Prediction of anatomical exposure to solar UV: a case study for the head using SimUVEx v2

Arianna Religi, Laurent Moccozet
University of Geneva
Institute of Services Science
Geneva, Switzerland

David Vernez, Antoine Milon, Claudine Backes
Institute for Work and Health
(IST)
Lausanne, Switzerland

Jean-Luc Bulliard, Claudine Backes
Lausanne University Hospital (CHUV),
University Institute of Social and Preventive Medicine (IUMSP)
Division of Chronic Diseases
Lausanne, Switzerland

Laurent Vuilleumier
Federal Office of Meteorology
and Climatology
MeteoSwiss
Payerne, Switzerland

***Abstract*—Excessive exposure to solar ultraviolet (UV) radiation is the main cause of skin cancer. The dose-response between UV exposure and skin cancer occurrence is not yet fully understood since UV exposure is highly heterogeneous and strongly influenced by host and behavioural factors, such as posture, orientation to the sun, skin complexion and clothing. To address this issue, a three-dimensional (3D) numeric model (SimUVEx) has been developed to assess dose and distribution of anatomical UV exposure. The model uses 3D computer graphics techniques to compute UV radiance on the basis of postural information and ambient irradiation data, without necessitating time-consuming individual dosimetry, ensuring a wide potential use in skin cancer prevention and research. With the purpose to improve simulation capabilities in order to obtain more realistic scenarios and quantify effective sun protection strategies, a new version has been released, SimUVEX v2. Among new features, a specific morphology for the most sun-exposed body area, the head, has been added. We selected three different styles of hat (cap, wide-brimmed hat and helmet) to compare scenarios with and without solar protections considering the relative contribution of the direct, diffuse and reflected radiation. It was found that, sites directly covered apart (e.g., forehead and top of the head), hats with a wide brim are necessary in order to provide reasonable protections around facial zones on which non-melanoma skin cancers commonly occur, such as nose and cheeks.**

I. Introduction

The solar ultraviolet (UV) radiation (290-400 nm) is one of the most relevant environmental factors for human health. While small amounts of UV can bear favourable effects and are essential in the production of vitamin D, protracted exposure may cause acute and chronic effects on skin, eyes and immune system [1]. In particular, UV radiation has a significant influence on the premature ageing of the skin [2] and on the development of skin cancers like cutaneous malignant melanoma (MM), basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) [3]. Over the past decades, because of the progressive increase in outdoor leisure activities, vacations in sunny regions and change in clothing habits [4] [5], the incidence of skin cancer has sharply increased in many industrialised countries. While MM is the most dangerous form of skin cancer, epithelial skin cancers (BCC and SCC) represent the most common cancer type worldwide [6]. These cancers tend to be located on chronically sun-exposed body parts, contrary to MM which is predominantly diagnosed on intermittently sun-exposed skin areas.

Individual UV exposure is related to the distribution of direct, diffuse, reflected UV radiation and to the body posture, along with the duration of exposure, skin complexion and sun protection habits [7]. UV distribution depends on various factors such as the total ozone, cloud cover, altitude, albedo (surface reflectance), aerosols, and solar elevation [8]. Some anatomical areas, such as the face, head and neck, are more exposed to the sun and it has been demonstrated that horizontal body parts, such as the top of the shoulder, exhibit higher exposure doses [9] [10]. The quantification of the anatomical distribution of UV radiation, along with a mapping of solar radiation on human skin, can help to understand the relationship between UV exposure and skin cancer and to guide the design of sun protection programs. Even if photosensitive dosimeters and captors are valid instruments to quantify the amount of individual UV exposure, their measurements are strongly related to the specific position, are costly and prone to behavioural biases. With the aim to collect more relevant information with respect to UV exposure of the whole human body and for particular parts of the skin, numerous efforts have been made to calculate solar irradiance in the directions of typically oriented surfaces of the human body [11] [12] using three-dimensional computer graphics techniques [13] [14] [15] [16]. In this regard, a numeric simulation tool (SimUVEx) has been developed and validated to predict the dose and distribution of UV exposure received on the basis of ambient irradiation data and 3D rendering and human modelling [17]. The objective

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is to model solar UV exposure patterns, taking into account daily measurements of UV irradiances by broadband detectors to derive doses on various body parts for different working postures and morphologies. In order to achieve more realistic scenarios, a new SimUVEx version has been developped with the purpose of improving temporal, spatial and simulation capabilities. The new morphologies, postures and resolutions enhancements gave us the possibility to focus only on the facial area, that is the anatomical zone most affected to skin diseases [18], taking into account typical protections for the head, such as hats.
This work intends to present a detailed description of the SimUVEx v2 model, discussing its performances and its potential perspectives in sun prevention messages. A general example of application for the anatomical region of the head is also provided. For this purpose we modelled three different hats and four sun protection scenarios (head without protection, head with cap, head with wide-brimmed hat and head with helmet) for the same time period (16/07/2009, from 10AM to 2PM) and location (Payerne, Switzerland). We compared the simulation outputs with and without protections, analysing the results.

