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RESEARCH ARTICLE

Erythemal UV radiation exposure during jogging

Alois W. Schmalwieser[1] | **Hannah Danhel**[1] | **Susanne S. Schmalwieser**[2] | **Sonja Reimoser**[3] | **Hanna Rummel**[3] | **Adrian Loy**[3] | **Jakob Heydenreich**[4] | **Philipp Weihs**[3]

[1]Unit of Physiology and Biophysics, University of Veterinary Medicine, Vienna, Austria

[2]Austrian Centre for Digital Humanities and Cultural Heritage, Austrian Academy of Sciences, Vienna, Austria

[3]Department of Water, Atmosphere and Environment, Institute of Meteorology and Climatology, University of Natural Resources and Life Sciences, Vienna, Austria

[4]Department of Dermatology, Bispebjerg Hospital, Copenhagen, Denmark

Correspondence
Alois W. Schmalwieser, Unit of Physiology and Biophysics, University of Veterinary Medicine, Vienna A-1210, Austria.
Email: alois.schmalwieser@vetmeduni.ac.at

Abstract

Jogging is one of the most popular recreational sport activities over four decades and is done at almost all ages to keep fitness and health. Joggers are exposed to solar UV radiation (UVR) and, due to enhanced heat production by physical activity, body coverage by clothes is reduced. This may imply a health risk due to overexposure. However, little research has been undertaken so far to estimate UVR exposure during jogging. Therefore, UVR exposure was measured at seven body sites during jogging under cloud-free conditions for solar elevations between 20° and 60°. Results show that the top of the shoulder is the most exposed body site by receiving 80% of ambient UVR on average and up to 110% under certain conditions. All other body parts receive up to 55% on average and up to 85% in special cases. This indicates further that monotonous body alignment to the sun holds a higher risk than a frequently alternating alignment. Assuming the longest recommended duration for cardiovascular beneficial jogging of 50 min, photosensitive persons need protection of the shoulders from a UV index of 2 onward on an unvaried path and from a UV index of 3 on an all-directional path. Further, results show that measurements of UVR exposure possess an uncertainty of ±15% including mounting.

KEYWORDS

exposure ratio to ambient, personal dosimetry, personal UV dosimetry, personal UV exposure, recreational outdoor sport, sun burn time, sun protection

INTRODUCTION

Jogging is a form of trotting or running performed at a leisurely pace (ca. 5–10 km/h, 4–6 miles/h). The modern concept of jogging was developed in the 1960s in New Zealand by Arthur Lydiard and aimed at promoting fitness and sociability.[1] Shortly after, jogging spread to the United States,[2] popularized by Bill Bowerman (a later co-founder of Nike Inc.) who invented a special running shoe (the so-called "Waffle Racer") that is responsive and adapts to uneven running surfaces.[3] Since its rise in popularity in the 1980s, jogging is one of the most popular recreational sports in western populations,[4] potentially shaping the lifestyle and outdoor activities of people over

Abbreviations: a.s.l., above sea level; ERTA, exposure ratio to ambient; FSPT, Fitzpatrick skin phototype; MED, minimal erythema dose; SBT, sun burn time; SED, standard erythema dose; UV, ultraviolet; UVI, UV index; UVR, ultraviolet radiation.

the past 40 years. In Austria, for example, around 25% of adolescents and adults (15–60 years) do jogging more or less regularly, with participation rates differing by gender, age, occupation, and other factors.[5]

Jogging was promoted by Bill Bowerman and the cardiologist Waldo Harris[6,7] as a medically approved physical fitness program for all ages. Over time, numerous studies have highlighted the health benefits of jogging, including its positive impact on cardiovascular health, obesity prevention, and overall well-being.[8] Furthermore, jogging has proven effective in increasing human lifespan[9] and decreasing the effects of aging.[10] Jogging, along with other aerobic exercises, has also been shown to potentially lower the risk of various cancers, including lung, colon, breast, and prostate cancers.[11–13] Most beneficial is light and moderate jogging with an amount of 1–2.4 h and a frequency of less than or equal to three times per week.[14] Compared to jogging on a treadmill indoors, jogging outdoors has additional benefits, such as increased energy and concentration and improved mood.[15] Additionally, outdoor jogging allows for the photosynthesis of vitamin D,[16] which may support several of these benefits.

