Journal of Exposure Science and Environmental Epidemiology (2007) 17, 58–68
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Effective exposure to solar UV in building workers: influence of local and individual factors

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Excessive exposure to solar UV light is the main cause of skin cancers in humans. UV exposure depends on environmental as well as individual factors related to activity. Although outdoor occupational activities contribute significantly to the individual dose received, data on effective exposure are scarce and limited to a few occupations. A study was undertaken in order to assess effective short-term exposure among building workers and characterize the influence of individual and local factors on exposure. The effective exposure of construction workers in a mountainous area in the southern part of Switzerland was investigated through short-term dosimetry (97 dosimeters). Three altitudes, of about 500, 1500 and 2500 m were considered. Individual measurements over 20 working periods were performed using Spore film dosimeters on five body locations. The postural activity of workers was concomitantly recorded and static UV measurements were also performed. Effective exposure among building workers was high and exceeded occupational recommendations, for all individuals for at least one body location. The mean daily UV dose in plain was 11.9 SED (0.0–31.3 SED), in middle mountain 21.4 SED (6.6–46.8 SED) and in high mountain 28.6 SED (0.0–91.1 SED). Measured doses between workers and anatomical locations exhibited a high variability, stressing the role of local exposure conditions and individual factors. Short-term effective exposure ranged between 0 and 200% of ambient irradiation, indicating the occurrence of intense, subacute exposures. A predictive irradiation model was developed to investigate the role of individual factors. Posture and orientation were found to account for at least 38% of the total variance of relative individual exposure, and were also found to account more than altitude on the total variance of effective daily exposures. Targeted sensitization actions through professional information channels and specific prevention messages are recommended. Altitude outdoor workers should also benefit from preventive medical examination.
Journal of Exposure Science and Environmental Epidemiology (2007) **17,** 58–68. doi:10.1038/sj.jes.7500521; published online 23 August 2006

Keywords: *UV measurements, dosimetry, building workers, posture, altitude, effective irradiation.*

Introduction

Health Effects

Ultraviolet (UV) irradiance relevant to human exposure ranges between 290 and 400 nm, and yields both positive and adverse health effects. Low doses of UV are sufficient to enable calcium and phosphorous metabolic regulation, vitamin D photosynthesis and to treat skin conditions such as psoriasis or eczema (Diffey, 1998). Antineoplastic effects of vitamin D produced by UV radiation around the time of cancer diagnosis have recently been advanced (Robsahm et al., 2004; Berwick et al., 2005; Egan et al., 2005; Lim et al., 2006). Excessive UV exposure can induce erythema (sunburn) and melanogenesis (suntan); in the long run, it could lead to premature skin aging, and cause cataract and cancer (IARC Monographs, 1992; McCarthy and Taylor, 2002).

UV is a carcinogenic agent which has the ability of both initiating and promoting skin cancers (IARC Monographs, 1992). It causes DNA damage and mutation of the p53 gene is considered as a specific outcome of UV exposure at the molecular level (Cesarini, 1996; Mukhtar and Elmets, 1996). Although UVB constitutes $<5\%$ of the solar spectrum, it accounts for 80–85% in erythema occurrence and plays a major role in skin cancer causation (Diffey, 1991). UVA (315–400 nm) and UVB (290–315 nm) probably act through different mechanisms and their carcinogenic effects might interact beyond their single effects.

Over the last 50 years, skin cancer rates have markedly increased in Caucasian populations worldwide (Hannuksela-Svahn et al., 1999; de Vries et al., 2003). This is particularly so for melanoma, the most biologically aggressive cutaneous cancer, for which the incidence is doubling about every 15 years (Boyle et al., 1995). Indeed, the incidence of melanoma has increased more rapidly than that of any other malignancy in Caucasian populations. By affecting a relatively young population (half of the cases are diagnosed before the age of 60), melanoma is a public health problem, which contributes significantly to lifespan reduction.

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Received 28 April 2006; accepted 6 July 2006; published online 23 August 2006

Although melanoma is the most lethal cutaneous cancer, it represents some 10% of all skin cancers. Cutaneous carcinomas (80% are basal cell carcinomas and 20% squamous cell carcinomas in fair-skinned populations) are the most common cancer type worldwide. These cancers tend, contrary to melanoma, to progress slowly and to be located on highly sun-exposed body parts (face, neck, arms). This facilitates early detection and explains the much more favourable prognosis for non-melanoma than melanoma skin cancers. The high number of cutaneous carcinomas induces, however, considerable treatment costs. Moreover, subjects affected by a skin carcinoma appear to increase their overall cancer mortality risk (Levi et al., 1999).

The incidence of skin cancer varies more than 100-fold worldwide. Australia and New Zealand have the highest incidence of melanoma, with about 40 new cases diagnosed per 100,000 inhabitants per year (Parkin et al., 2002). About 60,000 of the 160,000 melanomas registered each year in the world occurred in Europe, and another 54,000 in the US (Ferlay et al., 2001). While melanoma occurs slightly more often among women than men in Europe, the opposite is observed in the US and Australia. Adequate estimates of the number of non-melanoma skin cancers worldwide are not available, but the burden of this cutaneous malignancy is far greater than for melanoma.

In terms of mortality, melanoma accounts for about 40,000 deaths a year worldwide. Some 16,500 of them are notified in Europe and 7,650 occurred in the US. Trends in melanoma death rates somewhat reflect early detection and prevention activities. Countries with a long tradition of preventive campaigns, such as Australia and Scandinavia, have been the first to observe a decline in mortality (de Vries and Parkin, 2003). These decreases were systematically preceded by a levelling off in rates and started among women and younger age groups. Currently, melanoma mortality rates have stabilized in Western Europe, with some hints of decline in Swiss females (Levi et al., 2006), whereas they are still increasing in eastern and southern Europe (de Vries et al., 2003), as well as in the US (Jemal et al., 2000).

