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PAPER

Measurement errors in the assessment of exposure to solar ultraviolet radiation and its impact on risk estimates in epidemiological studies†‡

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To date, many studies addressing long-term effects of ultraviolet radiation (UVR) exposure on human health have relied on a range of surrogates such as the latitude of the city of residence, ambient UVR levels, or time spent outdoors to estimate personal UVR exposure. This study aimed to differentiate the contributions of personal behaviour and ambient UVR levels on facial UVR exposure and to evaluate the impact of using UVR exposure surrogates on detecting exposure-outcome associations. Data on time-activity, holiday behaviour, and ambient UVR levels were obtained for adult (aged 25–55 years old) indoor workers in six European cities: Athens (37°N), Grenoble (45°N), Milan (45°N), Prague (50°N), Oxford (52°N), and Helsinki (60°N). Annual UVR facial exposure levels were simulated for 10 000 subjects for each city, using a behavioural UVR exposure model. Within-city variations of facial UVR exposure were three times larger than the variation between cities, mainly because of time-activity patterns. In univariate models, ambient UVR levels, latitude and time spent outdoors, each accounted for less than one fourth of the variation in facial exposure levels. Use of these surrogates to assess long-term exposure to UVR resulted in requiring more than four times more participants to achieve similar statistical power to the study that applied simulated facial exposure. Our results emphasise the importance of integrating both personal behaviour and ambient UVR levels/latitude in exposure assessment methodologies.

Introduction

Ultraviolet radiation (UVR) is a major environmental hazard but also has beneficial effects.[1] The sun is the main source of UVR.[2,3] The skin and the eyes are at the greatest risk but UVR also modulates immunity, the significance of which is less clear.[1] The main known beneficial effect of UVR exposure is the production of vitamin D in the skin. Vitamin D is essential in calcium metabolism and for the maintenance of the skeletal system.[1]

The effects of UVR exposure on health can be categorised as short-term (*e.g.* immunosuppression, sunburn, and photokeratitis) and long-term (*e.g.* skin cancers, skin photoaging, and cataract) effects.[1] Many epidemiological studies addressing long-term effects of UVR exposure have used ecologic (area-based data on both outcome and exposure) or semi-ecologic (personal-based data on outcome and area-based data on exposure) designs and they have mainly relied on a range of surrogates like the latitude of the city of residence, ambient UVR levels, or questionnaire-based data on time spent outdoors or sun habits in order to estimate the UVR exposure.[1,4]

Ambient UVR varies by solar altitude, atmospheric attenuation, cloud cover, altitude, and albedo (surface reflection).[5] Solar altitude itself is a function of latitude, season, and time of day. Personal UVR exposure depends not only on ambient UVR levels but also on personal behaviour.[1,5–8] This includes time spent outdoors (*i.e.* frequency of exposure), timing of exposure (*i.e.* intensity of exposure, considering that about half of daily ambient levels occurs within 3–4 h around the solar noon[5]), attitude toward sun exposure (*e.g.* walking or eating in shade *vs.* under the sun), sun risky behaviours (*e.g.* sunbed use and sunbathing), sun protection behaviours (*e.g.* use of sunscreen, sunglasses, and clothing), and holiday habits (*e.g.* holiday duration and destinations).

The available evidence on objectively measured personal UVR exposures is scarce[9] and is mostly based on rather small sample sizes within specific exposure groups for a short period.[7,10–16] Two recent studies relying on personal UVR monitoring among small samples of indoor workers (285 and 164 participants) in Denmark have reported wide ranges of annual UVR exposure among

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their study participants (17–841 standard erythema dose (SED)[7] and 36–663 SED[8]). These large within-population variations, in conditions where the participants are exposed to almost the same ambient UVR levels, would indicate that personal behaviour has a considerable impact on UVR exposure. Comparing within-population and between-population variations in UVR exposure could be an indirect way of separating the relative impacts of personal behaviour and ambient UVR levels on UVR exposure. A more direct way of performing this differentiation would be to obtain objective measures of personal UVR exposure (*e.g.* by using personal monitors) and then to investigate how much of the variation in these measures can be explained by indicators of personal behaviour, ambient levels, *etc.* This differentiation is important because it can be employed to evaluate the exposure measurement errors and the effects of these errors on reported exposure-outcome associations that were derived using exposure surrogates like ambient UVR levels and latitude. In addition, this information can be used to fortify the design of new studies dealing with long-term effects of UVR exposure. The available evidence on the quantification of the relative importance of personal behaviour and ambient UVR levels on personal exposure is scarce, mostly because of practical limitations in measuring personal UVR exposure at a population level. Modelling and simulation can be useful alternatives to explore these and to provide helpful insights into the possible effects of ignoring within-population variations, in the context of health studies.[17]

Relying on survey-based data on time-activity and holiday destinations together with ambient UVR levels, we performed a simulation study aimed to differentiate the contributions of personal behaviour and ambient UVR levels on facial UVR exposure and to evaluate impact of using UVR exposure surrogates on the hypothetical exposure-outcome associations among the populations of six European cities at different latitudes.

