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UV Exposure during Cycling as a Function of Solar Elevation and Orientation

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Abstract: Although cycling is the most prevalent means of locomotion in the world, little research has been done in evaluating the ultraviolet (UV) radiation exposure of cyclists. In this study, a volunteer using a men's bike was equipped with 10 miniature UV-meters at different body sites. Besides erythemally effective irradiance, the ratio of personal UV exposure to ambient UV radiation was determined for solar elevations up to 65°, taking into account different orientations with respect to the sun. This method provides a universal model that allows for the calculation of UV exposure whenever ambient UV radiation and solar elevation are available. Our results show that the most exposed body sites are the back, forearm, upper arm, and anterior thigh, receiving between 50% and 75% of ambient UV radiation on average. For certain orientations, this percentage can reach 105% to 110%. However, the risk of UV overexposure depends on ambient UV radiation. At lower solar elevations (<40°), the risk of UV overexposure clearly decreases.

Keywords: UV exposure; sun burn time; UV dosimeters; cycling

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Citation: Weihs, P.; Helletzgruber, S.; Kranewitter, S.; Langer, L.; Lumerding, Z.; Luschin, V.; Schmidt, P.; Heydenreich, J.; Schmalwieser, A.W. UV Exposure during Cycling as a Function of Solar Elevation and Orientation. *Atmosphere* **2024**, *15*, 215. https://doi.org/10.3390/atmos15020215

Academic Editor: Richard Müller

Received: 7 December 2023
Revised: 30 January 2024
Accepted: 5 February 2024
Published: 9 February 2024

1. Introduction

Cycling has a long history dating back to the "running machine", invented in 1817 by Karl Drais in Germany [1]. This so-called "dandy horse" quickly became popular among the upper social classes of Europe and North America. The second generation of bikes, developed in the 1850s, was equipped with pedals on the front wheel and was quite heavy, as these bikes were made entirely of metal and therefore called "boneshakers". The high-wheel bicycle, or "penny-farthing", invented in the 1870s was the first model to become as fast as a horse. However, due to its statics and height, it was dangerous to ride and reserved for well-trained riders. The development of the chain-driven rear wheel in the 1880s was a breakthrough, and this so-called "safety bicycle", in conjunction with pneumatic tires, became popular all over the world [2]; it was affordable and, at the end of the 19th century, laborers' cycling clubs were founded across Europe. These clubs supported the acquisition of bikes and organized joint weekend tours and races. The bicycle found its way into all fields of daily life [3]. With that, cycling may have contributed to the ultraviolet (UV) radiation (UVR) exposure of recent populations.

Over the past decades, many different designs, like the folding bike, trishaw, or mountain bike, adapted the bicycle to various users' needs. Nowadays, a rise in bicycle production has resulted from the newly developed e-bike. To solve the intra-urban traffic crisis, many municipalities established special cycling paths and public bike-sharing systems. In 2022, 61.6 million cars were produced globally, compared to 130 million bicycles [4]. The bicycle is still a major conveyance method all over the world. With that, large parts of the world population are affected by UVR exposure from cycling.

Despite its many advantages, like other outdoor activities, cycling entails the risk of solar ultraviolet (UV) radiation (UVR) overexposure. Besides irradiance and radiant exposure (irradiance integrated over time), radiant energy (radiant exposure multiplied by area) is of relevance for UV exposure [5].

Casual cycling already leads to increased body heat that often causes cyclists to remove individual garments or wear fewer garments overall. Since the early days of recreational and sport cycling, special garments have frequently been worn that facilitate better heat loss but also cover a smaller part of the skin in comparison to everyday clothes at the same outside temperature [6].

However, little research has been done on UVR risk estimation for cycling to date. The so-called Exposure Ratio To Ambient (ERTA) enables risk estimation for individual body parts [7]. It expresses the relative UV irradiance received by a body part in relation to the ambient UVR, which refers to a horizontally oriented receiver. The ERTA mainly varies with the orientation of the body part with respect to the sun and with solar elevation [8–13]. Once the ERTA is established, the UVR exposure of the body part can be calculated from the ambient UVR. Measurements of ambient UVR are publicly available for many locations [14–18], as are forecasts of ambient UVR [19,20].

So far, most published case studies have focused on long-distance cyclists [21–25], and indicated that the radiant exposure can be high at the top and sides of the helmet, and between shoulders, hands, and ankles. For longer distance rides, it is difficult to determine the ERTA, due to the distance to the location where ambient UVR measurements are available. Additionally, most previous studies used integrating UV-meters (dosimeters), whereas electronic UV-meters that deliver time-stamped measurements are necessary to determine the ERTA. So far, for cycling, a solar-height-resolved ERTA is available for the chest only [26].

