Photochemistry and Photobiology, 2018, 94: 900–915

Invited Review

Review on Nonoccupational Personal Solar UV Exposure Measurements

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Received 31 January 2018, accepted 25 May 2018, DOI: 10.1111/php.12946

ABSTRACT

Solar ultraviolet (UV) radiation follows people during their whole life. Exposure to UV radiation is vital but holds serious risks, too. The quantification of human UV exposure is a complex issue. UV exposure is directly related to incoming UV radiation as well as to a variety of factors such as the orientation of the exposed anatomical site with respect to the sun and the duration of exposure. The use of badge-sensors allows assessing the UV exposure of differently oriented body sites. Such UV devices have been available for over 40 years, and a variety of measuring campaigns have been undertaken since then. This study provides an overview of those studies which reported measurements of the personal UV exposure (PE) during outdoor activities of people not related to their occupation. This overview is given chronologically to show the progress of knowledge in this research and is given with respect to different activities. Special focus is put on the ratio of personal exposure to ambient UV radiation. This ratio, when given as a function of solar elevation, allows estimating PE at any other location or date if ambient UV radiation is known.

INTRODUCTION

People are exposed to solar UV radiation during their entire life. The major part of this UV exposure is unintended, while only a small part is intended (*e.g.* sunbathing). Moderate exposure to the sun induces vitamin D production, which is the main favorable health effect, but there are also other positive effects (1). In addition, UV radiation possesses therapeutic capabilities (*e.g.* heliotherapy of psoriasis), but according to solid experimental and epidemiological evidences (2,3), solar UV exposure is responsible for negative effects on skin (erythema, DNA damage, photoaging and photocarcinogenesis), on eyes (*e.g.* cataract) and on the immune system. The optimal amount of UV exposure is a recent research topic in photobiology (4,5). An important step toward the identification of situations of overexposure and underexposure is to ascertain the UV exposure of people under different circumstances.

Individual exposure depends on the levels of surface UV radiation (which varies with the geographical site, period of the year, time of day, meteorological conditions, etc.) and on behavior (*i.e.* activity, clothing, personal habits, duration in the sun, posture) which is partly influenced by the same factors that control the surface UV levels (weather, location, date, time, etc.) too.

For the above reasons, a specific exposure assessment is necessary. The most reliable method to estimate the individual UV exposure is by using the dosimetric technique, usually called personal UV dosimetry. Generally, the UV dosimetry implies the use of badge-sensors attached on specific body sites of the targeted population.

However, the quantification of human UV exposure is a complex issue and the use of dosimetry does not deliver an all-embracing answer at once, because the personal UV exposure (PE) is influenced by a variety of factors. For a certain activity, the measured PE depends on the body part where the dosimeter is placed, on exposure duration, on the period of the year and on the geographical location. It is only valid for these specific conditions. To conclude from the PE of a certain body site to that of another body site is not feasible because it is crucial to know the inclinations of that body site against the sun, and this is not easy to assess. However, it is conceivable to compare different exposure conditions and periods using the ratio between PE and the corresponding ambient UV exposure (*i.e.* UV incoming radiation on a flat horizontal surface over the same exposure time period of PE). This so-called exposure ratio to ambient (ERTA) provides the percentage of the ambient UV exposure received by the chosen body site (*6). The ERTA should be investigated as a function of solar height because then the PE can be calculated for any solar elevations (*e.g.* other latitudes, other season) utilizing ambient UV measurements.

During the past decades, a variety of studies have been conducted addressing specific aspects of human UV exposure. In this review, we focus on studies of nonoccupational UV exposure denoting all the exposure which is not connected to outdoor working activities. With that, the amount of nonoccupational exposure can be chosen and controlled (*e.g.* duration, time of the day) by people themselves. We will provide a chronological overview of all studies (to our knowledge) found in the peer-reviewed literature, highlighting the specific aspects of each study as well as its contribution to the whole issue. We will summarize the studies with respect to the ERTA as this parameter, in contrast to individual exposure values, allows comparison between different activities and to stress individual habits.

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LITERATURE SEARCH

Studies on nonoccupational PE published in the literature were identified via the search engines "Scopus" (Elsevier, The Netherlands) and "PubMed" (U.S. National Library of Medicine National Institutes of Health). Titles, abstracts and keywords were searched through with the terms "Ultraviolet personal exposure." More than 600 articles matched these parameters. Analysis of articles and cross-references led finally to a variety of papers which were attributed to 53 studies, whereas a quarter of these papers were published in this journal. Figure 1 depicts the number of studies over the past decades. These studies are listed in "Studies—References" in chronological order and marked with an asterisk inside the text.

CHRONOLOGICAL OVERVIEW

The first documented approach to estimate the UV exposure on the human body was undertaken by Frank Urbach in the 1960s (7). He used as a dosimeter a chemical material which changed color in dependence of UV exposure. The dosimeters were not placed on a human being but on the surface of a manikin head and exposed to natural solar UV radiation. Urbach showed that most exposed areas of the head and the neck are those where squamous-cell carcinomas predominantly occur.

The pioneering studies

Almost one decade later, Davies, Deane and Diffey (8) presented the first personal dosimeter for quantitative measurements of exposure to ultraviolet radiation. They employed a polysulfone film (PSF) dosimeter, a polymer which increases its optical absorbance in the UV range when exposed to UV radiation. The use of this dosimetric technique requires the calibration (*9) against solar UV exposures provided by a reference UV instrument (broadband radiometer or spectroradiometer). Shortly after that, the first study on PE was undertaken by Challoner and colleagues (*10) which delivered fundamental data on people's solar exposure. The authors focused on a targeted population with low levels of vitamin D due to UV underexposure, like housebound elderly people (11). However, they paid attention to the fact that relatively low exposure to UV radiation resulted in measurable levels of vitamin D (12). Thus, they divided housebound geriatric patients into those who were able to sit on the balcony in the sun and those who were not. On the other hand, the authors focused on gardeners who were outside most of the day and were at risk of increased skin aging (13) and of skin cancer (14). In addition, PE of laboratory workers was investigated, distinguishing between working days and weekends. The study started just after the summer solstice and lasted 2 weeks under fine weather conditions. The volunteers were equipped with PSF badges on the lapel. Calibration was performed against a Robertson–Meter UV radiometer (15) that monitored the ambient UV radiant exposure in parallel with the exposure of the dosimeters.

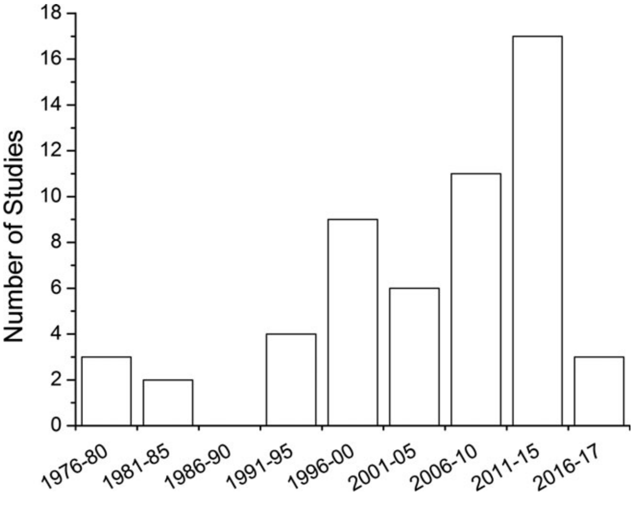

Figure 1. Number of studies on nonoccupational personal UV exposure.

