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A Behavioral Model for Estimating Population Exposure to Solar Ultraviolet Radiation†

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ABSTRACT

Determining the variability of solar UV exposure of different members of a population by direct measurement demands high compliance over an extended period of time by a large number of people. An alternative approach is to model the variables that affect personal exposure and this is the basis of the method reported here, which uses a random sampling technique to explore variability of exposure at different times of the year by habitués. It is shown that there are large variations in daily personal erythemal exposure, more so for indoor workers living in northern Europe than those resident in Florida, which are due not only to seasonal changes in ambient, but just as importantly to seasonal variation in behavior. Not surprisingly, holiday and summer weekend exposure account for the largest daily UV doses. Northern Europeans who take their summer vacation in Florida can double their exposure during this period compared with holidaying at home and this illustrates just how important sun protection measures should be during recreational exposure in areas of high insolation if the annual UV burden is to be sensibly controlled.

INTRODUCTION

Daily ambient erythemal UV radiation shows a clear-sky summer to winter ratio of about 20:1 in temperate latitudes (~50°), falling to about 3:1 in subtropical latitudes (~30°), with day-to-day perturbations superimposed on this annual cyclic pattern as a result of cloud cover. However, the UV exposure of an individual living at a specific location will exhibit much greater fluctuations than ambient variation because of differences in time spent outdoors and proximity to shade on different days throughout the year. Furthermore, the UV dose absorbed by the skin is further modified by the use of photoprotective agents such as hats, clothing and sunscreens.

Estimates of personal exposure are normally obtained by direct measurement using UV-sensitive film badges (1) or electronic dosimeters (2,3). The results obtained from a number of studies in northern Europe (3–11) indicate broadly that people receive an annual exemplary exposure of the order of 200 standard erythema doses (SED) (12) mainly from summer weekend and vacational exposure, and principally to the hands, forearms and face. This value is approximately 5% of the total ambient available. However, on a population basis, annual exposure can vary enormously depending on an individual's propensity for being outdoors. For example, in studies of the solar UV exposure of indoor workers in Denmark, Thieden *et al*. (3,11) measured a range of annual exposures of individuals within the cohort extending from a few tens of SED to several hundred SED.

There is a great deal of heterogeneity in published studies concerning factors such as numbers of subjects monitored, geographic location, period of study (ranging from a few days to sampling different periods throughout the year), anatomic site of dosimeter placement and data presentation.

In order to determine the variability of exposure of different members of a population, direct measurement demands high compliance over an extended period of time by a large number of people. An alternative approach is to model the variables that affect personal exposure. In this approach, studies (13,14) have taken a "typical" individual (*e.g*. indoor worker) and estimated how long (s)he spends outdoors in hourly intervals throughout the day for different months of the year. Whilst this method has been shown to give results in good agreement with the average obtained from personal dosimetry studies for similar exposure scenarios, it does not yield information about the variability in exposure of members of the same population, such as the population of adult indoor workers in a particular country.

The method reported here extends this approach by using a random sampling technique to explore variability of exposure at different times of the year by habitués (*i.e*. people who occupy a particular location).

MATERIALS AND METHODS

Consider exposure of the face to sunlight. This occurs on virtually every day throughout the year but we would expect much greater exposure during recreational outdoor activities on vacation and sunny summer weekends than during weekdays when most people are likely to be working indoors for a large part of the day. Also when outside, the UV radiation intensity on the face will be much less than ambient on an unshaded, horizontal surface because of factors such as activity, posture and especially shade from nearby structures. The fraction of solar UV received on the face relative to ambient during the same period of exposure is termed the *exposure fraction* (EF).

By assuming independence between the variables of time outdoors and EF, a random sampling technique was used to estimate the daily solar UV exposure to the face during different periods of the year. These are weekdays (Monday–Friday) and weekends (Saturday and

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Sunday) during the winter (November–February), the spring (March and April) and autumn (September and October) combined, and the summer (May–August). In addition, estimates were made of the variability of daily exposure during a 2 week summer vacation. Whilst the seasons defined here are not the classical 3 month periods, they were selected in order to represent different periods of solar exposure throughout the year.