Intermittent sun exposure, particularly during childhood, is the major environmental risk factor for melanomas (Elwood and Jopson, 1997), and probably basal cell carcinomas (Kricker et al., 1995). Indeed, rises in skin cancer rates are consistent with the increase in outdoor leisure activities and holidays in sunny areas, and the temporal changes in clothing favouring the exposure of a wider skin surface. Squamous cell carcinomas appear to be predominantly induced by chronic sun exposure. Outdoor workers, such as agricultural and building workers, are at a particular risk for this form of skin cancer (Armstrong and Kricker, 2001; Levi et al., 2001a, b). The association between occupational UV exposure and non-melanoma skin cancers, and the causal association between acute recreational exposure and melanoma have partly been postulated from differences in the anatomical distribution of skin cancers (Beral and Robinson, 1981). Although the importance of the anatomical location in the aetiology of cutaneous cancers has been established (Franceschi et al., 1996; Bulliard et al., 1997), exploitation of this variable remains limited, partly because of the lack of precise information on sun exposure of various body parts during at-risk activities.

Exposure: Control, Determinants and Measurements

Exposure limits Public and occupational exposure limits have been proposed to minimize the long-term, adverse effects of solar UV radiation and have been adopted in several countries. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends a daily (8 h) maximum of $30\,\mathrm{J\,m^{-2}}$ (0.3 SED), effective spectrally weighted, for a sensitive unprotected skin. This limit is for instance used as exposure threshold by the American Conference of Governmental Industrial Hygienists (ACGIH). However, this threshold can be reached within minutes under some ambient irradiation conditions, and should thus be seen as a desirable goal rather than an absolute value for skin exposure. As it does not account for the lower UV sensitivity of a tanned skin the ICNIRP recommendation is quite conservative.

Factors influencing exposure The elevation of the sun in the sky is the single most important factor affecting ambient irradiation. The higher the sun, the shorter the radiation path through the atmosphere and higher the levels of solar UV. Often measured as the solar zenith angle, the sun elevation depends on time of the day, latitude, altitude and season. Consequently, 75% of the daily irradiance occurs between 0900 and 1500, UV irradiance increases by 15% per km of altitude elevation and by 2% per latitude degree toward the Equator. Cloud cover, ozone thickness, air pollution and surface reflectance (albedo) also influence substantially ground irradiation. Some of these factors are interrelated, so that their individual effects can be difficult to assess.

The impact of the latitude has been evidenced in epidemiological studies around the world, which found a negative association between latitude of residence and melanoma incidence or mortality (Swerdlow, 1979; Scotto and Fears, 1987; Lee and Scotto, 1993; Bulliard et al., 1994; Gandini et al., 2005a, b). Surprisingly, the effect of the strong increase in UV radiation with altitude (Blumthaler et al., 1994), which can be experienced within a short travel distance, has seldom been studied on humans. Outdoor activities in mountainous areas entail, for workers and recreationists alike, a particularly increased risk of over-exposure to UV radiation (Moehrle et al., 2003).

When sun-exposed, the human body receives 24–61% of the total ambient irradiation, depending on the time and duration of exposure and the body orientation to the sun

(Parisi et al., 1996). Variations in UV doses received across individuals are even larger as they are strongly influenced by behavioural and host factors (Hill et al., 1992). Also, for a given individual and weather condition, exposure of various anatomical sites ranges from 13 to 76% of the exposure of the vertex of the head (Wright et al., 2004).

Outdoor occupational activities carry a substantial risk of short-term UV overexposure as they usually take place regardless of the ambient irradiation and, by often involving repeated tasks performed in the same posture, favour the continuous exposure of specific anatomical areas. Occupational exposure beyond 100% of the ambient irradiation have been measured on some body parts of outdoor workers (Gies and Wright, 2003) and body posture (i.e., standing and sitting positions) has been shown to be determinant in the exposure of various anatomical areas (Parisi et al., 2003). Week-days occupational exposure appears to exceed the UV exposure received during weekend leisure activities in some population of outdoor workers (Parisi et al., 2000).

Effective exposure measurement Increase in skin cancers as well as media coverage of the ozone layer depletion have dramatically increased public awareness towards UV exposure, and consequently, enhanced the need of reliable irradiation data. *In situ* measurements have been further developed and generalized, and efforts have been undertaken to develop predictive irradiation models based on routine meteorological measurements. Currently, ground radiation measurement stations operate in the US and most European countries, using either broadband detectors, spectroradiometers, or multifilter rotating shadowband radiometers.

The development of ambient irradiation measurements contrasts with the development of effective exposure data. Albeit various dosimetric techniques enable to assess individual exposure, such as photo-electrical captors or photosensitive chemicals/biologicals (e.g., polysulfone badges), dosimetric measurements remain tedious. Several dosimeters are required per subject to assess effective exposure of different body locations. Also, the exposure assessed by dosimetric measurements tends to be situation-specific and prone to epidemiological biases, so that their generalization remains difficult.

Further, individual factors (exposure time, body posture and orientation to the sun) often limit the extrapolation of exposure results to similar activities or occupations conducted in other conditions. The need to increase objective measures of UV exposure with personal dosimetry has recently been highlighted in an evidence review conducted in the US (Glanz and Mayer, 2005). This lack is particularly obvious for occupational exposure. When documented, effective exposure generally pertains to an average irradiation over long periods (e.g., seasonal exposure), giving little insight on the influence of local or individual factors such as body posture and orientation to the sun. Consequently, workplace exposure has seldom been measured despite the existing regulations and recommendations.

Prevention

Whereas secondary prevention focuses on early detection, primary prevention aims at informing the public about the risks of overexposure to UV light and means to protect oneself and one's children adequately from the sun. Wear of protective clothing and sunglasses, avoidance of the 1100–1500 irradiation peak time, use of natural or artificial shade and, as an adjunct protection, use of broad-spectrum sunscreen are the advocated prevention measures. The UV index is also increasingly used as a didactic risk indicator to raise public awareness.

