BJD
British Journal of Dermatology

Estimating personal solar ultraviolet radiation exposure through time spent outdoors, ambient levels and modelling approaches*

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Linked Comment: P. O'Mahoney. Br J Dermatol 2022; **186**:207–208.

Summary

Background Evidence on validation of surrogates applied to evaluate the personal exposure levels of solar ultraviolet radiation (UVR) in epidemiological studies is scarce.
Objectives To determine and compare the validity of three approaches, including (i) ambient UVR levels, (ii) time spent outdoors and (iii) a modelling approach integrating the aforementioned parameters, to estimate personal UVR exposure over a period of 6 months among indoor and outdoor workers and in different seasons (summer/winter).
Methods This validation study was part of the European Commission-funded ICEPURE project and was performed between July 2010 and January 2011 in a convenience sample of indoor and outdoor workers in Catalunya, Spain. We developed linear regression models to quantify the variation in the objectively measured personal UVR exposure that could be explained, separately, by the ambient UVR, time spent outdoors and modelled UVR levels.
Results Our 39 participants – mostly male and with a median age of 35 years – presented a median daily objectively measured UVR of 0·37 standard erythemal doses. The UVR dose was statistically significantly higher in summer and for outdoor workers. The modelled personal UVR exposure and self-reported time spent outdoors could reasonably predict the variation in the objectively measured personal UVR levels (R^2 range 0·75–0·79), whereas ambient UVR was a poor predictor (R^2 = 0·21). No notable differences were found between seasons or occupation.
Conclusions Time outdoors and our modelling approach were reliable predictors and of value to be applied in epidemiological studies of the health effects of current exposure to UVR.

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Accepted for publication
13 August 2021

Funding sources
This work forms part of the ICEPURE project which was funded by the European Commission Framework Program 7 (grant no. 227020). Spanish Ministry of Economy and Competitiveness: FJCI-2017-33842 (M.T.-M) and RYC-2012-10995 (P.D.). Spanish Ministry of Science and Innovation: CEX2018-000806-S. Generalitat de Catalunya: CERCA Program.

Conflicts of interest
None to declare.

*Plain language summary available online

DOI 10.1111/bjd.20703

What is already known about this topic?

- Most studies evaluating health effects of solar ultraviolet radiation (UVR) have relied on surrogates to assess personal UVR exposure.
- However, the available evidence validating these surrogates is scarce.

What does this study add?

- In the present study, we evaluated and compared the validity of three approaches to estimate personal UVR exposure (objectively measured using a personal dosimeter), including (i) ambient UVR levels, (ii) time spent outdoors and (iii) a modelling approach, during different seasons among indoor and outdoor workers.
- Modelled UVR exposure and time outdoors could predict more than three-quarters of the variation in the objectively measured personal UVR (and are therefore of value to be applied in epidemiological studies of the health effects of UVR), whereas ambient UVR could predict only around one-fifth.
- Our findings support a major role of personal behaviour in determining personal UVR exposure.

Ultraviolet radiation (UVR) is a major environmental hazard which also has health benefits.[1] Sunburn, photokeratitis and immunosuppression are among the short-term adverse effects of UVR exposure while skin cancers, skin photoageing and possibly cataracts are among adverse long-term effects.[2–5] The main beneficial effect of UVR is the cutaneous production of vitamin D which, among other possible benefits, is essential for calcium metabolism and the maintenance of the musculoskeletal system.[2–5]

The sun is the main source of UVR exposure at population level.[3] Personal exposure to solar UVR is a function of ambient UVR and behaviour,[2,6–8] which includes time spent outdoors in the sun, risky behaviours (e.g. sunbathing), photoprotection (e.g. sunscreen use, clothing) and holiday habits.[6] Epidemiological studies on the association between UVR exposure and long-term health outcomes have mainly relied on surrogates, such as ambient UVR (or latitude as its proxy) and self-reported time outdoors, to assess personal UVR exposure. However, in a previous simulation study[6] across six northern, central and southern European cities, we showed that each surrogate, when used alone, could only explain less than a quarter of the variation in personal UVR exposure. Our previous study also revealed that within-city variation (where ambient UVR is similar) was three times greater than the variation between cities, indicating the critical role of individual behaviour in exposure to UVR. These findings highlighted the need to develop more comprehensive measures integrating both ambient UVR and individual behaviour to assess personal exposure to UVR. In this context, modelling approaches that combine ambient UVR and individual behaviour to assess personal exposure to UVR have potential, despite having been rarely used so far in large-scale epidemiological studies. To the best of our knowledge, a limited number of occupational studies have developed models to estimate individual long-term UVR exposure of outdoor workers.[9,10]