Despite these benefits, there are concerns about health risks associated with ultraviolet (UV) radiation (UVR) overexposure, including acute erythema, immunosuppression, and an increased risk of skin cancer.[17,18] Several studies have investigated the knowledge, awareness, and habits of sun protection[19] in people doing outdoor sports, delivering a very heterogenic picture in connecting knowledge, awareness, and application.[20] Overall, these studies conclude that more advice and education with respect to sun protection are necessary.[21]

Additionally, to solar UVR exposure, body coverage by clothes is reduced compared to less physically exerting activities like walking because of thermoregulatory needs[22] comparable to an increase in air temperature of 10°C and with that providing a larger area for incident solar UVR.[23,24] The size of the exposed area is important for effects like DNA damage,[25] skin cancer risk[26] but also vitamin D photosynthesis.[27] Covered body parts are equally or even better protected by sportswear than by normal clothes,[28] mitigating any increased risk.

So far, little research has been undertaken to estimate UVR exposure during jogging or running. Research has primarily focused on long-distance and extreme athletes, such as triathletes or marathon runners, with measurements taken from limited body sites that may not represent the most exposed areas.[29–35] The translation of obtained values to UVR body exposure of casual joggers is hardly possible.

Therefore, in this paper we will provide UVR exposure measurements made at several body sites which are expected not to be covered by sportswear. Measurements will be set in relation to ambient UVR at several solar elevations. With that, it will be possible to estimate UVR body exposure at any date, time, and location (for solar elevations up to 65°) when solar elevation and ambient UVR are known.

MATERIALS AND METHODS

Instrumentation

The 12 miniature UVR meters that were used to conduct the measurements are of the SunSaver type[36] and consist of a silicon carbide photodiode with a spectral response that mimics the erythema action spectrum according to the International Commission of Illumination (CIE).[37] A diffuser in front of the diode ensures an angular response that is close to the ideal cosine function in relation to the skin. The Sunsaver demonstrates exceptional linearity and is unaffected by temperatures ranging from −20°C to +60°C. Designed to measure erythemally effective irradiance, measurements can be converted into mW_{ery}/m^2, UV index[38,39] and standard erythema dose[37] per hour (SED/h), whereas 25 mW_{ery}/m^2 corresponds to 1 UV index and 27.5 mW_{ery}/m^2 to 1 SED/h.[40]

From measured irradiance, one can estimate the so-called sunburn time (SBT) by dividing the minimal erythema dose (MED) of a person by measured irradiance. For the most sensitive skin phototype according to Fitzpatrick (FSPT I) it is assumed that the MED corresponds to an erythemally weighted radiant exposure of 200 J_{ery}/m^2 respectively 2 SED.

The UVR meter operates at a sampling interval of one second, enabling detection of irradiance fluctuations caused by motion. Measurement accuracy is ±2% under controlled conditions and ±10% in field applications. The UVR meters are depicted in Figure 1.

Calibration of the UVR meters was carried out by benchmarking them against a high-precision research instrument of the SL501 model (Solar Light Inc., Philadelphia, PA, USA) under sunlight conditions a couple of days before measurements were done (solar elevation 20°–60°, total ozone = 320 DU). The SL501 is a part of the Austrian UV index monitoring network[41,42] and is maintained in compliance with established international protocols.[43] During the experiment, this instrument was concurrently employed to measure ambient erythemally effective irradiance.

Experimental setup, location, time, and execution of measurements

A volunteer was equipped with 12 SunSavers (Figure 1). The UVR meters were mounted on both calves, thighs, forearms, upper arms, top of shoulders (further called shoulders), on the back of the nape, and on the forehead.

FIGURE 1 Experimental setup showing a volunteer equipped with 12 miniature electronic UVR meters of the type SunSaver on the Danube Island (48.247° N, 16.389° E, 165 m a.s.l.), Vienna, Austria.

Securely affixing the UVR meters on a moving body is crucial for reliable measurements (e.g., the avoidance of wobbling). Therefore, several test runs were necessary to find out the best mounting, and the top of the sternum (cleavage) was excluded as a measuring position.

