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The relationship between ambient ultraviolet radiation (UVR) and objectively measured personal UVR exposure dose is modified by season and latitude

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Despite the widespread use of ambient ultraviolet radiation (UVR) as a proxy measure of personal exposure to UVR, the relationship between the two is not well-defined. This paper examines the effects of season and latitude on the relationship between ambient UVR and personal UVR exposure. We used data from the AusD Study, a multi-centre cross-sectional study among Australian adults (18-75 years), where personal UVR exposure was objectively measured using polysulphone dosimeters. Data were analysed for 991 participants from 4 Australian cities of different latitude: Townsville (19.3 °S), Brisbane (27.5 °S), Canberra (35.3 °S) and Hobart (42.8 °S). Daily personal UVR exposure varied from 0.01 to 21 Standard Erythemal Doses (median=1.1, IQR: 0.5–2.1), on average accounting for 5% of the total available ambient dose. There was an overall positive correlation between ambient UVR and personal UVR exposure (r=0.23, p<0.001). However, the correlations varied according to season and study location: from strong correlations in winter (r=0.50) and at high latitudes (Hobart, r=0.50; Canberra, r=0.39), to null or even slightly negative correlations, in summer (r=0.01) and at low latitudes (Townsville, r=-0.06; Brisbane, r=-0.16). Multiple regression models showed significant effect modification by season and location. Personal exposure fraction of total available ambient dose was highest in winter (7%) and amongst Hobart participants (7%) and lowest in summer (1%) and in Townsville (4%). These results suggest season and latitude modify the relationship between ambient UVR and personal UVR exposure. Ambient UVR may not be a good indicator for personal exposure dose under some circumstances.

Introduction

Personal exposure to UVR (UVR_{per}) can be quantified using polysulphone film dosimeters [1-4] or electronic dosimetry [5, 6]. However, objective assessments of UVR_{per} are not always feasible in large-scale population studies due to cost and logistical reasons. Several studies have shown that ambient UVR (UVR_{amb}) is a significant contributor to UVR_{per} [7, 8]. The fraction of UVR_{amb} that is received by an individual can be described as the personal UVR exposure fraction (UEF_{per}) and expressed as a percentage (UVR_{per}/UVR_{amb}×100%). UEF_{per} has been previously estimated to be approximately 3-5% [9, 10]. In spite of this low fraction, UVR_{amb} or its surrogates, such as season and latitude of residence, are commonly used as proxies for UVR_{per} where the latter is not available [11-20]. The underlying assumption for this practice is that UVR_{per} and UVR_{amb} are highly correlated at an individual level and the relationship (i.e., the UEF_{per}) remains stable between populations.

UVR_{per} is strongly associated with sun-related behaviours, such as the total time spent outdoors especially during mid-day hours [6, 7, 21], which may change over time and space. Previous studies involving UVR_{per} dosimetry have usually had small sample sizes and often encompassed minimal seasonal and latitudinal variation [8, 22]. It is therefore unclear if and to what extent the relationship between UVR_{per} and UVR_{amb} varies by season and latitude. If there is effect modification and it is sufficiently large, the seasonal or latitudinal pattern in UVR_{per} may differ significantly from that in UVR_{amb}. Consequently, associations between UVR_{amb} and health outcomes observed in ecological studies [11-20] may not reflect underlying associations between UVR_{per} and the same health effects.

The aim of this analysis was to assess the seasonal and latitudinal effects on the relationship between UVR_{amb} and UVR_{per} both at the individual and population level, using correlation coefficients and UEF_{per}, respectively. We also described the patterns of UVR_{amb}, UVR_{per} and UEF_{per} in different seasons and locations over a wide range of latitudes.

Methods

Data source

The AusD Study was a multi-centre, cross-sectional study in adults (aged 18-75 years) from 4 Australian cities (two tropical/subtropical sites: Townsville, 19.3°S, 146°E; Brisbane, 27.5°S, 153°E and two temperate sites: Canberra, 35.3°S, 149°E; Hobart, 42.8°S, 147°E) conducted from May 2009 to Dec 2010 [23]. The primary aim of the study was to identify the determinants of vitamin D status in the adult Australian population. The ethics committees of all participating institutions (Queensland University of Technology #0600000224; James Cook University #H3124; Australian National University #2008/451; University of Tasmania #H0010277) approved the study before data collection began. The detailed methods of the AusD Study have been reported elsewhere [23].