Two of these authors prolonged the study from December 1975 to December 1976 (*16) by equipping 50 office workers with PSF badges on the lapel site. PE and ambient UV radiant exposures were measured for 2 weeks around both equinoxes and both solstices. Additionally, a housewife participated in the campaign. From these data, the authors retrieved the annual course of PE for the participants with the lowest PE, the mean PE of the office workers and the PE of the housewife who experienced the highest PE. The annual PE was also expressed in terms of ERTA.

In the same period, Corbett *et al.* (*17) took note of adverse effects from photosensitizing drugs because at that time about 60 oral approved drugs in the UK appeared to cause photosensitivity. PE of patients treated with phenothiazine was monitored, and adverse effects, the time spent outdoors and the time under the sun were recorded using diaries. PE and hours spent in bright sunshine were correlated with scored symptoms.

A few years later, Diffey and colleagues (*18) compared the UV exposure used in the photomedical treatment of psoriasis to that received under natural sunlight to estimate the carcinogenic risk with respect to actinic keratosis. Additionally, the effectiveness of sending psoriatic patients in winter to the Canary Islands was proven. Therefore, PE was measured during sun-seeking holidays in the Canary Islands (February) and for comparison at the island of Corfu (September), during skiing in Austria (March), and during sailing in Sweden (July). As before, PSFs were placed at the lapel site. For this study, Diffey and colleagues developed a special calibration procedure for PSF to correct for spectral sensitivity. Data of ambient erythemally effective UV radiation were provided by a so-called fast spectral model (19) using the erythema action spectrum derived by Mackenzie and Frain-Bell (20) as the weighting function. Altitude, albedo and cloudiness during measurements were used as input parameters for model calculations. This model delivers reliable values (*e.g.* 21,22) and is still in use with slight modifications (23) for a worldwide forecast of the UV Index (a unitless quantity used to provide the amount of UV radiation harmful to the public, *e.g.* 24,25). The authors investigated PEs of different activities during sun-seeking holiday (*e.g.* sitting by a swimming pool), and the exposure measurements were limited to intervals of 1 h. For skiing and sailing, PE was also analyzed with respect to weather conditions.

One year later, Holman *et al.* (*26) published a study focusing on occupational exposure and exposure during leisure activities of the eight most popular outdoor activities in Western Australia and sunbathing. Five PSF badges were attached each volunteer, and PSF badges were also used to measure ambient

UV radiation. A comparison between individual PE and those derived from dosimeters placed on a rotating manikin (27) led to the important conclusion that measurements on a manikin do not deliver appropriate values because some body parts (such as shoulders) receive more UV during human movement while other anatomical sites receive less, like the upper arm.

The 1990s: Improvement of the PSF dosimetric technique and alternatives to PSF

No studies on nonoccupational UV exposure were published over the following 10 years. However, there was an increasing interest on the assessment of PE because in this period the Commission Internationale d'Eclairage (CIE) issued a technical report (28) on personal dosimetry of UV radiation providing recommendations on the calibration and the usage of PSF dosimeters.

In the 1990s, it was a well-established practice to suggest to patients with psoriasis from northern Europe to go to the Canary Islands in winter for heliotherapy (*e.g.* by Finnish Social Insurance Institution). At the same time, Snelman *et al.* (*29) measured the PE of 10 Finnish patients with psoriasis who were sent to the Canary Islands in November. The PSF badges were worn near a particular psoriatic plaque during sunbathing. The ambient UV radiation was measured by a Robertson–Berger UV radiometer (30) which was oriented perpendicular to the sun to be representative for sunbathing. Both patients wearing PSF and patients without dosimeters filled in diaries the time spent to the sun to estimate indirectly the PE values.

As an alternative to PSF, Wong *et al.* (*31) used CR-39 dosimeters (32) for PE measurements. The CR-39 is another chemical UV-sensitive polymer, like PSF, which undergoes a change in absorbance which can be measured. This type of dosimeter was also very small in size, like PSF. The authors placed 117 dosimeters on the head of a life-size manikin. This approach delivered a highly resolved exposure pattern of the human head. Additionally, they equipped indoor and outdoor workers with these dosimeters at the wrist, mainly to demonstrate the applicability of these devices in PE measurements. Only personal exposure values related to those anatomical sites were reported.

Driven by the concern on detrimental effects from environmental UV radiation as a possible consequence of ozone depletion at middle latitudes observed since the 1970s (33), and after the discovery of the Antarctic ozone hole in 1985 (34), Herlihy *et al.* (*35) conducted a study in Australia. The PE of 94 volunteers was measured at seven anatomical sites during six different outdoor activities (tennis, sailing, swimming, walking, golf, gardening) using PSF. Ambient erythemally effective UV exposure (defined as the integrated erythemally weighted irradiance over a specified period of time) was determined by UV irradiances measured with a spectroradiometer. Before the field dosimetric campaign, participants were asked on their sun behavior during the weekend before to make sure that there is no change in behavior due to their study participation (so-called Hawthorne effect, *e.g.* 36). Participants filled in a diary on their activities, clothing, sunscreen use, surrounding environment and other issues. The authors calculated the PE of participants from information indicated in the diaries and from ambient UV measurements. The agreement between measured and calculated PE was good for unshaded open field activities (*e.g.* tennis and sailing) but not satisfactory for shaded environments (such as gardening).

On the other side of the globe, Knuschke and Barth (*37) studied the PE of indoor workers, housebound people of a nursing home and bedridden people who may be at risk of vitamin D deficiency in Germany. The spectral calibration procedure as proposed by CIE (28) was carried out taking into account the spectral change of sunlight when penetrating window glass for PE measurements of bedridden people.

Kimlin *et al.* (*38) studied the influence of the geographical location on PE comparing measurements made at two sites with different altitudes, but at the same latitude. Homeworkers, schoolchildren and outdoor workers in two relatively nearby cities were equipped with PSF placed at the shoulder. A significant difference in ambient UV was found, which was reflected also in PE. The authors confirmed the finding of Diffey *et al.* (39) that the ambient UV, although showing geographical differences, is not the only relevant parameter affecting PE. Even within the same targeted population (*e.g.* homeworkers), the type of activity, behavior and attitudes may be different at the two locations. An interesting outcome of this study was also that the PE of homeworkers is composed by many short exposures, which gives a completely different exposure pattern with respect to that found in most other groups.

In the mid-1990s, first approaches were undertaken to measure PE with high temporal resolution by developing an electronic personal UV meter. In 1994, Naggar and colleagues (40) presented a prototype of a button-like device which was designed for the use in arctic regions. However, the high price of this meter seems to have inhibited the dispersion of this device. No PE measurements could be found in the literature. Diffey and Saunders (*41) used a sensor connected to a separate data logger and presented measurements (southwest France, 43°N) with a temporal resolution of 2 s during a walk in the sun (on the beach) and compared with that taken in shady places (between trees). Further, they measured PE through an open car window during a 1 h lasting journey. This electronic device was well characterized and calibrated including the spectral response, angular response and linearity. A calibration matrix, which accounts for changes in the solar spectrum by taking into account changes in total ozone and solar elevation (*e.g.* like for broadband meters, Ref. 42), was introduced in PE measurements later by Schmalwieser *et al.* (43) because during long-term studies total ozone changes significantly at any location.