To fill this gap, we conducted a study under well-defined conditions by equipping a volunteer with ten miniature electronic UVR-meters.

2. Material and Methods

2.1. Instrumentation

For the measurements, we used ten miniature UV-meters of the Sunsaver type [27], as depicted in Figure 1. This meter consists of a silicone carbide photodiode with a spectral response that mimics the erythema action spectrum according to the International Commission of Illumination (CIE) [28]. Due to the presence of a diffuser in front of the diode, the angular response is close to the ideal cosine-function regarding the skin. The Sunsaver is highly linear and shows no temperature sensitivity in the range between −20 °C and +60°. This meter takes measurements of the erythemally effective irradiance according to the spectral sensitivity of human skin to sunburn [28]. With a sampling rate of 1 s, changes in irradiance due to movement can be recorded. The accuracy of measurements under well-controlled conditions is within ±2% and ±10% in the field. Crucial for the reliability of measurements is securely affixing the meters on a moving body (e.g., the avoidance of wobbling. . .).

The UV-meters were mounted on the calf, shin, anterior thigh, posterior thigh, chest, forehead, upper arm, forearm, and back.

The meters were calibrated by comparison with a high-grade research instrument of the SL501 type (Solar Light Inc., Philadelphia, PA, USA) in the sun. The SL501 participates in the Austrian UV-Index network [29] and is maintained according to international standard procedures [30]. This device was also used to measure ambient erythemally effective irradiance in parallel during the experiment.

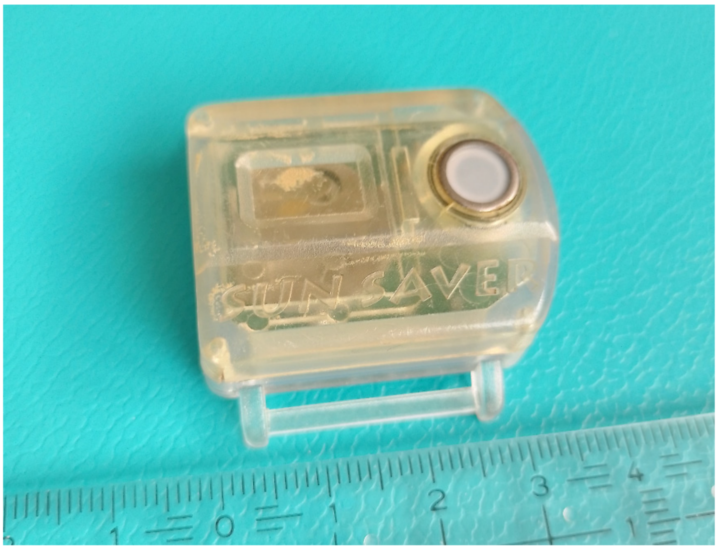


Figure 1. Electronic miniature UV-meter of the Sunsaver type [27].

2.2. Experimental Setup, Location, Time, and Execution of the Measurements

The term "measuring cycle" is used in this work to denote a sequence of measurements with the cyclist facing six different directions: the four cardinal directions as well as directly toward and away from the sun. Each measurement sequence proceeded as follows: southern, western, northern, and eastern directions, towards the sun, and away from the sun. Cycling was simulated in each of these orientations for approximately two minutes.

A men's bicycle was mounted on a roller trainer, which enabled stationary cycling while allowing for realistic cycling motions (Figure 2).

Figure 2. Measurement setup: men's model bicycle on a roller trainer and cyclist equipped with UV-meters (Sunsaver type) at Danube Island, Vienna, Austria.

Before each change in bicycle orientation, the volunteer was completely covered with a black blanket in order to create a zero baseline that allowed for the identification of the changes in orientation when analyzing measurements. A single measuring cycle took about 16 to 18 min.

A measurement day extended over a series of measuring cycles that were repeated every half hour.

The measurements started just before solar noon and extended into the evening until the sun was just 10° above the horizon.

The measurements were taken on three days with clear sky conditions: 19 May 2022, 31 May 2022, and 19 June 2022. Figure 3 depicts the erythemally effective irradiance, expressed in units of the UV Index, during these days. A UV Index of 1 is equal to 0.025 W/m^2 of erythemally weighted UV irradiance [31]. The study took place in Vienna on the Danube Island (48.247° N, 16.389° E, 165 m a.s.l.) in an open, asphalted area. The measurements were carried out at the same place on each of the three measurement days. The asphalted area adjoined a lawn to the southeast. The distance to this lawn area was about 10 m, with about 60 m to the nearest group of trees.

