary depending on the latitude;
- This research indicates that an improved approach to optimise UV exposures for the production of vitamin D_3 is to utilise diffuse UV under shade in and around the middle of the day.

Aims

Humans need to be protected from damaging UV radiation, but they also need to be exposed to solar UVB so that vitamin D_3 synthesis can occur. Vitamin D_3 is essential to maintain extracellular fluid concentrations of calcium and phosphorous; hence, it is important for the prevention of rickets in children, osteoporosis, osteomalacia, and fractures in the elderly. Epidemiological data and animal studies also indicate that low blood serum vitamin D_3 is linked to breast cancer, prostate cancer, colorectal cancer and numerous other disorders. Solar terrestrial UV radiation in the region of 290 to 330 nm is acknowledged as an initiator of the synthesis of vitamin D_3 for humans as it photolyses 7-dehydrocholesterol in the human skin, to pre-vitamin D_3 , which is then converted to vitamin D_3 by a heat induced process. After two separate hydroxylations (first in the liver, then in the kidney) the active form of the vitamin (i.e. $1\alpha, 25(OH)_2$ -vitamin D_3) is produced (Sliney, 1994; Webb et al, 1988). Although, over exposure to these UV wavelengths are known to cause skin damage, pre-vitamin D_3 synthesis generally occurs at sub-erythemal irradiances.

Due to the phenomena of Rayleigh and Mie scattering in the earth's atmosphere, there is a significant proportion of the solar UV present in shade due to scattered radiation. Studies on the levels of UV observed in the shade of different shade environments have shown that the relative proportions of UVA (315-400 nm) and UVB (280-315 nm) in the shade are significantly different to those in full sun. The relative proportions are decreased for UVA and increased for UVB. Therefore, in the shade there is an increase in the relative proportion of the biologically effective wavelengths associated with pre-vitamin D_3 production in the body and a decrease in the biologically damaging UVA irradiances compared to full sun. This is significant because exposure to harmful solar UVA radiation is linked to skin cancer, DNA damage, macular degeneration and immunosuppression in humans. Currently, there is a major gap in knowledge in order to optimise the beneficial effects related to vitamin D_3 effective wavelengths compared to reducing the biologically damaging overexposure to UV radiation.

The hypothesis for this project is that: at certain latitudes, the diffuse UV in shade may play an important role in providing the human body with adequate levels of UVB radiation for pre-vitamin D_3 production without experiencing the high levels of damaging UVA observed in full sun.

Specifically, this project aims to:

- 1. Quantify the amount of pre-vitamin D_3 effective UV wavelengths under different shade environments by undertaking extensive field work using dosimetry and spectral measurements;
- 2. Measure the distribution of pre-vitamin D_3 effective exposures over the human form using polysulphone dosimeters and human manikins;
- 3. Quantify the effect of a latitude gradient on pre-vitamin D_3 effective exposures in the shade.

Introduction

The health effects of solar UV radiation vary significantly, from initiating the synthesis of vitamin D_3 to the severe degradation of the human body. Excessive solar UV radiation exposure led to the premature deaths of approximately 60 000 people in the year 2000 (Lucas et al, 2006). It is well known that exposure to small amounts of UV radiation are beneficial for the human body and important in the production of vitamin D_3 , whereas excessive exposure to sunlight is known to cause skin cancer, immune suppression, DNA damage, erythema and sun-related eye disorders (Baron et al., 2003; Glerup et al., 2000; Terenetskaya, 2000; Sliney and Wengraitis, 2006; Setlow et al., 1993).

Solar UV radiation is acknowledged as the major provider of vitamin D_3 for humans. It is estimated that approximately 90-95% of our vitamin D_3 requirement comes from exposure to the sun (Holick, 1998; Holick, 2004). Terrestrial UV radiation in the 290 – 330 nm portion of the solar spectrum (CIE, 2006) photolyses 7-dehydrocholesterol in the human skin, to previtamin D_3 , which is then converted to vitamin D_3 by a thermal process (Glerup et al, 2000; Webb et al, 1988; Webb, 1993; Webb, 2006; Grant et al, 2007). The main function of vitamin D_3 in humans is to maintain extracellular fluid concentrations of calcium and phosphorous (Holick, 1997).

The incident terrestrial solar UV waveband is broken into two sections: UVB (280-315 nm) and UVA (315-400 nm). The UVB bandwidth is less than half that of the UVA bandwidth, with 90-95% of the incident terrestrial solar UV radiation consisting of UVA radiation (Miller et al, 1998). The longer wavelength UVA radiation (greater than 330 nm) plays no part in the synthesis of vitamin D_3 in humans. In comparison, research has shown that UVA plays a significant role in causing mutagenic and carcinogenic effects on human skin (Agar et al, 2004; Moan et al, 1999; Garland et al, 2003; Wang et al, 2001). UVA has longer wavelengths than UVB and thus penetrates deeper into skin. Research has shown that UVA radiation can stimulate melanocyte proliferation, cause abnormalities in DNA, and modify gene expression (Wang et al, 2001). It has been estimated that approximately 19-50% of UVA can reach the depth of melanocytes, whereas only about 9-14% of UVB reaches a similar depth (Schothorst et al, 1987; Kaidbey et al, 1979; Bruls et al, 1984). The specific long-wave property of UVA also allows it to penetrate most automobile, office and household windows, whereas UVB is blocked by window glass (Parisi et al, 2007; Kimlin et al, 2002; Wang et al, 2001).