UVR_{per}

All participants in the AusD Study were asked to wear a new polysulphone dosimeter on their left wrist each day for 10 consecutive days to quantify their daily total exposure to ambient UVR. Detailed instructions for using such a dosimeter have been previously reported [23]. For each participant, the average daily personal exposure in standard erythemal dose (SED) units was obtained by averaging all available daily results (on both weekdays and weekend days). Not all participants completed all 10 days' measurements but the majority (92%) had at least 7 days of usable data [24].

UVR_{amb}

We acquired daily total UVR_{amb} (in units of standard erythemal doses (SEDs)) data for 2009-2010 for three of the 4 AusD Study sites (Hobart, Townsville, Brisbane) from the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). UVR_{amb} data from ARPANSA for Canberra were not available throughout most of the study period. To estimate missing values, we used 2010-2011 data (Nov 2010–Dec 2011, n=386 days) for this site from ARPANSA and daily total solar radiation data from the Bureau of Meteorology (BOM), which is publicly accessible for all major cities in Australia through its website. Daily total UVR and daily total solar radiation were highly correlated (r=0.94) and the relationship varied across seasons, with the proportion of total UVR ranging from 0.009% in winter to 0.017% in summer. A regression model taking into account the seasonal effect was developed to estimate the ambient UVR on days where only total solar radiation was available. On days where both data were available, the estimated and actual values had high agreement (ICC=0.94, 95%CI: 0.93 to 0.95). This approach has been well established in earlier studies [25-27].

Each participant was assigned a set of UVR_{amb} values corresponding to their location and to the days that they wore the personal dosimeters. An aggregated ambient UVR dose was calculated for each participant by averaging all daily values of UVR_{amb}.

UEF_{per}

For each participant, UEF_{per} was calculated as UVR_{per} /UVR_{amb} × 100%. For example, a person receiving 1 SED on a day with a total dose of UVR_{amb} of 20 SEDs receives a UEF_{per} of 5%. The values of UEF_{per} for each participant over the index measurement period were averaged to calculate a mean UEF_{per}.

Statistical analysis

All analyses were conducted using the R Software (The R Project, Auckland, New Zealand) and all statistical tests were two-tailed with a significance level of p <0.05. Only participants with both personal UVR exposure and ARPANSA-provided or estimated ambient UVR data available were included in this analysis (991/1002). The sample was described against background factors, including season entered the study, study site, age, sex, country of birth, education, employment, occupation, self-reported skin color and body mass index (BMI) category (Table 1).

UVR_{amb} was normally distributed while UVR_{per} and UEF_{per} were positively skewed. To maintain consistency, we used medians and inter-quartile ranges (IQRs) to describe these variables by season and location, and Kruskal-Wallis non-parametric ANOVA Test to conduct comparisons within these variables.

Pearson correlation coefficients (r) with 95% confidence intervals (CIs) were used to test the linear relationship between UVR_{amb} and natural log-transformed UVR_{per}. The modifying effects of season and location on the relationship between UVR_{amb} and UVR_{per} were examined using a series of multiple regression models with the dependent variable being log-transformed UVR_{per}, and the interaction terms being the products of UVR_{amb}× season/location. A separate multiple regression model was developed to test the effects of season and location on natural log-transformed UEF_{per}.

All regression models were adjusted for the abovementioned participant characteristics. Because log-transformed values were used as dependent variables, relative changes (RCs) (95% CIs) at the actual scale were reported as the exponential of the original regression coefficients. We conducted additional analyses to check the stability of our major findings from the initial models for the effects of season and location by excluding data where only estimated UVR_{amb} was available.