Jogging was done following the recommended posture[6] by leaning the upper body slightly forward and by keeping the body straight, so that shoulders, ears, and lower back are aligned. Upper arms and forearms were positioned in a 90° angle to each other, and the swinging forearms did not cross the centre line of the body.

The volunteer jogged facing each of the four cardinal directions separately in the order of north, south, west, and east. Additionally, runs toward the sun and away from the sun were conducted. Each run lasted for approximately 1 min. The measuring interval was set to 1 s. Before each change in orientation, the volunteer was covered with a blanket in order to create a time stamp that allows for the identification of the changes in orientation when analyzing measurements.

The tests and measurements were taken on 2 days with almost clear sky conditions: June 18th and 19th (319 DU and 325 DU). For control, measurements were taken on September 4th. The measurements started just before solar noon and extended into the afternoon. Runs were conducted at solar elevations of 60°, 50°, 40°, 30°, and 20°.

The study took place on the Danube Island (48.247° N, 16.389° E, 165 m a.s.l., Vienna, Austria) in an open, asphalted area. The asphalted area adjoined lawns with about 60 m to the nearest group of trees (Figure 1). According to Castro et al.,[44] the albedo of asphalt is between 0.05 and 0.11, while the albedo of grass is around 0.08 to 0.09. Thus, less than 10 percent of the incident UV global radiation will be reflected upward and received by the person.

Mounting UVR meters on calves, thighs, forearms, upper arms, and the tops of shoulders of both hemibodies enables estimation of measurement uncertainty. When jogging directly toward or away from the sun, UVR meters of both hemibodies should deliver the same irradiance. The difference between both delivers the absolute uncertainty. The highest observed difference of all body sites and of both jogging directions is regarded here as measurement uncertainty.

Exposure ratio to ambient

The proportion of irradiance received by a specific part of the body relative to the ambient UVR is quantified through the exposure ratio to ambient (ERTA).[40] It is defined as the ratio of the irradiance E_i, measured at body part i, to the ambient irradiance E_{ambient}, recorded by the SL501 located 1500 m away on the university campus. The ERTA(h) for body part i is determined for various solar elevations h:

$$\text{ERTA(h)}_i = E_i\,(\text{h}) / E_{\text{ambient}}(\text{h})$$

With that, ERTA is a dimensionless quantity. A higher ERTA value indicates greater UVR exposure for a specific body site, facilitating the identification of areas most exposed to UVR. Typically, ERTA values range between 0 and 1. However, under certain circumstances—such as when the body site is oriented perpendicular to the sun—the ERTA may exceed a value of 1.

Once established, the ERTA can be applied to determine the UVR exposure of a specific body site at any location and time by multiplying the corresponding ambient erythemally effective irradiance by the ERTA(h) of the respective solar elevation. Publicly available measurements or forecasts of ambient erythemally effective irradiance exist for a wide range of locations.[45–47]

RESULTS

Erythemally effective UVR exposure during movement

Figure 2 depicts examples of measurements with the selected temporal resolution of 1 s on selected parts of the body. Four runs are shown (north to south, south to north, west to east, and east to west) which were carried out close to solar noon. It can be seen that the fluctuations in irradiance during a run are high for some parts of the body, while they are rather low for others. High variations occur in body parts that move a lot, such as the thighs or the calves, which frequently change their orientation. In contrast, the forehead and nape show low variation in irradiance because they change their orientation only slightly. As the frequency of steps is higher than the frequency of measurements, the measured irradiance does not show a clear sinusoidal curve but still indicates a periodically alternating orientation.

The extent of the fluctuations depends not only on the extent of movement, but also on the orientation of the body part in relation to the sun. When jogging away from the sun (south–north in Figure 2), the calves face periodically the sky and the solar disk and alternating parts of the sky and the ground. Therefore, the fluctuations are large. When jogging toward the sun, the calves are averted from the sun and alternatingly face a part of the sky and a smaller part of the sky together with parts of the ground. Therefore, fluctuations are lower.