Materials and methods

We used data on time-activity, holiday behaviour, and ambient UVR levels for six European cities – Athens, Grenoble, Milan, Prague, Oxford, and Helsinki – as inputs to a behavioural UVR exposure model to simulate annual facial UVR exposure levels for the population of each city. We then quantified the exposure measurement error due to use of surrogates of UVR exposure and its impact on the risk estimates in two hypothetical exposure-outcome associations.

Data sources

1 Study populations. The simulation was carried out for the populations of indoor workers in six European cities, namely Athens (37°N 23°E), Grenoble (45°N 5°E), Milan (45°N 9°E), Prague (50°N 14°E), Oxford (52°N 1°W), and Helsinki (60°N 24°E) during 1997.

2 Time-activity data. Data on time-activity patterns was obtained from the European study Expolis (http://www.ktl.fi/expolis/index.php). Expolis aimed to compare patterns of exposure to ambient air pollution among the populations of our included cities using a sample of randomly selected adults (25–55 years old) from the corresponding populations.[18] It used a time-microenvironment-activity-diary (TMAD) to estimate the time that the participants spend in various microenvironments and activities. Each participant was asked to record the microenvironment/activity category for every 15 min of two working days during autumn 1996 to winter 1998. For our study we used the sum of time spent on walk/bike, home out, work out and other out as the quantification of time spent outdoors. A total of 1091 TMAD records were available in Expolis for these six cities. We excluded those who worked more than four hours per day outdoors[16] (36 subjects). We also excluded subjects with no time spent outdoors from the dataset (99 subjects). This was because the Expolis data was limited to time-activity during two working days and thus 'no time spent outdoors' was not necessarily generalisable to the whole year for those subjects considering the working age of the Expolis study participants. The number of participants and the mean and standard deviation of time spent outdoors for each city are presented in Table 1.

3 Ambient UVR data. Data on daily ambient UVR levels were obtained from Cost Action 726 (www.cost726.org/), a study of long term changes and climatology of UVR over Europe.[19] It provides maps of daily erythemally effective UVR levels adjusted for cloud cover, stratospheric ozone and atmospheric particles for the area between 25°E to 35°W and 30°N to 80°N with a spatial resolution of 1° × 1° for the period 1958–2002. The daily

Table 1 Number of Expolis participants, mean, standard deviation (SD) of time spent outdoors during weekdays (excluding holidays), annual sum of daily ambient ultraviolet radiation (UVR), median (percent[a]) of annual and daily facial UVR exposure levels (standard erythema dose (SED)) separately for total, holidays, weekdays, and summer and winter weekends for each city, 1997

				Annual facial UVR exposure					
	Number of participants	Mean (SD) time spent outdoors per weekday (hours)	Total annual ambient UVR levels (SED)	Total	Holidays	Weekdays	Weekends	Summer weekends	Winter weekends
Athens	98	1.68 (1.28)	10113	532	89 (16.0%)	176 (41.6%)	225 (42.4%)	184 (35.5%)	33 (6.9%)
Grenoble	101	1.53 (1.32)	7446	339	70 (18.9%)	108 (41.8%)	129 (39.3%)	99 (31.6%)	22 (7.7%)
Milan	291	1.24 (0.93)	6941	297	66 (21.1%)	91 (38.4%)	120 (40.5%)	96 (33.2%)	20 (7.4%)
Prague	79	1.52 (1.15)	5238	254	54 (21.9%)	76 (38.8%)	98 (39.2%)	82 (33.5%)	13 (5.7%)
Oxford	104	1.67 (1.08)	5003	299	74 (23.8%)	87 (37.7%)	111 (38.5%)	92 (32.7%)	15 (5.8%)
Helsinki	418	1.58 (1.17)	3673	211	56 (27.2%)	58 (34.7%)	78 (38.1%)	71 (35.0%)	6 (3.1%)

[a] The contribution (%) of different day types to the annual levels has been calculated as the percentage of the annual mean exposure level in that day type relative to the total annual mean level.

ambient UVR levels for the central parts of the included cities were extracted for the whole of 1997.

