Biomarkers, 2012; 17(7): 634–641

ISSN 1354-750X print/ISSN 1366-5804 online
DOI: 10.3109/1354750X.2012.709881

informa
healthcare

RESEARCH ARTICLE

Quantification of ultraviolet radiation-induced DNA damage in the urine of Swedish adults and children following exposure to sunlight

Tove Sandberg Liljendahl[1], Natalia Kotova[2], and Dan Segerbäck[1]

[1]*Department of Biosciences and Nutrition, Karolinska Institute, Huddinge, Sweden and* [2]*Department of Genetics, Microbiology and Toxicology, Stockholm University, Sweden*

Abstract

Context: DNA damage following exposure to ultraviolet radiation (UVR) is important in skin cancer development. The predominant photoproduct, cyclobutane thymine dimer (T=T), is repaired and excreted in the urine, where it provides a biomarker of exposure.

Objective: To quantify urinary T=T levels after recreational sunlight exposure in adults and children.

Methods: Average UVR doses were measured with personal dosimeters. Urinary T=T was analysed with ^{32}P-postlabelling.

Results: Background levels of T=T increased significantly following exposure to sunlight. Amounts of T=T in urine of children and adults were not significantly different after adjusting for area of skin exposed and physiological differences. UVR dose and amounts of T=T correlated for both adults and children.

Conclusion: Recreational exposure to sunlight in Sweden induces levels of DNA damage, clearly detectable in urine.

Keywords: DNA damage, thymine dimer, sunlight, ultraviolet radiation, urine, ^{32}P-postlabelling

Introduction

Ultraviolet radiation (UVR) from the sun is implicated as a major cause of skin cancer and skin type is probably the most important determinant of individual susceptibility (Welsh et al., 2011), (Gandini et al., 2005). The incidence of skin melanoma in the Scandinavian countries is among the highest in Europe despite the stronger intensity of solar UVR further south (Ferlay et al., 2010). The world-wide increases in the incidences of both melanoma and other types of skin cancer (Parkin et al., 2001; Godar, 2005; Ferlay et al., 2010; Narayanan et al., 2010; Stern, 2010) have been attributed to more extensive outdoor leisure activities, in particular vacations at lower latitudes (Bentham & Aase, 1996; Agredano et al., 2006; Lea et al., 2007).

Moreover, it has been proposed that the risk of developing skin cancer, and especially melanoma, is enhanced by high-level exposure to UVR during childhood and adolescence in relation to total lifetime exposure (Holman & Armstrong, 1984; Weinstock et al., 1989). This hypothesis is based on epidemiological data on fair-skinned individuals who move at different ages to regions characterized by higher UVR (Autier et al., 1997; Armstrong & Kricker, 2001).

The actual UVR dose, which an individual receives while out in the sun, depends on the latitude, altitude, season, weather, time of the day and albedo (i.e. reflection from surrounding surfaces). The dosage determined with a stationary or personal dosimeter does not take skin types or personal habits (such as the use of sunscreen and clothing) into account, and a better estimate can be obtained by including a questionnaire regarding these latter factors. Furthermore, body position (e.g. standing up, walking or lying down) also influences exposure and can be taken into consideration with computer modeling. Nonetheless, the actual dose received by dermal cells may be difficult to assess accurately.

UVR, and in particular the shorter wavelength UVB, gives rise to specific pyrimidine dimers in DNA and

Address for Correspondence: Tove Sandberg Liljendahl, Department of Biosciences and Nutrition, Karolinska Institute, Novum, S-141 83 Huddinge, Sweden. Tel.: +4658583707. E-mail: tove.sandberg@ki.se

(Received 04 May 2012; revised 28 June 2012; accepted 04 July 2012)

these photoproducts are believed to play an important role in the development of skin tumours (Cleaver & Crowley, 2002). The formation and repair of DNA lesions in human skin following exposure to UVR can be analysed (Sutherland et al., 1980; Chadwick et al., 1995; Bykov et al., 1998; Yamaguchi et al., 2008), but taking skin biopsies is associated with both medical and ethical constraints and can therefore not be performed on larger populations, and normally not at all on children.