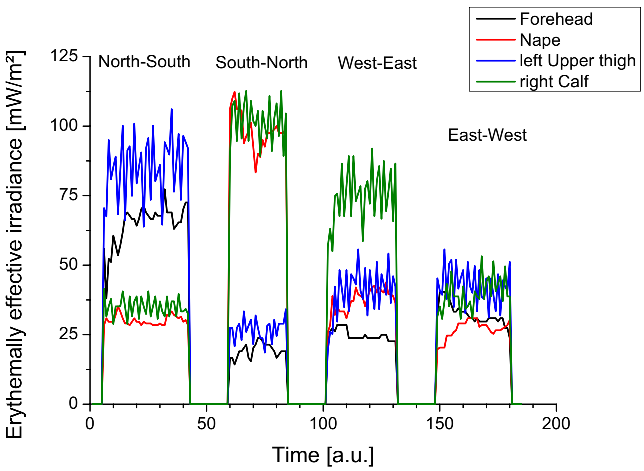

FIGURE 2 Measurements at different body parts and different orientations (running directions) with a temporal resolution of 1 s made close to solar noon.

Erythemally effective UVR exposure of body parts in dependence on solar elevation

A random pathway is gained by calculating the mean values over four runs along the cardinal directions. Figure 3 depicts these mean values at different solar elevations. Beside the forehead and the nape, mean values include measurements from both hemibodies (left and right site). Erythemally effective irradiance is scaled in units

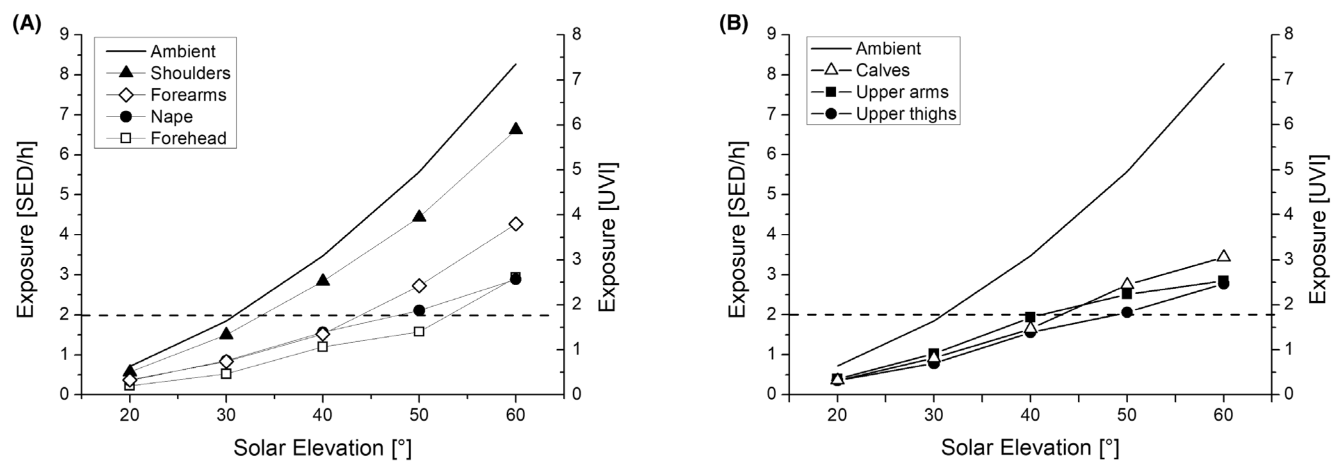

FIGURE 3 Mean erythemally effective irradiance (symbols; over all directions and both hemibodies) of body parts (A: shoulders, forearms, nape and forehead; B: calves, upper arms and upper thighs) in dependence of solar elevation expressed in units of the UV-Index (UVI) (right scale) and SED per hour (SED/h) (left scale) together with ambient erythemally effective irradiance (black line) during measurements (at around 320 DU).