4 Summer holiday destinations data. Population-based data on holiday destinations for the countries in which the study cities were located were obtained from the Eurostat report on tourism statistics.[20] Eurostat is the statistical office of the European Union. The report details the proportion of people who make holiday trips abroad (more than four days) and the three most frequent abroad destinations with the proportions that go to each destination. For each city, the population proportion for each destination was abstracted by assuming that all abroad travels were made to those three most popular destinations. The rest of the people were considered to stay in their home country. Supplementary table 1 (ESI†) summarises the holiday behaviour for the population of each city used in this study.

Exposure simulation

The libraries truncgof, lme, and Rlab in R statistical package (http://cran.r-project.org/) were used to carry out the following steps.

1 Facial UVR exposure model. A model developed by Diffey was applied to predict annual facial UVR exposure levels.[6] This model employs time-activity data separately for weekdays, weekends and summer holidays together with ambient UVR levels and day length to estimate the daily facial UVR exposure (More details on this modelling is presented in Appendix I).

2 Fitting distributions to the time activity data. A range of probability distributions were fitted to the time activity data for each city and the best fit was obtained using a log-normal distribution. This was in line with findings of previous reports on time-activity patterns dealing with UVR exposure.[6,13,21]

3 Simulation of annual facial UVR exposure. Expolis did not obtain time-activity data during weekends and holidays and we therefore relied on survey data in the UK to address this.[6] In that survey the modal time spent outdoors during summer and winter weekends were respectively four and two times as much as that of weekdays. The weekend distribution of time spent outdoors for each city was abstracted as a log-normal distribution with parameters derived numerically so that the mode of the distribution was the weekday mode multiplied by the respective coefficients (summer = 4 and winter = 2) while the variance remained the same.

Based on the findings of the same UK survey, a normal distribution with a mean of five hours and a standard deviation of one hour was used for the time spent outdoors during summer holidays.[6] This was consistent with findings of another study of the holiday behaviours among Danish holiday makers.[15] For estimating the exposure levels during summer holidays, data on ambient UVR levels were obtained for the commonest holiday destinations (Barcelona, Paris, Rome, Stockholm, Bratislava, Berlin, London and Athens, representing Spain, France, Italy, Sweden, Slovakia, Germany, UK and Greece). Since we did not have access to data on ambient UVR levels in the US, we used data for Malaga in Southern Spain (closest latitude in European mainland to that of Florida) instead, assuming that most trips to the US are made to Florida or southern states. For each subject, a two-week holiday period was randomly selected during July–August with northern cities mostly from July and southern cities mostly from August.

For each city, 10 000 individuals were simulated, each of them with an associated value of time spent outdoors randomly drawn from the corresponding time-activity distributions and ambient UVR levels in their city of residence and assigned holiday destination; assuming 10 percent of the population does not take summer holidays.

4 Quantification of between and within city variations and contributions of time-activity, ambient UVR, and latitude to annual UVR exposure. To compare the efficacy of time-activity, ambient UVR, and the latitude of the city of residence in predicting annual facial UVR exposure, univariate regression models were developed using simulated annual facial UVR exposure levels as the outcome, and each of these surrogates as the explanatory variable. The coefficients of determination (R^2) for these models were obtained.

The bivariate regressions were developed using simulated annual facial UVR exposure levels as the outcome, and personal time spent outdoors together with either annual ambient UVR levels or the latitude of the city of the residence, as explanatory variables. All variables were log-transformed to achieve linearity and normality of residuals. Total and partial R^2 for explanatory variables were calculated.

Mixed-effects models were used to split the total variance in facial UVR exposure into within- and between-city variance. Since facial UVR exposure levels had a skewed distribution and was log-transformed in the models, we reported the $R_{0.95}$ instead of variances, as suggested by Rappaport.[22] $R_{0.95}$ is the ratio of the 97.5th to the 2.5th percentiles and it is a measure of variation in the original scale of the variable. For example, a $R_{0.95}$ of two indicates that 95% of the values lie within a factor of two.