In the following years, the size of the sensor was reduced and different filters were used to mimic other spectral sensitivities than that of erythema (44,45) like pigmentation. However, the size of the data logger and the high price of such an electronic personal UV meter restricted application.

The cheapest method to estimate PE is a self-reported sun-exposure record (*e.g.* diary). However, the reliability of such records and retrieval of PE data is a matter of concern. Several groups of researchers have proven the reliability in different age cohorts (*35,46,47). This was also a task of the study undertaken by O'Riordan and colleagues (*48). They investigated the UV exposure of mothers and young children (less than 1 year of age) as well as the correlation between measurements (PSF) and estimates from self-reported exposure from Friday to Monday. However, the authors were not satisfied with the extent of agreement. Ambient exposure was recorded by PSF placed on horizontal surface and the calibration was performed using spectral measurements as before (*35,47,49). The results indicated that exposure of mothers was higher because they spent longer periods outside. Further, they found the wrist is a very practicable mounting position, especially for the infants.

At the same time, Thieden *et al.* (*50) investigated the reliability of measurements at the wrist in more detail using VioSpor badges (Biosense, Germany) (51,52). The VioSpor badge consists of a UV-sensitive detector, a special optic filter system and a protective casing. The UV detector of the VioSpor badge is a monolayer of spores which are damaged when exposed to UV irradiation. UV exposure is assessed by a densitometric quantification of produced proteins after stimulating the spore germination on the film surface. The capability of VioSpor detector is to allow long-term exposure measurements without the need of frequent replacements as is the case for PSF, which can be used only for limited exposure periods (*53). Participants wore the badges for one day at the beach (near Copenhagen) on several body sites and during a holiday (in Denmark and anywhere else in Europe) period of two weeks on top of the head (cap) and on the wrist. Ambient radiation was measured in Copenhagen with a Robertson–Berger meter (Biometer Model 501; Solar Light Inc.) and in parallel with a VioSpor badge. Thieden *et al.* (*50) showed that the exposure at the wrist is around 50% of that of the head and that the coefficient of variation is smaller than at the shoulder, upper arm or chest.

Parisi *et al.* (*54) conducted an analysis on the difference between weekday and weekend exposure of outdoor workers, indoor workers and adolescents. PSF dosimeters were worn on the shoulder and measurements were taken at three dates during the year. The rationale of this study was to develop prevention programs. The results reinforced the importance of targeting prevention programs to both weekend and weekday UV exposures.

Participants in long-lasting sport championships conducted in summer are predestined for high exposure. In this context, Moehrle *et al.* (*55) measured the PE of professional cyclists during the "Tour de Suisse" cycling race in June 1998. Six professionals were equipped with the VioSpor badge placed on the back, between the shoulders. PE up to 17.2 MED day^{-1} have been measured, whereas the minimal erythemal dose (MED) was assumed as 250 J m^{-2}, which corresponds to 2.5 SED (standard erythema dose, 56).

In the following year, Moehrle (*57) equipped four participants of the Ironman Triathlon World Championships 1999 in Hawaii (3.9 km swimming, 180.2 km cycling, 42.4 km running) with one VioSpor badge each on the back between the shoulders to measure PE during cycling and running. These athletes were overexposed not only during the championship but also during the time they spent for training (~20 h week^{-1}).

The 2000s: long-term exposure measurements and electronic devices

In 2001, Thieden *et al.* (*58) presented PE measurements (using VioSpor badges) at the wrist of indoor workers during a working period and during holiday. A sun-exposure diary was provided to the participants who filled in information on the location and clothing with a temporal resolution of 30 min. The campaign lasted 11 weeks in 1998. Besides the study conducted by Diffey *et al.* (39) on children, Thieden's study was the second longest research on PE. The analysis of PE was carried out with respect to gender, age and skin type, but no correlation was found. This study showed that the main factors influencing PE are time spent outside and holiday destination, reflecting the individual habits of the people.

At this time, the evolution of microcomputers and of UV-sensitive photodiodes offered new prospects. In 1998, Autier *et al.* (*59) developed a small electronic device (9.5 × 6.0 × 2.5 cm). This meter consisted of two different photodiodes. One was sensitive in the UVB, the other one in the UVA. Measurements of both diodes were stored separately every 20 min. Autier *et al.* investigated the influence of sunscreen use to intentional UV exposure during holidays. They found that participants who got a sunscreen with higher SPF stayed longer in the sun than those which received a lower SPF.

The research team from the Bispebjerg Hospital in Copenhagen developed a miniature electronic UV meter (SunSaver) similar to a wristwatch which can be easily worn (60). This device enables one to record UV *vs* time over longer periods (months). From 1999 to 2001, volunteers (children, adolescents, indoor workers and outdoor workers; 340 people in total) wore the SunSaver from spring to autumn (*61). The dosimeters were calibrated in summer against a broadband UV meter (Biometer Model 501; Solar Light Inc.) on five cloudless days. Volunteers answered six questions every day, with the main focus on risk behavior (beach, sunbathing, exposing shoulders or uncovered upper body, sunburn, sun screen use). Thieden *et al.* (*61) analyzed PE with respect to gender, age and profession, distinguishing between working days and off-work days. Monthly values of ERTA were delivered from April to October. A further analysis was performed to estimate the percentage of lifetime UV exposure during different stages of life (62). Another analysis (63) focused on sunburns and the risk behavior.

Thieden *et al.* (*64) prolonged above studies to the winter season. About 20 indoor workers wore the SunSaver for a whole year and filled in a diary. They found out that exposure of Danish indoor workers is low and they do not need precaution between November and February. Only during holidays at destinations lower than 45°N latitude, people can be at risk.

Shortly after that, Thieden *et al.* (*65) compared the exposure of Irish and Danish gardeners during working and during leisure time. Ambient radiation was measured with a Biometer Model 501 in Copenhagen and with a SunSaver in Dublin. Although ambient UV is higher in Dublin, the Danes experienced almost twice as much PE with respect to Irish gardeners during leisure time because they spent more time outdoors. Furthermore, Thieden *et al.* (66) analyzed sunscreen use in relation to PE and proved compliance and reliability of diaries with PE measurements. An overview of these studies can be found in the publication of Thieden (67).

Shortly after the research group in Copenhagen had developed a miniature electronic personal meter, a similar instrument was built in the United States. In December 2000, Rigel *et al.* (*68) equipped ten professional skiing instructors with a two-channel (UVA and UVB) electronic wristwatch-like meter (Advanced Medical Electronics Corp., Fridley, Minnesota) to estimate PE of people in a typical alpine site in the United States. Devices were placed on the distal arm, anterolateral forearm and wrist. Measurements of the UVB channel were studied with respect to the erythema while those of the UVA channel with respect to the melanogenic efficiency. Ambient UV was not measured and no information on the calibration and the characterization of the instrument was given.

In 2004, Allen and McKenzie (*69) assessed PE using a (self-developed) small-size electronic meter attached on the lapel of the skier ski-suit. The calibration and the characterization were described in detail. However, measurements were compared to ambient UV radiation from a distant location at sea level.