Results

Sample description

In the final sample (N=991, mean age = 48.1, SD=15.7 years), 54% of participants were females; 81% were Australian-born and 71% had predominantly indoor occupations (Table 1). The number of participants was well balanced (24-26%) by location but was considerably smaller in summer (10%) and autumn (20%) than the other two seasons (32-38%).

Table 1 Descriptive data on participants in the AusD Study that had sufficient data to be included in this analysis (N=991).

	n (%)		n (%)
Location		Education [a]	
Townsville (19.3 °S)	257 (26.0)	Below year12	152 (15.4)
Brisbane (27.5 °S)	254 (25.6)	Year 12	228 (23.0)
Canberra (35.3 °S)	244 (24.6)	Trade certificate	216 (21.8)
Hobart (42.8 °S)	236 (23.8)	Bachelor degree	236 (23.9)
Season of participation		Postgraduate degree	157 (15.9)
Winter (Jun-Aug)	320 (32.3)	Employment status [b]	
Spring (Sep-Nov)	373 (37.6)	Full time	477 (48.2)
Summer (Dec-Feb)	104 (10.5)	Part-time	171 (17.3)
Autumn (Mar-May)	194 (19.6)	Retired	189 (19.1)
Sex		Others	153 (15.4)
Female	538 (54.3)	Occupation type [c]	
Male	453 (45.7)	Mainly indoors	680 (71.1)
Age group (years)		Mainly or half outdoors	276 (28.9)
18-34	242 (24.4)	Self-reported skin color [d]	
35-44	185 (18.7)	Fair	622 (63.5)
45-54	174 (17.6)	Medium	253 (25.8)
55-64	198 (20.0)	Dark/black/olive	105 (10.7)
65-75	192 (19.4)	BMI [e]	
Country of birth		<25	381 (38.6)
Australia	798 (80.5)	25-29.99	344 (34.8)
Other countries	193 (19.5)	30+	263 (26.6)

Abbreviation: BMI, body mass index (=Weight (kg)/height (m)^2)
Missing values: [a] n=2; [b] n=1; [c] n=35; [d] n=11, [e] n=3

UVR_{amb}, UVR_{per} and UEF_{per} by season and location

The mean UVR_{amb} for each participant (over the days for which data were available) ranged from 3.1 to 65.4 SEDs with a median (IQR) of 26.5 SEDs (16.1 to 38.5). Across all locations, the highest median UVR_{amb} was in summer (47.8) and the lowest in winter (14.3). The median value was 23.1 and 34.5 in autumn and spring, respectively. Across all seasons, Townsville had the highest median value (41.7) followed by Brisbane (26.0), Hobart (19.6) and Canberra (19.1), reflecting both a latitudinal pattern and that fewer Canberra participants were interviewed in summer.

In this sample, daily UVR_{per} varied widely from 0.01 to 20.7 SEDs with a median of 1.1 SEDs (IQR: 0.5–2.1). The overall seasonal pattern (across all locations) in UVR_{per} was quite different to the pattern in UVR_{amb}, with the lowest UVR_{per} in summer (median=0.5 SEDs) and the highest in spring (1.6 SEDs), with 0.8 and 1.0 SEDs in autumn and winter, respectively. In relation to the pattern according to location (across all seasons), UVR_{per} was similar to UVR_{amb}, with the highest median UVR_{per} in Townsville (1.6 SEDs), and the lowest in Canberra (0.8 SEDs), and 1.1 SEDs in Brisbane and Hobart.

The overall median UEF_{per} was 4.8% (IQR: 2.5–8.6%), i.e. UVR_{per} was, on average, around 5% of the daily UVR_{amb}. UEF_{per} was lowest in summer (1.1%) and highest in winter (7.1%) in all study locations combined; and lowest in Townsville (3.7%) and highest in Hobart (6.7%) in all seasons combined.

Table 2 shows the median values of the three measures, by season and location. The highest median values of UVR_{amb} were in Townsville (lowest latitude) over all seasons, and in summer over all locations. The lowest values were in Hobart (highest latitude) all year round, and in winter for all locations.