To date, the available evidence evaluating the validity of the aforementioned surrogates of UVR exposure is still limited, with few studies validating UVR exposure modelling approaches.[9,11–13] Moreover, studies comparing validity of different surrogates of long-term UVR exposure are nonexistent. Previous studies have focused mainly on specific exposure groups such as indoor workers, outdoor workers, children or adolescents for limited duration (from 1 day to a few months) without comparing the validity of surrogates in different subpopulations.[10,14–22] Accordingly, the aim of this study was to determine and compare the validity of self-reported time spent outdoors, ambient UVR and modelled personal UVR levels in estimating current personal UVR exposure among outdoor and indoor workers and during summer and winter.

Materials and methods

This study was conducted in the context of the 'Impact of Climatic and Environmental factors on Personal Ultraviolet Radiation Exposure and human health' (ICEPURE) project funded by the European Commission (FP7, grant no. 227020).

Study setting and population

Our study included 39 participants, consisting of 18 indoor workers and 21 outdoor workers, living and working in Barcelona province, Catalonia, Spain (2010–11). This province (41·3850° N, 2·1733° E) is situated in the northeast of the Iberian peninsula. It covers an area of approximately 7726 km^2 including a Mediterranean coastline with a population of

approximately 5·7 million inhabitants (2020).[23] It has a Mediterranean climate with hot and dry summers and mild winters with precipitation occurring predominantly during spring and autumn months.[23,24]

We recruited a convenience sample of office workers (as indoor workers) and farmers (as outdoor workers) as described in Materials and Methods S1 (see Supporting Information). All participants gave written informed consent before enrolment. Ethics approval (nos 2009/3692/I and 2008/3017/I) was obtained from the Clinical Research Ethical Committee of the Parc de Salut MAR, Barcelona, Spain, to carry out this study.

Data collection

This study was performed over 6 months from 1 July 2010 until 10 January 2011.

Objectively measured personal ultraviolet radiation exposure

Personal erythemally effective UVR exposure was measured objectively with a personal electronic dosimeter (SunSaver),[25–27] which participants wore on their left wrist over any clothing, every day from 7:00 till 21:00. The SunSaver was produced by the Department of Dermatology, Bispebjerg Hospital, University of Copenhagen, Denmark.[28] More information about the SunSaver is provided in Materials and Methods S1. The wrist was selected because this position is better tolerated during a long-term study.[21,23–28] Furthermore, the UVR doses received on the wrist have been shown to correlate well (50% of the dose) with those received on the top of the head.[29] The personal SunSaver recorded time-stamped (every 5 min) erythemally weighted UVR exposures (Figure 1) measured in standard erythemal doses (SEDs). The participants were instructed to behave as they usually did on a regular day and to remove the SunSaver when swimming or taking a shower/bath.

Figure 1 The personal electronic ultraviolet radiation (UVR) dosimeter (SunSaver) used to monitor time-stamped UVR doses. It comprises a UVR sensor, a data logger and a battery mounted together with a digital watch in the form of a wristwatch.

Ambient ultraviolet radiation

Ambient UVR was obtained through continuous measurement of solar UVR using modified versions of the SunSaver housed in two unshaded UVR ground stations about 50-km apart, one in Torrelavit, where most outdoor workers were living (coordinates: 41·43904, 1·74228), and the other in Barcelona city, where most indoor workers were living (coordinates: 41·38522, 2·19421).

Questionnaire data

Data on sociodemographic characteristics and self-reported time spent outdoors were obtained through two types of questionnaires (see Materials and Methods S1 for further details). The participants answered Questionnaire 1 by telephone interview at the end of each month during the study period (i.e. this questionnaire was implemented six times for each participant). Through this questionnaire, we obtained data on the average time spent outdoors on working and non-working days and holidays, as well as holiday duration and location during the corresponding month. Questionnaire 2 was filled in and returned by the participants by post, 1 month after the end of the study. It enquired about the aforementioned factors included in Questionnaire 1 together with sun-protective and risky behaviours during the 6-month study period.