Variability of time outdoors. It is evident that there is a variation in the time spent outdoors during a specific exposure period (*e.g*. summer weekends) by habitués. To provide data on the form of the distribution and the parameters describing it for various exposure periods, a web-based survey, hosted by Cancer Research UK (http://info.cancerresearchuk.org/healthyliving/sunsmart/aboutsunsmart/sunlightsurvey07/) was carried out during the summer of 2007. Amongst the questions, respondents were asked the following:

> We would like to know how much time you spend outdoors over the summer months between May and August.
> First of all, think about how much time you might typically spend outdoors each day (excluding time in vehicles) on weekdays (Monday–Friday) when you may be at work, at college or at home (tick one of the following):

- Less than 15 min
- Between 15 and 30 min
- Between 30 min and 2 h
- Between 2 and 5 h
- More than 5 h

They were also asked the following two questions and given the same options for their response:

> Now think about how much time you might typically spend outdoors on summer weekends when you are not at work.
> And finally, think about how much time you might typically spend outdoors each day when you are on your summer holiday, either in this country or abroad.

As people do not behave in precisely the same way each day, there is a compromise between offering a choice of a larger number of time categories and the difficulty that imposes on respondents of selecting the one they feel most representative of their behavior. Hence the reason for limiting the choice to just one of five possible time periods, which increase in a pseudo-logarithmic manner.

Of the 2060 responses received, 1635 were from people who claimed they worked mainly indoors. From the distribution of answers to these three questions (see Fig. 1), it was found by nonlinear regression analysis using the Solver capability of Excel that the pattern of time outdoors for holiday exposure followed a normal distribution with a mean of approximately 5 h and standard deviation of 1 h.

For weekday and weekend exposure, however, the time outdoors was modeled more accurately by a lognormal distribution (Fig. 1), an observation in keeping with other studies (15–17). The modal time outdoors was found from regression analysis to be close to 0.5 h for weekday exposure and 2 h for summer weekend exposure, with a lognormal standard deviation of 0.3 in both cases. Although respondents were not asked about their winter exposure, the assumption here is that the modal weekday exposure is constant at 0.5 h throughout the year (excluding the holiday period) but that the modal weekend exposure during the 6 winter months is 1 h, again with a lognormal standard deviation of 0.3.

The justification for maintaining the modal weekday exposure constant at 0.5 h throughout the year is that for indoor workers there is generally no change with season in working hours and free time during the working day. Using the mathematical model described here it is, of course, very easy to see what impact season-dependent modal weekday exposure would have on overall annual UV burden.

The probability distributions of time spent outdoors during different periods of the year by indoor workers based on these modal values are shown in Fig. 2.

Variability of facial exposure relative to ambient. For an ambulant, upright subject outdoors who is not wearing a hat, the face may receive between 5% and 50% of ambient depending on the proximity of shade, solar altitude and orientation with respect to the sun (18). During weekdays, it is likely that an indoor worker may be outside only in urban areas, where tall buildings will often obscure direct sunlight and a large part of the sky. Under these conditions the face may only receive about 5–25% of the UV that is incident on an unshaded, horizontal surface. At weekends, especially during recreational exposure, more time may be spent in the countryside or at the coast where a much greater part of the sky will be visible and shade of direct sunlight less frequent. In these instances the face may be exposed to up to 50% of ambient.