Surprisingly, the lowest medians of UVR_{per} occurred in summer in all locations except Hobart. The highest values were observed in winter for the two tropical/subtropical locations and in spring for the two temperate locations. Importantly, in summer, the latitudinal trend in UVR_{per} was opposite to the pattern in UVR_{amb}; while in winter, the trend in UVR_{per} was similar to the trend in UVR_{amb} (Table 2).

At each location, UEF_{per} was lowest in summer and highest in winter. In each season, it was lowest in Townsville and highest in Hobart (Table 2). All comparisons between locations and seasons for the three measures were statistically significant based on Kruskal-Wallis non-parametric ANOVA tests ($p<0.05$).

Table 2 Median values and IQRs of UVR_{amb}, UVR_{per} and UEF_{per} by location and season

	Season			
	Summer (Dec-Feb)	Autumn (Mar-May)	Winter (Jun-Aug)	Spring (Sep-Nov)
UVR_{amb} (SED)				
Townsville (19.3 °S)	53.2 (49.7 to 59.3)	29.3 (26.1 to 37.9)	26.4 (24.9 to 31.2)	46.8 (43.6 to 55.3)
Brisbane (27.5 °S)	49.2 (43.3 to 56.1)	23.1 (19.5 to 30.7)	18.6 (14.9 to 22.8)	34.5 (26.1 to 42.2)
Canberra (35.3 °S)	37.5 (37.5 to 40.6)	17.3 (11.5 to 24.8)	11.1 (10 to 14.2)	32.6 (27.6 to 36.8)
Hobart (42.8 °S)	37.5 (34.1 to 45.5)	9.1 (6.3 to 18.7)	5.4 (3.8 to 9.0)	27.6 (21.7 to 33.8)
UVR_{per} (SED)				
Townsville (19.3 °S)	0.3 (0.2 to 1.0)	0.9 (0.5 to 2.3)	2.0 (1.1 to 3.4)	1.8 (1.0 to 2.8)
Brisbane (27.5 °S)	0.3 (0.2 to 0.6)	1.2 (0.7 to 1.9)	1.4 (0.8 to 2.2)	1.2 (0.6 to 1.8)
Canberra (35.3 °S)	0.5 (0.3 to 0.9)	0.6 (0.3 to 1.1)	0.6 (0.4 to 1.1)	1.4 (0.8 to 2.7)
Hobart (42.8 °S)	1.0 (0.5 to 1.6)	0.6 (0.4 to 0.7)	0.6 (0.3 to 1.1)	1.8 (1.1 to 3.0)
UEF_{per} (%)				
Townsville (19.3 °S)	0.6 (0.4 to 2.0)	2.9 (1.5 to 6.0)	7.9 (3.7 to 11.1)	3.7 (2.2 to 5.6)
Brisbane (27.5 °S)	0.7 (0.4 to 1.2)	4.9 (2.8 to 8.0)	7.2 (4.6 to 11.5)	3.0 (1.7 to 5.3)
Canberra (35.3 °S)	1.2 (0.7 to 2.5)	3.5 (1.7 to 6.5)	5.6 (3.6 to 9.4)	4.4 (2.6 to 7.4)
Hobart (42.8 °S)	2.7 (1.6 to 4.0)	6.6 (3.8 to 9.5)	10.7 (5.5 to 19.1)	6.6 (4.4 to 9.6)

Abbreviation: IQR, inter-quartile range; UVR_{amb}, ambient UVR; UVR_{per}, personal UVR exposure; UEF_{per}, personal exposure fraction; SED, Standard Erythemal Dose. Values outside brackets are medians and inside the brackets are IQRs.