The length of the lag time between sun exposure and severe cutaneous damage, along with the positive social perception of tanning, render compliance with sun protection messages challenging (Autier et al., 2000). Although knowledge of the dangers of excessive sun exposure and means to adequately protect one's skin has improved, its translation into attitudinal and behavioural changes toward sun protection remains modest (Hill et al., 1993; Arthey and Clarke, 1995; Stanton et al., 2004). For example, the observed impact of the UV index on behavioural changes has so far been limited (Geller et al., 1997; Bulliard and Reeder, 2001).

Educational messages and broad UV indicators are rather unspecific. The UV index is a composite measure that cannot include individual, local and geographical factors albeit these factors are known to strongly influence irradiation intensity and potential UV exposure. Sensitizing people on the importance of their own activity in their daily UV exposure appears to be a more efficient strategy. Compared to children who had access to direct UV measurement and exposure prediction, those not having access to this information received a 33% higher erythemal UV exposure to their left shoulder (Kimlin and Parisi, 2001).

Similar sun protection behaviours have been reported for indoor and outdoor workers despite the significantly greater time spent in the sun by outdoor workers, on working days and days off, and their higher number of skin lesions removed (Woolley et al., 2002). Besides, the use of protective clothing at work can be motivated by considerations, such as occupational hazards, which may detract from sun protection awareness. For example, Californian farmworkers wear skin (UV) protective clothes when handling pesticides or thorny branches but do not use wide-brimmed hats (Salas et al., 2005) even so this occupational group is at increased risk for non-melanoma skin lesions, particularly on the face and neck. As outdoor workers cannot completely avoid UV exposure, reinforcement of sun-safe policies and development of specific prevention strategies at workplaces have been recommended (Stepanski et al., 1998).

Goals

This study has focused on effective exposure of building workers in Southern, alpine Switzerland. Short-term UV exposures of various body parts have been investigated and workers' postural activities have been recorded concomitantly. The goal was to characterize outdoor workers exposure as well as individual and local factors which influenced the exposure (worksite altitude, body posture, orientation to the sun). A better understanding of effective occupational exposure and its determinants should assist occupational health regulatory bodies and public health authorities in devising targeted prevention strategies.

Switzerland has one of the highest incidence rates of melanoma in Europe (crude rate of 22 cases per 100,000 inhabitants per year) and this cancer has become the second most frequent in Swiss adults aged 20–40 years (Parkin et al., 2002). An excess relative risk of melanoma on the head and neck has recently been reported among agricultural workers in Switzerland (Bouchardy et al., 2002). Further, an estimated 12–15,000 non-melanoma skin cancers are diagnosed annually in this country (Bulliard et al., 2006). The frequent exposure to UV radiation in altitude and the relatively common occupational exposure (one man in six is occupationally exposed to the sun) in Switzerland provided a particularly relevant environment for such a study.

Methods

Field measurements

Exposure measurements were conducted at four building sites in Valais, an alpine area in Southern Switzerland. Sites were selected on the basis of: (1) their availability at the time of the study, (2) the lack of shade and (3) their altitude. Three levels were considered, corresponding to plain (500–600 m), middle- (1400–1500 m) and high-mountain (2000–2500 m) environments, respectively. Two sites were investigated in the high-mountain range. Foundation building (e.g., for cable car pylons) was the main activity in plain and high-mountain sites, while roofing was the main activity in the middle-mountain site.

Individual measurements of UV exposure were performed using CIE erythemaly weighted Spore film dosimeters with a limit of detection of $100\,\mathrm{J\,m^{-2}}$ (1SED) and a reproducibility of ±5 to 20% (dose dependent) (Furusawa et al., 1998; Moehrle et al., 2000) (BioSense, Bornheim, Germany). In all, 20 building workers wore dosimeters on five body locations: neck, left and right shoulder, low back and forehead (Figure 1a). The dosimeters were fixed on the external side of clothes and hats using safety pins. Measurements were performed during 20 working periods using 97 dosimeters (dosimetric measurements on specific body parts were not possible in three cases). Daily periods of highest irradiance (between 1000 and 1600) were investigated for durations of 2–4 h (short-term exposures). No measurements were performed during midday break to reflect solely occupational exposure.

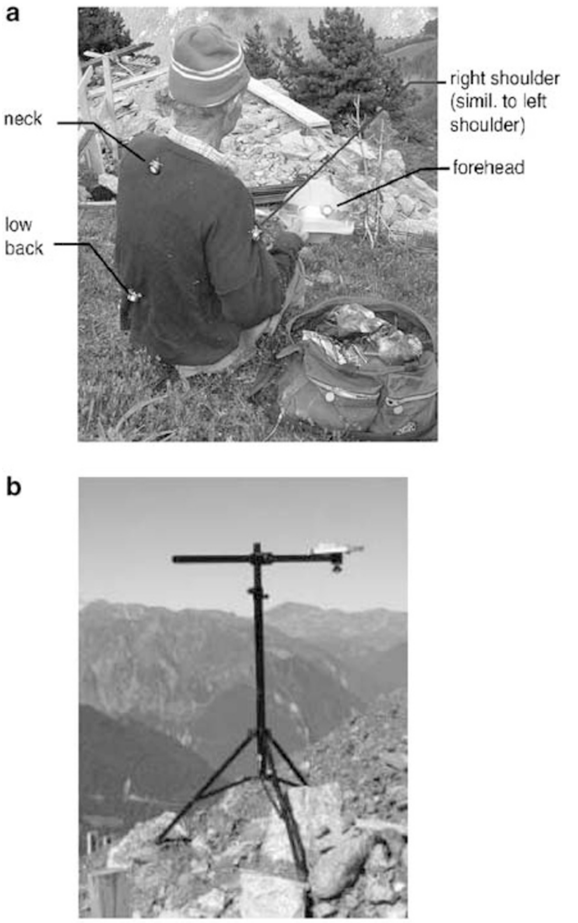

Figure 1. Irradiation measurements: (a) individual dosimetry (b) static UV measurements.