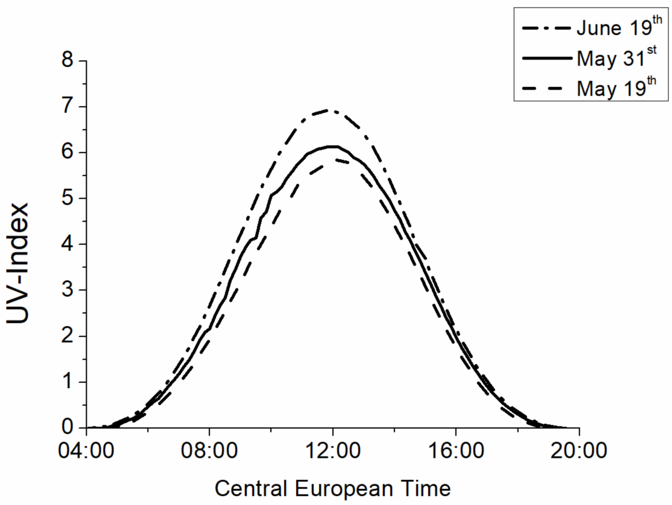


Figure 3. Erythemally effective irradiance (mean values over 10 min) during the measurement campaign (19 May, 31 May, and 19 June 2022) in Vienna (48.247° N, 16.389° E, 165 m a.s.l.), Austria.

2.3. Analysis of Exposure Ratio to Ambient (ERTA) Data

The Exposure Ratio To Ambient (ERTA) expresses the relative irradiance received by a body part in relation to the ambient UVR [6]. This is the ratio between the irradiance E_i, measured at body part i, and ambient irradiance $E_{ambient}$, measured by the nearby SL501 (located on the campus of the university at a distance of 1200 m). The $ERTA(h)_i$ is calculated at different solar elevations h:

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

The higher the ERTA is, the higher the UV exposure of a body site. This allows for the identification of the most exposed body sites. In most cases, the ERTA is between 0 and 1. Under certain conditions, it may exceed a value of 1, e.g., when the receiving body site is oriented perpendicular to the sun.

Once derived, the ERTA can be used to calculate the UVR exposure of a specific body site at any place and time by multiplying the corresponding ambient erythemally effective irradiance with the respective ERTA. Measurements or forecasts of ambient erythemally effective irradiance are publicly available for various locations [14,15].

3. Results

3.1. UV Exposure of Body Sites

Figure 4 depicts the ERTA during one measuring cycle, starting with the cyclist facing south, then west, north, east, directly toward the sun, and, lastly, with the sun behind the cyclist. Before reorienting the bicycle, all UV-meters were shaded, providing the sections of the measuring cycle where all values are 0.

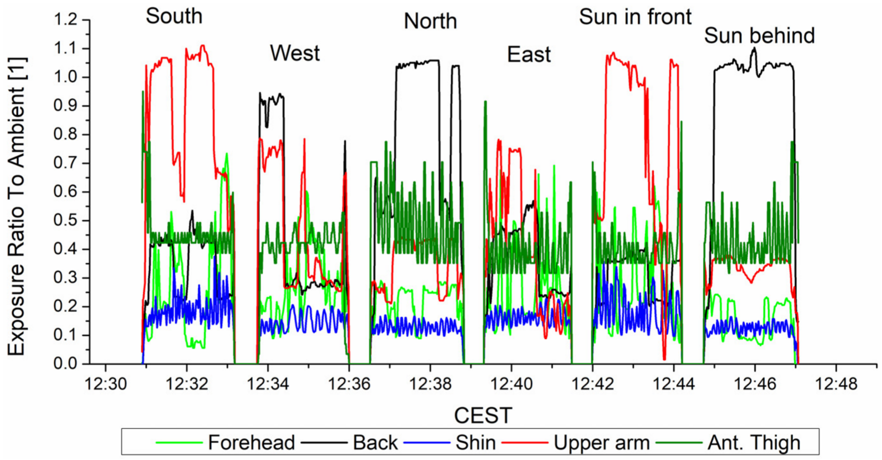


Figure 4. First measuring cycle on 19 May 2021, 12:30 MEST. The Exposure Ratio To Ambient (ERTA) for the forehead, back, shin, upper arm, and the anterior (frontal side of the) thigh is shown for the different cycling directions at a solar elevation of 61°.

The UV-meters mounted on the shin and on the front of the thighs show the movement of the legs when pedaling regularly. Both show no significant dependence of UV exposure on the orientation of the bike.

The UV-meters mounted on the back and upper arm show typical fluctuations due to changes in the cyclist's position while pedaling.

Figure 2 shows the cyclist's head tilted slightly forward, which agrees quite well with the measurements. The readings of the corresponding UV-meter on the forehead are relatively low, resulting in mean ERTA values of around 0.2. However, ERTA values at the forehead show rather large fluctuations, between 0.1 and 0.7, which can be attributed to the cyclist's head movements.