Effect simulation

We simulated a binary outcome, according to a logistic regression model with the logarithm of facial UVR exposure generated by our applied exposure model as the predictor variable. The simulations were performed under two hypothetical scenarios. The first one considered a hypothetical disease that affects 10% of the population (prevalence = 0.1), while the second considered a hypothetical rare disease that only affects one in 1000 individuals (prevalence = 0.001). We assumed that the risk of having the disease increases by 50% (relative risk (RR) = 1.5) when the facial UVR exposure increases 271 SEDs (inter-quartile range of facial UVR exposure in our simulations) in the two scenarios. Simulations included 1080 participants (180 per each city) for the high prevalence outcome and 198 000 (33 000 per each city) for the low prevalence outcome. These samples sizes were selected in order to achieve a statistical power of 80% when using the simulated facial UVR exposure as the predictor.

Once the outcome variable was simulated, alternative univariate models were fitted separately using time spent outdoors, ambient UVR levels, and the latitude of the city of residence as the predictors. To compare the efficiencies of using personal exposure *vs.* using the exposure surrogates, the asymptotic relative efficiency (ARE) was then calculated separately for each alternative model.[23] The ARE quantifies the ratio of required sample sizes to achieve the same statistical power (*i.e.* the ability of the analysis to detect the exposure-outcome association if there is any) as the reference model. For instance, if ARE = 2 the study using the surrogate needs twice the sample size as that of a study using simulated facial UVR exposure to detect the same effect.

Sensitivity analysis

To investigate the impact of using UK survey data on weekend and summer holiday time-activities on our detected exposure patterns, we carried out a sensitivity analysis assuming different scenarios for weekend time-activity and holiday behaviour. This sensitivity analysis has been described in the Appendix II.

Results

Annual facial UVR exposures generally showed a south–north decreasing trend; however, Oxford did not follow this pattern and showed higher or similar exposure levels compared to Prague and Milan that are more southern than Oxford (Table 1). As presented in Table 1, weekends were the major contributors to the annual facial exposure closely followed by the weekdays. Summer weekends contributed the most to the total weekends levels. The two-week summer holidays accounted for about one sixth to one fourth of annual facial exposure. Like annual facial exposures, the medians of weekday and weekend exposures showed a south–north decreasing trend with Oxford as an exception. There was a similar trend in the contribution (%) of weekday exposures to the annual exposure; conversely, the contribution of summer holidays showed a south–north increasing trend.

Table 2 presents R^2 and partial R^2 that resulted from the univariate and bivariate regression models of facial UVR against time spent outdoors, ambient UVR, and the latitude of the city. In univariate models, the explained variation of facial exposure levels by the time spent outdoors ($R^2 = 0.22$) was higher than that of the ambient UVR and latitude, which were very similar ($R^2 = 0.16$). Total R^2 were similar in two bivariate models and were about 2.5 times higher than the R^2 for univariate models of ambient UVR levels and the latitude of the city of residence. Within-city $R_{0.95}$ was 10.8, about three-fold higher than between-city $R_{0.95}$ of 3.4.

ARE values ranged between 4.0 and 6.4 for the included surrogates and RRs with the lowest values for time spent outdoors and the highest values for the latitude of the city of residence (Table 3). Table 3 shows the results for two simulations of the hypothetical exposure-outcome relationships. In these examples, although simulated facial UVR exposure was associated with an increased risk of the outcome, this was not true for any of the surrogates of UVR exposure (time spent outdoors, ambient UVR levels and the latitude of the city of residence). For these measures of exposure, although the direction of the effect was similar, the confidence intervals included the null value, indicating lack of a statistically significant effect.

Table 2 Coefficients of determination (R^2) and partial R^2 for univariate and bivariate regression models

	Surrogate	R^2
Univariate models	R^2 for time spent outdoors	0.22
	R^2 for ambient UVR	0.16
	R^2 for city latitude	0.16
Bivariate model 1[a]	Total R^2	0.40
	Partial R^2 for time spent outdoors	0.28
	Partial R^2 for ambient UVR	0.22
Bivariate model 2[b]	Total R^2	0.39
	Partial R^2 for time spent outdoors	0.28
	Partial R^2 for city latitude	0.22

[a] Facial exposure against personal time spent outdoors and ambient UVR levels. [b] Facial exposure against personal time spent outdoors and the latitude of the city of residence.

Discussion

This study compared the simulated facial UVR exposure patterns among the population of indoor workers (25–55 years old) within six European cities and investigated the impact of the use of UVR exposure surrogates on the estimated exposure-outcome effects. We found a considerable impact of time spent outdoors and holiday behaviour on facial UVR exposure levels. As a result, within-city variations were larger than between-city variation and ambient UVR levels and the latitude of the city of residence alone were relatively poor surrogates for estimating facial UVR exposure. Finally, our findings demonstrated that use of time spent outdoors, ambient UVR levels and latitude alone as surrogates of long-term exposure to UVR for investigating the link between this exposure and health outcomes results in a considerable loss of statistical power, making it harder to detect the true association.