The postural activity of workers wearing dosimeters was concomitantly recorded using observation techniques developed to assess physical strain in the field of occupational ergonomics. A lattice comprising five body postures (seated, kneeling, standing bowing, standing erect arms down, standing erect arms up) and five orientations to the sun (behind, lateral left, lateral right, above, front) was used. The body posture and orientation to the sun categories were completed with additional criteria corresponding to partial or total shade. The lattice was first used manually, with observations on a spreadsheet. For testing purposes, some observations were also implemented on a Palm Handheld, using a software dedicated to time studies (UmtPlus, trial version 7.1.14, Laubrass Inc., Montreal, Canada).

Static UV irradiances at the building sites were concomitantly measured on a flat horizontal surface 2 m above ground level (telescopic prop, Figure 1b), nearby the investigated workplaces. Direct and upward diffuse irradiation were measured on spore dosimeters and on a portable numeric monitoring dosimeter (Model X2000, Gigahertz-Optik GmbH, Puchheim, Germany). Downward diffuse irradiation was measured on spore dosimeters. A total of 20 dosimeters (10 upwards, 10 downwards) were used to perform static measurements. Daily irradiation cycles during measurement days were also collected at the Baseline Surface Radiation Network (BSRN, SolarLight 501A UV broadband radiometers) station of MeteoSwiss at Payerne (Payerne facility is part of the Baseline Surface Radiation Network (BSRN) of the WMO World Climate Research Programme. (located at 491 m above sea level, about 100 km from the measurements sites).

Measurements were performed between July and September 2005 during cloudless periods. Although not exceptionally high, irradiation conditions during measurements were above average.

Assessing Exposure

Each effective dose obtained during the measurement period was extrapolated to a daily effective dose in order to make comparisons possible. Assuming that ambient irradiation daily cycles at various altitudes were of different amplitudes but of similar shapes, the BSRN daily cycle was used as reference. The daily cycle was extrapolated to clear sky conditions using a simplistic Gaussian distribution. A weighting factor obtained from ambient dosimetric results was used for estimating the ambient irradiation daily cycle at the building site. Effective daily exposure in ($\mathrm{J\,m^{-2}}$) was then obtained by integration over the working periods. To assist with comparison, results were converted into standard erythema dose (SED), the internationally recognized unit for expressing UV dose (International Commission on Illumination, 1997). The SED ($100\,\mathrm{J\,m^{-2}}$) describes the erythemal effectiveness of various UV radiation sources while being unrelated to any individual susceptibility to erythema.

Percent of ambient exposure (PAE), defined as the ratio between effective and ambient irradiation during the same exposure period, were calculated. Being expressed as a fraction of ambient irradiation, PAE is less dependent from ambient exposure conditions than effective irradiation alone and enables various exposure conditions and measurements periods to be compared.

The mean individual exposure was defined as the mean of the four upper body parts exposure doses (forehead, right and left shoulder, neck). As these locations are oriented toward four quadrants, this average value reflects the solar-UV "panoramic surround" of exposed individuals. Low-back values were discarded "a priori" in order to avoid an overrepresentation of backside exposure. Relative individual exposure was defined as the ratio between the effective exposure of a specific captor and the mean individual exposure. It therefore reflects over- or under-exposure of a specific anatomic location.

Limits of the Study

Number of measurements For practical reasons, the number of dosimetric measurements has been limited. A total of 117 dosimeters were used (static, $n=19$ and individual measurements, $n=98$). Ambient irradiation daily cycles were not available for some working periods ($n=10$). Consequently, 88 daily effective doses could be calculated and were available for analysis and modelling.

Confounding factors Local, environmental factors such as albedo, cloudiness or ozone layer thickness can affect effective irradiation. Whenever possible, their effect was mitigated by the choice of measurements location (e.g., comparable environment) and period (e.g., cloudless spells). The use of PAE for comparisons should strongly attenuate the effect of environmental factors.

Measurements bias The concordance between spore dosimeters, BSRN broadband detectors and the portable numeric monitoring dosimeter was assessed. Comparative measurements were performed at the MeteoSwiss BSRN station in Payerne during a sunny day for a 250 min period. An excellent correspondence was found between the three spore dosimeters and the BSRN detector (maximal relative error 4%), while important differences were observed with the portable numeric dosimeter (relative error 36%).

The spectral response of UV-measurement should theoretically follow the erythemal response spectrum. In practice, deviations from the ideal curve occur and are known to produce differences in the response of various measuring devices. This is for instance the case for wavelengths around 280 nm. To avoid this bias, even though on-site measurements were systematically performed with the portable numeric dosimeter, only spore dosimeters and BSRN measurements were used to characterize daily exposure and PAE.

Relating Exposure to Postural Work

In order to relate exposure to postural work, a predictive irradiation model that combines individual body postures with individual positions relative to the sun was developed. The idea was to relate the position and posture recorded each minute by an observer to the measures of the detector. Basically, the model counts the number of times a worker is in a given position and posture, and maps this time-weighted sum to the measurement value by a defined mathematical equation.