Various studies have also shown that the global distribution of UVA may account for much of the global variation in the mortality rates from melanoma, in particular the high rates at increased latitudes (Garland et al, 2003). Some European studies have even found a south to north increase in serum 25 - hydroxyvitamin D that parallels a similar gradient in the incidence of colorectal, breast and prostate cancers (van der Wielen et al,1995; IARC, 2008). However, research from the USA shows that outdoor behaviour and obesity are better predictive factors of vitamin D_3 status than the association between latitude and vitamin D_3 status (IARC, 2008).

Epidemiological data and animal studies indicate that low blood serum vitamin D_3 is linked to breast cancer, prostate cancer, colorectal cancer, non-Hodgkin's lymphoma, multiple sclerosis, diabetes, bacterial infections, inflammatory bowel disease, elevated cholesterol, rheumatoid arthritis and common obesity (Holick, 2004; Garland et al, 2006; Foss, 2009). It has been estimated that the number of premature deaths from cancer due to insufficient vitamin D_3 in the USA is up to 85,500 annually and up to 25,000 in the UK annually (Grant et al, 2005; PT, 2008). The associated cost in the USA for 2004 due to insufficient vitamin D_3 has been estimated at \$40 to \$56 billion, whereas the costs of excess UV exposure were estimated at \$6-7 billion (Grant et al, 2005). Vitamin D_3 is also important for the prevention of rickets in children, osteoporosis, osteomalacia, and fractures in the elderly (Holick, 2004). The total direct cost related to fall injuries in the USA for people 65 and older in 2000 was more than \$19 billion (Stevens et al, 2006) and is expected to rise to approximately \$43.8 billion by 2020 (Englander et al, 1996). More recent research has now shown that the related benefits of vitamin D_3 are greater than previously known; consequently making the associated costs due to lack of sun exposure greater than once thought (Grant et al, 2007).

Although over exposure to UV wavelengths are known to cause damage, vitamin D_3 synthesis occurs at doses far below those needed for erythema to arise (Webb, 1993). Small amounts of vitamin D_3 can also be obtained from some foods, for example oily fish and eggs or by fortifying foods with vitamin D_3 . It has been shown that the vitamin D_3 from these sources cannot provide sufficient vitamin D_3 for the elderly (Mosekilde, 2005). Vitamin D_3 can also be obtained through vitamin tablets; however the simplest way to obtain vitamin D_3 is from moderate exposure to sunlight (Holick, 2004). Furthermore, this is also the cheapest way without the cost burden of vitamin tablets.

At present, Australia and Canada are among very few countries that have guidelines on how much UV exposure the public should receive for vitamin D_3 synthesis. The Australian guidelines suggest exposure to approximately 1/6 to 1/3 of a MED (minimum erythemal dose equivalent to approximately 34-67 Jm⁻² of UV radiation), depending on age, that would be appropriate to provide adequate vitamin D_3 levels (Samanek et al, 2006; CDHAA, 2004). Older people require more frequent exposures as vitamin D_3 production rates are about 1/5-1/4 for the elderly as for the young (Holick et al., 1989; MacLaughlin and Holick, 1985). Also, people with highly pigmented skin would require exposures 3-5 times greater than those necessary for fair skinned people (Harris, 2006; Pathak et al., 1999). Recent research suggests that the optimal serum vitamin D_3 level for bone health and protection against other diseases is between 800 and 4000 IU per day (Aloia and Li-Ng, 2007; Lappe et al., 2007; Vieth et al., 2007; Dawson-Hughes et al., 2005; Giovannucci et al, 2006; Gorham et al, 2007; Garland et al, 2007; Rostand, 1997; Heaney et al, 2003). 1000 IU is equivalent to exposing 15% (or the face, neck and hands) of the human body to approximately 1/3 MED (PS, 2006).

A position statement was recently approved by the Working Group of the Australian and New Zealand Bone and Mineral Society, Endocrine Society, Osteoporosis Australia, Australian College of Dermatologists and the Cancer Council Australia recommending five minutes solar UV exposure either side of the peak UV periods on most days of the week in summer and approximately 2-3 hours solar UV exposure over a week in winter (PS, 2006). The Canadian Cancer Society has also recommended that people try to obtain 1000 IU of vitamin D₃ (CCS, 2007). The Canadian Paediatric Society recommends that pregnant or breast-feeding women get 2,000 IU of vitamin D daily (DM, 2008). These recommendations are still behind emerging scientific findings (e.g. Giovannucci et al., 2006; Grant et al., 2007; Gorham et al., 2007; Garland et al., 2007). Nevertheless, they are still the most up to date statements that have been distributed to the public. These statements are also very generalized reports as sun exposure varies significantly with latitude and atmospheric conditions.