Ultraviolet radiation exposure modelling

We applied the modelling framework developed by Diffey,[7] which was used in our previous simulation study,[6] to estimate the UVR exposures of participants during the course of the study. This modelling framework integrates ambient UVR levels with time spent outdoors, an exposure fraction, and hours of daylight to estimate the personal exposure to UVR. We developed two separate modelling estimates based on the time spent outdoors obtained from Questionnaires 1 and 2. Further details on this modelling approach are presented in Materials and Methods S1.

Statistical analysis

Nonparametric tests were used to generate summary statistics. Univariate regression models were developed using the log-transformed measured personal UVR dose as the outcome and each of ambient UVR levels, self-reported time spent outdoors and modelled personal UVR exposure as the predictor. We log-transformed the outcome variable (measured personal UVR exposure) in order to obtain approximate normality and linearity. The coefficient of determination (R^2) was used to assess the variation in the measured personal UVR exposure explained by each surrogate. We then stratified the regression analyses based on occupation type (indoor vs. outdoor workers) and season (winter vs. summer). The season variable was constructed by grouping July, August and September as the summer months and October, November, December and

Table 1 Description of study variables, participant characteristics and exposure characteristics, stratified by occupation type

Variable	All N = 39	Indoor workers N = 18	Outdoor workers N = 21	P-value
Age, years: median (IQR)	35 (15)	29 (7)	42 (9)	< 0·01
Sex, females, n (%)	15 (38·5)	13 (72)	2 (9·5)	< 0·01
Education, n (%)				
High school	4 (10)	0 (0)	4 (19)	< 0·01
Technical school	16 (41)	1 (5·5)	15 (71)	
University and/or higher	19 (49)	17 (94)	2 (9·5)	
Ambient UVR, SEDs: median (IQR)[a]	25·46 (11·44)	18·23 (6·66)	28·78 (5·66)	< 0·01
Objectively measured personal UVR exposure, SEDs: median (IQR)[a]	0·37 (1·22)	0·08 (0·10)	1·32 (0·93)	< 0·01
Summer	1·85 (2·39)	0·98 (0·82)	2·91 (1·76)	< 0·01
Winter	0·51 (1·23)	0·19 (0·25)	1·30 (1·18)	< 0·01
Objectively measured personal UVR exposure during high-risk hours, SEDs: median (IQR)[a]	0·27 (0·30)	0·11 (0·09)	0·20 (0·30)	< 0·01
Self-reported time spent outdoors, hours: median (IQR)[a]				
Based on Questionnaire 1[b]	4·93 (4·60)	2·25 (1·07)	6·92 (2·12)	< 0·01
Based on Questionnaire 2[b]	5·65 (5·62)	1·85 (1·07)	7·40 (1·90)	< 0·01
Modelled personal UVR exposure, SEDs: median (IQR)[a]				
Based on Questionnaire 1[b]	1·22 (1·92)	0·71 (0·21)	2·59 (0·92)	< 0·01
Based on Questionnaire 2[b]	1·30 (1·90)	0·73 (0·22)	2·61 (0·90)	< 0·01

P-values correspond to a permutation test, for equal medians in the case of continuous variables, or for equal distribution in the case of categorical variables. IQR, interquartile range; SEDs, standard erythemal doses; UVR, ultraviolet radiation, [a]Daily average measurement; [b]see Materials and Methods S1.

January as the winter months. Stata for windows version 14 was used for conducting all analyses (StataCorp, College Station, TX, USA). A P-value of less than 0·05 was considered as statistically significant.

Results

The sociodemographic characteristics of the study participants, combined and separately for indoor and outdoor workers, are shown in Table 1. The median age of the participants was 35 years [interquartile range (IQR) 15 years], of whom 24 (61·5%) were male. The median (IQR) daily ambient UVR levels and daily measured personal UVR exposure were, respectively, 25·46 (11·44) and 0·37 (1·22) SEDs for all participants combined. Following stratification by season, the median (IQR) of daily measured personal UVR exposure was 1·85 (2·39) (SEDs) in summer and 0·51 (1·23) (SEDs) in winter ($P < 0·01$). As expected, the median (IQR) measured personal UVR exposure in outdoor workers was significantly higher than that of indoor workers, both for the entire day [SEDs: 1·32 (0·93) for outdoor workers and 0·08 (0·10) for indoor workers] and during high-risk hours (12:00–15:00) [SEDs: 0·20 (0·30) for outdoor workers and 0·11 (0·09) for indoor workers] (Table 1). A similar pattern was also observed for self-reported time outdoors and modelled personal UVR exposure (Table 1).

