Int Arch Occup Environ Health (2000) 73: 575–580

SHORT COMMUNICATION

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Bacillus subtilis spore film dosimeters in personal dosimetry for occupational solar ultraviolet exposure

Received: 21 October 1999 / Accepted: 10 June 2000

Abstract ***Objective:*** Ultraviolet (UV) radiation is noted to be one of the most important risk factors for non-melanoma and melanoma skin cancers. The recent development of a spore film test chamber containing spores of *Bacillus subtilis* resulted in a new method of UV measurement with a spectral sensitivity profile similar to erythema-weighted data calculated from spectroradiometric measurements. ***Methods:*** The practical application of dosimeters was tested on 11 persons for 43 days, under different conditions of UV exposure in five different geographical regions. Four professional lifeguards at a public swimming pool carried dosimeters attached to their shoulders or to their caps, for 11 days. Three mountain guides attached dosimeters laterally to their heads on 27 different occasions of mountaineering activity in different mountain regions. Four ski instructors carried lateral head dosimeters during eight days of skiing in the Alps. ***Results:*** The life guards received daily UV exposures ranging from 3.6 to 9.5 minimal erythema doses (MED) (mean 5.9, SD ± 1.9). The mountain guides had personal daily UV exposures of from 4.4 to 17.1 MED (11.9 ± 3.9) and ski instructors from 2.8 to 8.8 MED (6.1 ± 1.8). ***Conclusions:*** *Bacillus subtilis* spore film dosimeters can be applied effectively for personal solar UV measurements of occupationally exposed persons, such as lifeguards, mountain guides and ski instructors. UV levels in these occupations exceed international limits of exposure.

Key words Occupational UV radiation · Lifeguard · Mountain guide · Ski instructor · Occupational disease

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Introduction

An epidemic increase in skin cancer has been observed during the past decades in industrial countries with major Caucasian populations. A rise in non-melanoma skin cancer has been noted particularly in Australia, the United States, and central as well as northern Europe [20, 21, 30]. Ultraviolet (UV) exposure is considered to be the most important risk factor for development of non-melanoma skin cancer [20, 21]. In addition, there is increasing evidence that UV radiation (UVR) is also the most important environmental risk factor for development of cutaneous melanoma [2, 17, 29, 41]. High occupational UV exposure is assumed to be associated with skin cancer [26, 45–47], but we know of only one case recognized as work-related by the German Berufsgenossenschaften (professional associations) [38].

Numerous epidemiological studies have explored the relationship between skin cancer development and UV exposure [3, 7, 8, 16, 18, 22, 23, 25]. In these retrospective studies, quantification of UV exposure was a significant problem. Questionnaires concerning periods of sun exposure (daily, yearly, seasonal, recreational and so on) were constructed to estimate UV exposure of the persons studied. Technical measurements of UV exposure, however, were complicated and often unclear in such investigations.

The degree of sensitivity of the human skin is dependent on the wavelength of UV radiation between 250 and 400 nm [27, 32]. Biologically-weighted dosimeters integrating the UVR effect over the whole spectrum should simulate the relative sensitivity curve critical for human skin for each individual wavelength within this range.

Measurement of UVR is normally done by radiometers and spectroradiometers, which are instruments that use photo detectors to convert the incident radiation directly into an electric signal. Problematical is that a large number of measurements must be integrated, in order for data to be compiled to determine the minimal erythema dose [14].

Thin-film polymer (e.g. polysulphone) dosimeters have been used as small portable badges to monitor UV doses on mobile subjects. The optical absorbency of the film material increases in a dose-dependent manner upon exposure to UVR especially in the UV-B range (280–315 nm) [9, 19, 24]. Polysulphone dosimeters have been employed to determine the anatomical distribution of sunlight in dummies and living subjects during different occupational and recreational activities [11–13, 19, 24, 31, 40, 43].

Recently a new approach to UV dosimetry has been developed. The biological effects of UV light are measured by determination of the harmful effects on spores of *Bacillus subtilis*.

A Japanese group found a good correlation between spectral irradiance of solar irradiation and the inactivation of UV-sensitive *Bacillus subtilis* spores (TKJ6321) [34, 35]. The spores had been fixed on a membrane and attached to a slide mount or cardboard to measure ambient UV radiation and personal UV exposure [36].