Solar UV radiation is incident on the earth's surface in two distinct components, direct and diffuse (or scattered). The direct component is straight forward to minimise by simply blocking its path, whereas the diffuse component is incident from all directions and is difficult to minimise. UV protection from direct UV (full sun) is very important and many strategies can be adopted to reduce overall UV exposure including the use of sunscreen, shade, hats and sunglasses. However, due to the phenomena of Rayleigh and Mie scattering

in the earth's atmosphere, there is a significant proportion of the solar UV present in shade. Atmospheric scattering is influenced by factors such as solar zenith angle (SZA), clouds and atmospheric constituents play a major role in determining the relative proportions of UVA and UVB in diffuse UV, with greater scattering occurring at the shorter UVB wavelengths than at the longer wavelength UVA. Studies on the levels of UV observed in the shade of different shade environments have shown that the relative proportions of UVA and UVB in the shade are significantly different to those in full sun. The relative proportions are decreased for UVA and increased for UVB. Turnbull et al. (2005) found that UVA was reduced by as much as 65% when utilising a shade umbrella, whereas UVB exposures were only reduced by approximately 48%. Consequently, in the shade there is an increase in the relative proportion of the biologically effective wavelengths associated with pre-vitamin D_3 production in the body and a decrease in the total UV exposure compared to full sun.

Currently, there is a major gap in knowledge in order to optimise the beneficial effects related to vitamin D_3 effective wavelengths compared to reducing the biologically damaging overexposure to UV radiation. The goal of this research is to find a way to expose the human body to solar UV radiation that will maximise vitamin D_3 synthesis and also minimise the risk of cancer (specifically skin cancer due to overexposure). The importance of this research is that it provides a basis for public health campaigns aimed at reducing the incidence of hypovitaminosis D and its attendant disorders, as well as reducing over exposure to harmful solar UV radiation. In the light of the considerable body of evidence regarding the harm done by excessive UV exposure and the public awareness of skin cancer, any new public health program would need to avoid confusing the public with seemingly opposing messages.

Utilising diffuse solar UV radiation to obtain beneficial amounts of UV, while at the same time minimising personal overexposure to total UV radiation may prove to be absolutely necessary for an improvement in public health. Studies have shown that shade structures are important as a UV minimisation strategy; however, shade settings may also play an important role in providing exposures to the human body with adequate levels of UV radiation for vitamin D_3 production without experiencing the higher levels of total UV experienced in full sun. The lengths of exposure to solar UV at noon in major Australian cities to produce exposures of 1/3 and 1/6 MED has previously been reported (Samanek et al., 2006). Shade as a protective device has been discussed numerous times before (e.g. Turnbull and Parisi, 2006) and it is not the aim of this research. This current research is about the exposures that humans may receive when utilising solar UV for vitamin D_3 synthesis and the possible methods to optimise this radiation. The researchers are unaware of any similar research or attempts to show how solar UV exposures can be optimised so humans can receive adequate vitamin D_3 levels as well as reducing their total UV exposure.

Materials and Methods

Global and diffuse UV spectra

Global and diffuse solar UV spectral data from 280 to 400 nm in 0.5 nm steps have each been collected in ten minute intervals at Toowoomba (27.6° S, 151.9° E, 693 m above sea level), Australia. The period of data collection was in the Southern Hemisphere late spring and summer from 1 November 2006 to 28 February 2007. The minimum SZA in this period was 4.1°. The spectroradiometer system is based on a double monochromator system model (DTM300, Bentham Instruments, Reading, UK) with the gratings having 2400 grooves/mm. The input and output slit widths on the monochromator of 0.37 mm have been selected to provide a bandwidth of 0.5 nm. The input optics are provided by a diffuser (model D6) with the manufacturer determined error associated with the cosine response as less than $\pm 0.8\%$ for a SZA up to 70° and $\pm 3.3\%$ for an SZA of 80°. Wavelength and irradiance calibration of the spectral UV system was undertaken by employing the 365 nm mercury spectral line and a 150 Watt quartz halogen lamp with calibration traceable to the National Physical Laboratory, UK standard.

An automatic rotating shadow band (model RSB, Bentham Instruments, Reading, UK) that is 0.015 m wide and 0.11 m above the spectroradiometer input optics was employed for the collection of the spectral diffuse UV data. This shadow band rotates into position to block the solar disc from the input optics for the collection of the diffuse UV spectrum and rotates to a position in the horizontal plane for the recording of the global UV spectrum. Control of the instrumentation is provided by the BenWin+ software (version 1.0.4.13, Bentham Instruments, Reading, UK). The software is configured to start scanning at 5:00 EST (Australian Eastern Standard Time), with the last scan for the day at 19:00 EST. The time taken to collect a spectrum from 280 to 400 nm is approximately one minute. The correction due to the shadow band has been determined according to the technique described by Rosales et al (2006). The values of the spectral irradiances at each 0.5 nm increment for each scan were multiplied by this correction factor.