Exposure for a given body part i of a given individual j: E_{ij}, is expressed as the combination of an matrix M_{i} and postural and orientation vectors, as follows:

$$E_{ij} = \int_{t_j^0}^{t_j^1} (P_j(t) \otimes M_i \otimes O_j(t)) \cdot I_{\mathrm{UV}}(t)\mathrm{d}t + w_{ij} \qquad (1)$$

where $P_j(t)$ is a vector of dimension $(1, 5)$ that represents the observed posture of the exposed individual j at time t. $O_j(t)$ is a vector of dimension $(4, 1)$ that depicts the observed orientation to sun of the exposed individual j at time t. $O_j(t)$ and $P_j(t)$ are step functions, meaning that their coordinates equal 1 when the worker is in the corresponding orientation or posture, and 0 otherwise. For instance, $O_j(t)[\text{face, left, right, back}]^t$ is $(0, 0, 1, 0)^t$ for an individual having the sun predominantly on its right shoulder at time t.

I_{UV} is a weighting factor that gives the relative intensity of ambient UV radiation at time t. M_i is the incidence matrix of dimension $(5, 4)$ corresponding to the body part i, while w_{ij} is a residual value.

M_i reflects the potential impact of incident solar UV radiation on the detector located in i depending on body posture and position to sun. Four classes $m_k (k = 1–4)$ were used to depict the relationships between body surface (detector) and incoming radiations: m_1-frontal (facing direct radiation), m_2-angular (receives partial direct radiation and diffuse radiation), m_3-diffuse (no direct radiation, diffuse radiation only) and m_4-albedo (albedo only). As an example, the incidence matrix obtained for forehead exposure is given in Equation (2).

$$M_{\text{Forehead}} = \underbrace{\left.\begin{vmatrix} m_1 & m_2 & m_2 & m_3 \\ m_4 & m_2 & m_2 & m_4 \\ m_1 & m_2 & m_2 & m_3 \\ m_1 & m_2 & m_2 & m_3 \\ m_4 & m_2 & m_2 & m_4 \end{vmatrix}\right\}}_{\text{Face}\quad\text{Left}\quad\text{Right}\quad\text{Back}} \times \begin{cases} \text{Erect arms down} \\ \text{Kneeling} \\ \text{Erect arms up} \\ \text{Seated} \\ \text{Standing bowing} \end{cases} \qquad (2)$$

In this matrix, the upper left value m_1 means that the face of the worker (the columns) receives direct radiation in the position "erect arms down" (the lines) when he is oriented towards the sun (forehead exposure). This matrix has been defined prior to any calculation. In particular, we did not try to optimize the matrix in function of the measured exposures.

For each measured exposure E_{ij}, the integration of Equation 1 results in a linear combination of the m factors, as follows:

$$E_{ij} = \left[\sum_{k=1}^{4} (\alpha_{ij} \cdot m)_k\right] + (\alpha_{ij})_{k=5} + (w_{ij}) \qquad (3)$$

where, for $k = 1–4$, α is a weighting factor giving the influence of m on the exposure of body part i. And, for $k = 5$, α is an additional constant parameter reflecting the influence of external unknown factors. This model captures the whole information available with only five parameters: four parameters representing angular radiation plus an unknown external bias. Developing a model with a higher number of parameters could gain in prediction accuracy, but we believe that such approach could also lead to some overfitting of our relatively small data set.

In practice, the model was applied to each exposed individual body part. In all, 88 E_{ij} equations were thus obtained, one for each effective exposure measurement. A multiple linear regression using least squares method was used to determine the influence of the four known parameters on exposure. A statistical significance level of $P < 0.05$ was considered for the regression. The model was implemented on Matlab version 6.1.0 with statistics toolbox version 3.0 (Mathworks Inc.).

Results and discussion

Daily Effective Exposure

The daily effective doses obtained for various body sites and altitudes showed high exposure to solar UV radiation (Figure 2 and Table 1). For type III skin, the most common skin type amongst the Swiss population, the ICNIRP recommendation of $30\,\mathrm{J\,m^{-2}}$, corresponds to 0.3 SED. This value was exceeded for all workers in at least one body location and, in some cases, by several orders of magnitude.

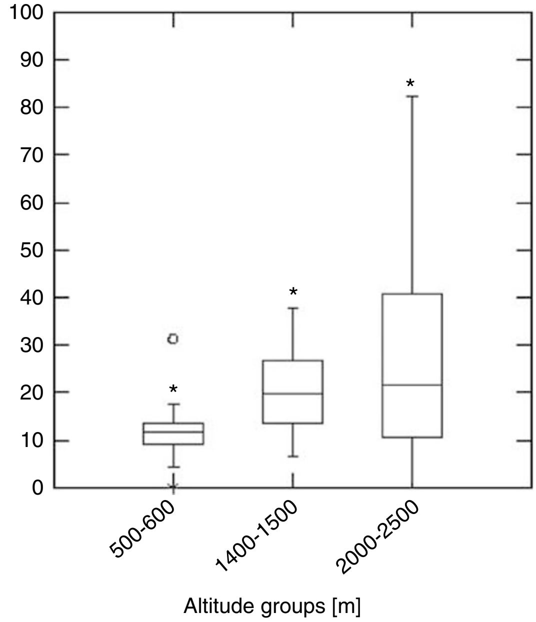

Figure 2. Daily effective exposure (in SED) at various altitudes (Systat Boxplot, default parameters).

Table 1. Average daily effective dose (in SED) at various altitudes.

Altitude groups (m)	Mean daily exposure (SED)	Standard deviation (SED)	Number of samples (n)
500–600	11.9	7.0	24
1400–1500	21.4	10.1	30
2000–2500	28.6	24.7	43

In average, the daily exposure obtained for an altitude group was 40–95 times higher than the recommended exposure. The mean daily exposure obtained in this study is several times higher than the values reported by previous authors for long-term dose measurements (Moehrle et al., 2003).

The extent to which the ICNIRP recommendation was exceeded supports the systematic use, in such conditions, of protective measures against solar UV (e.g., protective clothing, sunscreen). By comparison, similar individual exposure in leisure activities (e.g., bathing, mountain trekking) is considered as highly exposed.