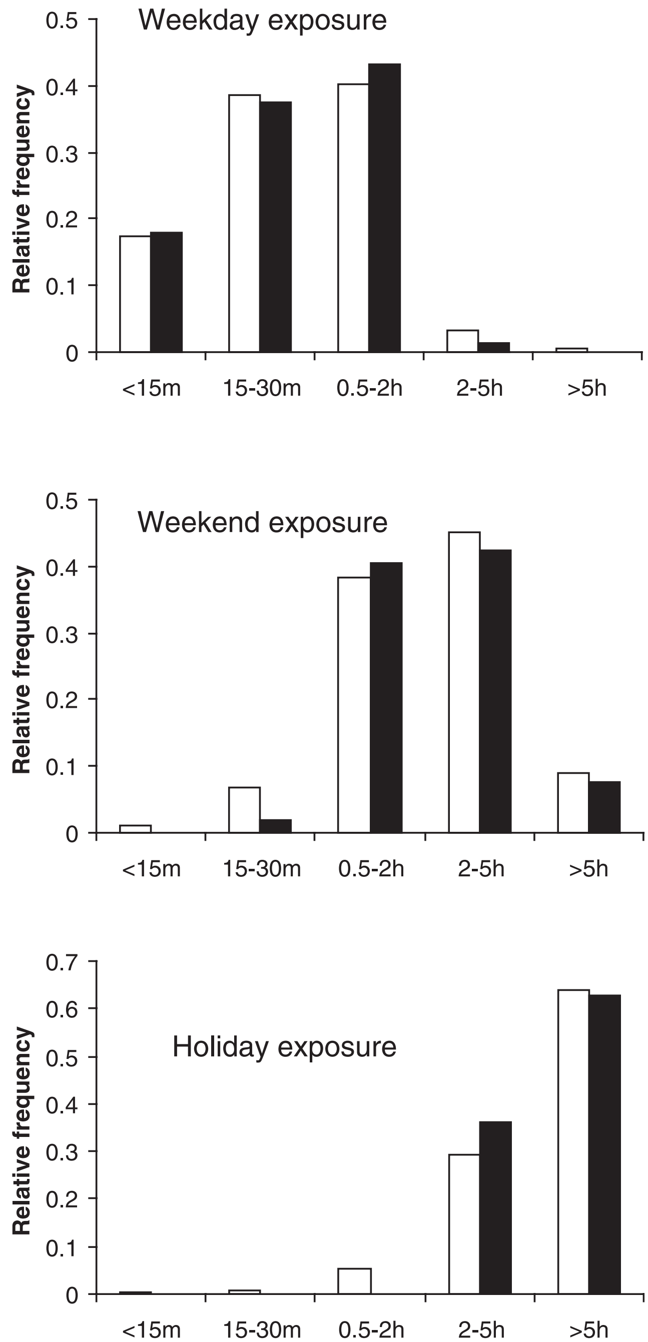

Figure 1. The distribution of times spent outdoors during the summer from a web-based survey (open block) and the fitted probability distributions (solid block) assuming a lognormal distribution for weekday and weekend exposure and a normal distribution for holiday exposure.

The EF on any given day was assumed to be distributed with a rectangular probability distribution, and is expressed as:

$$\mathrm{EF} = \mathrm{EF}_{\min} + r(\mathrm{EF}_{\max} - \mathrm{EF}_{\min}). \quad (1)$$

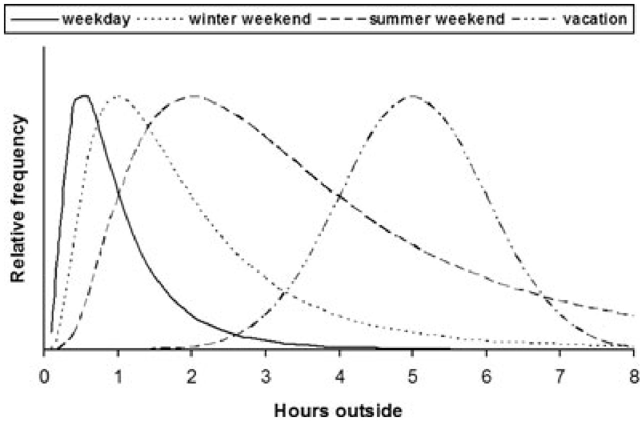

Figure 2. Probability distributions of time spent outdoors by indoor workers at different times of the year used in the calculations. Winter is taken from October through to March, and summer from April to September.