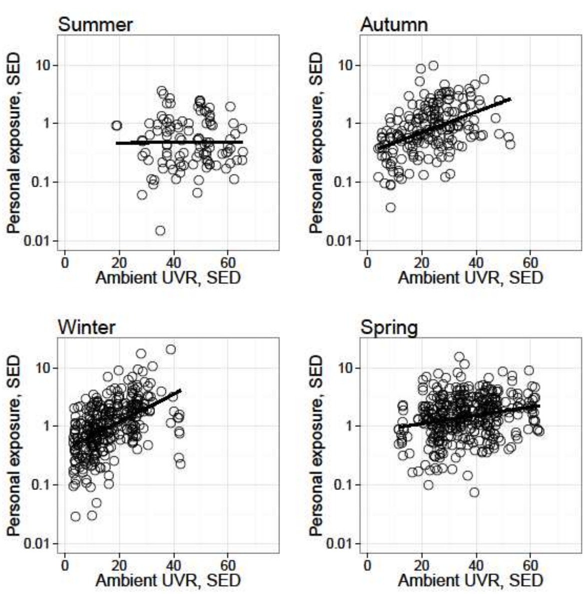

Fig 1 Correlations between ambient UVR (SED) and log-transformed personal UVR exposure (SED) by season.
UVR=ultraviolet radiation; SED=Standard Erythemal Dose.

Correlations between UVR_{amb} and UVR_{per}

Overall, there was a positive correlation between UVR_{amb} and natural log-transformed UVR_{per} (r=0.23 [95%CI: 0.17 to 0.28], $p<0.001$). The correlations were much stronger in winter (r=0.50 [0.41 to 0.58], $p<0.001$) and autumn (r=0.45 [0.33 to 0.55], $p<0.001$) than in spring (r=0.23 [0.14 to 0.33], $p<0.001$) and summer (r=0.01 [-0.19 to 0.20], p=0.933) (Fig 1); and were substantially stronger in higher latitude locations (Hobart: r= 0.50 [0.40 to 0.59]; Canberra: 0.39 [0.28 to 0.49], both p< 0.001) than in lower latitude locations (Townsville: r=-0.06 [-0.18 to 0.07], p=0.380; Brisbane: r=-0.16 [-0.28 to -0.04], p=0.010) (Fig 2). These results suggest modifying effects of season and location on the relationship between UVR_{amb} and UVR_{per}.

Modification effects of season and location on the association between UVR_{amb} and UVR_{per}

A series of regression models were developed to examine the modifying effects of season and location (Table 3). All models were adjusted for participant characteristics. A positive association between UVR_{amb} and UVR_{per} was observed in all models. Assuming similar effects across seasons and locations (Model

1), every SED increase in UVR_{amb} was on average associated with a relative increase of 4% (RC=1.04, 95%CI: 1.03–1.05, p<0.001) in UVR_{per}. Models 2 and 3 show significant effect modification on this relationship of season and location, respecttively, which resulted in considerable increases in model R^2: 4% (from 38% to 42%) for season and 6% (from 38% to 44%) for location.

The strength of association between UVR_{amb} and UVR_{per} was significantly stronger in winter (RC= 1.02×1.05 = 1.07, $p<0.001$) and autumn (RC=1.02× 1.03=1.05, $p<0.01$) compared to that in summer (RC=1.02) (Model 2). It was significantly stronger in Canberra (RC= 1.02×1.04 = 1.06, $p<0.001$) and Hobart (RC= 1.02×1.05 = 1.07, $p<0.001$) than that in Townsville (RC=1.02) (Model 3).

Residual analysis on these models did not show evidence of homoscedasticity and multicollinearity. Similar results were derived when participants with estimated UVR_{amb} (rather than ARPANSA-provided UVR) were excluded from the analysis..

Seasonal and latitudinal effects on UEF_{per}

We next developed a multiple linear regression model to assess the seasonal and latitudinal effects on natural log-transformed UEF_{per}. After controlling for participant characteristics, compared to summer, UEF_{per} was significantly higher in other seasons, with a remarkable 7.10 (95%CI: 5.96 to 8.45, $p<0.001$) fold increase in winter. UEF_{per} in Hobart was 1.84 (1.60 to 2.11, p<0.001) times the value in Townville (Table 4). There was no significant difference in UEF_{per} between Townsville and Brisbane. This model explained 47% of the total variance in UEF_{per}, with a majority (61%) of the variance attributed to season, 12% to location and the remaining (27%) to all demographic variables. There was no material change when participants with estimated UVR_{amb} (rather than ARPANSA-provided UVR) were excluded from the analysis.