ERTA values higher than 1 were obtained by the UV-meters mounted on the back and upper arm. These values were reached when the meters were oriented perpendicular to the sun. The back received the highest UV irradiance when the bicycle was oriented north (back facing south) and when the sun was behind the cyclist. The upper arm received the highest irradiance when the cyclist was facing south or facing the sun.

3.2. Influence of Solar Elevation

Figure 5 shows the ERTA values calculated at all body sites as a function of solar elevation. These are mean values from measurements performed for the four cardinal directions from all 3 days. This figure shows that body sites which are more or less vertically oriented (such as the calf and shin) have a decreasing ERTA with increasing solar elevation (panel a). The calf and shin receive a much lower UV irradiance than the anterior thighs, upper arm, and forearm.

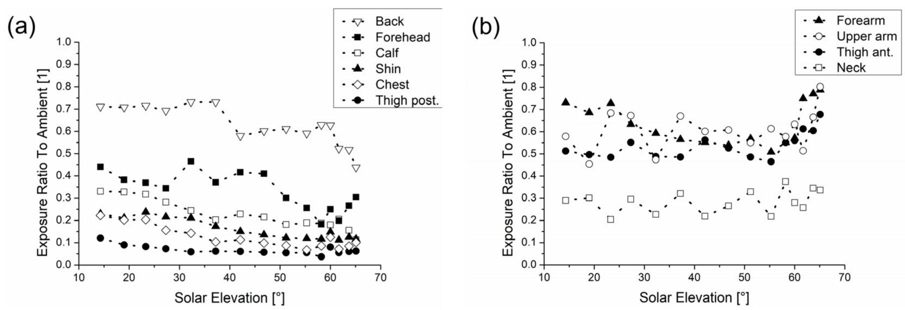


Figure 5. Mean Exposure Ratio To Ambient (ERTA): (**a**) back, forehead, calf, shin, chest, posterior thigh; and (**b**) forearm, upper arm, anterior thigh, and neck, dependent on the solar elevation. Mean values were calculated as the average over all four cardinal directions on all 3 days.

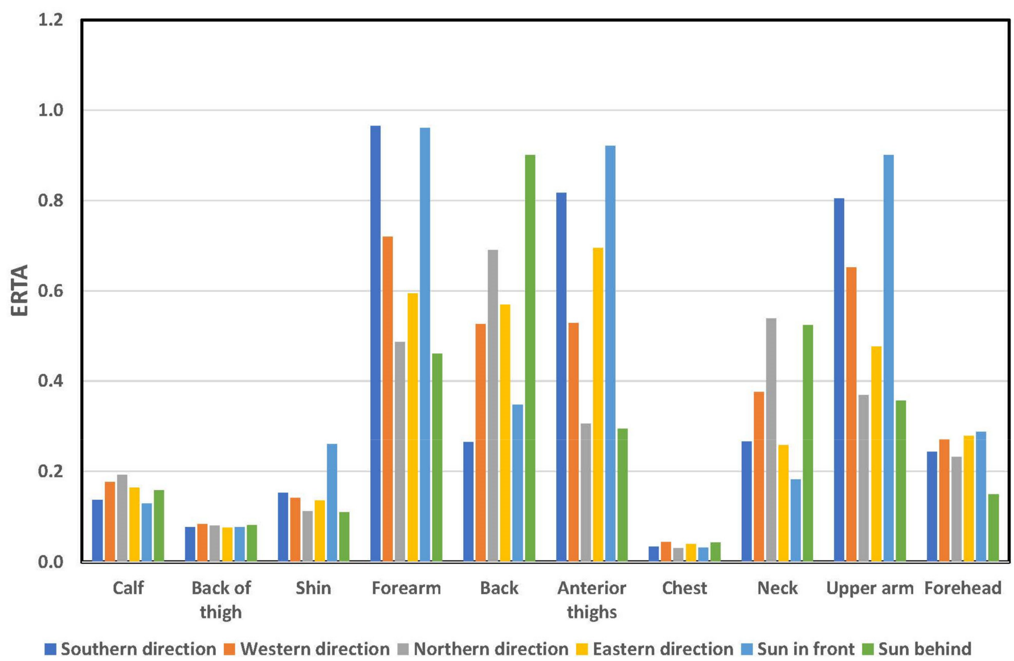
For other sites (panel b), the ERTA remains constant or shows an increase with solar elevation. The rather large fluctuations result from the slightly different postures of the cyclists, the different body sizes and shapes of the different volunteers, and from slight differences in the mounting position of the UV-meters on the three measurement days. These fluctuations show the limitations in the accuracy of the UV-meter measurements.