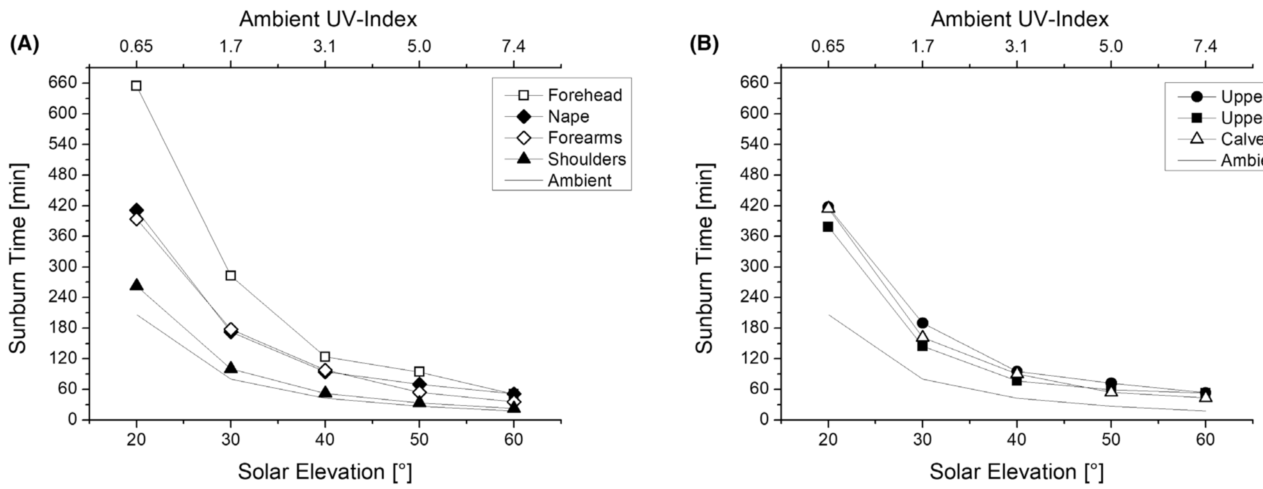

FIGURE 4 Mean sunburn times (over all directions and both hemibodies) in minutes for photosensitive human skin (Minimal Erythema Dose = 2 SED) of body parts (A: shoulders, forearms, nape and forehead; B: calves, upper arms and upper thighs) in dependence of ambient UV-Index respectively solar elevation (at around 320 DU).

of the UV index (UVI, 1 UVI = 25.0 mW_{ery}/m^2) and SED per hour (1 SED/h = 27.8 mW_{ery}/m^2). It can be seen that under cloud-free conditions, UVR exposure of body parts changes with solar elevation. The higher solar elevation is, the higher is UVR exposure. At a solar elevation of 60°, the most exposed body parts are the shoulders (7 SED/h, 6 UVI) followed by forearms (4.5 SED/h, 4 UVI). UVR exposure of calves, forehead, thighs, upper arms, and nape are very similar (3.3–2.5 SED/h, 3–2.5 UVI). Ambient irradiance is around 7.5 UVI or 8.3 SED/h, respectively. As solar elevation decreases, differences in irradiance between most body parts are vanishing. Only the shoulders clearly exhibit a higher level of exposure and therefore are the body part with the highest exposure at all solar elevations. At a solar elevation of 40°, UVR exposure of the shoulders is still somewhat lower than ambient irradiance and just below 3 UVI or 3 SED/h, respectively. For all other parts, it is less than 2 UVI, respectively 2.0 SED/h. At 20°, ambient irradiance as well as UVR exposure of all body parts is obviously below 1 UVI or 1 SED/h.

Sunburn times of body parts

Sun burn times (SBT) were calculated using the irradiance values from above, considering the most sensitive skin phototype FSPT I by assuming 1 MED equals a radiant exposure of 2 SED. The results are depicted in Figure 4. It can be seen that SBT (mean over all directions and both hemibodies) is 60 min or less at a solar elevation of 60°, while the ambient irradiance was 7.4 UVI. SBT increases with decreasing solar elevation. At 40° and 3.1 UVI, all SBTs are longer than 52 min. As SBT is reciprocally proportional to irradiance, a steep increase can be observed with decreasing irradiance, so that at 20° (0.65 UVI) even the SBT for the shoulders exceeds 4 h. It should be noted that the UV Index under clear sky at a certain solar elevation can vary with total ozone by around ±25% compared to the conditions during our measurements.

Exposure ratio to ambient

To keep it independent of ambient irradiance, the ERTA was calculated at different solar elevations from irradiance values above, as depicted in Figure 3. Figure 5 depicts the ERTA of body parts in dependence on solar elevation. The ERTA of shoulders is highest on average at a level of 0.8 with no dependence on solar elevation (Figure 5A). For forearms and forehead, there is no clear tendency (Figure 5A), too, at a level of 0.5 and 0.3, respectively. ERTA of the upper arms, calves, thighs, as well as of the nape decreases with increasing solar elevation, starting with a value of 0.5 at 20° down to around 0.4 and 0.3 at 60° (Figure 5B).