IARC estimated that the annual facial exposure among indoor workers in mid-latitudes (40°–60°N) would range between 100–400 SED.[24] Apart from Athens (37°N), our simulated annual facial exposure levels for other cities fall within this range. The results of our simulation (excluding Athens) when we did not include the summer holidays effect (Appendix II) are also in line with the estimates of another review study suggesting personal annual exposure levels of 100–200 SEDs for European indoor working adults without considering the exposure during holidays.[25] Using personal UVR dosimeters, a recent study reported median annual

Table 3 Asymptotic relative efficiency (ARE) for ambient ultraviolet radiation (UVR) levels, the latitude of the city of residence, and time spent outdoors and estimated relative risks (RRs) and 95% confidence interval (CI) for surrogates of UVR exposure and simulated exposure

	Outcome prevalence of 0.1				Outcome prevalence of 0.001			
	Simulated exposure	Ambient UVR	Latitude	Time spent outdoors	Simulated exposure	Ambient UVR	Latitude	Time spent outdoors
ARE	1	5.8	6.4	4.6	1	5.2	5.5	4.0
RR	1.37 (1.03–1.81)	1.39 (0.72, 2.67)[a]	0.48 (0.13, 1.75)[b]	1.27 (0.85, 1.88)[c]	1.46 (1.20, 1.78)	1.43 (0.90, 2.26)[a]	0.59 (0.24, 1.47)[b]	1.20 (0.91, 1.58)[c]

[a] RR for an interquartile increase in ambient UVR levels. [b] RR for an interquartile increase in latitude (*i.e.* moving toward northern latitudes resulting in decrease in ambient UVR levels). [c] RR for an interquartile increase in time spent outdoors.

and daily UVR exposure levels of 264 and 0.7 SEDs, respectively, for indoor workers in Copenhagen (55°N), which are comparable with our estimates for Oxford (51°N) and Helsinki (60°N).[7] Another Danish study reported daily UVR exposure levels of 2.1 and 4.9 SEDs, respectively, for holidays in Northern Europe and Southern Europe.[15] Our estimates of daily exposure levels during holidays are comparable with their findings considering different holiday destinations (with different latitudes) for each city included in our simulations.

Our estimated higher annual exposure levels for Oxford than those of Prague and Milan located in more southern latitudes can be explained by larger time spent outdoors and a higher population proportion going abroad for summer holidays with more southern destinations amongst Oxford population. Weekends were major contributors to the annual exposure despite the fact that the sums of weekday time spent outdoors were higher than that of weekends. This was mainly due to higher EF values during weekends. We detected an increasing south–north trend in the contribution of exposures during summer holidays to the total annual facial UVR exposure. This trend is likely to be due to the tendency of people in northern countries to take summer holidays in Southern Europe where they are exposed to much higher levels of UVR than what they usually receive in their latitudes of residence.[6,15]

Both univariate and bivariate models showed that time spent outdoors is a better predictor for annual facial UVR exposure than ambient UVR and latitude. They also showed that using ambient UVR levels alone, instead of the latitude of the city of residence, does not lead to considerably better exposure estimates and therefore they could be used interchangeably. R^2 for ambient UVR and latitude in univariate models was 0.16, which implies that about 84% of variation in annual exposure could not be explained by these surrogates alone. Fortifying these surrogates with time-activity data (bivariate models) increased the R^2 to 0.40.

Our study showed relatively large (11-fold difference between 2.5 and 97.5 percentiles) within-city variations. Other work has suggested that exposure levels within a population are likely to differ by at least 10-fold, which is consistent with our findings.[1,21,26] Since within-city variation is mainly due to differences in personal behaviour,[1] these large within-city variations emphasise the importance of the personal behaviour in UVR exposure and are in line with the results of univariate models showing the highest explained variation was for time spent outdoors. In our study, the within-city variation was three-fold larger than the between-city variation. Ambient UVR levels and the latitude of the city of residence fail to fully estimate simulated facial UVR exposure levels in univariate regression models because they do not take account of this within-city variation. Our simulations showed that the two-week holiday period can account for up to one fourth of the total annual exposure in Northern cities. Therefore, in studies that want to characterize personal UVR exposure, it is also crucial to correctly characterize this short period of time.