Like other UVR-induced lesions in DNA, the major cyclobutane thymine dimer (T=T) is removed by nucleotide excision repair (Galloway et al., 1994), giving rise to oligonucleotides, 24–32 base pairs in length (Sancar et al., 2004). Following further enzymatic processing of this oligomer, the intact T=T dimer (as TpT cyclobutane thymine dimer) is finally excreted in the urine. T=T was initially analysed in urine samples of psoriasis patients and healthy volunteers with an immuno assay (Ahmad et al., 1999; Cooke et al., 2001). ^{32}P-Postlabelling quantification of urinary T=T in as little as 10 μL of urine was developed, tested on two individuals vacationing in the Caribbean (Le Curieux & Hemminki, 2001) and later validated in our laboratory using a sunbed for controlled dosing (Kotova et al., 2005).

Our validation demonstrated a direct relationship between the UVR dose and the amount of T=T excreted in the urine, indicating that T=T can be employed as a biomarker of exposure. Samples of urine can be easily collected and with virtually no discomfort, so that this biomarker can be monitored in large populations, including children. Since epidemiological evidence suggests a link between childhood exposure and the risk of developing skin cancer later in life, our present aim was to test the hypothesis that children are more sensitive to UVR than adults, i.e. have more T=T in their urine following a brief recreational exposure to sunlight.

Experimental procedures

Study design

In the first set of experiments (referred to hereafter as "unintentional UVR exposure") the effect of unintentional exposure to sunlight on urinary levels of T=T was investigated during a summer (July–August) and a winter (November–December) period. Ten adult volunteers (5 men and 5 women; 27–54 years of age) were each monitored during both these periods, when they were all working indoors full-time. During their leisure time, they had agreed not to stay out in the sun with bare legs and/or arms and not to use a sunbed for 2 weeks prior to the study. During both the summer and winter periods a urine sample was collected once each week for 6 weeks (normally on Saturday morning to minimize the influence of unintentional exposure to sun during the weekends). Personal UVR dosimeters were not utilized in this part of the investigation.

In the second approach (referred to as "sunbathing") children (6 boys and 6 girls, 3–12 years of age) and their parents or other guardian (8 women and 3 men, 21–54 years of age) spent in general two consecutive days in August–September on different beaches in central Sweden. Three of the adults spent only one day on the beach and two men and two women also participated in the unintentional UVR exposure. Three of the adults went to the beach on two separate weekends (with at least one week in-between) and for these three individuals the doses and urinary levels of T=T for the two separate occasions were pooled.

All of the adult participants filled out a questionnaire for both themselves and their children concerning age, sex, skin type, weight and height, clothing worn on the beach and use of sunscreen and they also kept a record of the hours they spent at the beach. The three self-reported skin types for the adults were; two of type 1, three of type 2 and six of type 3 and for the children; one of type 2, one of type 2–3 and ten of type 3. Skin type was self-reported, or for the children reported by the parents. Skin type 1 was in the questionnaire defined as "burn easily, never or seldom tan", skin type 2 as "often burn, sometimes tan" and skin type 3 as "sometimes burn, always tan eventually".

The participants agreed to avoid exposure of any larger portion of their bodies to sunlight or to a sunbed for one week prior to going to the beach, as well as during the period of sample collection. On the beach most of our volunteers wore short trousers/skirt and a T-shirt or swimsuit. For logistical reasons, only 4 urine samples were collected from each individual. Since we had previously observed that after a single exposure most of the T=T is excreted in the in urine within 3–4 days (Le Curieux & Hemminki, 2001), one urine sample was collected before the start of exposure and one additional sample on the morning of days 3, 4 and 5 (the first or second day of exposure to sunlight being designated as day 0 and 1, respectively).

Informed consent was obtained from all of the adult participants and, in the case of the children, from their parents. The study design was pre-approved by the Regional Ethical Review Board in Stockholm (Dnr 246/03 and 247/03).

UVR exposure and urine analyses

For "sunbathing" UVR exposure was monitored with the validated, commercially available biological spore dosimeters (VioSpor® blue-line type; Biosense VioSpor, Borheim, Germany) (Quintern et al., 1997; Wester et al., 2002) strapped to the left forearm and the doses obtained were erythema-weighted (McKinlay & Diffey, 1987). The data from one dosimeter (worn by a child) that broke and from another that indicated an extremely low value (and may have been hidden under clothing or left indoors) were excluded from the statistical analyses. For comparison with other reports the standard erythema dose (SED) was determined, where one SED is equivalent to an effective erythemal exposure of 100 J/m^2 (CIE, 1997). The area of skin exposed was estimated from the questionnaire information concerning clothing, together with the Haycock

equation (Haycock et al., 1978) and the Lund and Browder classification (rule of nines) (Lund & Browder, 1944).