The regression analyses showed that while modelled personal UVR exposure ($R^2 = 0·77$) and self-reported time

Table 2 Coefficients of determination (R^2) for univariate regression models of the long-term exposure between modelled personal UVR exposure, self-reported time spent outdoors and ambient UVR against log-transformed objectively measured personal UVR exposure – for the overall study population, and separately for occupation type and season

Averaged semi-annual exposure	Overall[a] (N = 37)	Indoor workers[a] (N = 20)	Outdoor workers[a] (N = 17)	Summer[a] (N = 35)	Winter[a] (N = 36)
Questionnaire 1[b]					
Modelled personal exposure	0·77***	0·39**	0·26*	0·65***	0·58***
Self-reported time spent outdoors	0·75***	0·15	0·12	0·46***	0·43***
Ambient UVR	0·21**	0·02	0·0002	0·20**	0·18**
Questionnaire 2[b]					
Modelled personal exposure	0·77***	0·38**	0·25*	0·63***	0·58***
Self-reported time spent outdoors	0·79***	0·12	0·17	0·40***	0·41***
Ambient UVR	0·21**	0·02	0·0002	0·20**	0·18*

P-values: * < 0·05, ** < 0·01, *** < 0·001. UVR, ultraviolet radiation, [a]All values are R^2; [b]see Materials and Methods S1.