Our simulation of two hypothetical exposure-outcome associations showed that using time spent outdoors, ambient UVR levels and the latitude of the city of the residence alone as surrogates of facial UVR exposure would lead to a considerable loss of statistical power, *i.e.* it increased the required sample size to obtain similar statistical power compared to when using the simulated personal UVR exposure. In keeping with this, our hypothetical example showed that, if the surrogates are used as the measure of exposure, there is failure to detect a statistically significant association, which is evident when using the more detailed measure, simulated facial UVR exposure (Type II error). Although the magnitude of the point estimates was similar when ambient UVR levels or simulated facial UVR exposure were used as the exposure measure, in the former, the confidence intervals were wide and contained the null value (RR = 1) due to Berskson type measurement error[27,28] that also operates in the context of latitude. Since time spent outdoors was assigned at a personal level, a Berkson type measurement error was thus not expected for this surrogate. In a real study collecting data, classical measurement error is likely for the time spent outdoors due to the inaccuracy of study subjects in reporting their time activity patterns. The classical measurement error, if it is non-differential (*i.e.* independent of the outcome of interest), biases the regression coefficient toward null and widens the confidence interval.[27,28]

We did not have data on objectively measured personal exposure levels but used an established model to simulate facial exposure. Since other behavioural characteristics contributing to personal UVR exposure (*e.g.* sun risky and protection behaviours) were not included in our analysis, it is expected that in studies collecting data on personal UVR dose, ambient UVR levels, latitude and time spent outdoors, would explain a smaller part of the total variability. Therefore, the loss in efficiency when using surrogates of exposure could be stronger than that shown by our study. This study focused on facial exposure and we are aware that anatomical variation in exposure may produce slightly different results. However, examination of exposure to other sites was outside the scope of this paper and could be attempted in future studies.[29] In addition, our analysis did not include the population of outdoors workers and did not address the possible impact of age and gender on exposure patterns. Incorporating these would inflate the within-city variation – inclusion of these other factors could also be investigated in future studies. Finally, the UK survey data on weekend and holiday time-activities in the analysis are not necessarily generalisable to the populations of our included cities. However, our sensitivity analyses did not show a considerable impact of this on our detected patterns.

Conclusion

Our study showed that because of the time-activity patterns, within-city variation in simulated facial UVR exposure can be three times larger than the variation between cities. As a consequence, studies examining the effect of UVR exposure on health outcomes using ecological measures, such as ambient UVR or latitude which account for less than one-fifth of the variation in an individual-level measure, simulated facial UVR exposure, can be highly inefficient. Such studies could require five times more participants to have similar power to detect a significant effect, as a study using a simulated personal exposure measure. Compared to these surrogates, time-activity was a better predictor for the facial UVR exposure, although if used alone it would still result in a considerable exposure measurement error. Our findings emphasise the importance of integrating both personal behaviour (time-activity and holiday behaviour) and ambient UVR levels/latitude in UVR exposure assessment methodologies. Data on personal behavioural characteristics can be obtained by questionnaires and if the data on ambient UVR levels are not available, the latitude

Table A1 Median of total annual and daily facial UVR exposure levels (standard erythema dose) for each weekend scenario and for each city separately for no-holidays, all-holidays, and 90%-holidays sets

		No-holidays		All-holidays		90%-holidays	
City	Weekend scenario	Annual	Daily	Annual	Daily	Annual	Daily
Athens	$S^a = 1, W^b = 1$	325	0.89	415	1.14	405	1.11
Athens	S = 2, W = 1.5	379	1.04	459	1.26	457	1.25
Athens	S = 3, W = 1.5	409	1.12	498	1.36	486	1.33
Athens	S = 4, W = 2	463	1.27	534	1.46	532	1.46
Athens	S = 4, W = 4	466	1.28	552	1.51	548	1.50
Grenoble	S = 1, W = 1	206	0.56	279	0.76	272	0.75
Grenoble	S = 2, W = 1.5	235	0.64	306	0.84	291	0.80
Grenoble	S = 3, W = 1.5	252	0.69	323	0.89	313	0.86
Grenoble	S = 4, W = 2	277	0.76	343	0.94	339	0.93
Grenoble	S = 4, W = 4	287	0.79	354	0.97	347	0.95
Milan	S = 1, W = 1	171	0.47	241	0.66	237	0.65
Milan	S = 2, W = 1.5	196	0.54	265	0.73	257	0.70
Milan	S = 3, W = 1.5	218	0.60	280	0.77	275	0.75
Milan	S = 4, W = 2	239	0.65	304	0.83	297	0.81
Milan	S = 4, W = 4	252	0.69	319	0.87	312	0.86
Prague	S = 1, W = 1	145	0.40	210	0.58	202	0.55
Prague	S = 2, W = 1.5	164	0.45	230	0.63	227	0.62
Prague	S = 3, W = 1.5	182	0.50	243	0.67	239	0.65
Prague	S = 4, W = 2	202	0.55	263	0.72	254	0.70
Prague	S = 4, W = 4	207	0.57	269	0.74	257	0.70
Oxford	S = 1, W = 1	168	0.46	245	0.67	235	0.64
Oxford	S = 2, W = 1.5	194	0.53	271	0.74	265	0.72
Oxford	S = 3, W = 1.5	211	0.58	287	0.79	276	0.76
Oxford	S = 4, W = 2	233	0.64	303	0.83	299	0.82
Oxford	S = 4, W = 4	238	0.65	314	0.86	300	0.82
Helsinki	S = 1, W = 1	108	0.30	173	0.48	167	0.46
Helsinki	S = 2, W = 1.5	129	0.36	186	0.52	180	0.50
Helsinki	S = 3, W = 1.5	145	0.40	201	0.56	193	0.54
Helsinki	S = 4, W = 2	156	0.43	218	0.61	211	0.59
Helsinki	S = 4, W = 4	164	0.45	218	0.61	213	0.59