EF_{max} and EF_{min} are the maximum and minimum exposure fractions, respectively, on that particular day, and r is a random number between 0 and 1. In every case EF_{min} was taken to be 0.05 but values chosen for EF_{max} varied according to time of week and season (Table 1).

Daily erythemal UV exposure of the face. In order to maintain a simple approach to modeling, it is assumed that the hours (h) spent outside on any given day are symmetrical about solar noon and that the irradiance of solar erythemal UV exhibits a triangular distribution between sunrise and sunset, peaking at solar noon, the latter assumption being well supported from the diurnal variation of erythemal UV at different latitudes (19). The fraction of daily ambient UV to which the face is potentially exposed is then estimated as:

$$1 - [1 - h/H]^2 \tag{2}$$

where H is the hours of daylight for the mid-point of the relevant month and at the latitude of interest. This can be calculated using an established astronomical equation as:

$$H = 24 \times \cos^{-1}(1 - (1 - \tan(L) \times \tan(0.409088 \times \cos(0.0172024 \times \mathrm{DN}))))/\pi. \tag{3}$$

L is the latitude expressed in radians and DN is the day number for the relevant mid-month, where DN = 0 for 21 December. So DN = 25 for mid-January, 55 for mid-February and so on.

The mean daily ambient erythemal UV (in units of SED) for the latitude and month of interest is expressed as $<\mathrm{UV}>$ and so by combining these factors, we estimate the facial exposure (in SED) to an individual on any particular day as:

$$<\mathrm{UV}> \cdot \mathrm{EF} \cdot \{1 - [1 - h/H]^2\}. \tag{4}$$

By repeating this calculation many times, we can determine the range of exposures received by a population of habitués at different times throughout the year. Each time a calculation is repeated, values for EF and h are generated randomly using the appropriate probability distributions described above. All calculations and graphical displays were achieved using an Excel workbook.

Table 1. Maximum exposure fractions (EF_{max}) for sun exposure during weekdays and weekends at different times of the year.

	Winter (October–March)	Summer (April–September)	Summer holiday
Weekday	0.25	0.25	0.50
Weekend	0.30	0.40	0.50

RESULTS

Exemplar results are given for northern Europe using a representative latitude of 50°N and longitude of 0°, and for Florida using a latitude of 28°N and longitude of 82°W. Estimates of the mean daily ambient erythemal UV were obtained by combining satellite data from 1996 to 2004 published by the International Research Institute for Climate and Society (http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GSFC/.TOMS/.EPTOMS/.monthly/.uv/), which are applicable for clear-sky conditions, corrected by the mean cloud cover for different months at the relevant geographic locations from maps constructed using data acquired by the International Satellite Cloud Climatology Project (http://home.cc.umanitoba.ca/˜jander/clouds/globalclouds.html). These data are shown in Table 2.

The modal times outdoors used in this analysis are consistent with the estimated time spent outdoors by Americans in different seasons (21) and by an earlier survey of British indoor workers (22). That the same modal times outdoors are used for people living in northern Europe and Florida is based on the observation by Godar *et al.* (21) that data from the Environmental Protection Agency's National Human Activity Pattern Survey showed little difference in the seasonal patterns of time spent outdoors by people living in the northern and southern parts of the United States.

Finally, Eq. (4) was used to calculate representative erythemal exposure doses to the unprotected face on a daily basis throughout the year for both northern Europe and Florida using as input data the tabulated values in Tables 1 and 2 and the probability distributions shown in Fig. 2. In making these calculations, it was assumed that indoor workers resident in both northern Europe and Florida take a vacation at their home latitudes, respectively, during the last 2 weeks of July.

The results of these calculations are shown in Fig. 3. Figure 4 illustrates the percentage of annual facial erythemal UV exposure at different times of year for indoor workers resident at these two locations.