3.3. Influence of Bicycle Orientation

Figure 6a–c shows the ERTA values at the different body sites as a function of the bicycle orientation for measurements performed at solar elevations between 60 and 65° (Figure 6a), 40 and 45° (Figure 6b), and 20 and 25° (Figure 6c). The forearms, back, anterior thighs, and upper arms are the body sites that receive the highest UV irradiance. ERTAs even reach values above 1. At solar elevations above 40°, UV irradiance may increase to above 100% when the body sites are facing the sun. At solar elevations below 25°, the difference in UV irradiance between the bicycle orientations decreases. This may be attributed to the increasing proportion of the diffuse component of UV radiation.

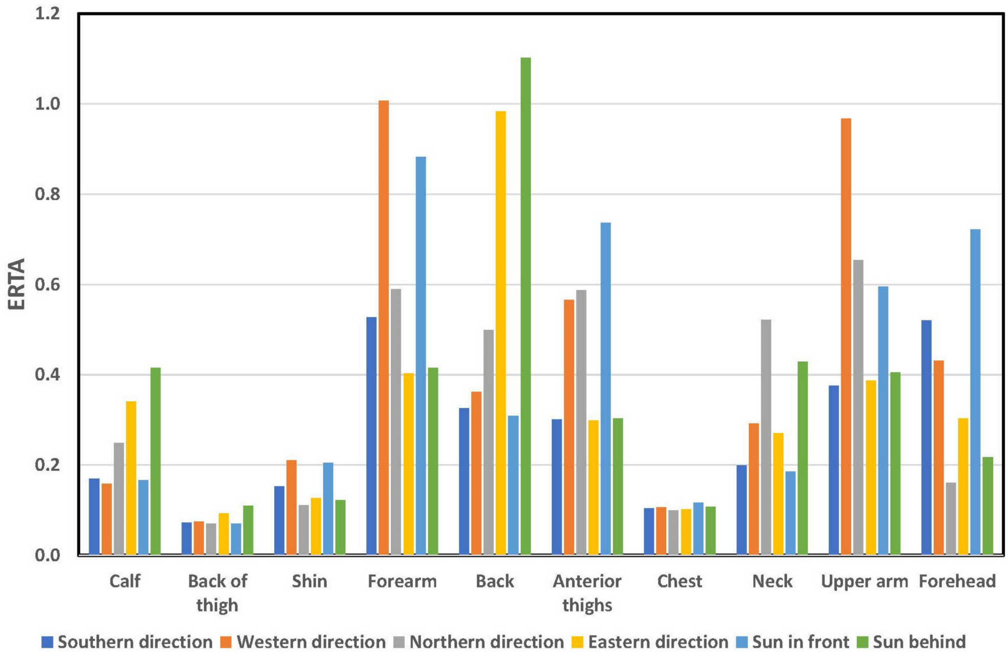
The posterior thigh, chest, and shin show much lower ERTA values, mostly below 0.2. These body sites seem to be better protected from the sun, partially due to the shade provided to the lower body by the bicycle and cyclist.

Figure 7 shows box plots of the mean ERTA values over all directions (including facing the sun, the sun behind the cyclist, and the four cardinal directions) measured on the different days. The box indicates the range of the values between the 25th and the 75th quantiles. The largest fluctuations in UV irradiance occurred at the forearm, upper arm, back, and anterior thighs. The lowest UV irradiance and the lowest fluctuations were measured on the calf, the back of the thigh, and the chest. These are body sites that are shaded or that show that the cyclist's upper body is bent forward or oriented downwards. Two body sites are at risk of receiving excessive UV exposure: the back and the upper arm.



(**a**)

Figure 6. *Cont.*



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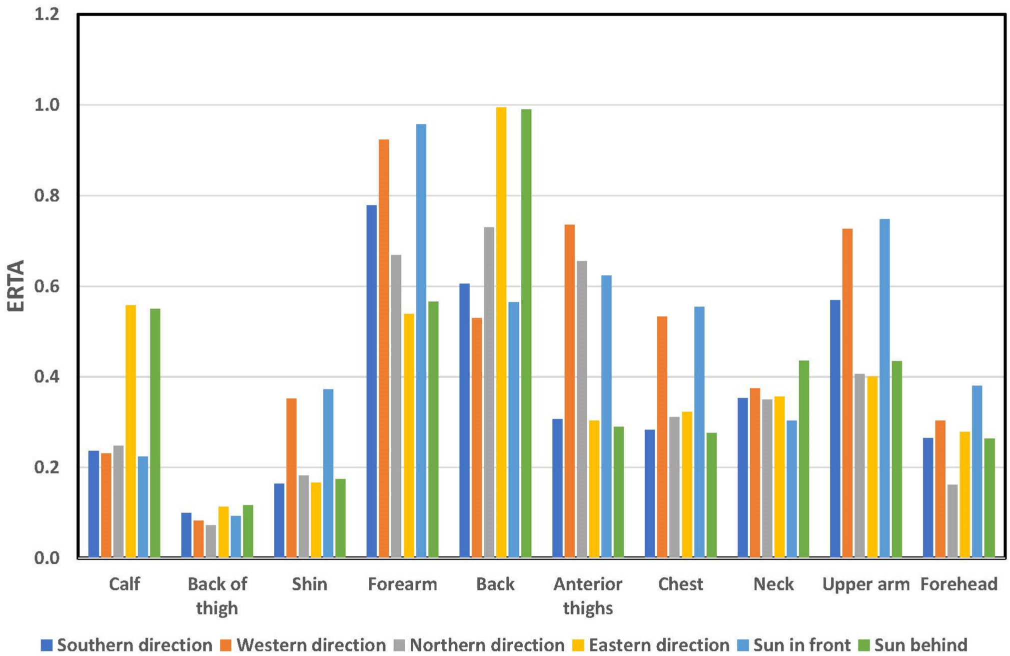