A German group has incorporated the spores into a polyester spore film. After UV irradiation the spore film is allowed to germinate in culture. The proteins synthesized by the bacteria exposed to UVR are photometrically quantified and compared to controls with defined radiation exposures. With the application of this new method, standardized personal dosimeters have already been produced and tested under different conditions in stationary dosimetry [37–39].

A comparison of different dosimeters demonstrated that the spore film plus correction filter are effective between 290 and 380 nm. Thus this wide-spectrum dosimeter is able to complete minimal erythema doses (MED) measurements in the solar spectral UVB as well as in the UVA region. The Robertson Berger meter is sensitive for wave lengths between 300 and 355 nm, the region most important for erythema induction in solar radiation [9, 39]. Polysulphone and CR-39 films show sensitivities markedly too high compared with the MED curve between 312 and 330 nm. However, sensitivities are too low at wavelengths below 305 nm and above 335 nm [9, 39].

The aim of the present study is to confirm the practical applicability of the personal dosimeters and to estimate the UV exposure of lifeguards, mountain guides, and ski instructors under different occupational exposures and geographical conditions.

Material and methods

Dosimeters: The dosimeter system is enclosed in a plastic or an aluminum capsule with a diameter of 32 mm, a thickness of 9 mm, and a weight of 15 g. Preparation and processing of the spore film detectors (VioSpor, Blue Line Type II, BioSense, Bornheim, Germany) were performed as described previously [37, 39]. Briefly, the spore film (Fig. 1) is composed of dried spores of *Bacillus subtilis* which are immobilized on transparent polyester plastic sheets. The measurement zone is exposed during personal dosimetry, the calibration areas are irradiated with defined UV doses from calibrated UV sources. After irradiation the spore film is incubated in a growth medium, and the proteins synthesized during spore germination are stained and evaluated by photometry. The UVR response of the spore film is additive, consistent with the law of reciprocity in the investigated range. The biologically effective dose of each spore film is calculated using a calibration curve. The response is independent of temperature (−20 °C to 70 °C) and humidity. The spore film can be stored for several years at room temperature without significant changes [37]. The dosimeter system (VioSpor) integrates the UVR effect over the whole spectrum in the solar UVB and UVA region (290–380 nm) with a good correlation with the CIE/MED reference spectrum [15, 32, 39]. Thus the sensitivity of the spore film dosimeter represents the action spectrum for erythemal reaction in human skin. In cutaneous photobiology, radiant exposure is frequently expressed as 'exposure dose' in units of J/m^2. 'Biologically effective dose', derived from radiant exposure weighted by such an action spectrum, is expressed in units of J/m^2 (effective) or as multiples of 'minimal erythema dose'. One MED has been defined as the lowest radiant exposure to UVR that is sufficient to produce erythema with sharp margins 24 h after exposure. When the term MED is used as a unit of exposure dose, a