Unsurprisingly, effective dose tends to increase with altitude. This increase was statistically significant between 500 and 1500 m as well as between 500 and 2500 m ($p<0.05$, two-samples non-parametric Kolmogorov–Smirnov test, $n_{500}=24$, $n_{1500}=30$, $n_{2500}=43$). A significant increase in the variability of daily effective dose has also been found for these altitude groups. An analysis of variance with the altitude as single variance component confirms this result ($p<0.0004$, $n=88$), but this ANOVA model suggests that altitude is a minor contributor in the effective dose (14% of the variance explained).

As shown in Figure 2, the range of effective doses for various body parts is very wide. This raises two concerns:

Local or/and individual factors (e.g., albedo, site location, activity, posture, etc.) play a determinant role in effective individual exposure. If these factors are of stochastic nature, their effects should be mitigated by exposure duration and are unlikely to affect chronic dose. If these factors are of repetitive nature, for instance being intrinsic to the occupation, they will affect long-term dose and lead to chronic overexposures of some body parts.

Intensive subacute exposures occur in outdoor workers. Such kind of exposure, which is difficult to prevent and mitigate, plays an important role in skin cancer induction.

Postural Activity

The workers' postural activity during measurement, expressed in percents of total working time, is presented in Figure 3. Standing erect arms down (49%) and standing bowing (20%), are the predominant postures. Kneeling is less frequent while seated and standing erect arms up represent <5% of working time. This postural profile is easily explained by the nature of building work, for which mobility is the rule, not the exception. Although some tasks requires specific postures, the frequent changes in activity and movements (e.g., bringing material, tools) make standing erect arms down the default posture. The predominance of standing bowing amongst the "static" postures may be attributed to the foundation building and roofing activities. In both cases, most of the work is performed at the ground/roof level.

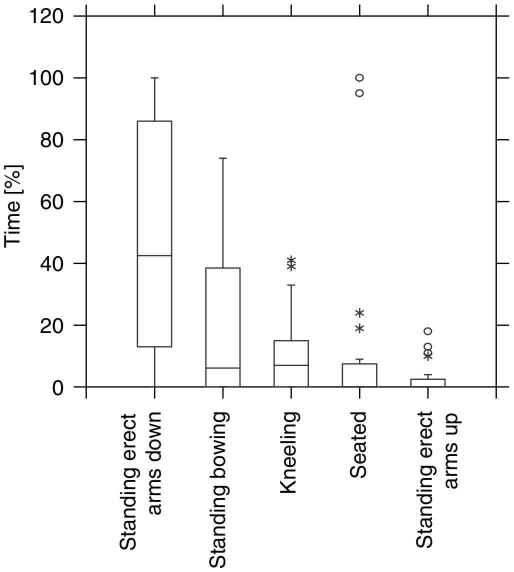

Figure 3. Distribution of postural activity during measurement (Systat Boxplot, default parameters).

The workers' orientation during measurement, expressed in percents of working time, is presented in Figure 4. Orientation is supposed to be unrelated to occupation and to occur in a random fashion. The time distribution between orientations does indeed appears rather regular, although a slight discrepancy between left and right orientation can be observed. Workers appear to spend more time with the sun on their right side than on their left side. In this regard, it must be stressed that the middle- and high-mountain building sites were on north-west- and west-facing slopes. Facing the slope is a natural orientation which favors an exposure on the right side.

Exposure of Various Body Parts

Effective exposure obtained for five body parts, expressed as PAE and relative individual exposure (fraction of mean individual dosimetry), are presented in Figure 5. The PAE and individual relative exposure are, in principle, unaffected by local irradiation conditions (altitude, cloudiness, period of the day) and reflect the impact of individual factors (posture, orientation, movement) on exposure.

The mean PAE ranged between 0.27 and 0.54 and the mean relative individual exposure ranged between 0.69 and 1.17. In accordance with the posture and orientation patterns previously observed, low–back and left shoulder are the least

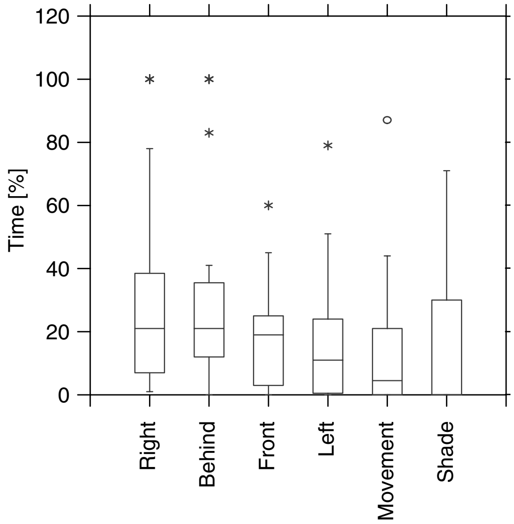

Figure 4. Orientation to sun during measurement (Systat Boxplot, default parameters).