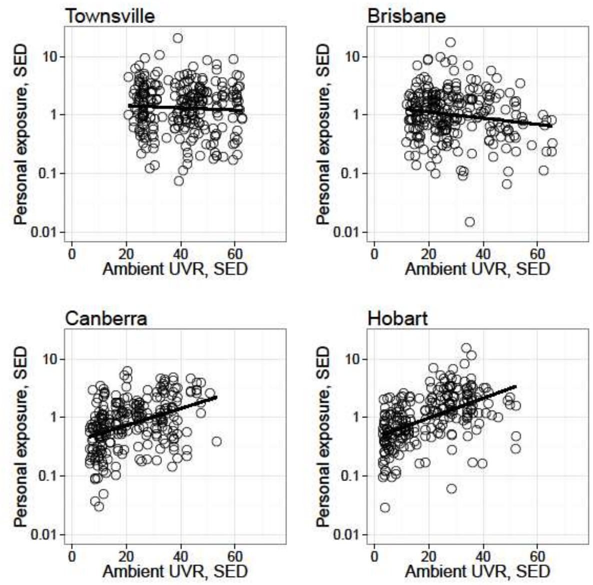

Fig 2 Correlations between ambient UVR (SED) and log-transformed personal UVR exposure (SED) by location.
UVR=ultraviolet radiation; SED=Standard Erythemal Dose.

Table 3 Independent and modifying effects of season and location on the relationship between ambient UVR and personal UVR exposure [a]

	Regression models		
	Model 1 (R^2=0.38) RC (95%CI)	Model 2 (R^2=0.42) RC (95%CI)	Model 3 (R^2=0.44) RC (95%CI)
UVR_{amb} (SED)	1.04 (1.03 to 1.05) ***	1.02 (1.00 to 1.03)*	1.02 (1.01 to 1.03) ***
Season of participation			
Summer (Dec-Feb) [b]	1.00	1.00	1.00
Autumn (Mar-May)	4.09 (3.17 to 5.28) ***	1.32 (0.62 to 2.81)	3.93 (3.08 to 5.01) ***
Winter (Jun-Aug)	6.68 (5.09 to 8.75) ***	1.58 (0.76 to 3.27)	6.65 (5.14 to 8.61) ***
Spring (Sep-Nov)	5.08 (4.19 to 6.17) ***	2.84 (1.34 to 6.02) **	4.85 (4.03 to 5.84) ***
Location			
Townsville (19°S) [b]	1.00	1.00	1.00
Brisbane (27°S)	1.20 (1.02 to 1.41) *	1.22 (1.05 to 1.43) *	0.86 (0.56 to 1.31)
Canberra (35°S)	1.17 (0.97 to 1.42)	1.28 (1.07 to 1.55) **	0.36 (0.24 to 0.54) ***
Hobart (43°S)	1.54 (1.26 to 1.90) ***	1.73 (1.41 to 2.13) ***	0.40 (0.27 to 0.60) ***
Modifying effect of season			
UVR_{amb} × Summer [b]	-	1.00	-
UVR_{amb} × Autumn	-	1.03 (1.01 to 1.05) **	-
UVR_{amb} × Winter	-	1.05 (1.03 to 1.07) ***	-
UVR_{amb} × Spring	-	1.01 (0.99 to 1.03)	-
Modifying effect of location			
UVR_{amb} × Townsville [b]	-	-	1.00
UVR_{amb} × Brisbane	-	-	1.00 (0.99 to 1.01)
UVR_{amb} × Canberra	-	-	1.04 (1.02 to 1.05) ***
UVR_{amb} × Hobart	-	-	1.05 (1.04 to 1.06) ***

Abbreviation: UVR_{amb}, ambient UVR dose; SED, Standard Erythemal Dose; RC, relative change; CI, confidence interval.
[a] All models were adjusted for participant characteristics (variables in Table 1). Model 1, no interaction included; Model 2, includes the interactions only between season and UVR_{amb}; Model 3, includes interaction only between location and UVR_{amb}.
[b] Referent group
T-test for regression coefficients * $p<0.05$; ** $p<0.01$; *** $p<0.001$