DISCUSSION

A numerical method is described for estimating the variability of population daily solar UV exposure throughout the year by combining ambient UV, time spent outdoors and exposure of the face relative to ambient. One advantage of mathematical modeling is to predict how a system will behave without the need to undertake expensive, time-consuming, impractical or even impossible experiments. In the context of population exposure to solar UV radiation, this is a very real benefit.

Whilst there exist survey data on how people spend their time (23,24), the data are not sufficiently detailed to provide robust parameters for estimating the variability of outdoor exposure. Consequently, it was necessary to collect these data using a web-based survey hosted by the UK's largest cancer organization. Although the time spent outside by an individual on any particular day is assumed to be independent of any other factor, this assumption is questionable as ambient temperature and precipitation do influence, to some extent, time spent outdoors (15).

One of the criticisms of questionnaire-based surveys is bias recall. However, in this case, respondents were not asked to

Table 2. Average daily ambient erythemal exposures (in SED) and mean cloud cover.

	January	February	March	April	May	June	July	August	September	October	November	December
Average daily SED from satellite data (relevant to clear sky)												
Northern Europe	2.09	4.60	9.93	19.25	29.50	34.50	33.25	28.43	17.88	7.73	2.90	1.55
Florida	17.88	26.00	37.75	46.88	52.71	51.13	52.25	48.75	39.63	30.75	21.50	16.38
% mean cloud cover												
Northern Europe	75	75	75	75	65	75	75	75	75	75	75	75
Florida	65	55	55	45	45	55	55	65	55	55	55	65
Average daily SED corrected for cloud cover*												
Northern Europe	1.37	3.03	6.54	12.69	22.47	22.74	21.91	18.73	11.78	5.09	1.91	1.02
Florida	13.61	21.92	31.82	42.42	47.70	43.10	44.04	37.13	33.40	25.92	18.12	12.47

*Satellite (clear-sky) data multiplied by $\{1 - 0.7(\% \text{ mean cloud cover}/100)^{2.5}\}$ (20).

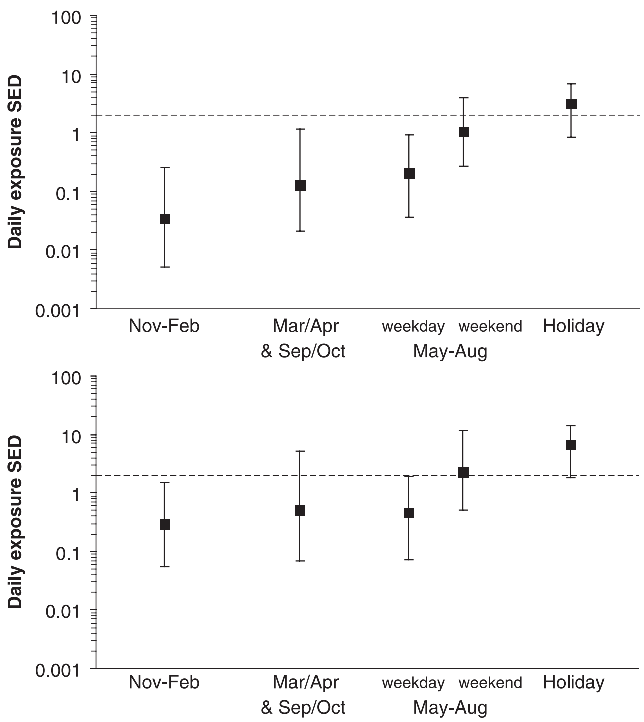

Figure 3. Representative distributions of daily facial UV exposures throughout the year received by indoor workers in northern Europe (top) and Florida (bottom). The solid squares are median values and the error bars encompass the 95% range of individual exposures. The broken line represents the approximate threshold for minimal erythema in unacclimatized, sensitive white skin.