The urine samples were maintained at –20°C until analysis, when they were allowed to thaw at room temperature and solid material removed with a 0.22 µm filter. Ten µL aliquots were further purified by HPLC and T=T levels determined as described previously (Kotova et al., 2005). All urine samples were analysed at least twice. A child, for whom urine samples were not available on day 4 and 5, was excluded from the statistical analysis.

To correct for dilution of the urine creatinine was determined employing the picrate method of Jaffe (Seaton & Ali, 1984). The creatinine adjusted T=T levels in the morning urine samples were assumed to be representative of the entire 24-h period and, using the average excretion rates for children (Remer et al., 2002) and adults (Kampmann et al., 1974) of different ages and body size, the total daily excretion of T=T was calculated.

Statistical analyses

For comparisons between children and adults the Mann–Whitney *U*-test was applied, and the Spearman Rank correlation was used for testing associations. Comparison of the amounts of T=T excreted on different days was performed with the Wilcoxon Matched Pairs Test. All data were processed with version 10 of the Statistica software (StatSoft Inc, Uppsala, Sweden).

Results

Unintentional UVR exposure

During the summer period, 11 of the 60 urine samples collected contained background levels of T=T that were above the limit of detection (>1 fmol per 10 µL urine, corresponding to approximately 4 fmol/µmol creatinine), and 6 of the 10 adults tested had at least one positive sample. The levels ranged from 2.7 to 27.3 fmol/µmol creatinine. None of the 60 samples collected during the winter period contained detectable levels of T=T.

Sunbathing

Exposure

The total time the participants spent at the beach varied from 2 to 14 h, with means of 7.7 h (4.3 h/day) for the adults and 7.4 h (3.8 h/day) for the children. The average exposure to UVR (as indicated by the personal dosimeter) was 348 J/m^2 (range 75–675) for the adults and 638 J/m^2 (range 150–1388) for the children (Table 1), corresponding to daily doses of 198 J/m^2 and 319 J/m^2, respectively (p = 0.29). The average exposed area of skin was 1.11 m^2 for the adults and 0.64 m^2 for the children, corresponding to 66% and 69% of the total skin surface area, respectively. Accordingly, the total mean UVR dose was 389 J for the adults and 459 J for the children (Table 1).

Levels of T=T

All of the 102 urine samples analysed exhibited T=T levels above the limit of detection (>4 fmol/µmol creatinine), and the average pooled levels on day 0 and days 3–5 for all the adults and children are depicted in Figure 1. The mean urinary level of T=T on day 0 (before going to the beach) of 90 fmol/µmol creatinine had risen by 46% on day 3 (p = 0.016) and remained elevated on days 4 (p = 0.009) and 5 (p = 0.024), with the maximal level occurring on day 3 in most cases. The mean maximal urinary level of T=T (the peak level during days 3–5) was 127 fmol/µmol creatinine (range 47–247) for the adults and 258 fmol/µmol creatinine (range 46–343) for the children (Table 1). In 3 cases (2 adults and 1 child), this level was not elevated by exposure to sunlight, but was actually highest on day 0.

Using correction for urinary creatinine, (see Materials and methods), the mean total amount of T=T excreted during days 3–5 was calculated to be 3.0 nmol (range 0.9–6.3) for the adults and 2.4 nmol (range 0.8–6.6) for the children (not significantly different) (Table 1). This total amount of T=T was strongly correlated to the total UVR dose per m^2 exposed skin for adults and children combined (r_s = 0.68, p = 0.0009). This was also the case for the adults separately (r_s = 0.65, p = 0.0289) and for the children (r_s = 0.83, p = 0.0053) (Figure 2). The yield of T=T (i.e. the total amount excreted divided by the UVR dose per m^2 exposed skin; columns 3 and 6 in Table 1) was somewhat, but not significantly, lower in the children. Upon pooling the data for the adults and children, the yield of T=T was found to be negatively correlated to skin type (r_s = –0.46, p = 0.04).