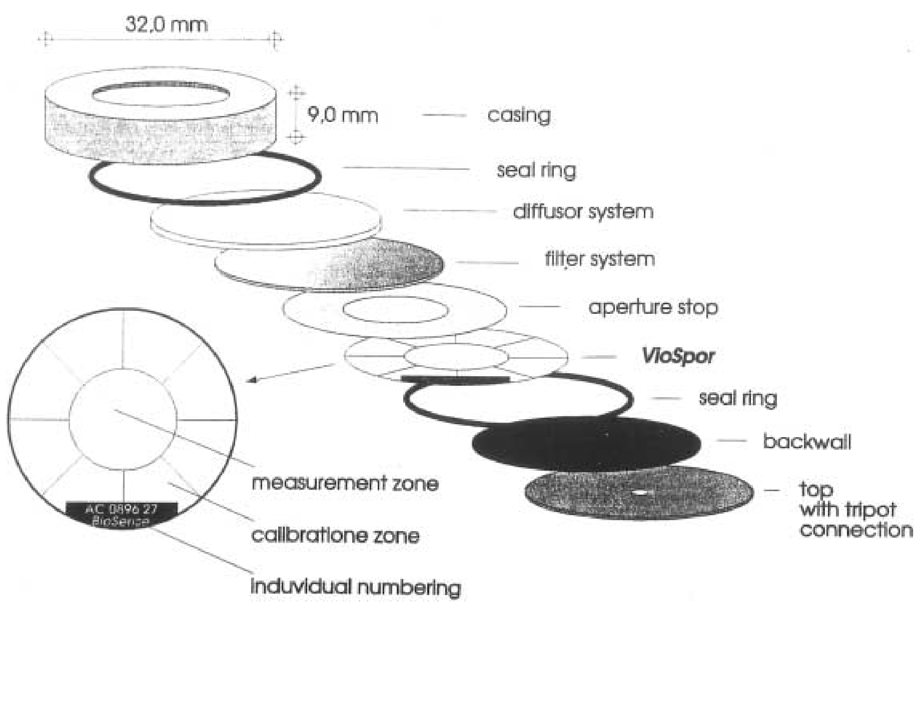

Fig. 1 Spore film dosimeter. Principle of construction

representative value is chosen for sun-sensitive individuals [26]. The MED will vary according to the wave length range over which the effective UVR is summed, and for radiation protection purposes is generally taken in the range 200 to 300 J/m^2 effective [14]. The UV doses measured by spore film dosimeters are given in "biologically-weighted" MED. One MED corresponds to 250 J/m^2 normalized to 298 nm.

Study subjects and dosimetry:

(1) Four professional lifeguards at a public swimming pool in southern Germany carried spore film dosimeters during their working shifts on 11 days in August 1997. The dosimeters were fixed either to their cap or shirt (shoulder) in a horizontal orientation. The lifeguards worked for 7 h 30 min to 13 h 30 min/day (mean 11 h 46 min ± 1 h 46 min). The weather was sunny on 8 days, cloudy on 2 days and overcast on 1 day. On one sunny day dosimetry of ambient UVR was performed simultaneously. A spore film dosimeter was horizontally placed on top of a building next to the swimming pool. Ambient UVR was measured including during rest and lunch breaks.

(2) Three mountain guides wore dosimeters on 23 different occasions of mountaineering activity in the Swiss Alps, in Alaska, in Bolivia, and in Tibet. In the Alps in April 1997, alpine skiing was the principal mountaineering activity. In these experiments altitudes varied from 1764 m to 4206 m above sea level. In Alaska, dosimetry was performed during a climbing expedition on Mount McKinley (6194 m) in May 1997. In Bolivia in August 1997, dosimeters were carried while the guide climbed Sajama (6542 m) and Huayna Potosi (6088 m). During an expedition to the Tibetan Himalayan mountain, Cho Oyu (8201 m) in May 1998, dosimeters were worn from 5700 m to 7100 m. The face is the most exposed part of an alpinist, therefore we chose a vertically oriented dosimeter attached to the side of the head. This orientation registers both incident UVR from the sun at moderately low solar elevation angles, and UVR reflected from the snow or ice covered ground (Fig. 2). The mountain guides in general started working before sunrise. They worked for 7 h to 18 h 30 min/day during their mountaineering activities (mean 10 h 40 min ± 3 h 12 min). On 6 days the weather was cloudy and overcast, on 2 days cloudy, and on 15 days it was sunny (two of them with fog).

(3) Four ski instructors carried lateral head dosimeters during 13 individual workshifts on eight different days of skiing in the French Alps (1800 m to 3600 m) in March, April and June 1998. Ski instructors were exposed to the sun for 4 h 15 min to 7 h 45 min/day (mean 7 h 5 min ± 1 h 6 min). The conditions were sunny on 3 days, overcast on 1 day, cloudy on another day and foggy on 3 days.

Fig. 2 Alpinist, lateral head dosimeter attached to glasses

Results

(1) The four lifeguards working at a public swimming pool had a personal daily UV exposure of 3.6 to 9.5 MED (5.9 ± 1.9) (Table 1). The lifeguards' work requires walking around an unshaded public swimming pool. Only one of them wore a baseball cap. In this case the dosimeter was attached to the visor, while on the others it was attached to one of the shoulders in a horizontal orientation. Personal dosimetry registered 55% of ambient UV radiation on a horizontal plane next to the workplace. The ambient radiation was 10.7 MED, including rest and lunch breaks.