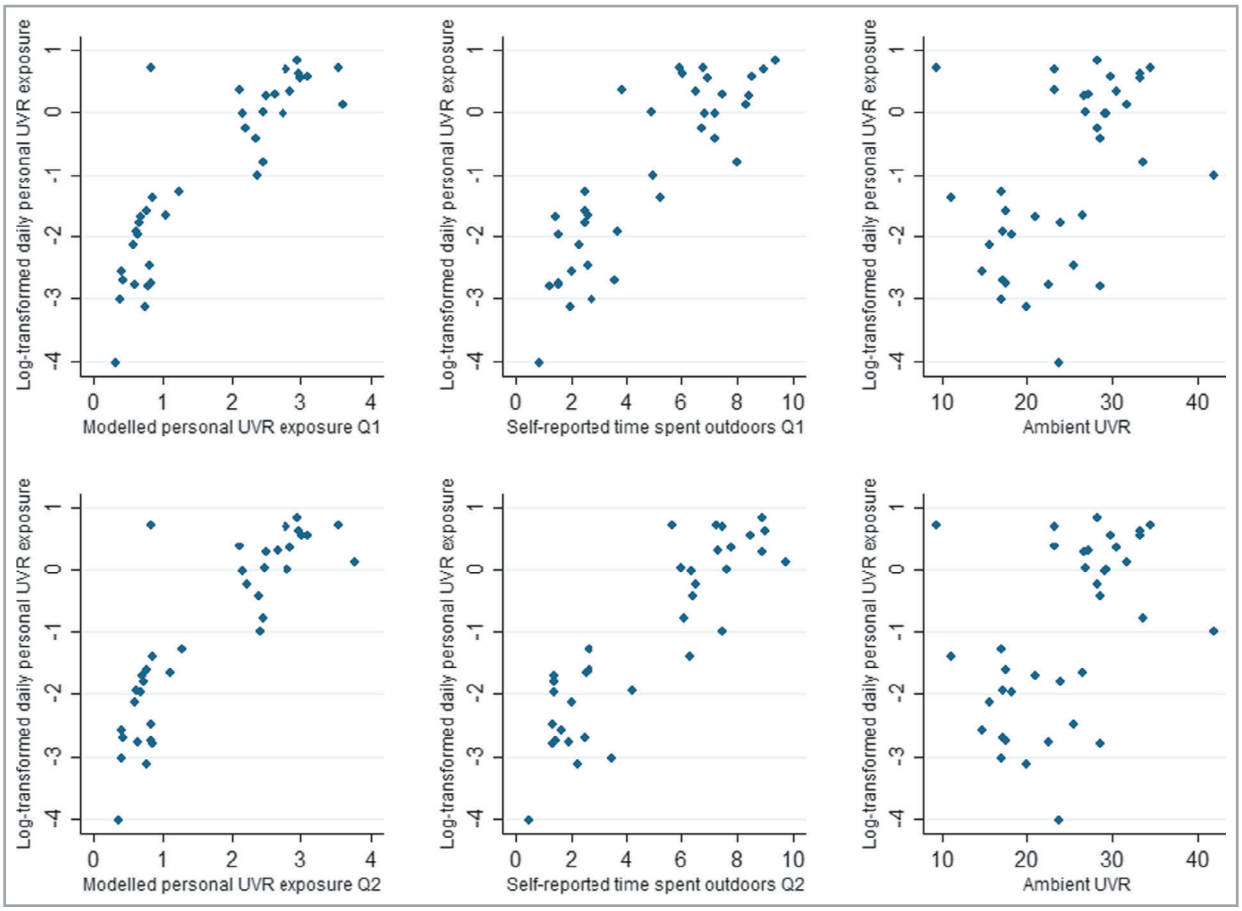

Figure 2 Scatterplots of the daily averages of log-transformed measured personal ultraviolet radiation (UVR) exposure (standard erythemal doses, SEDs) against each of the modelled personal UVR exposures (SEDs), self-reported time spent outdoors (hours) and ambient UVR levels (SEDs) for both questionnaires (see Materials and Methods S1).

outdoors (R^2 = 0·75 and 0·79 for Questionnaires 1 and 2, respectively) could reasonably predict measured personal UVR exposure, ambient UVR was a relatively poor predictor (R^2 = 0·21) (Table 2). Figure 2 shows scatterplots of these associations in which we mostly noted two different clusters of observations, which could indicate differences between the indoor and outdoor workers or between the summer and winter seasons. Consequently, we performed the regressions stratified by two groups of occupation and two seasons.

The regression analyses stratified by occupation showed that modelled personal UVR exposure was the best predictor of measured personal UVR exposure among indoor workers (R^2 = 0·39 and 0·38 for Questionnaires 1 and 2, respectively), whereas modelled personal UVR exposure explained less variation in measured personal UVR exposure for outdoor workers but was still the best predictor (R^2 = 0·26 and R^2 = 0·25 for Questionnaires 1 and 2, respectively) (Table 2). Furthermore, the regression analyses stratified by occupation showed lower R^2 than when occupations were combined. This was expected as, within groups, the differences in time spent outdoors and consequently in UVR levels between workers were lower and more difficult to predict.

The results of the regression analyses stratified by season (summer/winter) showed very similar coefficients of determination (R^2) for each surrogate for winter and summer, as well as between questionnaires (Table 2). We observed that modelled personal UVR exposure was the best predictor of measured personal UVR exposure in summer (R^2 = 0·65 or 0·63 for Questionnaires 1 and 2, respectively) and winter (R^2 = 0·58 for both questionnaires). Variation of measured personal UVR exposure explained by self-reported time outdoors was slightly lower, with R^2 = 0·46 or 0·40 for summer and 0·43 or 0·41 for winter, based on Questionnaires 1 and 2, respectively. On the other hand, the variation of measured personal UVR exposure explained by the ambient UVR was the lowest among the evaluated surrogates (modelled personal UVR exposure, self-reported time outdoors and ambient UVR) (R^2 = 0·20 for summer and R^2 = 0·18 for winter, based on Questionnaires 1 and 2, respectively).

Discussion

To the best of our knowledge, this study is one of the first to (i) validate a modelling approach to assess personal UVR

exposure; (ii) compare the validity of modelled personal UVR exposure, self-reported time spent outdoors and ambient UVR to assess personal UVR exposure; and (iii) compare the validity of this combination of surrogates of UVR exposure among indoor and outdoor workers as well as across different seasons (summer/winter). Moreover, the 6-month duration of the study is, to our knowledge, one of the longest continuous periods among the studies assessing the validity of these surrogates, enabling us to address seasonal variations in personal behaviour. We found that individually, modelled personal UVR exposure and self-reported time spent outdoors could predict more than three-quarters of the variation in the measured personal UVR levels, whereas ambient UVR levels could predict only around one-fifth of this variation. When we stratified our analyses by season and occupation, we observed similar predictive capability of each surrogate between winter and summer as well as between indoor and outdoor workers.