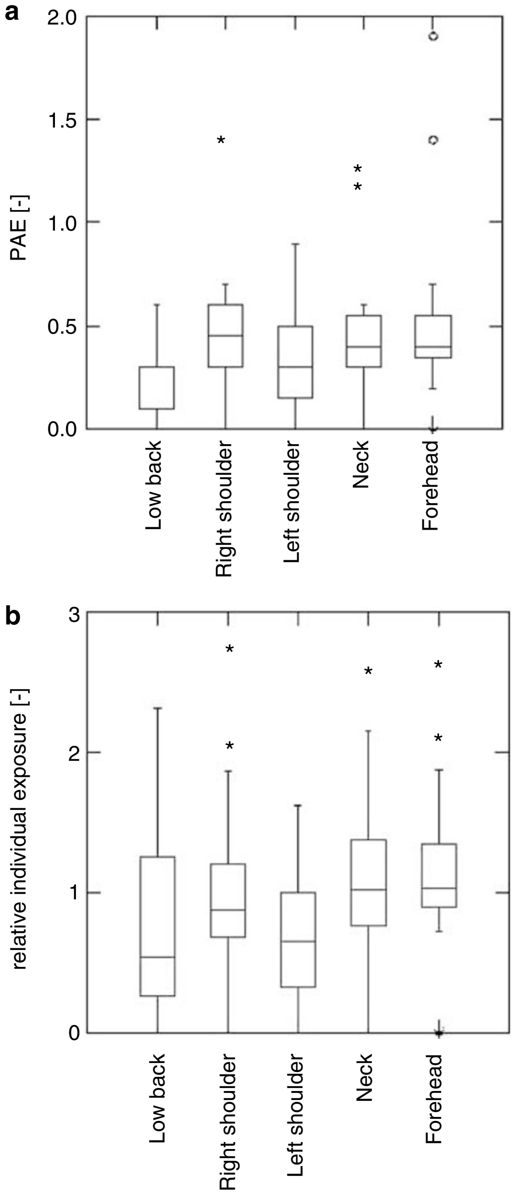

Figure 5. Exposure of 5 body parts ($n = 97$) (a) percent of ambient exposure, (b) relative individual exposure (Systat Boxplot, default parameters).

exposed parts while, neck (1.13) and forehead (1.17) are the most exposed ones. For these latter body parts, some PAEs were measured beyond ambient irradiation ($>100\%$). Such situations may occur when the incoming radiation is closer to orthogonality with respect to the body surface than to the horizontal plane (e.g., being standing bowing with the sun behind you). Both exposure indicators exhibit similar tendencies, although relative individual exposure is spread on a wider range than PAE.

The wide range of PAEs and relative individual exposures obtained suggests that local or individual (posture and orientation) factors are important in effective exposure. Indeed, body parts of a single individual measured over the same period were found to be exposed quite differently (mean intra-individual $SD = 0.25$, $n = 20$). Factors influencing the body surface orientation (posture and sun position) appear to be determinant and should be accounted for in public and occupational health messages, regarding sun prevention for outdoor activities with postural prevalence. In a more general sense, the range of PAEs obtained questions the use of ambient irradiation data (e.g., through solar UV indices) as an indicator of exposure risk.

Body site-specific PAE for different altitudes are presented in Figure 6. The lower exposure of low-back compared to neck and forehead remains significant at each altitude group. The picture is less clear for shoulders exposure, which does not follow a regular pattern.

No statistically significant increase of PAE has been found with altitude. However, dispersion of PAE is significantly greater ($p = 0.0036$) at 2000–2500 m altitude compared to 1400–1500 m and 500–600 m altitudes. This higher variability in altitude may be due to reflection on clouds, turbidity areas coming from below, or from variation in direct/diffuse radiation intensity between measurements sites. It must be emphasized that, radiation has a "broader" incidence angle at high altitude than at middle altitude and plain (narrow valleys). Unfortunately, radiations coming at extreme incidence angles could not be captured by detectors positioned on an horizontal surface.

Exposure vs. Postural Work

Given the limited data available and the numerous potential confounding factors, the relationship between posture, orientation to the sun and effective exposure is difficult to disentangle. A linear regression showed no evidence of a direct correlation between posture, orientation and exposure.

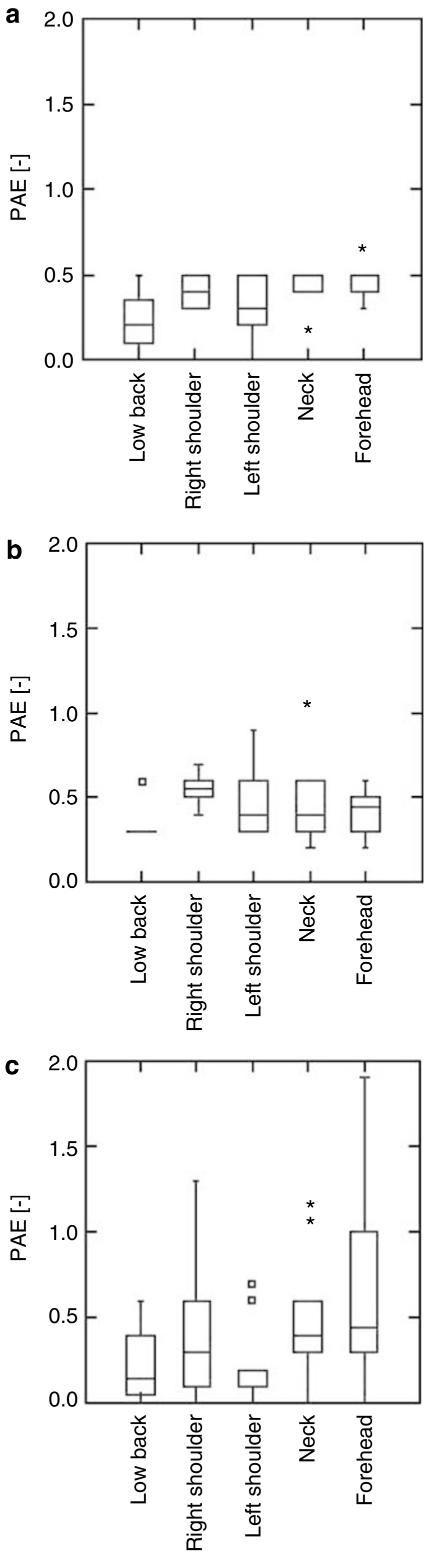

Figure 6. PAE for different body parts (Systat Boxplot, default parameters).

Their relationships were further investigated with the exposure model described in the method section. We applied the model using (1) PAEs, (2) daily effective doses (3)relative individual exposures based on daily effective doses as E_{ij} values daily effective doses and (4) logarithm of daily effective dose.