Discussion

Although a positive correlation (r=0.23, $p<0.001$) was observed between ambient UVR and personal UVR exposure, the relationship varied substantially across seasons and locations. The strongest correlations were for data from winter (r=0.50, $p<0.001$) and for higher latitudes (Hobart, r=0.50; Canberra, r=0.39, both $p<0.001$) when and where the UVR_{amb} is relatively low. In contrast, there was no significant correlation, or even slightly negative correlations for summer (r=0.01, $p>0.05$), and at low latitude locations (Townsville, rho=-0.06, p>0.05; Brisbane, r=-0.16, $p<0.05$). In the multiple regression analysis, a modifying effect was observed for both season and location: the strength of association between ambient UVR and person UVR exposure was significantly stronger in non-summer seasons (especially winter vs. summer) and at higher latitudes (Canberra and Hobart vs. Townsville). These data suggest that when it is very sunny, people may stay indoors more and therefore the association between ambient UVR and personal exposure diminishes. At an individual level, daily ambient UVR seems to provide quite poor estimation of the individual's exposure especially in summer and in tropical or subtropical environments.

Table 4 Effects of season and location on personal UVR exposure fraction (%) [a]

	RC (95%CI)	p-value
Season of participation		
Summer (Dec-Feb) [b]	1.00	-
Autumn (Mar-May)	3.84 (3.18 to 4.62)	<0.001
Winter (Jun-Aug)	7.10 (5.96 to 8.45)	<0.001
Spring (Sep-Nov)	4.54 (3.82 to 5.39)	<0.001
Location		
Townsville (19°S) [b]	1.00	-
Brisbane (27°S)	1.11 (0.97 to 1.28)	0.122
Canberra (35°S)	1.17 (1.01 to 1.36)	0.034
Hobart (43°S)	1.84 (1.60 to 2.11)	<0.001

Abbreviation: UVR, ultraviolet radiation; RC, relative change; CI, confidence interval.
[a] The model was adjusted for participant characteristics listed in Table 1. The dependent variable was natural log-transformed personal UVR exposure fraction.
[b] Referent group

Surprisingly, we found that the pattern of variation in UVR_{per} across seasons was very different from, or even opposite to, that of UVR_{amb}. For example, summer has the highest median UVR_{amb}, yet overall individuals received the lowest median UVR_{per} dose. Consistently, personal UVR exposure fraction (UEF_{per}) was found to be lowest in summer (1.1%) and highest in winter (7.1%). Regardless of location, winter compared with summer was on average associated with a much higher UEF_{per} (RC=7.1 (95%CI: 6.0 – 8.5)). These analyses provide further evidence of the modifying role that season has: it not only modifies the association between ambient UVR and personal UVR exposure at an individual level, but is also linked to a substantial change in the average personal UVR exposure fraction for comparisons across cities at a population level.

In this study, we observed an average personal UVR exposure fraction of 5%, which is similar to that previously described in other populations[9, 10]. The strong seasonal effect on this fraction has also been reported in other studies[28, 29]. In an earlier study in subtropical Australia, the personal exposure fraction in winter was found to be more than twice the fraction in summer (6.5% vs. 2.7%) [28]. Interestingly, a Danish study identified a much lower personal exposure percentage in winter (0.82%) than in summer (3.4%) [29]. Thus, both studies suggest a strong modifying effect of season on exposure behaviours, but in the opposite direction. In tropical or subtropical Australia, the UV Index often reaches the extreme level (11+) in summer months [30], and is commonly associated with high temperatures and humidity. These factors, combined with strong sun-safety campaigns aimed at reducing the incidence of skin cancer, may lead to sun avoidance in summer. On the contrary, residents of high latitude northern hemisphere climates may not be able to take advantage of any ambient UVR in winter due to extremes of cold and shortened day length.