The amount of cloud cover at the time of each UV spectral scan was quantified by a Total Sky Imager (TSI) (model TSI-440, Yankee Environmental Systems, MA, USA) that is installed on the same building roof and several metres from the UV spectroradiometer. This instrument and associated software package allows determination of the fractional cloud cover at one minute intervals. The minimum and maximum values over the period of the total column ozone as obtained from the OMI satellite (OMI, 2007) on each day were 244 DU and 311 DU with an average of 274 DU.

Shade structures and latitudinal field measurements

For this research, measurements were conducted beneath numerous shade structures (see appendix 1 to investigate the influence of a number of different factors, namely sky view, cloud cover and solar zenith angle. A portable spectrometer (model USB4000, Ocean Optics, USA) was employed to measure the solar UV radiation spectrum both outside and inside the shade as outlined in the following sections. The spectrometer was wavelength and irradiance calibrated following standard techniques against the Bentham spectroradiometer system (discussed above) for the summer and winter seasons.

A range of different shade environments (at least ten shade environments) were utilised in this research. These shade environments included gazebos, verandas, shade umbrellas, trees, sides of buildings, doorways, etc. The shade environments were chosen so a range of differently sized and shaped shade environments with different sky views could be investigated.

Spectral UV field measurements were conducted at different latitudes to establish the effect that an increase or decrease in latitude has on vitamin D_3 effective UV wavelengths in the shade (this information is currently unavailable and could not be obtained from radiative transfer models). Measurement sites were:

Darwin	(lat 12° 28' S; long 130° 51' E)
Toowoomba	(lat 27° 36' S; long 151° 54' E)
Canberra	(lat 35° 18' S; long 149° 08' E)
Hobart	(lat 42° 52' S; long 147° 19' E)
London	(lat 51° 30' N; long 00° 05' W)

These measurements were necessary as solar UVB radiation levels decrease as the latitude increases and the extent that this affects exposures in the shade needs to be understood. Hence, this research assisted in providing a more complete picture of how diffuse UV exposure levels in the shade related to vitamin D_3 synthesis varied for changing latitudes. The measurement protocol was the same as that stated previously. Spectral measurements were gathered throughout the day to account for the change in solar zenith angle. The measurement protocol consisted of measuring the full sun spectral irradiance for the horizontal and sun normal planes in full sun, followed by measurement of the spectral UV in the shade for the horizontal, 45° and vertical planes (the 45° and vertical measurements were directed to the north, south, east and west). Measurements in the shade were conducted at: different distances from the edge of the shade cast by the structure depending on the level of sky view being observed. Measurements were also conducted at various times throughout the year to account for seasonal changes in solar UV irradiances levels and atmospheric conditions.

Human form measurements

UV radiation dosimeters fabricated from polysulphone were placed at various locations (total of 29) across a life size manikin, which was used to model humans in both standing and sitting postures while in the centre of the shade and facing different directions. The use of manikins in the measurement of UV exposures has been validated and extensively employed (for example, Parisi et al., 2000a; 2000b; Turnbull and Parisi, 2005; Airey et al., 1995). The 29 dosimeter sites on the manikin were located at: the vertex of the head, forehead, back of the head, nose, lips, chin, left cheek, left ear, right cheek, right ear, front of neck, back of neck, right side of neck, left side of neck, left shoulder, right shoulder, left forearm, right forearm, back of right hand, back of left hand, lower sternum, front of left thigh, front of right thigh, back of left thigh, back of right thigh, front of left shin, front of right shin, back of left shin and back of right shin. Manikins were exposed to UV radiation in the shade from 9:00 to 12:00 EST for relatively clear sky conditions. Cumulative solar UV exposures outside the shade environment were quantified by a set of 18 dosimeters (one dosimeter removed every 10 minutes of exposure) placed in full sun on a horizontal plane positioned near the shade environment. A series of measurements were conducted in Toowoomba in summer and winter to account for the variation in exposure levels, SZA and atmospheric conditions experienced during the different seasons. The exposure ratios, ER, were calculated according to the following equation:

$$ER = \frac{UV_s}{UV_{FS}} \times 100\% \tag{1}$$

where UV_S is the UV_{D3} in the shade for a specific anatomical site and UV_{FS} is the full sun UV_{D3} on a horizontal plane.