An unbeatable advantage of such electronic meters is the high temporal resolution in conjunction to an unlimited duration of its usage. In combination with diaries, temporally resolved PE measurements provide the ability to identify behavior patterns, for example the risky behavior or risky situations, where PE exceeds the individual MED within a certain period (*e.g.* >2.5 SED per hour as defined by Thieden *et al.* (*63) or 10 SED per day in tanned people as used by Schmalwieser *et al.* (43).

Outdoor recreational activities, like cycling, are pursued for health benefits for several reasons, but there may be the risk of UV overexposure. For this reason, Kimlin *et al.* (*70) conducted a study on the exposure of 22 cyclists during a seven day charity ride (approx. 7 h day^{-1}) from 23°S to 27°S around the winter solstice. Every participant wore four PSF each on head, backs of hands and ankles). PE was reported in MED and in relation to the top of the helmet. Here, 1 MED was 200 J m^{-2} (2 SED). It was found that the ankle, the back of the hand and the side of the head received on average 51%, 71% and 64% of the UV exposure on top of the helmet. The mean PE was 1.80 MED day^{-1}.

In a pilot study, O'Riordan *et al.* (*71) validated self-reported UV exposure and additionally sun protection practices among lifeguards, parents and children at a swimming pool in Hawaii in 2005. PSF was clipped on the wrist and also used to measure ambient UV. Again it was found that a time resolved diary delivers good agreement with the exposure measurements. In summer 2006, Glanz *et al.* (*72) repeated the validation of self-reported UV exposure involving more than 500 participants (lifeguards, parents and children) at 16 pools in the United States over 4 days covering the weekend. As the main purpose of measurements was to validate diaries and questionnaires (daily time spent outdoor between 10:00 and 16:00), PE and ERTA were given only as mean values for the whole United States with no further distinguished with respect to location or date. The authors reported a good agreement between measurements and diaries records and a moderate agreement between measurements and the survey, which had only few questions.

Chodick *et al.* (*73) investigated the reliability of diary records as a cheap possibility for epidemiological research. In this study, 125 radiologic technologists (some retired) from two regions in the United States were equipped with PSF on the left shoulder. The field campaign was carried out in September 2004. Ambient UV was measured with PSF. Diaries were filled in 30 min intervals on seven consecutive days, separating week days from weekend. The diary comprised the type of activity, shading, clothing and sun protection. They found a significant correlation between PE and the reported time spent outdoors.

Behavior outdoors and thereby UV exposure is influenced by weather. Therefore, Cahoon *et al.* (74) analyzed PE measurements with respect to meteorological parameters. It was shown that increasing wind speed, as well as an increase in relative humidity, leads to a lower PE. In the case of temperature, PE increases first, but seems to go down after a certain temperature is exceeded. Something similar to that was found for beach goers (75).

Another important meteorological parameter for UV exposure is snow. During the snow-covered period, the synergetic effect of high altitude and albedo can lead to high UV exposure (76,77). This exposure may even increase in the presence of broken clouds and may become higher than that under clear sky conditions (78). A change of skin color is a frequently observed phenomenon after exposure to solar UV like after a skiing holiday. Siani *et al.* (*6) equipped skiing instructors and skiers with PSF on the forehead in winter and in spring. ERTA was derived every 2 h from 10:00 to 16:00. This was the first study which showed the change in skin color (expressed in L*a*b* tristimulus system, Ref. 79) after exposure at the skiing field. Additionally, this is one of the few studies where daily course of irradiance is expressed in units of the UV Index (80,81). This gives a straightforward connection to the WHO suggestion of using the UV Index as a tool for sun protection (25).

PE is a complex issue as it is directly linked to personal behavior. Siani *et al.* (*82) investigated whether systematic differences exist in already suntanned, nontanned and abnormally high photosensitive beach goers. Besides PE (PSF at the chest), changes in skin color, in skin temperature and in free radical amounts were monitored during a day at the beach. Interestingly, PE (ERTA) did not differ between the three groups. This indicates that knowledge on sun sensitivity does not influence behavior.

One of the rare studies with respect to the positive effects of UV was undertaken by Downs *et al.* (*83). The authors studied the PE of golfers on the upper body in the late afternoon using PSF calibrated for vitamin D photosynthesis (84) and erythema (85). Results (PE and ERTA) were presented as a function of solar elevation and day of the year and can be used for modeling. Only a few studies achieved this useful result for further application.

Approximately at the same time, Hall *et al.* (*86) investigated the annual course of PE and of vitamin D concentration in the blood. Volunteers, students of different skin phototypes, wore PSFs on the wrist. Ambient UV was measured with PSF next to a broadband meter type UVB-1 (Yankee Env. Instruments). The authors estimated from PE measurements the necessary oral vitamin D intake in dependence on the time of the year and skin phototype.

The role of PE in determining the vitamin D status was investigated at this time also in the UK. Webb *et al.* (*87) equipped participants with PSF on the upper chest or anterior shoulder. Measurements took place in spring, summer autumn and winter. Weekdays and weekend were distinguished. As this study focused mainly on the vitamin D level of volunteers, PE values and ERTA values have not been published.

The 2010s: Clothing and behavior

The PE on top of the helmet of five cyclists during their training schedule was measured using VioSpor badges by Serrano *et al.* (*88) on a couple of days in summer days and in late winter. Exposure values have been reported which are close to those measured on a horizontal plane.

In their next study, Serrano *et al.* (*89) investigated the PE of mountaineers and a few tennis players and runners by VioSpor badges placed on the cap and the wrist. Ambient UV was measured by a UVB-1 (YES Inc.) applying a calibration matrix which takes into account total ozone and solar elevation (90,91).

Although PE measurements lasted only a couple of hours, no information on time or solar elevation was provided. One year later, Serrano *et al.* (*92) repeated the same study. Ambient erythemal UV for locations away from a broadband meter was taken from the Giovanni online data system.

Snorkeling may be one of the most risky leisure activities with respect to sun exposure. Downs *et al.* (*93) investigated the exposure of tourists at the Great Barrier Reef during spring and summer months (September to January). The PSF was also calibrated on the air–water interface as these were mounted at the neck and the back of the snorkelers. PE was analyzed for SZAs from 0° to 25° and from 26° to 50°. Exposure on the neck went up to 1.0 SED/10 min and on the back up to 0.6 SED/10 min. Ambient radiation was measured on land with a Biometer model 501.

One of the authors (*94) investigated the UV exposure during typical lifestyle behavior (walking, cycling, sightseeing, shopping, sitting in a sidewalk café, or at a swimming pool) in an urban environment using an electronic two-channel instrument (X-2000; Gigahertz Optics, Germany) clipped on the chest. The erythemally effective irradiance is gained by the combination of the UVB and the UVA channel. A calibration matrix with respect to total ozone and solar elevation was applied as described by Schmalwieser *et al.* (43). PE was analyzed with respect to solar elevation, sunburn times for different phototypes and UV Index. It was shown that the ERTA (Biometer Model 501) depends on duration: As shorter the period, the higher the ERTA can be.