Discussion

Unintentional UV exposure

In a number of unpublished studies we have found that background urinary levels of T=T, prior to any exposure to UVR, vary substantially between individuals and between the studies themselves. The background levels in the current sunbathing investigation ranged from 29 to 210 fmol/µmol creatinine (mean 106) for the adults. In a yet-to-be published series of measurements on lifeguards the mean level before entering the study was very similar, i.e. 124 (range 20–217) fmol/µmol creatinine. The obvious reason for this is that both of these latter investigations were performed in the summer, so the participants had been pre-exposed to sunlight. In spite of the fact that we had, for the current sunbathing investigation, asked them to avoid such sun exposure and not to use a sunbed prior to participation, some individuals obviously experienced substantial pre-exposure and in a few cases urinary levels of T=T were not even enhanced by sunbathing (Table 1).

We had observed earlier (Kotova et al., 2005) that in the spring and autumn, the T=T levels in 84% of the urinary samples were below the limit of detection (4 fmol/µmol creatinine) and the remaining background levels were also very low (<9.4 fmol/µmol creatinine). Therefore, we examined here the influence of unintentional exposure to sunlight during the summer and winter on urinary levels

Table 1. Doses of ultraviolet radiation and urinary excretion of thymine dimer (T=T) for adults who sunbathed on the beach for one (day 0) or two days (day 0 and 1), and for children for two days.

		Dose	Individual dose[a]	T=T on day 0[b]	Peak T=T[c]	Total amount of T=T excreted[d]	Yield of T=T
	Skin type	J/m^2	J	fmol/μmol creatinine		nmol	pmol/J
Adults	3	125	147	182	153	3.43	23.4
	3	350	387	8.5	189	2.65	6.8
	3	275	326	9.1	87	2.23	6.8
	2	475	615	118	247	6.29	10.2
	3	500	411	73	88	3.16	7.7
	3	325	341	161	58	1.04	3.1
	1	75	62	45	47	0.92	15.0
	2	675	665	31	70	2.94	4.4
	3	350	331	22	98	1.21	3.7
	1	375	525	78	228	5.81	11.1
	2	300	464	83	134	3.81	8.2
	Mean ± SD	348 ± 84	389 ± 90	74 ± 30	127 ± 34	3.05 ± 0.89	9.1 ± 2.9
Children	3	675	545	127	144	2.02	3.7
	2	675	511	154	218	3.54	6.9
	2-3	150	69	204	180	0.80	11.6
	3	250	174	29	183	1.47	8.4
	3	200	109	75	86	1.04	9.6
	3	575	239	210	482	2.28	9.6
	3	329	144	68	-*	-*	-*
	3	-*	-*	199	312	1.40	-b
	3	1107	1037	34	411	6.63	6.4
	3	1388	1075	23	343	3.27	3.0
	3	-*	-*	94	168	1.52	-*
	3	1028	689	53	311	2.43	3.5
	Mean ± SD	638 ± 212	459 ± 189	106 ± 35	258 ± 61	2.40 ± 0.82	7.0 ± 1.5

[a]The dose corrected for the exposed surface area of skin according to the rule of nines (Lund & Browder, 1944).
[b]T=T level in the morning prior to exposure during day 0.
[c]The highest T=T level detected during days 3-5.
[d]The total excreted during days 3-5 estimated on the basis of daily rates of creatinine excretion (Kampmann et al., 1974) (Remer et al., 2002).
[e]Total amount of T=T excreted/total dose.
*Data missing.

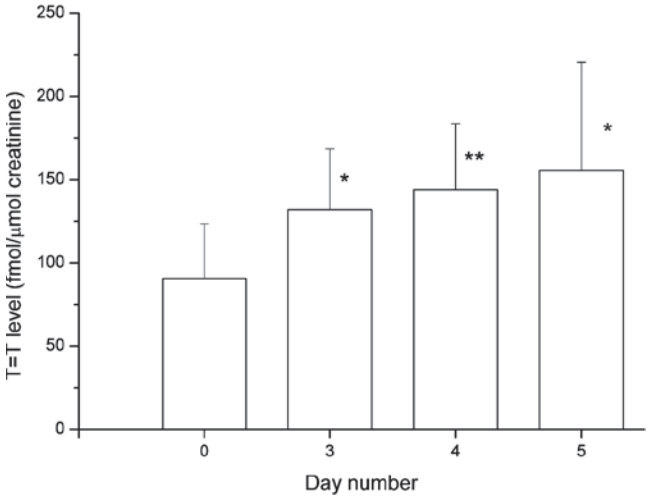

Figure 1. Urinary levels of thymine dimer (T=T) levels before (day 0) and after sunbathing on the beach for 1–2 days (day 0 and 1). The values shown are pooled means SD for all the 11 adults and 12 children. *$p < 0.05$, **$p < 0.001$ in comparison to day 0 (as determined by the Wilcoxon matched pairs test).