Results and Discussion

Global and diffuse spectral UV

An example of diffuse and global UV spectra is shown in Figure 1 for a cloud free period on 5 January 2007 for an SZA of (a) 5° and (c) 50° . This illustrates the variation in the relative proportions of the different wavelengths when comparing diffuse UV to global UV. These spectral measurements were obtained using the spectral measurement system described earlier. For Figure 1a, the diffuse spectral irradiance summed over the UVA waveband was 20.7 W/m² compared to 68.4 W/m² for the global UVA. Similarly, the diffuse UVB was 1.2 W/m^2 compared to 2.6 W/m^2 for global UVB. For this specific date and time, the UVA was reduced by approximately 70% in the shade, whereas the UVB in the shade was only reduced by approximately 54%. Figure 1(b) and (d) provide the vitamin D_3 biologically effective UV (UV_{D3}) for the global and diffuse solar UV that has been calculated by weighting the spectra (from Figure 1a and c) with the pre-vitamin D₃ (CIE, 2006) action spectrum. For Figure 1(b), the diffuse UV_{D3} irradiance was 0.36 W/m² compared to 0.81 W/m² for the global UV_{D3}. For Figure 1d, the diffuse UV_{D3} irradiance was 0.13 W/m² compared to 0.21 W/m² for the global UV_{D3}. For these specific weighted irradiances, UV_{D3} was reduced by approximately 56% for the smaller SZA, whereas the higher SZA UV_{D3} irradiance was only reduced by approximately 38% when comparing global and diffuse. Even though the reduction in diffuse UV_{D3} irradiance was lowest for the higher SZA (Figure 1d), the diffuse UV_{D3} measured at the smaller SZA (Figure 1b) was still nearly three times greater.



Figure 1. Global (thick) and diffuse (thin) UV spectra for a cloud free period on 5 January 2007 for a SZA of approximately 5° (a) and 50° (c). The corresponding spectra weighted with the vitamin D₃ action spectrum are shown in (b) and (d).

Variation in global and diffuse UV irradiance

The variation in the UV_{D3} irradiances and the UVA for all sky conditions and a changing SZA are shown in Figure 2. Over 2,000 data points are provided in each figure for diffuse and global UV for a changing SZA and relatively clear sky conditions. For a SZA of approximately 5°, the observed maximum UV_{D3} irradiances were 0.80 W/m² and 0.46 W/m², for global and diffuse respectively. For the larger SZA of approximately 70°, maximum UV_{D3} irradiances of 0.05 W/m² and 0.04 W/m² for global and diffuse were observed. For a SZA of approximately 5°, observed maximum UVA irradiances were 79.0 W/m² and 36.2 W/m², for global and diffuse respectively. For the larger SZA of approximately 70°, maximum UVA irradiances of 18.6 W/m² and 12.9 W/m² for global and diffuse were observed. The proportion of diffuse UV in global UV for UV_{D3} and for the UVA is illustrated in Figure 3 as a function of the SZA. Each data point is the average of the data up to 1° either side of the respective data point (e.g. the 5° data point is the average of all the values from 4° to 6°). The error bars are ± one standard deviation of the data for each data point. The average difference (15% to 20%) between the proportions of diffuse in global were at a maximum for SZAs below approximately 55°.



Figure 2. Global and diffuse UV irradiances as a function of SZA related to UV_{D3} (a and b) and UVA (c and d) exposure. (Sourced from Turnbull and Parisi, 2008a).



Figure 3. Change in proportion of diffuse UV in global UV for the UV_{D3} (•) and the UVA (\blacktriangle) irradiances. Errors bars provide the standard deviation of the data. (Sourced from Turnbull and Parisi, 2008a).

The diffuse UV irradiances throughout the day for the two consecutive days of 12 December 2006 (day 346) and 13 December 2006 (day 347) with the first being relatively cloud free and the second one being relatively cloudy are shown in Figure 4. For the first day, the cloud fraction was up to 0.4 for a total period of 30 minutes and less than 0.2 for the majority of the day. On the second day, the cloud fraction ranged from 1 to 0.1. The total column ozone from the OMI satellite (OMI, 2007) on each day is 276 DU and 272 DU respectively. The data is shown at 10 minute intervals, except for any small intervals where there was no data collected. The scatter of the global UV data is considerably higher on the cloudy day. The scattering of the diffuse UV data is slightly higher on the cloudy, but significantly less compared to the level of scattering seen in the global data.



(a)

Figure 4. Global (black) and diffuse (grey) UV_{D3} (a) and UVA (b) irradiances for relatively clear skies (left) and for changing cloud conditions (right). (Sourced from Turnbull and Parisi, 2008a).

Ratio of UV_{D3} to UVA

The average percentage ratios of UV_{D3} wavelengths compared to UVA wavelengths for diffuse and global UV are shown in Figure 5 for all sky conditions. For diffuse UV, the maximum ratio of UV_{D3} to UVA was 1.75% at a SZA of approximately 10°. The maximum ratio for global UV was 1.27% at 10°. The change in the average ratio of UV_{D3} to UVA with SZA is shown in Figure 6 for the global and diffuse UV. Each data point is the average of the data that is up to 1° either side of the data point. The error bars are one standard deviation of

the data for each range. The maximum difference between the ratio of UV_{D3} wavelengths and the UVA wavelengths for global and diffuse UV occurs for SZAs of approximately 55° and less. Therefore for SZAs of roughly 55° and less, more UV radiation is contributed toward vitamin D₃ synthesis than toward UVA exposure by utilising diffuse UV compared to global UV.



Figure 5. Ratio of UV_{D3} compared to UVA for global (a) and diffuse (b) as a function of SZA for all sky conditions. (Sourced from Turnbull and Parisi, 2008a).