Weihs *et al.* (*95) investigated the exposure of six different body sites during basic activities as lying, sitting up, sitting, standing and walking using the same electronic meter. Due to a high temporal resolution, even the exposure pattern of the moving arm during walking becomes visible. This study showed the influence of posture and orientation to the sun on the exposure of different body areas. Other studies using the X-2000 dosimeter for recreational PE have been made for a family on a beach holiday (*96) and for tennis players (*97).

Another study of Serrano *et al.* (*98) focused on skiing. Ten children were equipped with VioSpor badges at the top of the shoulder: The campaign took place in late December. The chosen body site did not allow any inclusion for the face. Ambient UV radiation was calculated by a radiative transfer model (FastRT, Ref. 99), using the meteorological conditions of each day as input parameter.

VioSpor badges were also used by Curtis *et al.* (*100) to measure the PE of cyclists (Utah). In a short communication, values in MED were presented and compared to vitamin D serum levels. Also the sun protection by worn jerseys was investigated.

Cargil *et al.* (*101) focused on the validation of a brief questionnaire by objective measures of PE, of colorimetric skin pigmentation and of vitamin D serum concentration in volunteers aged 45 years and over. Correlation analysis was presented but no measured values of PE or ERTA were reported. It was shown that the questionnaire correlated with these observations to a satisfactory extent.

A large progress in investigating the influence of personal behavior and country-specific differences on PE was made in a European project (ICEPURE) which took place between 2010 and 2013. Besides occupational and recreational PE of adults, PE of children was also studied. Volunteers of different nationalities were sent for a skiing (Danes and Austrians) and for a beach holiday (Danes and Spaniards). A very valuable analysis of PE including temporal resolved records of activities and clothing during a beach holiday was presented by Petersen *et al.* (*102). The daily courses of PE (SunSaver at the wrist) from 25 Danish volunteers at the Canary Islands in March were analyzed. From these, very detailed behavior patterns could be derived, showing where tourists spend their time, specifying the activity and type of clothes worn in time steps of 30 min. The comparison between Danish and Spanish volunteers shows that Spaniards receive lower PE. It was found that the Spaniards spent less time on the beach and receive comparably lower PE (*e.g.* use of parasols) than the Danes. Differences in behavior between Danes and Austrians could be also observed during a skiing holiday in Austria (*103). Also here, the Danes were longer time outside and have shown an every-moment sun-seeking attitude. Besides PE, changes in vitamin D level and DNA damage (due to UV-induced formation of T-T dimer) during these short term holidays were investigated (*104). Changes in skin pigmentation have not been published yet.

An attractive recreational activity for Europeans to escape unpleasant winter weather is golfing in southern destinations like Spain. Golfers spend several hours outdoors in an open environment. Gurrea Ysasi *et al.* (*105) equipped fair-skinned volunteers with VioSpor badges at the wrist and at the top of the cap. It was shown that PE can exceed the individual MED of skin types I and II (2 SED) even in January.

It was shown earlier that marathon runners may receive high PE during a contest. However, many training sessions are necessary before participating in such a competition. Nurse *et al.* (*106) equipped marathon runners with electronic meters (*69) during training to identify exposure patterns. Measurements showed that PE is rather low because the training took place in the morning and late afternoon hours. Results are also applicable to the more popular jogging, a typically fitness sport of office workers.

Outdoor behavior and PE depend strongly on weather. Xiang *et al.* (*107) investigated the influence of air temperature, humidity and ambient UV radiation on weekend exposure in four cities in Australia (AusD-Project, 108). Volunteers were equipped with PSF on a wristband and filled in a diary to document time spent outdoor and the clothing on different body parts on an hourly base. A regression analysis was performed but without detailed information on PE values. A reasonable suspicion occurs that at a certain temperature, people reduce PE due to high temperature. This analysis expanded that of Sun *et al.* (*109) where it was shown, as many times before, that ERTA changes with season and with latitude. Both may be influenced by weather.

Extreme UV radiation environments can be found in alpine regions with high albedo. Several of them have been made easily accessible for the public in summer for skiing. Casale *et al.* (*53) investigated the PE at an Alpine site (3500 m asl) in July where ambient irradiance exceeds 12 UV Index. ERTA of most skiers (vertical on the cap) was close to 100%. Due to the application of sunscreen, no immediate change of skin color was observed in participants. Besides PSF, poly–dimethyl phenylene oxide dosimeters (8) have been used. This polymer-based chemical dosimeter has similar properties like PSF, but has a larger dynamical range (110).

The omnipresent smartphones are ideal as sun-exposure diaries because they are always with the participants. Køster *et al.*

(111) have investigated the feasibility of smartphone diaries by PE measurements from wristwatch-like electronic miniature UV meters (*69) in Denmark. Later, they (112) analyzed the effects of smartphone diaries and personal dosimeters on behavior of the volunteers. Finally Køster *et al.* (*113) presented a validated sun-exposure questionnaire. For this, more than 660 participants (aged 15 to 65 years), reflecting a representative sample of the Danish population, have worn electronic dosimeters. Measurements (expressed in SED) were analyzed in dependence of gender, age, education, location and others. This provides a detailed exposure pattern of the Danish population. An interesting detail of this study is the following: As shown by several studies, there is a good correlation between the duration spent outdoors reported by questionnaire and duration spent outdoors measured by the dosimeter. However, the duration from the questionnaires is several times longer than that measured. The authors did not comment that fact.

Wainwright *et al.* (*114) used a dual film dosimeter which contains a PPO film and an 8-methoxypsoralen film (8-MOP) (115). The dosimeters were calibrated for erythemal UV (PPO), vitamin D effective UV (PPO) and for UVA (8-MOP). Around 30 indoor office workers have worn the dosimeter horizontally on the shoulder for one week in each season. It was shown that erythemal and vitamin D effective PE was highest in spring followed by summer autumn and winter. PE from UVA was highest in autumn, followed by summer, winter and spring. This exposure patterns are hard to explain, maybe by seasonal-dependent behavior. Measured PE of the participants differed partly by a factor of 1000 within a season.

The latest development in UV dosimetry is a very thin, soft, stretchable, epidermal sensor which is stuck on the volunteers like an adhesive plaster (*116). The patch changes color due to photochemical reactions initiated by UV radiation. Quantitative exposure values are gained via smartphone camera (taking a picture of the patch) and a provided smartphone app which sends the data to a central computer. Some quantitative measurements gained during beach activities and during walking were presented.

SUMMARY ON EXPOSURE RATIOS

Exposure ratio

Already in the first study (*11), the measured PE was set in relation to the ambient exposure measured on a horizontally oriented plane H_{amb} with the same device. For a certain activity (*act)*, this ERTA depends mainly on the inclination between the body site and the sun when the surrounding is similar. Such an ERTA can be used to calculate the PE for the same body site (*BS)* and the same solar elevation (but at different dates, locations, etc.) by multiplying ambient UV exposure H_{amb} and ERTA. If the ERTA is given as a function of solar elevation (*sh)*, then the PE can be calculated for any solar elevation, any date, time and location from ambient UV.

$$\mathrm{PE}_{act,BS}(sh) = H_{amb} * \mathrm{ERTA}_{act,BS}(sh)/100$$

To calculate the PE of a certain body site from the PE of another body site is not a simple issue and needs a sophisticated body model.