[a] Summer coefficient. [b] Winter coefficient.

of the city of residence can be used instead. We recommend future studies of the impact of long-term UVR exposure on human health to rely on modelling approaches taking into account both personal behaviours and ambient UVR levels/latitude and if possible to fortify their exposure assessment by objectively measured personal UVR exposure levels for a subset of their study population.

Appendix I

The following model[6] was used to estimate the personal exposure levels:

$$E_{id} = UVR_d \times EF_{id} \times (1 - (1 - h_{i,d}/H_d)^2)$$

where E_{id} is the facial UVR exposure in subject i during day d, UVR_d is the average ambient UVR level for day d, EF_{id} is the facial exposure fraction (fraction of ambient UVR received by subject i during the same period of exposure), $h_{i,d}$ is the time spent outdoors for subject i during day d, and H_d is the hours of daylight for the mid-point of the relevant month and at the latitude of interest. The EF on any given day was assumed to be distributed with a rectangular probability distribution, and is expressed as:

$$EF_{id} = EF_{min} + r_i(EF_{max} - EF_{min}),$$

where EF_{min} and EF_{max} are the maximum and minimum exposure fractions, respectively, on that particular day, and r_i is a random number between 0 and 1 drawn from a rectangular probability distribution. In every case, EF_{min} was taken to be 0.05 and the values chosen for EF_{max} were 0.25. 0.30, 0.40, and 0.50 for the weekdays, winter weekends, summer weekends, and summer holidays respectively.

Appendix II

Expolis survey did not include data on weekend time-activity and holiday behaviour. Based on a UK survey, we applied coefficients of four and two for summer and winter weekends respectively to transform weekday time-activity patterns. We also assumed that 90% of population take summer holidays (90%-holidays set). To investigate the impact of these factors on the simulated exposure patterns, we carried out a sensitivity analysis using two extra scenarios of holiday behaviours and four extra scenarios for the weekend time-activity. Two sets of simulations were performed: one assuming all the population takes summer holidays (all-holidays set) and the other assuming no one takes summer holidays (no-holidays set). For each set, in addition to the applied weekend scenario in the manuscript (scenario 4 below), we tested the following four extra weekend scenarios:

- Scenario 1: summer coefficient (S) = 1, winter coefficient (W) = 1
- Scenario 2: S = 2, W = 1.5
- Scenario 3: S = 3, W = 1.5
- Scenario 4: S = 4, W = 2
- Scenario 5: S = 4, W = 4

Table A2 Coefficients of determination (R^2) and partial R^2 for univariate and bivariate regression models for no-holidays, 90%-holidays, and all-holidays sets separately for each weekend scenario