(**c**)

Figure 6. (**a**) Mean ERTA of different body sites dependent on orientation for solar elevations between 60° and 65°. (**b**) Mean ERTA of different body sites dependent on orientation for solar elevations between 40° and 45°. (**c**) Mean ERTA of different body sites dependent on orientation for solar elevations between 10° and 25°.

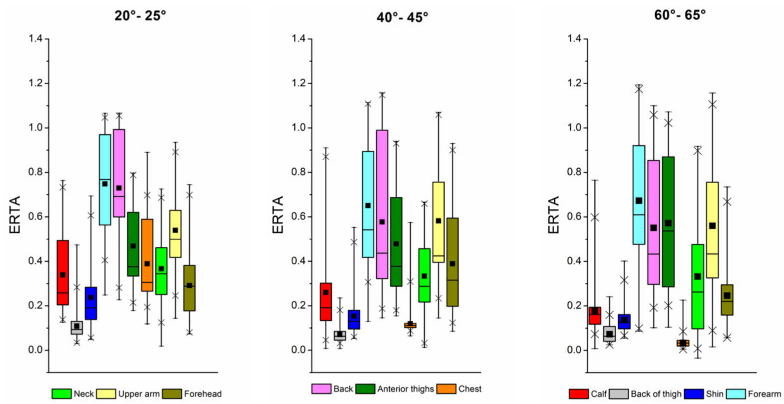


Figure 7. Box plot of the ERTA (all orientations, including facing the sun, the sun behind the cyclist, and the four cardinal directions) at the different body sites as a function of solar elevation. Maxima are indicated by thin vertical lines above the boxes and minima by thin vertical lines below. The boxes span the range from the 25th to the 75th quantiles. Averages are depicted by filled squares and medians by horizontal lines inside the box. The 1st and 99th percentiles are indicated by "x".

4. Discussion and Conclusions

Although cycling is a highly prevalent means of transportation, little research has been carried out in evaluating the UV exposure of cyclists. To date, UV exposure from sport cycling has only been estimated for a few body sites at different locations, different times of the year, and for different distances [21–25]. For example, Curtis et al. [24] reported that up to 125 SED (Standard Erythema Dose; 1 SED = 100 J/m^2 erythemally weighted UV radiant exposure [28]) accumulated at the top of the helmet over an unspecified period in summer in Utah, USA. During long-distance rides in Australia, Downs et al. [25] measured values up to 4.1 SED/hr at the top of the helmet, which corresponds approximately to a mean ERTA of 0.3 over the whole day. Similar values (also at the top of a helmet) of 2.5 SED/h (ERTA = 0.37) in summer and 1.2 SED/h in winter (ERTA = 0.40) were measured by Serrano et al. [23]. Moehrle et al. [21] found values up to 43 SED per day during the Tour de Suisse between the shoulder blades (above the cycling jersey). Kimlin et al. [22] evaluated the UV exposure of the hand, ankle, and side of the head in relation to the top of the helmet over longer distances (4 to 9 h) in the Australian winter. At the top of the helmet, radiant exposure was 4.5 SED per day on average. The ankle received 52% of this, the hand 71%, and the side of the head 63%. These results lead to the conclusion that UV exposure may be high. However, the numbers can hardly be transferred to other locations, other times of the year, short-term exposure, or other body parts. In any case, long-distance rides hold a risk of UV overexposure manifested in sunburn and pathological alterations of the skin [32,33], whereas appropriate clothes can protect well [24].

Therefore, this study was undertaken to fill this gap and to provide a universal model for the UV exposure of different body sites by determining the ERTA as a function of solar elevation.