The ERTA indicates on a first glance whether exposure is generally high or not. Values of ERTA are generally ranging between 0% and 100% but can exceed 100% if the body site is oriented to the sun or if it receives reflected UV radiation from the ground. Aside from the anatomical site, activity and solar elevation, the ERTA depends also on a first order on the duration of exposure. The shorter the duration, the higher can the ERTA be (*94). Cloud cover of the sun decreases ERTA to values below 100%.

Further on, it is worth mentioning that the frequency distribution of PE and ERTA of a group of people rarely follows a normal distribution. In general, the distribution shows skewness (often positive). Therefore, the frequently used mean and standard deviation are not appropriate descriptors. During this review, we found examples that reported standard deviations were larger than the mean or median value, denoting a certain probability for negative PE. Appropriate descriptors are at least the extreme values of the range values, and the mode or median as well as percentiles. Inappropriate statistical descriptors are the mean (average) and the standard deviation.

Exposure ratio in dependence of activity

PE was measured for around 30 different activities at 15 different positions all over the body. Unfortunately, there are only a few studies on the same activity that used the same position at different solar elevations or different position at the same solar elevation. Therefore, similar studies do not complement each other. In the following, the knowledge on the ERTA for the different activities is summarized.

Commonplace exposure. Everyday UV exposure in general does not last long and it is either intended or not. Short distances are often covered by walking (Table 1). It was shown that ERTA on the face, neck and décolleté (*94, *95) during a short walk can reach 112% in the morning and afternoon. At higher solar elevations, the ERTA becomes lower (70%) and a longer duration of walking also lowers the ERTA, till 30%. The same is valid for shopping and walking in an urban environment where the ERTA is significant lower due to the obstructed horizon (*94).

Another possibility to cover short distances is cycling. ERTAs of the head region are similar as for walking (*94). Thigh, calf and arms may receive UV radiation similar like during sitting.

Longer distances can be accomplished by motor vehicles. Interestingly, only one rudimentary PE measurement has been taken till today for motoring (*41), only studies using manikins. Window glass absorbs UVB (117) but open windows or open sun roof leads to remarkable exposure (118). In convertibles, ERTA reaches that of sitting in the sun. Although protective clothing is expected when driving a motorcycle or a moped, drivers can often be seen in shorts and T-shirts, especially in summer. From the body posture, it can be expected that arms and legs are similar exposed as during sitting or during cycling. Open helmets will lead to an exposure of the head region similar to cycling. However, no measurements are available.

Taking a break during the day from work and sitting outside on a seating accommodation or on the lawn (sitting up) entails that head and chest have ERTA = 30%, and shoulders have ERTA = 50%, but the thighs have ERTA = 60%, and in the second case, the shin has ERTA = 60% (*18, *95). Resting in a

Table 1. Exposure ratio to ambient (ERTA) (expressed in %) for commonplace exposures. Listed is also the range of ERTA if provided by authors. Some studies provided ERTA for a certain range of solar heights (sh min–sh max)—which are independent ("indep.") of the time of the year—together with time span. For others, time of the year and duration of measurements are given.

Activity	Body site	ERTA mean (%)	ERTA range (%)	Time of the year	Duration	sh min (°)	sh max (°)	Location	Ref.
Walking	Chest	69		indep.	10 min	45	70	Vienna, AUT	Schmalwieser *et al.* 2010a (94)
	Chest	45			1 h	45	70		
	Chest	112			10 min	10	30		
	Chest	35			1 h	10	30		
	Chest	25	13–35	indep.	>1 h	46	64	Vienna, AUT	Weihs *et al.* 2013 (95)
	Forehead	28	10–59		>1 h				
	Shoulder	50	30–96		>1 h				
	Upper arm	17	7–48		>1 h				
	Thighs	24	13–32		>1 h				
	Lower leg	10	2–27		>1 h				
Cycling every day	Chest	72		indep.	10 min	45	70	Vienna, AUT	Schmalwieser *et al.* 2010a (94)
	Chest	35			1 h	45	70		
	Chest	70			10 min	10	30		
	Chest	26			1 h	10	30		
Sitting	Lapel site	42		indep.	11:30–16:00	26	47	Lanzarote	Diffey *et al.* 1982 (18)
	Forehead	31	15–57	indep.	>1 h	46	64	Vienna, AUT	Weihs *et al.* 2013 (95)
	Shoulder	53	29–95		>1 h				
	Chest	29	15–54		>1 h				
	Upper arm	14	6–21		>1 h				
	Thighs	57	48–60		>1 h				
	Lower leg	7	6–22		>1 h				
Sitting up	Forehead	59	40–77	indep.	>1 h	46	64	Vienna, AUT	Weihs *et al.* 2013 (95)
	Shoulder	32	28–71		>1 h				
	Chest	46	40–52		>1 h				
	Upper arm	11	4–30		>1 h				
	Thighs	66	51–69		>1 h				
	Lower leg	56	52–67		>1 h				
Shopping	Chest	17		indep.	10 min	45	70	Vienna, AUT	Schmalwieser *et al.* 2010a (94)
	Chest	7			1 h	45	70		
	Chest	36			10 min	10	30		
	Chest	23			1 h	10	30		
Sidewalk cafe	Chest	71		indep.	10 min	45	70	Vienna, AUT	Schmalwieser *et al.* 2010a (94)
	Chest	51			1 h	45	70		
	Chest	98			10 min	10	30		
	Chest	58			1 h	10	30		
Gardening	Cheek	15		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Spine (thoracic)	23							
	Dorsum of hand	24							
	Ant. thigh	22							
	Post. calf	17							

side walk café may lead to ERTA of up to 100% on the chest (*94).

During gardening (*26) and outdoor repair work, the hands, back and shoulders have the highest exposure, whereas ERTA = 25%. However, ERTAs are not yet resolved with respect to solar elevation and duration.

Sports. Sport is recommended for general health benefits for many reasons (Table 2). There are large differences in the popularity of different sports by countries, by the social and economic status as well as by the gender and age of a person. For some sports, a dress code is expected. Exemplary for a culture-dependent popularity and a dress code is cricket. Holman *et al.* (*26) have used the cheek and the dorsum of the hand as measuring positions because only parts of the face, the forearm and the hands (if not covered by gloves) are exposed during the game. For solar elevations between 18° and 73°, the ERTA was 18% on the cheek and 32% at the dorsum of the hand. Another clichéd sport is golf. Four studies have been undertaken (*26, *35, *61, *83, *105), but ERTA on comparable or the same positions shows large variations. This may be caused by the surrounding vegetation or by weather conditions.

Playing tennis in a tank top may cause high exposure on the shoulders (ERTA = 60%). For hands and legs, the ERTA is around 40% and 30% for the face on average. However, players are directed to opposite sides during a match so that big differences could appear. Maier *et al.* (*97) reported an ERTA on the forehead from 70% to 100% when the player is directed toward the sun and a much lower ERTA when the player is directed away from the sun. Therefore, the mean ERTA may not represent the risk for overexposure because the mean ERTA may overestimate, for example, the sunburn time. Two (*35, *92) of the five studies on tennis are simple repetitions of two of the others (*26, *89) and did not bring any new insights.

Table 2. Exposure ratio to ambient (ERTA) (expressed in %) for different sports (as Table 1).