		Univariate models			Bivariate model 1[a]			Bivariate model 2[b]		
	Weekend scenario	R^2 for time spent out	R^2 for ambient UVR	R^2 for city latitude	Total R^2	Partial R^2 for time spent out	Partial R^2 for ambient UVR	Total R^2	Partial R^2 for time spent out	Partial R^2 for city latitude
No-holidays	S[c] = 1, W[d] = 1	0.43	0.17	0.16	0.61	0.53	0.31	0.61	0.53	0.31
	S = 2, W = 1.5	0.38	0.18	0.17	0.57	0.47	0.30	0.56	0.47	0.29
	S = 3, W = 1.5	0.34	0.18	0.17	0.53	0.43	0.29	0.53	0.43	0.29
	S = 4, W = 2	0.31	0.20	0.19	0.51	0.39	0.29	0.51	0.39	0.29
	S = 4, W = 4	0.29	0.20	0.19	0.50	0.37	0.29	0.49	0.37	0.29
90%-holidays	S = 1, W = 1	0.30	0.14	0.14	0.45	0.36	0.21	0.45	0.36	0.21
	S = 2, W = 1.5	0.27	0.15	0.15	0.43	0.33	0.22	0.43	0.33	0.22
	S = 3, W = 1.5	0.24	0.16	0.15	0.41	0.30	0.22	0.41	0.30	0.22
	S = 4, W = 2	0.22	0.16	0.16	0.40	0.28	0.22	0.39	0.28	0.22
	S = 4, W = 4	0.21	0.18	0.17	0.39	0.26	0.23	0.39	0.26	0.23
All-holidays	S = 1, W = 1	0.28	0.14	0.14	0.43	0.33	0.21	0.43	0.33	0.21
	S = 2, W = 1.5	0.25	0.15	0.15	0.41	0.31	0.21	0.41	0.31	0.21
	S = 3, W = 1.5	0.24	0.16	0.15	0.40	0.29	0.22	0.40	0.29	0.21
	S = 4, W = 2	0.21	0.16	0.16	0.38	0.26	0.22	0.38	0.26	0.21
	S = 4, W = 4	0.20	0.17	0.17	0.38	0.25	0.22	0.38	0.25	0.22

[a] Facial exposure against personal time spent outdoors and ambient UVR levels. [b] Facial exposure against personal time spent outdoors and the latitude of the city of residence. [c] Summer coefficient. [d] Winter coefficient.

Table A3 Between-city and within-city $R_{0.95}$ and the ratio of between-city on within-city $R_{0.95}$ for no-holidays, 90%-holidays, and all-holidays, separately for each weekend factor

City	Weekend scenario	Within-city $R_{0.95}$	Between-city $R_{0.95}$	Ratio
No-Holidays	S[a] = 1, W[b] = 1	16.4	4.2	3.9
	S = 2, W = 1.5	14.2	4.1	3.4
	S = 3, W = 1.5	13.1	4.0	3.3
	S = 4, W = 2	12.0	4.1	2.9
	S = 4, W = 4	11.7	4.0	2.9
90%-Holidays	S = 1, W = 1	12.9	3.3	3.9
	S = 2, W = 1.5	11.8	3.4	3.5
	S = 3, W = 1.5	11.3	3.4	3.4
	S = 4, W = 2	10.8	3.4	3.2
	S = 4, W = 4	10.6	3.5	3.0
All-holidays	S = 1, W = 1	11.9	3.2	3.7
	S = 2, W = 1.5	11.4	3.3	3.5
	S = 3, W = 1.5	11.0	3.4	3.3
	S = 4, W = 2	10.6	3.4	3.2
	S = 4, W = 4	10.4	3.4	3.1

[a] Summer coefficient. [b] Winter coefficient.

Table A4 Asymptotic relative efficiency (ARE) for ambient ultraviolet radiation (UVR) levels, the latitude of the city of residence, and time spent outdoors (90%-holidays set)

	Outcome prevalence of 0.1			Outcome prevalence of 0.001		
Relative Risk	Ambient UVR	Latitude	Time spent outdoors	Ambient UVR	Latitude	Time spent outdoors
1.2	4.6	4.7	5.2	5.0	5.2	5.0
1.5	5.8	6.4	4.6	5.2	5.5	4.0
2	4.9	5.3	4.9	4.8	5.1	3.5

For ease of comparison, the sensitivity analyses are presented together with results already presented in the manuscript (90%-holidays set with weekend scenario of (S = 4, W = 2)) leading to 75 series (5 cities × 3 sets × 5 weekend scenarios) of 10 000 individuals for which the results are shown in Tables A1–A3.

To study the impact of different hypothetical relative risks (RR) on asymptotic relative efficiency (ARE), we tested two extra scenarios by assuming RR of 1.2 and 2 using the 90%-holidays set with weekend scenario of (S = 4, W = 2) (Table A4).

Abbreviations

ARE	Asymptotic relative efficiency
CI	Confidence interval
EF	Exposure fraction
RR	Relative risk
SED	Standard erythema dose
TMAD	Time-microenvironment-activity-diary

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