Influence of orientation in respect to the sun

While during a random path, a body part takes all azimuthal directions relative to the sun, jogging in a certain direction may expose body parts obviously higher or lower (as indicated in Figure 2). ERTA and UVR exposure, respectively, are highest when body parts are aligned toward the sun. Figure 6 depicts the ERTA of body parts from runs toward the sun, away from the sun, and runs having the sun on the right and on the left side. For anterior sites like

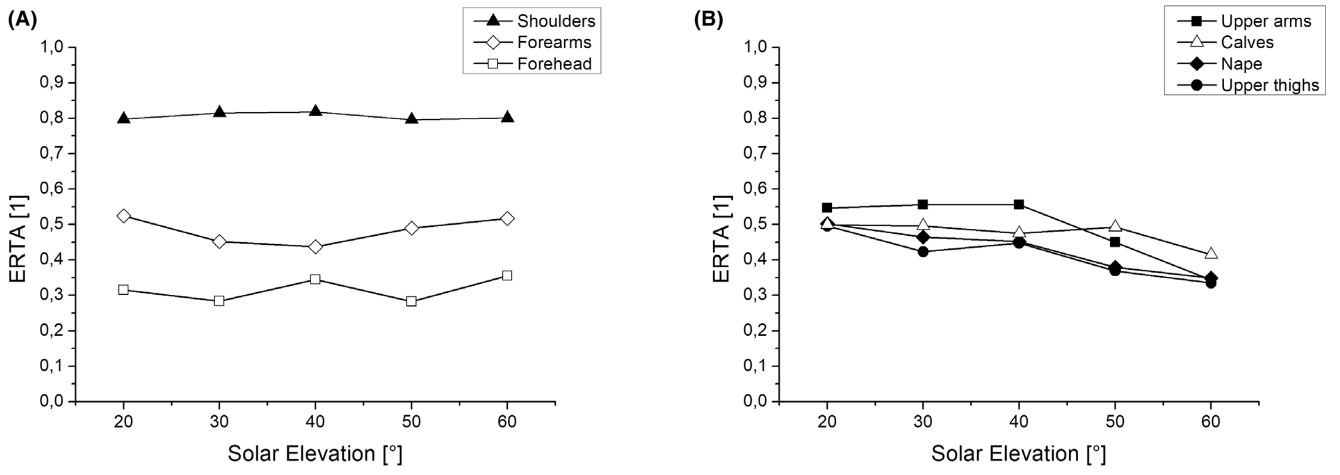

FIGURE 5 Mean Exposure Ratio To Ambient (ERTA) (over all directions and both hemibodies) of body parts (A: shoulders, forearms and forehead; B: calves, upper arms, nape and upper thighs) in dependence of solar elevation. ERTA is dimensionless quantity.

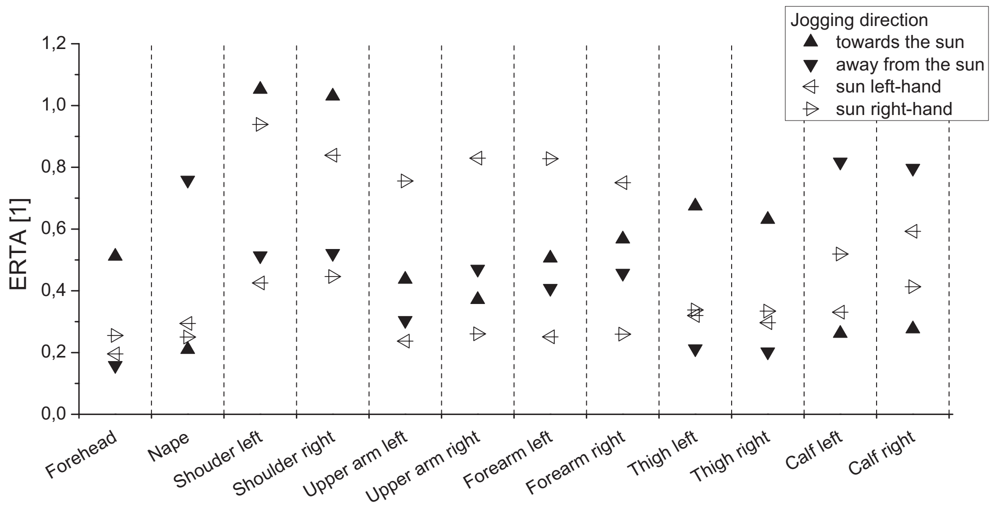

FIGURE 6 Exposure ratio to ambient (ERTA, dimensionless quantity) for all alignments in respect to the sun for all body parts at solar elevations between 20° and 60°.