The model did not return a significant result when using the PAE (relative to ambient irradiation) ($R^2 = 0.03$ $P = 0.67$). The physical link between incoming radiation and effective dose is obvious. But it appears that the numerous influencing factors make this relationship too remote to be captured through a model based on a simple incidence matrix. In this regard, a poor correlation was found between ambient irradiation and average individual exposure ($R^2 = 0.003$, $P = 0.84$, $n = 20$). This emphasizes the lack of reliability of ambient irradiation data to depict effective individual exposure

When using daily effective doses as E_{ij} values, the model was yielded a significant result and accounted for 24% of the total variance of daily effective doses ($R^2 = 0.24$, $P = 0.0001$). The influence of posture and orientation (24%) bear therefore a greater influence on daily effective doses than altitude (14%).

We obtained the best predictive power when the model used an exposure variable E_{ij} adjusted for both daily effects and individual mean exposure (E_{ij} = daily effective dose relative to individual panoramic surrounding exposure) ($R^2 = 0.38$, $P < 1.e\text{-}7$). Given the relative crudeness of the model, the influence of 38% found for posture and orientation factors is probably underestimated. The model was also tested for possible bias using only three upper body parts measurements as mean individual exposure (removing the dosimeter under study). Significant correlations were also found between postural observations and exposure. Note that a physical interpretation of the model parameters M_i is difficult, since they were not consistently represented by the same monotonic relationship for the different choices of E_{ij}. In particular, the parameter M_1 representing the frontal direct radiation was not significantly larger than the parameters representing angular, diffuse and albedo radiations respectively.

Finally, we also applied the model on the logarithm of the daily effective doses since lognormal distributions have successfully been fitted for UV exposures (Gies et al., 1998). We found that: (1) the exposure variable is highly asymmetric and closer to a log–normal than a normal distribution (Jarque-Bera test), (2) the model has better predicting power for low exposures than for high exposures (3) the model produced a worse result on the log-transformed data, suggesting that non-linear effects might play an important role in the exposure levels. A more sophisticated model is needed for the detection of intense subacute exposures.

Observed Protective Practices

At the visited building sites, clothing was mostly driven by thermal comfort considerations. On the one hand, thermal comfort tends to increase UV exposure. At a given altitude, sunny conditions are expected to produce warm environments and thus encourage workers to wear light clothing (e.g., working stripped to the waist). On the other hand, temperature drops rapidly with altitude and high-mountain workers were proner to wear more clothing and thus to protect their arms, shoulder and torso. The "thermal-comfort based" clothing behaviour makes neck and face less systematically protected. Measurements of effective irradiation support that these body parts were the most exposed in altitude workers.

Overall, workers were aware of some deleterious effects of solar-UV. Although the risk was perceived in relation to erythema only, indicating little knowledge of the long-term effects of UV exposure. Sunburns endured early in summer were a concern for the workers, while an existing tan or a pigmented skin (type III–IV) was considered as a sufficient protection. The observed thermal-comfort and tanning at work practices contrasted strongly with the recommended prevention measures.

Conclusions

Short-term UV dosimetric measurements in building workers during cloudless periods showed high exposures. The daily effective exposure exceeded, in most cases, international recommendation for solar occupational exposure of unprotected skin by several orders of magnitude. Construction workers cannot usually choose their work location and schedule or decide whether to perform their tasks in the shade or in the sun. Therefore, clothing and sunglasses remain the main individual protective measures against UV exposure. Consequently, specific protective measures against solar UV should be developed and applied during building activities. Work-related risks are perceived differently from leisure risks and are more under-estimated because they occur on a regular basis and lead to financial gain. Preventive strategies adapted to the specific, occupational setting are lacking. In order to reduce occupational UV exposure, we recommend to undertake targeted sensitization actions through professional information channels (e.g., inspectorates, professional associations). Prevention messages need to be tailored to exposure conditions encountered by outdoor workers in mountainous areas.

Intra- and inter-individual measurements exhibited a high variability in our workers' population. The wide range of predicted daily exposure doses and PAEs indicated that local exposure conditions and individual factors played a key role in effective exposure. This questions the reliability of ambient irradiation data (e.g., through solar UV indices) to predict effective exposure. The variability in exposure appears to increase with altitude, so that intense subacute exposures, which are difficult to control, are more likely to occur at high altitude.

The conditions in which (sub)acute exposure take place are numerous and difficult to control: tasks with an unusual static posture, high albedo, high ambient irradiation. Populations at high risk of subacute exposure should benefit from a regular preventive medical examination.

Posture and orientation appear to play an important role in subacute exposure and warrant further investigated. Some postural prevalence, due to work activity or construction site location, were identified in this study. If obvious from a qualitative point of view, the relationships between postural activity and effective exposure was difficult to quantify because of the limited data available and the presence of confounding factors. Still, a significant correlation was found, through a specific exposure model, between relative individual exposure and posture/orientation factors. Results suggest that posture and orientation play a key role on both relative individual exposure and daily effective exposure. Also, the contribution of posture and orientation to the daily effective exposure has been found to be greater than the influence of altitude.

These results emphasize the need of better indicators taking into account individual factors and local exposure conditions to depict effective exposure risk. Further work should be undertaken to: (1) characterize the postural activity of highly exposed occupation and (2) develop (non-linear) exposure models to weigh the impact of posture and orientation to the sun on effective exposure.

A better understanding of the influence of specific outdoor activities on exposure should enable to better identify and monitor high-risk occupational situations. In the long run, job-exposure and activity-exposure matrices in regards of solar-UV should be developed.

Acknowledgements

We are indebted to the companies Epiney SA (Sierre, Switzerland) and Tapparel Alexis (Montana, Switzerland) who allowed us to perform exposure measurement on their worksites.

The authors acknowledge Dr. Laurent Vuilleumier (MeteoSwiss) for providing data and expertise in the field of ambient irradiation.

This work was supported by a grant from the worker and work relations protection office (SPT) of Valais.

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