We measured the erythemally effective personal UV exposure of a cyclist without a helmet on an everyday bike by mounting miniature electronic UV-meters on several body sites. Besides enhancing safety, a helmet can also reduce the UV exposure of the forehead and nose. However, the latest surveys from Austria and Germany show that around 40% of adult cyclists never use a helmet [34,35], and around 40% sometimes use one. In Chinese cities, the frequency of helmet wearing is less than 5% [36]. Opposite to this, helmet wearing finds broad acceptance in countries like The Netherlands or Denmark, and is mandatory in only a few countries (Finland, Malta. . .). In Austria, bicycles are used for many different purposes; the typical distance for cycling is below 25 km and is 6–7 km on average [34]. Clothing is mainly selected (disregarding rain) on the basis of temperature [32], and the percentage of those engaging in well-equipped sport cycling (with a helmet, cycling jersey. . .) is rather low; less than 10% of Austrian cyclists do so [34].

Therefore, in casual cycling, when not enough sun protection is provided, some body parts may be at risk of overexposure.

The measured UV irradiance shows a clear dependence on the orientation of the body site with respect to the sun. UV-meters, or body sites, which are oriented perpendicular to the solar beam receive the highest UV irradiance. The Exposure Ratio To Ambient (ERTA) shows the same behaviour. In general, the forearm, back, upper arm, and anterior thigh receive the highest UV irradiance and have the highest ERTA, with values up to 0.7.

With the measured ERTAs, it is possible to calculate the UV exposure during cycling whenever ambient UV irradiance and solar elevation (up to 65°) are known. In an earlier study, we determined the ERTA only for the chest when cycling on a ladies' model bicycle [24]. At that time, UV-meters were very expensive and rather big and inconvenient compared to today's miniature UV-meters. Due to the more upright orientation of the upper part of the body when using a ladies' model bike, the ERTA at the chest is around 0.4 and thus significantly higher than for a men's bike (0.2).

A detailed analysis also shows that measurements were subject to fluctuations due to changes in the position of the volunteer during cycling, slight differences in UV-meters' position between the different days, and the body shape and size of the three cyclists. These fluctuations indicate the limitations in the accuracy and validity of personal UV exposure measurements.

A comparison of UV exposure in other sports shows ERTA values lower than 0.7 (which corresponds to the higher values obtained in the present study) on the head [25], upper arm [37], and wrist [38] for running; for playing tennis, measured on the cheek, hand, calf, and wrist [38]; for cricket measured, on the cheek and hand [39]; and for golf, measured on the cheek, hand, back, forearm, and wrist [39,40].

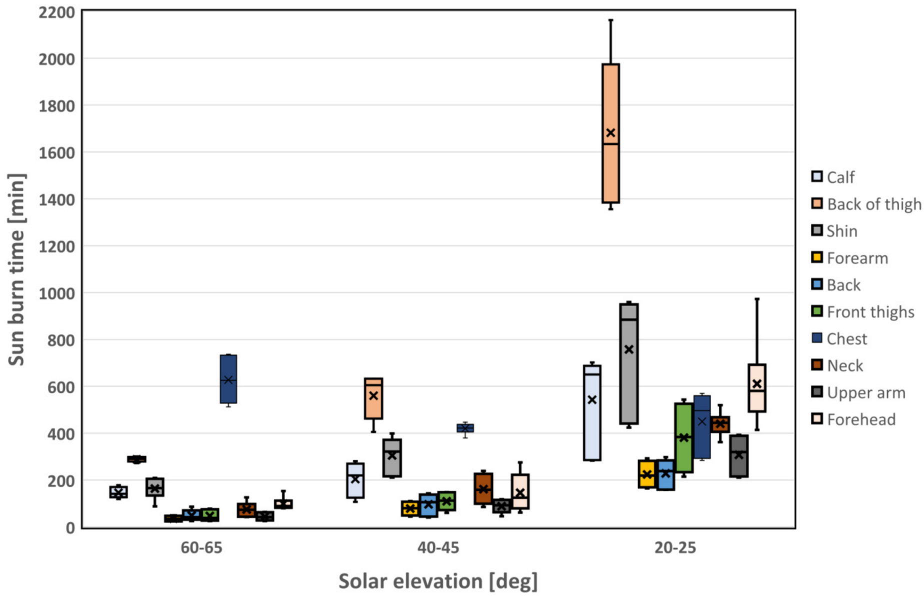
Higher ERTA values were reported for golf on the vertex and upper back [40] and for tennis players on the forehead [41]. According to Schmalwieser and Siani [42], for other activities and commonplace exposure, higher ERTA values above 0.7 were reported during walking, sight-seeing, or sitting in a café on the chest [26]; swimming, on the hand and back [34]; and sunbathing, on the back [43]. We may draw the conclusion that cycling belongs among the sports with higher exposures on some body sites.