Activity	Body site	ERTA mean (%)	ERTA range (%)	Time of the year	Duration	sh min (°)	sh max (°)	Location	Ref.
Cricket	Cheek	18		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Dorsum of hand	32							
Golf	Cheek	24		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine								
	Dorsum of hand	51							
	Anterior thigh								
	Posterior calf								
	Vertex	55	46–64	indep.	2 h	15	49	Toowoomba, AUS	Downs *et al.* 2009 (83)
	Upper back	33	29–41						
	Forearm	23	17–34						
	Vertex	113	104–123	indep	2 h	11	41		
	Upper back	80	74–86						
	Forearm	60	45–74						
	Vertex	68	30–112	indep.	2 h	0	38		
	Upper back	52	10–130						
	Forearm	29	2–61						
	Vertex	32	15–63	Indep.	2.5 h	17	33	Valencia, ESP	Gurrea Ysasi *et al.* 2014 (105)
	Wrist	24	15–54						
	Wrist	75	3–24.1	April–September	n.a.	0	57	Copenhagen, DK	Thieden *et al.* 2004a (61)
Tennis	Cheek	26		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Dorsum of hand	32							
	Anterior thigh	34							
	Posterior calf	30							
	Wrist	12		indep.	3.5 h	37	72	Valencia, ESP	Serrano *et al.* 2011 (89)
	Forehead		40–72	indep.	1 h	60	65	Vienna, AUT	Maier *et al.* 2013 (97)
	Calf		20–37		1 h	60	65		
	Forehead		78–100		1 h	45	50		
	Calf		30–33		1 h	45	50		
Running	Wrist	2		indep.	2 h	0	26	Valencia, ESP	Serrano *et al.* 2011 (89)
	Upper arm	7	6–8	indep.	4 h	7	55	Cape Town,	Nurse *et al.* 2015 (106)
	Upper arm	23	12–33	indep.	3 h	13	53	Pretoria, RSA	
	Upper arm	21	3–33	indep.	2 h	0	22	Pretoria, RSA	
Cycling (sportive)	Ankle	51		indep.	10 h	0	43	Queensland, AUS	Kimlin *et al.* 2006 (70)
	Back of hand	71							
	Side of head	63							

Sports that are not confined to a playing field are, for example, cycling and running. Although jogging is quite popular, we found little information on it. Only the ERTA of the wrist (2%) and of the upper arm (20%) at rather low solar elevations (*89, *106) have been reported.

For cycling in a more sportive position (bent forward), only data over a whole day at low solar elevation are available. The ERTA at the ankle is 50%, at the back of the hand it is 70% and 60% at the side of the head (*70). For riding a mountain bike, we did not find any measurements.

At and in the water. Many people find recreation near the water (Table 3). The studies on boating and fishing (*26) did not specify both activities more clearly. It is therefore hard to say if boating refers to a motorboat, a sailboat or a rowboat and also the term fishing is wide-ranging. The only study on sailing where solar elevation could be derived indicates an ERTA of 15% on the lapel site (*18).

For swimming, the knowledge is also rather poor as ERTA are available only for unknown solar elevations. Data indicate clear differences in ERTA between swimming in the ocean or in the pool (*26).

Contrary to that, a well-defined study on snorkeling was published (*93). Besides a restricted range of solar elevation, also the special requirements on calibration at the air–water interface have been considered. The ERTA at the neck and at the back decreases with decreasing solar elevation.

Sunbathing, beach and pool side. Sunbathing is related to postures that provide maximum working surface for the sun (lying, sitting up) (Table 4). Corresponding ERTA are generally high compared to other activities. For short periods, the ERTA can be around 120% (*94). Over periods of 1 h, the ERTA may reach 80% (*18) on several body sites like the chest, and during afternoon, the ERTA of most positions is within 40–50% (*26).

Not all people spend all the time sunbathing at the pool or at the beach. However, ERTA at the beach and at the pool are close to those of sunbathing. An important factor is whether the beach/pool location is part of a person's everyday environment or not. It was shown that at the same time and location natives receive less than tourists do (*103).

Tourists and sightseeing. Holiday and spare-time activities in a town may also hold risk (Table 4). Mean ERTA at the chest

Table 3. Exposure ratio to ambient (ERTA) (expressed in %) for different activities at and in the water (as Table 1).

Activity	Body site	ERTA mean (%)	Time of the year	Duration	sh min (°)	sh max (°)	Location	Ref.
Boating	Cheek	29	February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine	60						
	Dorsum of hand	60						
	Anterior thigh	58						
	Posterior calf	40						
Sailing	Lapel site	15	indep.	11 h	14	54	Gothenburg, SWE	Diffey *et al.* 1982 (18)
Swimming (pool)	Cheek	26	February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine	36						
	Dorsum of hand	57						
	Anterior thigh	16						
	Posterior calf	9						
Swimming (ocean)	Cheek	47	February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine	71						
	Dorsum of hand	70						
	Anterior thigh	58						
	Posterior calf	50						
Snorkeling	Neck	42	indep.		65	90	14°S–24°S 148–178°E AUS	Downs *et al.* 2011 (93)
	Neck	27			40	74		
	Lower back	65			65	90		
	Lower back	45			40	74		
Fishing	Cheek	23	February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Dorsum of hand	48						
	Anterior thigh	51						
	Posterior calf	17						

Table 4. Exposure ratio to ambient (ERTA) (expressed in %) for different holiday activities (as Table 1).

Activity	Body site	ERTA mean (%)	ERTA range (%)	Time of the year	Duration	sh min (°)	sh max (°)	Location	Author
Lying	Forehead	47	44–49	indep.	>1 h	46	64	Vienna, AUT	Weihs *et al.* 2013 (95)
	Shoulder	5	3–6		>1 h				
	Chest	26	29–33		>1 h				
	Upper arm	5	2–9		>1 h				
	Thighs	65	59–70		>1 h				
	Lower leg	57	50–65		>1 h				
Sitting up	See Table 1								
Sunbathing	Lapel site	80		indep.	1 h	41	47	Lanzarote	Diffey *et al.* 1982 (18)
	Lapel site	51	30–72	indep.	8 h	5	51	Corfu	
	Cheek	35		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine	58							
	Dorsum of hand	48							
	Anterior thigh	44							
	Posterior calf	56							
Sight seeing	Lapel site	17		indep.	4.5 h	26	47	Lanzarote	Diffey *et al.* 1982 (18)
	Chest	74		indep.	10 min	45	70	Vienna, AUT	Schmalwieser *et al.* 2010a (94)
	Chest	44			1 h	45	70		
	Chest	71			10 min	10	30		
	Chest	52			1 h	10	30		
Hiking	Cheek	27		February–May	12:00–16:00	18	73	Perth, AUS	Holman *et al.* 1983 (26)
	Thoracic spine	47							
	Dorsum of hand	46							
	Anterior thigh	46							
	Posterior calf	33							

during 1 h of sightseeing is around 50% (*94). For longer periods, the ERTA decreases (*18). Resting in a side walk café (Table 1) may result in an ERTA of up to 100% on the chest (*94).