The overall pattern of UVR_{per} by location was similar to the pattern in UVR_{amb}: Townsville had the highest UVR_{amb} and the highest UVR_{per}, and the lowest values for both occurred in Canberra. However, the pattern of locational variation differed markedly between seasons. When season was controlled, participants from Canberra (RC=1.2, 95%CI: 1.0–1.4) and Hobart (RC =1.8, 95%CI: 1.6–2.1) received significantly higher levels of UEF_{per} than those from Townsville. There may be location-specific factors, such as awareness and intensity of sun-safety campaigns that may have influenced individual sun exposure behaviours. While the latitudinal pattern in ambient UVR (the lower the latitude, the higher the UVR_{amb}) may roughly represent the pattern in personal exposure all year round, the latitudinal variation in UVR_{amb} is likely to be an overestimation of the latitudinal variation in UVR_{per}, due to the higher UEF_{per} at higher latitudes. Further, in summer, people living in lower latitude locations (where the ambient UVR is higher) appeared to receive less personal exposure than those living in higher latitude locations (Table 2). These findings should be considered in the interpretation of observed associations between ambient UVR (or latitude) with health outcomes.

As this study measured personal UVR by dosimetry, which measures only daily accumulated exposure to the wrist dosimeter, caution should be exercised in the interpretation of our findings in relation to health outcomes. Although we observed a much lower UVR_{per} dose in summer at lower latitudes, population vitamin D levels in the AusD Study and other studies have been shown to be highest in summer [28, 31, 32]. One explanation is that skin area exposed to UVR is strongly associated with increased vitamin D levels [33], and is much higher in summer versus winter. In any assessment of the health effects of UVR_{per} dose, it is therefore crucial to measure multiple factors such as personal UVR dose using a dosimeter, total skin area exposed, as well as the daily pattern of UVR exposure. Notwithstanding, this analysis increases the understanding of the important relationship between ambient UVR and personal UVR exposure in relation to season and latitude.

This analysis used data from the largest study to date involving personal UVR dosimetry (The AusD Study). The strengths of the study were the size of the sample (N=1002), the rolling, cross-seasonal recruitment, the 8 degrees of latitude separation between each of the study sites [23], and the objective measurement of personal UVR exposure using polysulphone dosimetry. The great majority of participants had at least 7 days' dosimeter data, enabling stable estimates of personal exposure. Ambient UVR data were also objectively measured by ARPANSA - the agency responsible for monitoring levels of ionising and non-ionising radiation throughout Australia. These unique features have enabled us to accurately and comprehensively assess the dose and fraction of personal UVR exposure in Australian adults in relation to ambient UVR by season and latitude.

Our findings may be subject to a number of limitations. First, this analysis was conducted with a cross-sectional sample with different participants recruited in different seasons. The number of summer participants was much smaller than the number in other seasons (Table 1), due to recruitment difficulties during the holiday season. Ultimately, a longitudinal investigation with the same participants over the course of a year may provide better insights into the modifying effect of season on the relationship between ambient UVR and personal exposure. Second, Australia is a unique country in terms of ambient UVR and UV-related health outcomes. For example, Australia has the highest skin cancer incidence in the world and the strongest sun protection campaigns, possibly limiting the generalizability of our study findings. Lastly, ambient UVR data were not available for Canberra and were estimated based on total solar irradiation data. This may have resulted in some measurement error and inconsistency of the data. However, no material changes were found by repeating the analyses with data from Canberra participants excluded.

Conclusions

This study has identified strong modifying effects of season and latitude on the relationship between ambient UVR and personal UVR exposure, at both individual and population levels. At an individual level, the strength of association between ambient UVR and personal UVR exposure appeared to be much stronger in temperate sites (versus the tropical site) and in autumn/winter (versus summer). At a population level, individuals received smaller fractions of the available ambient UVR in summer than in other seasons, especially if they lived in tropical/subtropical regions, because of very different patterns of personal UVR exposure. Ambient UVR may thus not be an accurate proxy indicator of UVR_{per}, and future studies that aim to use ambient UVR as a proxy measure should consider weighting their measure for the modifying effects of season and location.

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