We found that modelled personal UVR exposure (based on a combination of self-reported time spent outdoors and ambient UVR levels) and self-reported time outdoors were equally good and better predictors of measured personal UVR exposure than ambient UVR. Previous studies[9,11–13] exploring UVR exposure modelling approaches include an algorithm (Genesis-UV) to retrospectively estimate lifetime occupational exposure, and a 3D numeric model (SimUVex/SimUVex v2) that estimates site-specific erythemal doses received at an individual level; therefore, it is not possible to compare their findings with ours. However, our observation that self-reported time outdoors and a modelling approach could better predict measured personal UVR exposure compared with the ambient UVR is in line with our previous simulation study,[6] which showed that ambient UVR alone could explain only 16% of the variability in the annual measured personal UVR exposure whereas self-reported time spent outdoors along with ambient UVR increased the explained variation to 40%. Furthermore, previous studies[6,30] have shown a larger within-city (where ambient UVR is similar) variation in personal UVR exposure compared with between-city variation, supporting a more important role of personal behaviour than ambient UVR in determining personal exposure to UVR.

Moreover, previous studies[9,10,14,16,20,22,31] exploring ambient UVR as a surrogate of measured personal UVR exposure over a period of 7 days to 7 months have shown a predictive capability (R^2) ranging from 0·02 to 0·74, which is in line with our findings for this surrogate (R^2 = 0·21). Studies exploring the ability of the self-reported time spent outdoors to predict measured personal UVR exposure were performed over a period of 4–26 days and reported a predictive capability ranging between 0·03 and 0·74,[15–17,19–21] while for this surrogate our observed R^2 ranged from 0·75 to 0·79.

We did not observe any notable difference between the two questionnaires that we used to obtain information on time spent outdoors. This observation could indicate that the same data validity can be obtained by collecting data monthly (as in Questionnaire 1) or 1 month after finishing the 6-month-long study (as in Questionnaire 2). This finding can have important implications in reducing the burden of data collection in future epidemiological studies of the health effects of UVR exposure.

In our study, outdoor workers received approximately 16 times more erythemal UVR than indoor workers, as recorded by the SunSavers. Such higher exposure is expected, especially when indoor workers probably spent time outdoors only later during the day, when ambient UVR was low. Furthermore, as expected, our measured personal UVR exposure levels in summer were higher than those in winter. Moreover, our observed predictive capability of different surrogates across strata of occupation (indoor vs. outdoor) and season (winter vs. summer) were comparable. However, our stratified analyses resulted in smaller coefficients of determination (R^2), maybe because the variation due to important factors determining personal UVR, namely occupation and season, were effectively removed from these analyses.

One strength of this study was the high compliance rate, especially considering our relatively long study period. A total of 94·9% of questionnaires were returned along with data from 94·9% of the SunSavers. Low compliance has been a problem in previous studies of the validity of the surrogates of exposure to UVR.[15,17,19] Furthermore, our study included both rural (outdoor workers) and urban (indoor workers) populations. Also, the continuous study period of 6 months was sufficient to capture most seasonal behavioural variability.

Our study also faced some limitations. Our nonrandom convenience sampling as well as differences in cultures, sun habits and personal behaviours could limit the generalizability of our findings to other populations and settings. Moreover, considering that our study area was relatively small, we did not have a large variation in ambient UVR levels, which could have resulted in our underestimation of the proportion of the variation in the personal UVR exposure that could be explained by the variation in ambient UVR levels, especially in indoor workers who spent much of their time indoors. Furthermore, our modest sample size could have limited our statistical power to detect patterns, especially for our subanalysis of indoor/outdoor workers. The model we used[7] to assess exposure to UVR assumes that outdoor exposure is symmetrical around the solar noon, but this assumption is less likely to be true for indoor workers, whose exposure more likely occurs early and late in the day. Moreover, the absence of differences between the questionnaires could have been biased by Questionnaire 2 being tied to having undertaken Questionnaire 1. Additionally, the SunSavers were not completely waterproof, leading to some loss of data. Finally, we did not ask about high-risk hours outdoors in our questionnaire and, we measured it only objectively. This aspect could be added to questionnaires in future epidemiological studies.