Figure 6. Average ratios (expressed as percentages) of UV_{D3} to UVA for global (black) and diffuse (grey) UV as a function of SZA. Error bars denote the standard deviation of the data. (Sourced from Turnbull and Parisi, 2008a).

Global, diffuse and shade exposures

The variation in the UV irradiances for relatively clear sky conditions, changing latitude and a changing SZA are shown in Figure 7 for (a) UV_{D3} and (b) UVA. The error bars are \pm one standard deviation of the data for each data point. For a SZA of approximately 5°, the average UV_{D3} irradiances were 0.67 W/m² and 0.35 W/m² for global and diffuse respectively. Whereas, average irradiances in the shade were 0.20 W/m² and 0.11 W/m², for a sky view greater than 40% and a sky view of less than 40% respectively. For the larger SZA of approximately 65°, average UV_{D3} irradiances were comparable for global, diffuse and shade at roughly 0.06 W/m².

For a SZA of approximately 5°, average UVA irradiances were 64.8 W/m² and 24.5 W/m², for global and diffuse respectively. Whereas, average irradiances in the shade were 12.2 W/m² and 5.0 W/m², for a sky view greater than 40% and a sky view of less than 40% respectively. For the larger SZA of approximately 65°, average UVA irradiances of 16.5 W/m² and 12.7 W/m² for global and diffuse were observed. Whereas, average irradiances in the shade were 8.5 W/m² and 5.4 W/m², for a sky view greater than 40% and a sky view of less than 40% respectively. The proportion of diffuse UV in global UV for UV_{D3} and for the UVA is illustrated in Figure 3 as a function of the SZA. Each data point is the average of the data up to 1° either side of the respective data point (e.g. the 5° data point is the average of all the values from 4° to 6°). The error bars are ± one standard deviation of the data for each data point. The average difference (15% to 20%) between the proportions of diffuse in global were at a maximum for SZA's below approximately 55°.



Figure 7. Variation between full sun (\blacklozenge), diffuse (\blacksquare) and shade (\blacktriangle for sky view $\ge 40\%$ and \bullet for sky view < 40%) for UVD₃ (a) and UVA (b) irradiances during relatively clear sky conditions. Error bars denote the standard deviation of the data.

Time required for exposure to reach approximately 66.7 J/m^2 of UV_{D3}

The times required for an exposure equivalent to 66.7 J/m^2 on a horizontal plane for a SZA greater than 4° during 2007 are shown in Figure 8a for global UV_{D3} and Figure 8b for diffuse UV_{D3}. 66.7 J/m^2 of UV_{D3} is used here as the time needed for exposure to this amount of radiation is generally much shorter (e.g. Turnbull and Parisi, 2008b) than that needed for 1/3 MED of exposure that the Australian guidelines recommend (Samanek et al, 2006; CDHAA, 2004). This difference is due to the negligible response of the vitamin D₃ action spectrum in

the UVA region above 330 nm, whereas the response of the erythemal action spectrum continues throughout the UVA waveband. Over 2,000 data points are provided in each figure for global and diffuse UV_{D3} for all SZA and clear sky conditions. The average times for an exposure equivalent to 66.7 J/m^2 for vitamin D₃ are shown in Table 1 for diffuse and global UV. For a SZA of 5°, the average time needed to receive an exposure of 66.7 J/m^2 due to UV_{D3} was 1.7 and 3.2 minutes for global and diffuse respectively. Whereas, the average time needed to receive an equivalent exposure of 66.7 J/m² for vitamin D_3 in the shade (sky view greater than 40%) was approximately 5.7 minutes. However, for a SZA of 65°, the average time needed to receive an exposure of 66.7 J/m² due to UV_{D3} was 19.1, 19.3 and 22.6 minutes for global, diffuse and shade respectively. These times are based on exposing 15% of the human body to UV radiation. Increasing the exposed body surface will subsequently decrease the time needed for vitamin D_3 production (e.g. exposing three times more body surface will reduce the exposure times presented in this research by a factor of three). However, the time for 1/3 MED of erythemal effective UV will remain the same. Turnbull and Parisi (2008b) have shown that the time needed for 66.7 J/m^2 of UV_{D3} and 1/3 MED is substantially different with times varying by roughly a factor of two for the smaller SZAs. Latitudinal measurements (from all sites) have been included in Figure 8b to illustrate the similarity of the shade observations to the diffuse observations.

The smallest noon SZAs for summer for each site (Darwin 0° , Toowoomba 4° , Canberra 13° , Hobart 20° and London 28°) are also included in the Figure 8(b) to illustrate where the respective exposure times for the different latitude sites lies. The largest noon SZAs for the middle of winter for each site are approximately: Darwin 26° , Toowoomba 50° , Canberra 58° , Hobart 66° and London 74° . Cloud data is not included as previous research (Turnbull et al, 2006; Turnbull and Parisi, 2008b) found that 1 to 7 okta of cloud cover has a considerably reduced effect on diffuse UV levels compared to global UV. Therefore, variations in cloud cover (below 8 okta) are far less likely to cause an obvious change in UV_{D3} exposure times in the shade; whereas global UV_{D3} exposure times will vary significantly depending on cloud cover and solar disc cover.