(2) Dosimetry of mountain guides under alpine conditions measured a mean personal daily exposure of 11.9 MED (SD ± 3.9) (Table 1). Personal UV doses ranged from about 4.4 MED/day to more than 17 MED/day (4268 J/m^2). Doses of UV exposure during alpine skiing in the Alps were only slightly lower than exposure during climbing expeditions in Alaska, Bolivia, or Tibet. In the Alps, UV doses ranged from 4.4 to 16.6 MED per day and person. In the Mount McKinley (Alaska) area, doses from 11.4 to 17.1 MED/day were recorded. The mountain guide climbing in Bolivia (Mount Sajama and Huayna Potosi) registered UV doses from 9.1 to 16.0 MED/day. During an expedition to Cho Oyu in the Himalayas, daily UV doses from 5.5 to 16.0 were registered.

(3) The faces of ski instructors were exposed to UV doses in the range of 2.8 to 8.8 MED per day (mean 6.1 MED; SD ± 1.8) (Table 1).

The dosimeters were well accepted by all study subjects. No dosimeter has been lost. The subject performed their ordinary activities. Behaviour did not seem to affect the recordings.

Discussion

The aim of the present study was principally concerned with the practical application of personal dosimetry. Therefore, we used dosimeters on very different groups

Table 1 Occupational ultraviolet (UV) exposure of lifeguards, mountain guides and ski instructors. Number of subjects (*n*), days of measurements (days), exposure in minimal erythema doses (MED). Mean, standard deviation (SD) and range are given

	n	Days	MED		
			Mean	± SD	Range
Life guards	4	11	5.9	± 1.9	3.9–9.5
Mountain guides	3	23	11.9	± 3.9	4.4–17.1
Ski instructors	4	13	6.1	± 1.8	2.8–8.8

and situations of sun exposure. Professional lifeguards in public swimming pools were selected as examples of everyday exposure in our geographic region, while mountain guides and ski instructors were chosen as representatives of groups with extremely high solar exposure.

The measured relative exposure on the shoulders of lifeguards was 55% of the ambient UVR (10.7 MED). This fraction corresponds well with data from previous studies [24]. Their absolute daily exposure to UVR at the workplace averaged 6 MED, with a peak of 9.5 MED. In contrast, lifeguards in Australia, monitored by dosimetry, showed an average dose of 2.6 MED per day, with a relative exposure of only 0.12 on their shoulders [19]. These lifeguards used shelters and were educated in sun-protection behavior, which apparently led to the favorable reduction of occupational UV exposure.

The mountain guides presumably received the highest personal doses reported thus far in the literature [12, 13, 19, 24, 31].

In the mountain environment recreational alpinists and professional outdoor workers, such as mountain guides, ski instructors and other technical staff, encounter increased erythemogenic UVR due to increased effects of altitude and reflection from snow and ice.

Ski instructors received considerable UV doses, less however, than the exposures of mountain guides. Such differences might be due to lower altitudes, less outdoor time, protection from the sun in cable car cabins, for example. On one occasion in the past, personal exposure during skiing was monitored by UV dosimetry by another research group. About 70 J/m^2 (0.35 MED) was recorded, under clear and sunny conditions [12]. However, dosimeter badges were worn on the lapel, a site that is not representative of facial skin exposure during skiing.

An increase in elevation of 1000 m leads to an increase in UV irradiation of 9% at 370 nm and of 11% at 320 nm per 1000 m. This altitude effect increases dramatically to 24% at 300 nm. Light dispersion in air is more intense for short-wave UVR than for long-wave visible light. As a result, the proportion of (short-wave) UV-irradiation increases with increasing altitude [5, 6].

The albedo of a horizontal terrain is defined as the proportion of reflected radiation in relation to incident radiation. The highest values were found in new snow, where the albedo for erythemogenic UVB radiation reaches nearly 100%, even greater than the albedo for total radiation [4].

Climbing and skiing mountain guides and ski instructors permanently change altitude and encounter varying surrounding surfaces, so dosimetry of personal UV exposure cannot be correlated with 'static' measurements of ambient UVR at arbitrarily chosen locations. Therefore no measurements of ambient UVR were performed in the alpine workplaces.