the forehead and thighs, maximum values are achieved when jogging toward the sun, and minimum values when jogging away from the sun. For posterior sites like the nape and calves, it is vice versa. Maximum UVR exposure on the shoulders and forearms is received when jogging toward the sun, but also when jogging perpendicularly to the sun at the sun-facing hemibody. In the latter case, for example, the left shoulder and the left forearm face the sun when jogging from East to West at solar noon. In both cases (toward and perpendicular), UVR exposure is very similar. While the forearms receive the lowest amount of irradiance when jogging away from the sun, a shoulder receives the lowest irradiance when averted from the sun, that is, when the solar disk is masked by the head. For lateral positions, such as the upper arms, the highest UVR exposure occurs for the sun-facing hemibody, for example, the right side when jogging from west to east at solar noon. From Figure 6, it can be seen that the maximal and minimal ERTA of the shoulders is highest, and the maximum exceeds a value of 1.0, followed by upper arms, forearms, calves, nape, and thighs. As the forehead usually is oriented slightly downward, both ERTAs are the lowest of all. Values higher than 1.0 occur on the shoulders when jogging toward the sun at solar elevations between 40° and 60°.

Uncertainties

Mounting UVR meters on both hemibodies allows estimating uncertainties from mounting. Although UVR meters were mounted as symmetrically as possible, differences in irradiance between the left and right sites were observed. Differences can be estimated best by directly comparing runs toward the sun and directly away from the sun because, in both cases, the left and right sites should receive the same irradiance. In these cases, differences between mean values of the left and right body sites varied between 0.5% and 30%. The largest differences were found for the shoulders, with differences up to 30%, followed by the thighs and upper arms, with up to 24% each. The smallest differences occurred for calves (up to 13%) and forearms (up to 12%). With that, uncertainties from mounting have to be considered as 30% or ±15% from the mean value, respectively.

DISCUSSION AND CONCLUSIONS

Although jogging is a very popular recreational activity and may have contributed to recreational UVR exposure of people in the past four decades, little research has been conducted to estimate UVR exposure of joggers or runners until today. The few studies that estimated UVR exposure of professional runners like triathletes and marathon runners during competition and training[29–35] agreed in so far as they found high radiant exposure when exposure lasts long and when ambient UVR is high. As different measuring positions were used, the results of these studies are only partly comparable. Additionally, little information about ambient UVR, solar elevation, or the UVR environment of runners is provided and therefore, results cannot be transferred to other durations, dates, locations, or body parts.

To tackle this desideratum, we derived a UVR exposure model for jogging by measurements under controlled conditions at seven sun-exposed body sites and at different solar elevations between 20° and 60° under a cloud-free sky in an open environment.

Our results show that the top of the shoulder is the body site with the highest risk of UVR overexposure at all solar elevations and for all running directions or all body alignments in relation to the sun. On a random pathway (mean over all directions), the shoulders receive 80% of the ambient irradiance. When jogging toward the sun, the UVR exposure may reach up to 117% and thus significantly exceed ambient UVR (at solar elevations between 40° and 60°). This is caused by the torso bending slightly forward during jogging. Body exposures that exceed ambient UVR (ERTA >1.0) have been reported in the past for other recreational activities like cycling,[48] walking,[49,50] and skiing,[51] but also for monotone occupational workflows[52,53] for sun-exposed body parts. All other body sites (forehead, forearms, nape, upper arms, thighs, and calves) receive a similarly significantly lower irradiance of around 35%–70% of that of the shoulders when jogging.