(a)



Figure 8. Time needed for exposure to (a) global and (b) diffuse UV_{D3} radiation that is equivalent to 66.7 J/m². Combined latitudinal (**■**) from Darwin, Toowoomba, Canberra, Hobart and London is provided in Figure 8(b). Minimum noon SZAs for summer are also included for each site.

Table	1. Aver	age tir	nes f	or an e	xposu	re equ	iivale	ent to	66.7 J	m^2	of U	V _{D3}	radiation	duı	ring
2007	for clea	ar sky	cond	litions.	The	standa	ard d	eviatio	on of	the	data	is	provided	in	the
parentl	neses.														
	Gl	obal U	V_{D2}	Diffus	e UV	D2	Shade		,						

	Global UV _{D3}	Diffuse UV _{D3}	Shade UV _{D3}
SZA	(min)	(min)	(min)
5°	1.7 (0.3)	3.2 (0.3)	5.7 (1.0)
15°	1.7 (0.2)	3.3 (0.4)	5.9 (1.1)
25°	2.0 (0.4)	3.8 (0.4)	6.0 (1.0)
35°	2.6 (0.4)	4.5 (0.5)	6.9 (2.6)
45°	4.3 (0.9)	6.1 (0.6)	7.0 (1.7)
55°	7.2 (1.4)	9.7 (1.0)	12.0 (2.9)
65°	19.1 (8.6)	19.3 (2.7)	22.6 (5.6)
75°	58.2 (56.7)	70.0 (10.7)	N/A

Vitamin D₃ and total UV exposure

Figure 9 illustrates the average total UV exposures received when exposing 15% of the human body to the equivalent of 66.7 J/m^2 of UV_{D3} radiation. This was calculated by taking the average time to receive approximately 66.7 J/m² of UV_{D3} for specific SZAs and summing the total UV irradiance over this time. This data is for relatively clear sky conditions and a changing SZA. The error bars denote \pm one standard deviation of the data for each data point. For a SZA of 5° , the average total UV exposures were 6637.9 J/m² and 4165.5 J/m² for global and shade (sky view greater than 40%) respectively, which equates to an approximate reduction of 37% in total UV exposure. For the larger SZA of approximately 65°, average total UV exposures were 20178.7 J/m² and 12141.5 J/m² for global and shade (sky view greater than 40%) respectively, which equates to an approximate reduction of 40% in total

UV exposure. The largest variation between global and shade exposures was observed for a SZA of roughly 45° with a 58% reduction in total UV exposure.



Figure 9. Total UV exposures received for global (\blacklozenge) and shade - sky view greater than 40% (\blacktriangle) when exposed to approximately 66.7 J/m² of UV_{D3} radiation. Error bars denote the standard deviation of the data.

Human form measurements

The exposure ratios, ER, to each anatomical site are provided in Figure 10. Compared to full sun UV_{D3} exposures, the shade reduced exposures to the nose to approximately 38% and 63% of full sun exposures in summer and winter respectively. The shade was found to reduce exposures to the hands to roughly 47% and 51% of full sun exposures in summer and winter respectively. The largest variation in exposure ratios between the seasons was for the nose with a 25% decrease in exposure ratio from winter to summer.



Figure 10. UV_{D3} exposure ratios for specific anatomical sites for summer and winter. Error bars denote the standard deviation of the data.

Conclusions

Studies on the levels of UV observed in the shade of different shade environments have shown that the relative proportions of UVA and UVB in the shade are significantly different to those in full sun (Turnbull et al., 2005; Turnbull and Parisi, 2003; Turnbull et al., 2003; Parisi et al., 2001). The relative proportions of the UVA in shade to those in full sun are decreased compared to the relative proportions of the UVB in shade to those in full sun. At certain latitudes and SZA, unprotected exposure for short periods to the UV under shade structures is the best course of action as it will contribute more toward vitamin D_3 production than toward erythema compared to exposing the body to full sun UV due to the reduced relative component of the UVA in the shade.

Humans need to be protected from damaging UV radiation, but they also need to be exposed to sub-erythemal solar UV so that vitamin D_3 synthesis can occur. Research has shown that UVA plays a significant role in causing mutagenic and carcinogenic effects on human skin (Agar et al, 2004; Moan et al, 1999; Garland et al, 2003). Further research is also suggesting that increased UVA exposures and inadequately maintained vitamin D_3 levels increases the chances of melanoma development (Godar et al., 2009). Therefore, reducing personal exposures to UVA radiation is essential. For a SZA of 55° and less, more UV radiation is contributed toward vitamin D_3 synthesis than toward UVA exposure by utilising diffuse UV compared to global UV. Therefore, this research indicates that a new approach to optimise UV exposure is to utilise diffuse UV in or around the middle of the day. Although the results were obtained at a sub-tropical site for 4 months over summer, they were collected for a range of SZA from approximately 5° to 80°. This should allow extension to other latitudes and other seasons where these SZA are encountered.