of T=T, requesting that the participants not be outdoors with bare arms and/or legs and not use a sunbed prior to sample collection. The dimer could not be detected in any of the 60 winter samples. However, 11 out of 60 summer samples contained low but detectable T=T levels (up to 27 fmol/μmol creatinine). Altogether, these findings reveal that urinary T=T is a very sensitive biomarker and that during the summer it is difficult to avoid detectable levels of UVR-induced DNA damage in the urine, as a consequence of unintentional exposure to sunlight.

Sunbathing

Exposure

The UVR doses received on a beach can be much higher in countries like Australia than in Sweden (Godar, 2005). It is even difficult to compare measurements at similar latitudes, in part because the body position of the personal dosimeter employed will influence the proportion of the ambient exposure detected. The shoulder, which is the most common position normally gives somewhat

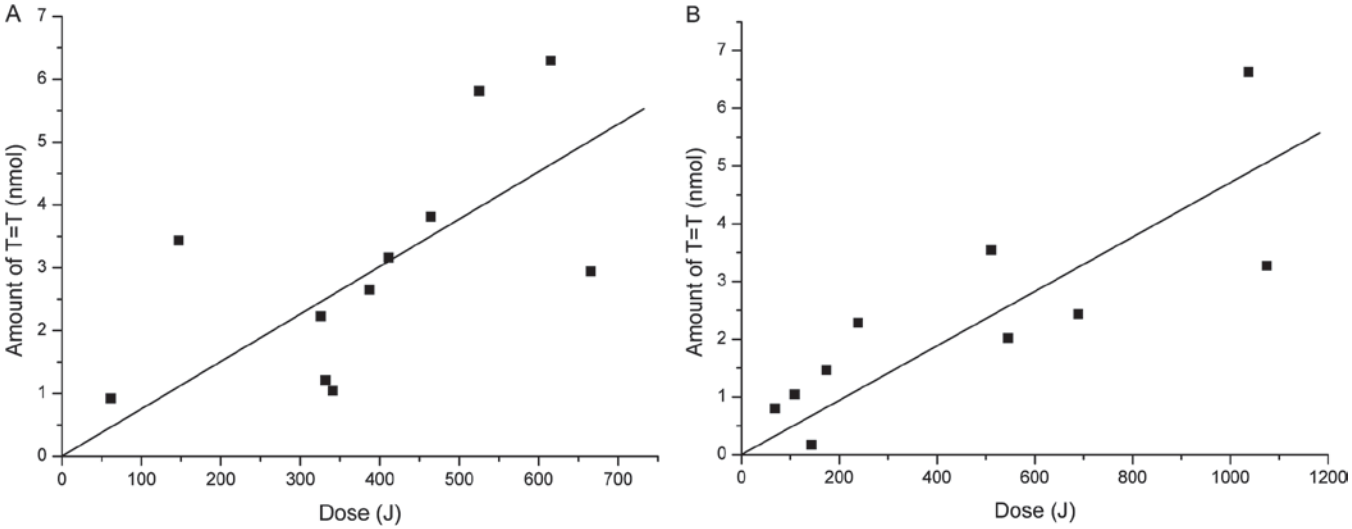

Figure 2. The amount of T=T excreted as a function of dose (adjusted for area of skin exposed) received for the adults (A) and the children (B). Both associations were significant; adults: $r_s = 0.65$, $p = 0.0289$, children: $r_s = 0.83$, $p = 0.0053$.

higher dosage values than, e.g. the wrist, another relatively common site (Vishvakarman et al., 2001; Serrano et al., 2011).

In the unpublished measurements on life-guards the average daily UVR dose was 598 J/m^2 (dosimeter on the shoulder), which is three times higher than the 198 J/m^2 found for adults here (dosimeter on the wrist). Moreover, the UVR doses for individuals going to the beach in Denmark (around 5 SED per day with the dosimeter on the wrist) (Thieden, 2008) were higher than the 2 SED we observed here. Thus, doses received by the adults in our investigation were relatively low, both in comparison to other studies involving leisure exposure at the beach and, certainly, in comparison to occupational exposure.