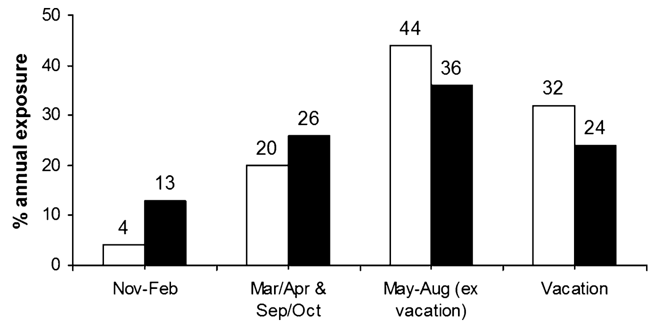

Figure 4. The percentage of annual facial erythemal UV exposure at different times of year in indoor workers in northern Europe (open block) and Florida (solid block).

recall events from the past but to indicate how they behaved currently with respect to time spent outdoors. Also the anonymity of a web-based survey eliminates bias associated with responding in the way the interviewee believes the interviewer expects.

It is clear from Fig. 3 that there are large seasonal variations in personal erythemal exposure, especially for indoor workers in northern Europe, which are due not only to seasonal changes in ambient, but just as importantly to seasonal variation in behavior. Not surprisingly, holiday and summer weekend exposure account for the largest daily UV doses, a conclusion reached from personal UV monitoring studies in Denmark (3,10,11).

So whilst there is only a 20-fold difference in clear-sky daily erythemal UV from mid-winter to mid-summer at latitudes of about 50°N, there is something like a 1000-fold variation in daily personal dose throughout the year with a dose to the face of more than 2 SED (roughly equivalent to one minimal erythema dose [MED] in unacclimatized, sensitive white skin) on about 16–22 days of the year in northern Europe, with a corresponding figure for Florida of 40–50 days. For 7–8 months of the year in northern Europe an indoor worker can expect to receive a facial exposure of less than 0.2 SED (roughly equivalent to one-tenth of an MED), but for people living in Florida this exposure would be exceeded on about 80% of days per year.

The annual facial exposure for people living in Florida is around 400 SED. Of this total, about 100 SED is the result of 2 week vocational exposure, which makes the annual exposure (excluding vacation) of indoor workers in Florida (28°N) of around 300 SED, an estimate consistent with that of 280 SED made by Godar *et al.* (21) for American indoor workers at a latitude of 34°N.

For indoor workers living in northern Europe, a typical annual exposure is estimated to be about 150 SED. In two personal monitoring studies of northern Europeans, the median annual exposure of indoor workers was found to be 132 SED (range 17–841 SED) in one study (3) and 162 SED (range 36–663 SED) in the other (11). These observational findings support the results of modeling.

About one-third of the annual facial exposure of approximately 150 SED in northern Europe is received during the 2 week summer vacation when this is taken at home latitudes, a finding in accordance with the results of a personal monitoring study using electronic dosimeters carried out in Denmark (11). When the calculations are repeated assuming northern Europeans spend their 2 week summer vacation in Florida (but retaining the same distribution of time spent outdoors in holiday), the facial exposure on vacation doubles to about 100 SED and the annual exposure increases from around 150 to 200 SED. This illustrates just how important sun protection measures should be during recreational exposure in areas of high insolation if the annual UV burden is to be sensibly controlled. The assumption of equal times outdoors for holidaymakers in northern Europe and Florida might be challenged but again, the model described here makes it very easy to assume these times differ with location and examines the impact this would have on overall exposure.

The trend for overseas holidays to sunny destinations has increased dramatically with a 10-fold increase in the number of overseas holidays taken by British residents in the period 1971–2005 (25). Furthermore, in recent years the most rapid increases in foreign holiday travel have been to long-haul destinations at low latitudes, such as Florida, where UV levels are typically high. It therefore seems likely that with the current availability of low-cost air travel, overseas sun exposure will continue to be an important factor tending to increase the overall UV doses received by the UK population and the associated health risks.

In conclusion, the model described here is straightforward to implement using Excel spreadsheets, rapidly adapted to different populations and situations, such as duration and location of vacations or changes in lifestyle, and yields results that are consistent with dosimetric field studies with human subjects.

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