In conclusion, in our sample of adult indoor and outdoor workers, modelled personal UVR exposure and self-reported time outdoors could equally predict over three-quarters of the variation in our objectively measured personal UVR exposure over a period of 6 months. In contrast, ambient UVR was a relatively poor predictor of the variation in the measured

personal UVR exposure. We did not observe major differences in the relative validity of each surrogate to predict measured personal UVR exposure between indoor and outdoor workers or between summer and winter. Moreover, we did not find any notable benefit from obtaining monthly data on self-reported time outdoors compared with a single acquisition 1 month after the study. These findings could enable future epidemiological studies of the health effects of long-term UVR exposure to optimize their assessment of this exposure. At the same time, our findings highlight, again, the critical role of individual behaviour in determining personal exposure to UVR. Further multicentric studies are required to replicate our findings in other settings with different cultures and climates, relying on a larger sample size as well as different study areas to maximize the variation in personal behaviour as well as ambient UVR level.

Acknowledgments

This work forms part of the ICEPURE project which was funded by the European Commission Framework Program 7 (grant no. 227020). We are thankful to Mr Juan R. Moreta from the State Meteorological Agency (AEMET) for supplying us with the ambient UVR data. M.T.-M. is funded by a Juan de la Cierva fellowship (FJCI-2017-33842) and P.D. is funded by a Ramón y Cajal fellowship (RYC-2012-10995); both are awarded by the Spanish Ministry of Economy and Competitiveness. We acknowledge support from the Spanish Ministry of Science and Innovation through the 'Centro de Excelencia Severo Ochoa 2019–2023' Program (CEX2018-000806-S), and support from the Generalitat de Catalunya through the CERCA Program. The sponsor or funding organizations had no role in the design or conduct of this research, and all the authors declare that they have no conflict of interests.

References

1 Alfredsson L, Armstrong BK, Allan Butterfield D *et al.* Insufficient sun exposure has become a real public health problem. *Int J Environ Res Public Health* 2020; **17**:1–15.

2 Lucas RM, Yazar S, Young AR *et al.* Human health in relation to exposure to solar ultraviolet radiation under changing stratospheric ozone and climate. *Photochem Photobiol Sci* 2019; **18**:641–80.

3 Public Health England. Report RCE-30. Ultraviolet radiation, vitamin D and health: report of the independent Advisory Group on Non-ionising Radiation. March 2017; 10–14. Available at: https://www.gov.uk/government/publications/ultraviolet-radiation-and-vitamin-d-the-effects-on-health (last accessed 12 September 2021).

4 van der Rhee H, de Vries E, Coomans C *et al.* Sunlight: for better or for worse? A review of positive and negative effects of sun exposure. *Cancer Res Front* 2016; **2**:156–83.

5 Vecchia P, Hietanen M, Stuck BE *et al.* Protecting workers from ultraviolet radiation. International Commission on Non-Ionizing Radiation Protection, in collaboration with: International Labour Organization and World Health Organization, 2007; 12–29. Available at: http://www.who.int/uv/publications/Protecting_Workers_UV_pub.pdf (last accessed 12 September 2021).

6 Dadvand P, Basagaña X, Barrera-Gómez J *et al.* Measurement errors in the assessment of exposure to solar ultraviolet radiation and its impact on risk estimates in epidemiological studies. *Photochem Photobiol Sci* 2011; **10**:1161–8.

7 Diffey B. A behavioral model for estimating population exposure to solar ultraviolet radiation. *Photochem Photobiol* 2008; **84**:371–5.

8 Schmalwieser AW, Siani AM. Review on nonoccupational personal solar UV exposure measurements. *Photochem Photobiol* 2018; **94**:900–15.

9 Wittlich M, Westerhausen S, Kleinespel P *et al.* An approximation of occupational lifetime UVR exposure: algorithm for retrospective assessment and current measurements. *J Eur Acad Dermatology Venereol* 2016; **30**:27–33.

10 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.

11 Vernez D, Milon A, Vuilleumier L *et al.* A general model to predict individual exposure to solar UV by using ambient irradiance data. *J Expo Sci Environ Epidemiol* 2015; **25**:113–18.

12 Cheng W, Brown R, Vernez D, Goldberg D. Estimation of individual exposure to erythemal integral calculation. *Sensors (Basel)* 2020; **20**:4068.