Children were included in the present investigation because of the epidemiological evidence for increased skin cancer risk after childhood exposure (Autier et al., 1997; Armstrong & Kricker, 2001), but also since it has been proposed that children in general are both more sensitive and more extensively exposed to environmental health hazards than adults (Wild & Kleinjans, 2003). The children in our study received a mean daily UVR dose of 319 J/m^2, which corresponds to 3.2 SED. Among comparable dosimetry-based studies performed in central-northern Europe, a British report on school children of different ages during 13 weeks in the summer at unspecific locations (beach or not), documented average median doses ranging from 0.2 to 1.1 MED/weekend (corresponding to 0.4–2.2 SED/day) (Diffey et al., 1996). The average daily doses of 2.0 SED observed at two day-care centres in the Stockholm area (Boldeman et al., 2004), were considerably lower than those found here, in spite of the similar number of hours spent outside (3.9 h per day for the day-care centres and 3.8 h per day for our sunbathing children).

The differences between the latter two studies include shading of the yards of the day-care centres by trees; the fact that the day-care children were often inside at the time when the UVR intensity of sunlight was highest; and the higher albedo at the beach. In the Danish study mentioned above (Thieden, 2008) the median UVR dose received by children at the beach was 4.2 SED per day, which is higher than the 3.2 SED documented here, with a similar period of exposure in both cases (4.2 versus 3.8 h, respectively). In summary, the daily doses received by our children can be considered typical for those on a beach in northern Europe.

Urinary levels of T=T

The levels of T=T were elevated after spending time at the beach (Figure 1) and reached maximal values for most of the subjects on day 3, as was also observed in our previous sunbed study (Kotova et al., 2005).

There was a strong correlation between total amount of T=T excreted and the dose (adjusted for exposed skin surface area) for both adults and children (Figure 2). Dose-response relationships are very important in the validation process of biomarkers and this observation strengthens the usefulness of T=T as a biomarker of UVR exposure. A dose-response relationship was also found in the sunbed investigation within subjects, but not for the pooled material (probably due to the small number of participants and limited range of doses).

The sunbed experiments ($n = 10$) were carried out primarily in the early spring and late autumn and involved a controlled average dose of 312 J/m^2 (Kotova et al., 2005), or correcting for area of skin exposed 549 J. This exposure resulted in a peak urinary level of T=T 3–5 days later averaging 86 fmol/μmol creatinine. The mean dose received by the adults here was 348 J/m^2 (389 J after correction for exposed skin area) and the average peak level of T=T reached during days 3–5 was 127 fmol/μmol creatinine. Thus our sunbathing participants exhibited twice the peak T=T concentration per unit dose.

The average background levels of T=T were much higher prior to sunbathing (71 fmol/μmol creatinine for

adults) than in the sunbed study (2 fmol/μmol creatinine). It is therefore likely that pre-exposure in the case of our sunbathing individuals contributed to the peak urinary levels of T=T observed per unit dose. Other differences include the fact that in the sunbed investigation most of the skin faces the UVR source in an optical manner and, consequently, the dose measured at one location will be more accurate for all parts of the body. Moreover, some individuals of skin type 1 participated in the current study, but not in the sunbed experiments.

Comparison of adults and children

In the study by Thieden (2008) the adults received 3.6–6.1 SED UVR per day at a beach in Denmark (during 2–3 days per year); while the children spent an average of 5 days at the beach each year, with a similar mean daily dose 4.2 SED (Thieden, 2008). Here, the children were exposed to a somewhat, but not significantly, higher daily dose (3.2 SED versus 2.0 SED for the adults, $p = 0.29$). Recent reports (Thieden et al., 2004; Godar, 2005) indicate that children, adolescents and adults receive more-or-less the same annual dose of UVR, but several epidemiological studies suggest that childhood exposure is most strongly linked to the development of skin cancer (particularly melanoma) later in life (Weinstock et al., 1989; Autier et al., 1997; Dennis et al., 2008). One proposed explanation for this is that melanoma often originates in naevi that develop primarily in response to exposure to UVR during childhood (Holman & Armstrong, 1984; Thomas et al., 2007; Veierod et al., 2010).