Alpine exposure. One of the earliest studied activities was skiing (*18). The only exposed body site during skiing is the face; and the face receives high amounts of UV radiation (*6, *53). Besides the face, the measuring position has been the nearby lapel (*18). Unusual positions have been the upper arm, the wrist and the shoulder because the skin at these parts is not exposed during skiing and a conversion factor would have been needed to conclude to the exposed face. Measurements on the face deliver an interesting exposure pattern (Fig. 2). At low solar

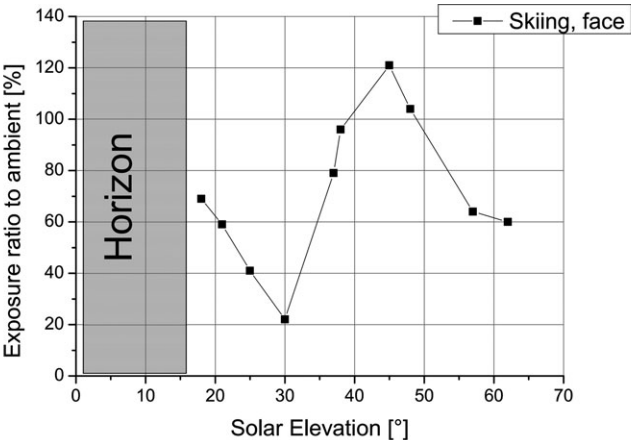

Figure 2. Ratio of the personal exposure on the face to ambient UV radiation (erythemally weighted exposure) as a function of solar elevation. For low solar elevations, the height of horizon is significant (gray area).

elevation (20°), the ERTA is around 70% and decreases with rising sun. At a solar elevation of 30°, the ERTA is smallest, taking a value around 25%. This agrees with the expectation for a vertical oriented receiver. When the sun is rising further, then the ERTA increases rapidly. At 40°, the ERTA exceeds 100% and reaches a maximum of 120% at 45°. This demonstrates the influence of albedo in an impressive way. At higher solar elevations, the ERTA decreases. The highest measured solar elevation was 62°, whereas the corresponding ERTA was 60%. For low solar elevations, the height of the horizon has major impact.

Although it was shown that PE during hiking (Table 4) may be high (*26), there is only little more general information available. The ERTA at the wrist could be around 20% on average during a whole day.

SUMMARY

During the past four decades, a variety of studies on nonoccupational PE measurements have been carried out. The number of studies per year increased continuously (Fig. 1) over the past decades. PE of around 30 different activities was measured at 15 different body sites. Most of the studies were performed in Australia and Europe; a few in the United States and South Africa (see Fig. 3). For a large part of the world, PE seems not to be a topic yet. One of the reasons could be that PE is not always a considered priority in research funding applications. However, it is well known that health damage due to solar UV overexposure is not limited to the light-skinned population (119). It was shown that skin cancer, although less common in persons with skin of color (*e.g.* skin types V and VI), is often associated with greater morbidity and mortality (120). On the other hand, high rates of hypovitaminosis D are even reported for the Middle East and North Africa regions (121).

The purposes of the studies were manifold. Most studies focused on local PE values focusing on risk situations for overexposure and underexposure. Almost all of those focusing on overexposure showed that 1 MED (for light skin) can be retrieved easily during outdoor activities. Only morning and evening hours (respectively low solar elevation) could be regarded as sun-safe.

Some studies focused on distinct activities over short periods (walking, etc.) and results, expressed as the ERTA, can be used to estimate PE anywhere else.

Other studies were designed to analyze sun behavior (time, location, clothes, etc.) of people using accompanying diaries with a high temporal resolution. Besides PE, the clothing habits have been investigated. Reduced clothing enlarges the exposed body area which is important for systemic effects (*e.g.* vitamin D, immunosuppression) and exposes body sites which may be at higher risk (*e.g.* shoulders) than others (*e.g.* hands).

Figure 3. Locations (marked gray) of studies on personal UV exposure measurements.

With respect to the body site, there are, on the one hand, exposure-relevant positions (*e.g.* face, chest) used and on the other hand more comfortable positions (*e.g.* wrist). The later can be used for comparative studies between different groups or also in conjunction with biomarkers.

For this overview, we have analyzed the results from 55 different studies extracted from peer-reviewed literature. The knowledge on PE of people during nonoccupational activities has clearly increased especially in the past decade. However, for most activities, we still lack the possibility to predict the UV exposure of exposed body sites under any condition because ERTAs are not fully available.

The use of radiative transfer models together with 3D-body models would be another promising technique. It would allow calculating the UV distribution over the whole body for any photobiological effect like erythema (122,123) or vitamin D (124,125). For this, a variety of input parameters are necessary. For certain postures, these models work well. However, detailed information on the composition of an activity with respect to posture (*e.g.* percentage of standing, sitting, walking) and behavior (*e.g.* percentage of time in the shade) is necessary. However, till this day, such data are rarely available. Further on, PE data are needed to calibrate and to validate such simulations.

In any case, additional studies are necessary to fill the gaps. Our review should encourage the adaption of a standard protocol in dosimetric studies and to provide a reliable basis for the critical analysis of the risks associated with solar UV exposure.

STUDIES—REFERENCES

This section list all studies on nonoccupational personal solar UV exposure measurements in chronological order. These references are marked with an asterisk (*) in the text.

1976–1990: Challoner *et al.* 1976 (11), Corbett *et al.* 1978 (17), Leach *et al.* 1978 (16), Diffey *et al.* 1982 (18), Holman *et al.* 1983 (26).

1991–1995: Snellman *et al.* 1992 (29), Wong *et al.* 1992 (31), Herlihy *et al.* 1994 (35), Diffey and Saunders 1995 (41).

1996–2000: Knuschke and Barth 1996 (37), Kimlin *et al.* 1998 (38), Autier *et al.* 2000 (59), Moehrle *et al.* 2000 (55), Moehrle M. 2000 (57), O'Riordan *et al.* 2000 (48), Parisi *et al.* 2000 (54), Thieden *et al.* 2000 (50).

2001–2005: Thieden *et al.* 2001 (58), Rigel *et al.* 2003 (68), Thieden *et al.* 2004a (61), Allen and McKenzie 2005 (69), Thieden *et al.* 2005b (65).

2006–2010: Kimlin *et al.* 2006 (70), Thieden *et al.* 2006a (64), Chodick *et al.* 2008 (73), O'Riordan *et al.* 2008 (71), Siani, *et al.* 2008 (6), Downs *et al.* 2009 (83), Siani *et al.* 2009 (82), Glanz *et al.* 2010 (72), Hall *et al.* 2010 (86), Schmalwieser *et al.* 2010a (94), Serrano *et al.* 2010 (88), Webb *et al.* 2010 (87).

2011–2015: Downs *et al.* 2011 (93), Serrano *et al.* 2011 (89), Curtis *et al.* 2012 (100), Maier *et al.* 2012 (96), Cargill *et al.* 2013 (101), Maier *et al.* 2013 (97), Petersen *et al.* 2013 (102), Serrano *et al.* 2013 (98), Weihs *et al.* 2013 (95), Gurrea Ysasi *et al.* 2014 (105), Serrano *et al.* 2014 (92), Petersen *et al.* 2014 (104), Sun *et al.* 2014 (109), Casale *et al.* 2015 (53), Nurse *et al.* 2015 (106), Petersen *et al.* 2015 (103), Xiang *et al.* 2015 (107).

2016–2018: Køster *et al.* 2017 (113), Wainwright *et al.* 2017 (114), Shi *et al.* 2018 (116).

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