13 Religi A, Moccozet L, Farahmand M *et al.* SimUVEx v2: a numeric model to predict anatomical solar ultraviolet exposure. Proceedings of the 2016 SAI Computing Conference (13–15 July 2016, London, UK). *SAI* 2016; **2016**:1344–8.

14 Cahoon EK, Wheeler DC, Kimlin MG *et al.* Individual, environmental, and meteorological predictors of daily personal ultraviolet radiation exposure measurements in a United States cohort study. *PLoS One* 2013; **8**:e54983.

15 Cargill J, Lucas RM, Gies P *et al.* Validation of brief questionnaire measures of sun exposure and skin pigmentation against detailed and objective measures including vitamin D status. *Photochem Photobiol* 2013; **89**:219–26.

16 Chodick G, Kleinerman RA, Linet MS *et al.* Agreement between diary records of time spent outdoors and personal ultraviolet radiation dose measurements. *Photochem Photobiol* 2008; **84**:713–18.

17 Dwyer T, Blizzard L, Gies PH *et al.* Assessment of habitual sun exposure in adolescents via questionnaire – a comparison with objective measurement using polysulphone badges. *Melanoma Res* 1996; **6**:231–9.

18 Gies P, Roy C, Toomey S *et al.* Solar UVR exposures of primary school children at three locations in Queensland. *Photochem Photobiol* 1998; **68**:78–83.

19 Glanz K, Gies P, O'Riordan DL *et al.* Validity of self-reported solar UVR exposure compared with objectively measured UVR exposure. *Cancer Epidemiol Biomarkers Prev* 2010; **19**:3005–12.

20 Køster B, Søndergaard J, Nielsen JB *et al.* The validated sun exposure questionnaire: association of objective and subjective measures of sun exposure in a Danish population-based sample. *Br J Dermatol* 2017; **176**:446–56.

21 Thieden E, Ågren MS, Wulf HC. Solar UVR exposures of indoor workers in a working and a holiday period assessed by personal dosimeters and sun exposure diaries. *Photodermatol Photoimmunol Photomed* 2001; **17**:249–55.

22 Kovačić J, Wittlich M, Malte S, Macan J. Personal ultraviolet radiation dosimetry and its relationship with environmental data: a longitudinal pilot study in Croatian construction workers. *J Photochem Photobiol B Biol* 2020; **207**:111866.

23 Statistical Institute of Catalonia. Population on 1 January. Provinces. 2020. Available at: https://www.idescat.cat/pub/?id=aec&n=245&lang=es (last accessed 28 September 2021).

24 Council of Europe. Barcelona, Spain – Intercultural City. 2018. Available from: https://www.coe.int/en/web/interculturalcities/barcelona (last accessed 27 September 2021).
25 Bodekær M, Harrison GI, Philipsen P *et al.* Personal UVR exposure of farming families in four European countries. *J Photochem Photobiol B Biol* 2015; **153**:267–75.
26 Heydenreich J, Wulf HC. Miniature personal electronic UVR dosimeter with erythema response and time-stamped readings in a wristwatch. *Photochem Photobiol* 2005; **81**:1138–44.
27 Heydenreich J, Wulf HC. Personal electronic UVR dosimeter measurements: specific and general uncertainties. *Photochem Photobiol Sci* 2019; **18**:1461–70.
28 Thieden E, Philipsen PA, Heydenreich J, Wulf HC. UV radiation exposure related to age, sex, occupation, and sun behavior based on time-stamped personal dosimeter readings. *Arch Dermatol* 2004; **140**:197–203.
29 Thieden E, Ågren MS, Wulf HC. The wrist is a reliable body site for personal dosimetry of ultraviolet radiation. *Photodermatol Photoimmunol Photomed* 2000; **16**:57–61.
30 Lucas R, McMichael T, Smith W, Armstrong B. Solar ultraviolet radiation: global burden of disease from solar ultraviolet radiation. *Environmental Burden of Disease Series*, no. 13. Geneva: World Health Organization, Public Health and the Environment, 2006.
31 Sun J, Lucas RM, Harrison S *et al.* The relationship between ambient ultraviolet radiation (UVR) and objectively measured personal UVR exposure dose is modified by season and latitude. *Photochem Photobiol Sci* 2014; **13**:1711–18.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Materials and Methods S1 Estimating personal solar ultraviolet radiation exposure through time spent outdoors, ambient levels and modelling approaches: Study setting and population; Data collection; Questionnaires.