In connection with analysis of spot urine samples, expressing the level of an analyte in relationship to the creatinine correction is the standard procedure for correcting for dilution. However, this approach cannot be applied for comparison of subjects with different muscle masses and height/weight ratios, such as children and adults (Barr et al., 2005). As a consequence of their small body size and renal function children excrete relatively small amounts of creatinine; for instance the difference in 24-h creatinine excretion between a 3- and an 18-year-old may be as great as 6-fold (Remer et al., 2002). Thus, if the lower concentration of creatinine in a child's urine is used for correction the levels of analytes will be overestimated (Barr et al., 2005).

An alternative approach, suggested by Remer and co-workers is to correct on the basis of 24-h rates of creatinine excretion individualized for height and gender (Remer et al., 2002). In order to individualize these rates for adults as well, the tables constructed by Kampmann and co-workers may be employed (Kampmann et al., 1974). With this approach and utilizing our spot urinary levels of T=T to calculate the total amounts excreted during days 3–5, children were found here to excrete smaller amounts than the adults (2.4 nmol versus 3.0 nmol, respectively). Furthermore, the yield of T=T per J was not significantly, higher in adults (Table 1), i.e. we did not find that children had more UV-induced DNA damage than adults, as reflected in urinary excretion of T=T.

There are several limitations involved in this comparison of children to adults. The dose of UVR received by the children might have been underestimated as a consequence of their different ratio of skin surface area to body size and proportionally larger heads (Boniol et al., 2008). In addition, children at a beach probably move around much more and also spend more time on their knees (digging in the sand, etc.) than adults so that their personal dosimeters might not be detecting the same fraction of the average UVR dose per unit surface area of skin. An approach for body modelling of exposure is being investigated in a project in which we are participating.

Other factors that could have influenced the difference between children and adults with respect to the yield of T=T per unit dose were the relatively small number of subjects and potential reporting bias (the adults who accompanied the children may have reported more accurately for themselves than for the children). Such potential bias concerns mainly the clothing and the use of sunscreen, although sunscreen was used by only one adult and two children. Although skin type could be another confounding factor, it has been shown previously that the difference in formation of T=T between individuals of skin type 2 and 3 is small (Xu et al., 2000). Here, the formation of T=T per unit dose was negatively correlated to skin type. Since all but two of the children were of skin type 3, whereas 5 out of the 11 adults were of skin type 1 or 2, this factor might partially explain the lower amount of T=T excreted per unit dose in the children.

The relationship over time between the levels of this lesion in skin cells and the urinary levels of T=T is not very well known, and also whether a morning urine sample contains the same proportion of excreted T=T during a 24-h period. This assumption is supported by the observations made by Poulsen and co-workers for excretion of 8-hydroxy-2'deoxyguanosine (Poulsen et al., 1998). For T=T, these associations are currently being investigated by us. Furthermore, we have assumed that the rates of repair and excretion of T=T are independent of age. There is some evidence that DNA repair is attenuated in older adults (Moriwaki et al., 1996), but our adult subjects were relatively young and no data on repair of DNA lesions in children are presently available. However, metabolism and rates of excretion do differ between children and adults, at least for certain compounds (Hattis et al., 2003), and this might also be the case for excretion of T=T.

Thus, we found no difference between sunbathing children and adults with respect to sensitivity to UVR, as reflected in formation of T=T. Larger studies needs to be performed in order to draw any definitive conclusion in this matter. However, UVR exerts other effects that may be important in the development of skin cancer, such as immunosuppression (Halliday et al., 2011; Rangwala & Tsai, 2011; Schwarz & Schwarz, 2011). Accordingly, effects on the immune system due to childhood exposure to UVR could influence the risk for skin cancer in later life (Jaspan et al., 2006; Norval, 2011).

Conclusion

Here, in the first investigation on urinary levels of T=T following exposure to sunlight in northern Europe, we have shown that such recreational exposure in Sweden elevates these levels in both children and adults. UVR-induced photoproducts in DNA contribute to the development of skin cancer and must be considered to be a risk factor. In this limited study we found no difference between children and adults in the amounts of UVR-induced T=T excreted in the urine. Nonetheless, it is important to protect children from extensive exposure to UVR, which has been linked to an elevated risk of developing skin cancer later in life.

Declaration of interest

This work was supported financially by the Swedish Radiation Protection Authority, the Swedish Cancer Society, Dagmar Ferb´s Fund and the EU-funded project Environmental Cancer, Nutrition and Individual Susceptibility (ECNIS) (contract no. FOOD-CT-2005–513943). The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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