Unintentional, undesirable UV exposure from the sun results in great part from occupational exposure. In particular, outdoor workers (e.g. construction workers, farmers, gardeners, sailors, policemen, lifeguards, ski instructors and mountain guides) are exposed to solar UV.

Annual exposure of indoor workers in northern Europe is estimated to be 100 MED (20% occupational, 50% daily leisure time, 30% during vacation time) [33]. One MED was defined as being equivalent to an erythemally weighted exposure of 200 J/m^2 [33]. For outdoor workers in general it is assumed that occupational exposure adds another 180 MED annually. However the author did not give his definition of MED [10]. In watermen, the personal average annual exposure of facial skin was estimated to range from 33–260 MED (1 MED = 350 J/m^2) [45]. However in this study, facial exposure was assumed to be 1% to 8% of ambient. Based on measurements of facial exposure of both mannequins and human subjects, it was suggested that the exposure of an unprotected face is probably close to 20% of ambient. Using this estimate, the annual facial exposure doses reported in the watermen outdoor worker group would be approximately 80–500 MED [26].

According to our results, we estimate the occupational exposure of a lifeguard to be more than 500 MED during a summer season (100 working days at 5 MED per day). Mountain guides with work-related outdoor exposure of about 200 annual workdays, are exposed to about 2000 MED per year. Professional ski instructors spend at least 100 days skiing per year. Their work-related UV exposure is an estimated 500 MED during a winter season.

For ultraviolet radiation exposure, threshold limit values (TLV) have been issued by the American Conference of Governmental Industrial Hygienists (ACGIH), the International Radiation Protection Association (IRPA) and the International Commission for Nonionizing Radiation Protection (ICNIRP) [1, 27, 28].

TLV's are given for defined wavelengths. However, exposure to solar UVR is cumulative over the whole spectrum. Theoretically, exposure to each wavelength could be measured with spectroradiometers, a procedure which is not practicable in personal dosimetry. For comparison, the integrating action spectrum of the spore film dosimeter, which is similar to the CIE/MED reference spectrum [32], was normalized at a defined wavelength (298 nm). At this wavelength, the TLV is about 80 J/m^2 per 8-h workshift, corresponding to approximately 0.3 MED. The occupational exposure examined in this study exceeded the TLV from nine to 53 times.

In the study of Maryland watermen, the estimates of individual annual and cumulative exposure to UVR were positively associated with the occurrence of squamous cell carcinoma but not with the occurrence of basal cell carcinoma [45, 46]. The risks of solar and ultraviolet radiation to humans are summarized in an IARC monograph [26]. There seems to exist an association between occupational solar UV exposure and non-melanocytic skin cancer. However, the distribution of basal cell carcinoma is not as closely related to the distribution of exposure to the sun as is that of squamous cell carcinoma. Chronic exposure as assessed through occupational exposure, appeared to reduce melanoma risk. Most studies showed positive associations with measures of intermittent exposure such as particular sun-intensive activities, outdoor recreation and vacation [26]. Thus high occupational UV exposure is assumed to be associated with an increased risk for skin cancer [47]. Skin tumors with a corresponding occupational UV exposure can fulfill the criteria to be regarded as an occupational disease (''Berufskrankheitenliste, Öffnungsklausel'', §551 Reichsversicherungsordnung) [47]. However, only one case was recognized by the German Employers' Liability Insurance (Berufsgenossenschaften) as work-related [42], in accordance with section 9.2 of SGB VII (social book of laws [44]).

In conclusion, the *Bacillus subtilis* spore film dosimeter was tested as a personal dosimeter to measure occupational UV exposure. Occupational UV exposure of outdoor workers, lifeguards, mountain guides and ski instructors, is far above international UV exposure limits. Mountain guides were exposed to the highest personal UV doses that have been measured up to now. UV doses encountered by lifeguards could be effectively reduced by protective means, such as shelters and sunscreens. High quality protection equipment and education in sun protection behavior is required for occupationally exposed persons, in order to prevent UVR-related skin damage and/or skin cancer, which should be considered an occupational disease, given confirmed exposure.

Acknowledgement We would like to thank all the mountain guides, ski instructors and life guards who participated in this study.

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