These results clearly show that the orientation of the body in relation to the sun plays a major role in UVR exposure of body sites and that a frequent change of alignment reduces the risk of sunburn compared to a monotonous/constant alignment. For a random route (without any specific or constant orientation in respect to the sun), ERTAs as depicted in Figure 5 apply. Sometimes, however, the topography or the available path network restricts freedom of movement. For example, the Danube Island, where measurements were taken, is a very popular place for recreational athletes in Vienna. It is a long (10 km) but narrow (width <0.5 km) island oriented from northwest to southeast. Jogging along its bank paths would therefore cause a different exposure pattern than a random pathway. In such cases, the maximum ERTAs, as depicted in Figure 6, must be taken into account.

Our measurements show that shoulders are the most exposed parts of the body, significantly more so than other parts. Therefore, the protection of the shoulders is essential. Covering the shoulders with clothes would be the safest way. However, women in particular tend to wear off-the-shoulder tops at warm temperatures (median at 27°C)[23] for thermal comfort. As jogging increases body temperature and heat exchange, people feel up to 10°C warmer[54] and off-the-shoulder tops are preferred at corresponding lower temperatures for thermal comfort.

Some caution is required when applying sunscreens: The sunscreen must have an appropriate sun protection factor. It should be applied 20–30 min prior to UVR exposure.[55] Sweating reduces the effectiveness of sunscreens,[56] and in general, people tend to apply less than the amount recommended by the manufacturers.[55] Additionally, suberythemal UVR exposure may accumulate over consecutive days.[57] For these reasons, the so-called "sunscreen paradox" (receiving a sun burn despite the application of sunscreen) is not an uncommon phenomenon.[54] Therefore, covering the shoulders with clothing may be the safest method, as clothing and especially sportswear provide adequate sun protection.[28]

In respect to clothing, it should be mentioned that wetness (sweating, spraying with water for cooling, …) may alter the ultraviolet protection factor (UPF)[58] of textiles. Due to wetness, the UPF can both increase and decrease.[59–61] The underlying process is a rather complex mixture of soakage, swelling, adhering, and others, and differs for organic and inorganic materials. In general, changes in UPF are rather small (±10%). The exception is pure cotton, which loses noticeably (approximately up to −50%) of its protection ability mainly by stretching due to the weight of absorbed water, especially when close to the saturation level.[60,61]

A loose clothing fit increases the UPF minimally, while stretched or stretched-out clothes have reduced protection abilities.[61] Washing and drying may lead to a slight shrinking, which leads to a noticeable increase in the

UPF.[62] On the other hand, clothes that are treated with special substances (e.g., UVR absorbers) to have enhanced UV radiation protection may lose UPF by washing out.[63] Overall, sunburn despite the coverage by clothes may appear in cases of very thin textiles only,[64] but not in typical sportswear.[28]

Studies on the health benefits of jogging have shown that it is most beneficial to jog one to three times a week for 1–2.4 h in total, resulting in a duration of 20–50 min per jog. Assuming that the longest duration of jogging for cardiovascular benefits is 50 min, our results indicate that a photosensitive person (Skin phototype I according to Fitzpatrick) needs sun protection in relation to sunburn starting at an (ambient) UV index of 3 (ca. 40° solar elevation) on a random path and at a UV Index of 2 on an unvaried path. If the shoulders are protected, jogging for 50 min needs protection starting at 5 UVI on a random path and at 3.5 UVI on an unvaried path. To be on the safe side, photosensitive persons should therefore protect shoulders from 2 UVI onward and all other body parts from 3.5 UVI onward.

Limitations of the present study depend on the one hand on the inaccuracy of the mounting of the UVR meters to the body, which can lead to maximum uncertainties in received UVR of 30%. On the other hand, these measurements are performed under certain atmospheric and environmental conditions: first, the turbidity of the atmosphere weakens the incident solar radiation and may change to a minor extent the ratio of diffuse to global radiation. An increase in the proportion of diffuse radiation would reduce the fluctuations related to changes in body orientation. Second, another site-specific component is the soil albedo. The asphalt albedo is relatively low with maximum values of up to 11%. In other environments, for example, in the case of a specular reflection from water or over a surface of snow, the stronger ground reflection could lead to a relative increase in the UVR exposure received by especially the upright parts of the body. Results were gained at solar elevations between 20° and 60° and may not be necessarily applicable at higher solar elevations as found at subtropical and tropical latitudes.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Alois W. Schmalwieser https://orcid.org/0000-0003-0719-391X

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