To estimate the risk of UV overexposure, we transformed irradiance to sunburn time (SBT) for a light-skinned person of Fitzpatrick skin photo type I [44], assuming a minimal erythema dose of 200 J/m^2 [45]. Figure 8a,b depicts the mean SBT (averaged over all six orientations) at different solar elevations for different body sites from different trials. As can be seen in Figure 8a, SBTs cover a wide range from several minutes to more than 20 h. Figure 8b only depicts the SBT range up to 120 min.

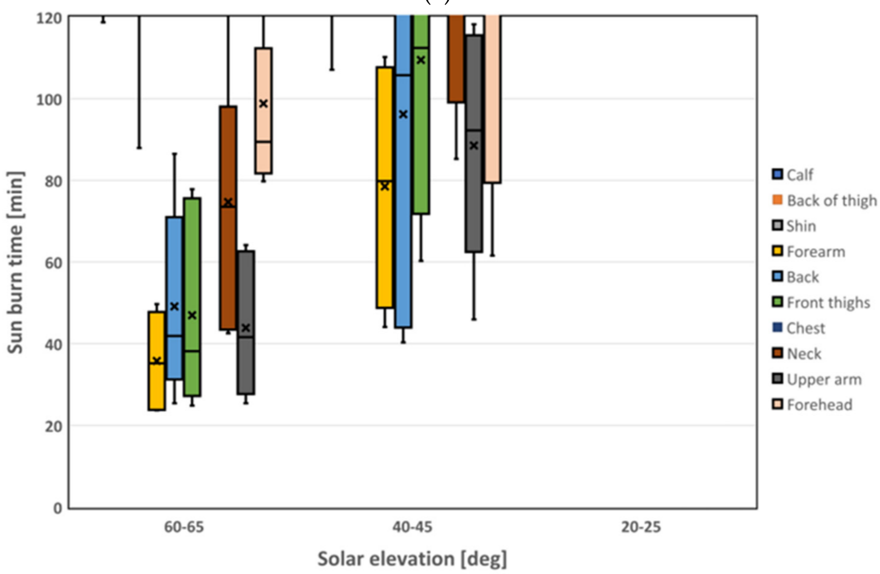
On the given days, the maximum UV Index reached values of 6 to 7 at noon (Figure 3), around 3 to 3.5 at solar elevations between 40° and 45°, and values that dropped below 1 (average value 0.86) at solar elevations between 20° and 25°.

Given an ERTA of up to 0.6 at the calf (Figure 6), this does not represent a risk, as SBTs are longer than 60 min.

In general, a risk of sunburn with respect to UV overexposure is present largely at higher solar elevations, where the SBT is below 1 h for some orientations. Therefore, attention should be paid when the solar elevation exceeds 40° to especially protect the arms, the back (including the nape), and the frontal side of the thighs. Contrary to our expectations, the forehead is less at risk, since the cyclist's head is slightly bent forward and typically protected by a helmet.



(**a**)



(**b**)

Figure 8. (**a**) Box plot of the mean sunburn time (averaged over all orientations: facing the sun, the sun behind the cyclist, and the four cardinal directions) from different days for skin photo type I at the different body sites as a function of the solar elevation. Maxima are indicated by thin vertical lines above the boxes and minima by thin vertical lines below. The boxes range from the 25th to 75th quantiles. Averages are depicted by crosses and medians by horizontal lines inside the boxes. (**b**) Same as (**a**), but for sunburn times of less than 120 min only.

It should be noted that our measurements do not cover the whole body. The geometry and topography of the human body is complex, and even within small distances, sun traps may appear (e.g., at the top of the ears, nose. . .) under certain solar elevations, and individuals may have differently developed characteristics like cheekbones, collarbones, and others.

It should also be noted that measurements were carried out in an open environment on a rather low-reflecting asphalt-paved ground. At locations with restricted sky exposure (with nearby buildings, trees. . .), the received irradiance may be lower [8].

Our results can support people in undertaking the manifold advantages of cycling as an outdoor activity, while, at the same time, protecting their upper arms and back from overexposure to UV.

Author Contributions: Conceptualization, P.W., J.H. and A.W.S.; Methodology, P.W., J.H. and A.W.S.; Validation, J.H. and A.W.S.; Formal analysis, P.W., V.L., L.L., S.K., Z.L., P.S. and A.W.S.; Investigation, V.L., L.L., S.K., Z.L. and P.S.; Resources, J.H.; Data curation, V.L., L.L., S.K., Z.L. and P.S.; Writing—original draft, P.W., S.H. and A.W.S.; Writing—review & editing, P.W., S.H. and A.W.S.; Visualization, P.W., S.H. and A.W.S.; Supervision, P.W. and A.W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to required organization of time unlimited server space, and edition of a manual.

Conflicts of Interest: The authors declare no conflict of interest.

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