The influence of atmospheric ozone on solar UV_{D3} radiation increases with decreasing wavelength; as a result there is almost no influence of ozone at wavelengths greater than 320 nm (Blumthaler, 1993). The influence of a decrease in atmospheric ozone is both the increase in the irradiances of the shorter wavelengths and a shift of the short wavelength cut-off to shorter wavelengths. This coincides with the higher effectiveness of the shorter wavelengths for biological change. Therefore, a reduction in ozone will cause a decrease in the exposure time necessary for vitamin D₃ synthesis. Conversely, an increase in ozone levels will mean an increase in exposure time. Turnbull (2005) concluded that decreases in atmospheric ozone concentrations have an increasing effect on diffuse erythemal UV levels; however this is not to the same extent as for global erythemal UV. To what extent a change in ozone levels will affect vitamin D₃ exposures in the shade is currently being determined.

Nevertheless, the findings in this paper may have significant ramifications for future public health policy regarding sun exposure, which is currently being debated in many countries (Diffey, 2006; Gillie, 2006). Also, the findings of this research may prove useful to those that work from 9 am to 5 pm, where solar UV exposure at noon or during a lunch break may be the only option for the necessary UV exposures to initiate the synthesis of vitamin D_3 . Therefore, advice to stay out of the sun in the middle of the day, which is best for vitamin D_3 synthesis in the skin, can be adjusted to advocate the possible use of appropriate shade environments. This research shows that a specifically designed shade structure is not needed for vitamin D_3 exposure. Any shade can be utilised to optimise UV exposure as long as you can see roughly 40% or more of the sky. Also, it is a huge misconception that a person can sit behind a closed window and still receive UV_{D3} radiation; as numerous studies have shown that window glass attenuates all UV_{D3} radiation. However, in the shade there is the potential danger due to the filtering of the infrared waveband, which may cause prolonged exposures.

Vitamin D_3 deficiency, along with the problems associated with over exposure to UV is a worldwide problem. The position statement released by the Working Group of the Australian and New Zealand Bone and Mineral Society, Endocrine Society, Osteoporosis Australia, Australian College of Dermatologists and the Cancer Council Australia recommends a few minutes solar UV exposure either side of the peak UV periods on most days of the week in summer and approximately 2-3 hours solar UV exposure over a week in winter. Therefore, this position statement has the potential to be extended significantly by including new scientific findings and recommendations about UV in shade for different latitudes and this research provides strong scientific data to further improve these recommendations.

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Appendix 1: Shade Environments The following are examples of the shaded environments used in this research.





Appendix 2: Publications, Conferences, Radio Interviews and Media Articles

The following is a list of publications, conferences, radio interviews and media articles arising from this research.

Publications

- 1. Turnbull, D.J. & Parisi, A.V. 2008, "Utilising shade to optimise UV exposure for vitamin D₃," *Atmospheric Chemistry and Physics*, vol.8, pp.2841-2846.
- 2. Turnbull, D.J. & Schouten, P.W. 2008, "Utilising polyphenylene oxide for long term solar UVA dosimetry," *Atmospheric Chemistry and Physics*, vol.8, pp.2759-2762.
- 3. Turnbull, D.J. & Parisi, A.V. 2008, "Optimising Solar UV Exposures for Vitamin D₃: Comparing Global and Diffuse Spectral UV," *Radiation Research*, vol.169(3), pp.344-349.

Conference presentations

- 1. Turnbull, D.J. & Parisi, A.V. "Utilising Shade to Optimize UV Exposure for Vitamin D," A UV Conference Celebrating One century of UV Radiation Research, 18-20 September 2007.
- 2. Turnbull, D.J. & Schouten, P.W. "Development of a Long Term Solar UVA Dosimeter," A UV Conference Celebrating One century of UV Radiation Research, 18-20 September 2007.
- 3. Turnbull, D.J. & Parisi, A.V. "Scattered UV Radiation, Shade Structures and Vitamin D," 12th Congress of the European Society for Photobiology, 1-6 September 2007.
- 4. Turnbull, D.J. & Schouten, P.W. "Utilising polyphenylene oxide for long term solar UVA dosimetry," 12th Congress of the European Society for Photobiology, 1-6 September 2007.

Radio Interviews

- 1. 4GR, 17 December 2007;
- 2. ABC Gold Coast, 14 December 2007;
- 3. ABC Southern Queensland, 12 December 2007;
- 4. ABC Southern Queensland (Drive Time), 7 December 2007;

Media Articles

- 1. Sunday Age, August 2008;
- 2. USQ Phoenix, March 2008;
- 3. The Daily Telegraph, 13 December 2007;
- 4. Science Alert, 13 December 2007;
- 5. Toowoomba Chronicle, 4 January 2007;
- 6. USQ News, 7 December 2007;
- 7. USQ Phoenix, January 2007;
- 8. Toowoomba Chronicle, 4 & 8 January 2007;