II. Materials And Methods

A. Definitions

Irradiance (E) is defined as the amount of energy received by a surface per unit area, in W/m^2. Biological effect of UV radiation may be computed by multiplying a spectral weighting function (action spectrum). In this study we use the erythemally weighted spectrum, so that the spectral irradiance can be defined as following:

$$E_{ery} = \int_{\lambda_1}^{\lambda_2} E(\lambda) S_{ery}(\lambda), d\lambda \qquad (1)$$

where $E(\lambda)$ is the spectral irradiance over a specified wavelength region, e.g. (λ_1, λ_2), where $\lambda_1 < \lambda_2$, and $S(\lambda)$ is the erythemal action spectrum [19]. The radiance (H) is defined as the amount of energy received by a surface, per unit solid angle and unit projected area during a given time interval and has units of J/m^2. The term dose refers to the fraction of radiant exposure that is absorbed per unit area and depends on reflectance and absorptivity of the irradiated material.

B. The SimUVEx v.2 Modelling

SimUVEx v.2 is a prediction model of individual solar exposure based on SimUVEx v.1 [17]. It uses continuous irradiance datasets, 3D rendering techniques and human modelling to estimate the dose and the anatomical distribution of UV received. The application is based on VCG (Visualization and Computer Graphics Library) [20], an open source C++ library for handling and processing triangle meshes, and implemented as a plug-in in MESHLAB [21], an open source system for computing and editing 3D triangular meshes. A general schema of SimUVEx v2 is shown in Fig.1 and a detailed overview of the second version is presented hereunder. A comparison between the first and second version has already been discussed in [22].

C. Input data: ambient radiation and body postures

The inputs of the model consist in ambient irradiance datasets and postural and morphological data. The irradiation is provided by a .csv file containing the date, the sun position (defined by its azimuth and zenith angles) and the direct, diffuse and reflected radiation for every minute of the day. This kind of data can be obtained from meteorological stations equipped with multiple broadband radiometers or from atmospheric radiation transfer model (RTM), such as libRadtran [23]. RTM programs can give accurate estimates of the irradiance components for clear sky situations, moreover several efforts have been recently made to reconstruct UV irradiance in cloudy atmosphere, even in the framework of our research project.
Regarding the body postures, we firstly used the MakeHuman software [24], an interactive modelling tool for 3D human characters based on articulated skeleton techniques [25] [26] to create 3D surfaces of five human morphologies: adult man, adult woman, child, heavy man and head-form. Each morphology is depicted as a single 3D mesh of connected triangles, whose size density depends on the quality of the resolution; the relative anatomical precision of irradiance exposure calculations change according to the number of triangles comprising the model. The whole body has been described using 800-1800 vertices and 13000-14000 vertices for the low and high resolution, respectively, whereas 4333 vertices have been used for the head. Thereafter we used Blender [27], an open source 3D computer graphics software, to set the postures based on the articulated skeleton previously built with MakeHuman. In total, we designed six working postures (seated, kneeling, standing-arms-down, standing-arms-up, standing-bowing, lying on the ground on the back) and three leisure time postures (seated position on the sand, lying on the ground on the belly, seated position with stretched legs). The duration of the simulation depends to the resolution used. As an example, considering a simulation of 24 hours, it takes less than one minute for the low resolution and less than fourteen minutes for the high resolution (about 1 minute per 1000 vertices).

D. Anatomical zones and protection factors

Anatomical zones and protection factors constitute other optional parameters of the model. The former are loaded from a .xml file which consists of regions and subregions for the body postures and the head. Each sub-zone is represented by a different RGB color and a region is just an aggregate of various sub-zones (e.g., the region ”Neck” include two subregions, ”Neck-Front” and ”Neck-Back”). We selected 45 anatomical zones for the body low resolution and 46 for the high resolution, whereas for the head we decided to distinguish 36 zones according to the nomenclature provided by the third version of the International Classification of Disease for Oncology [28]. Protection factor is another optional parameter

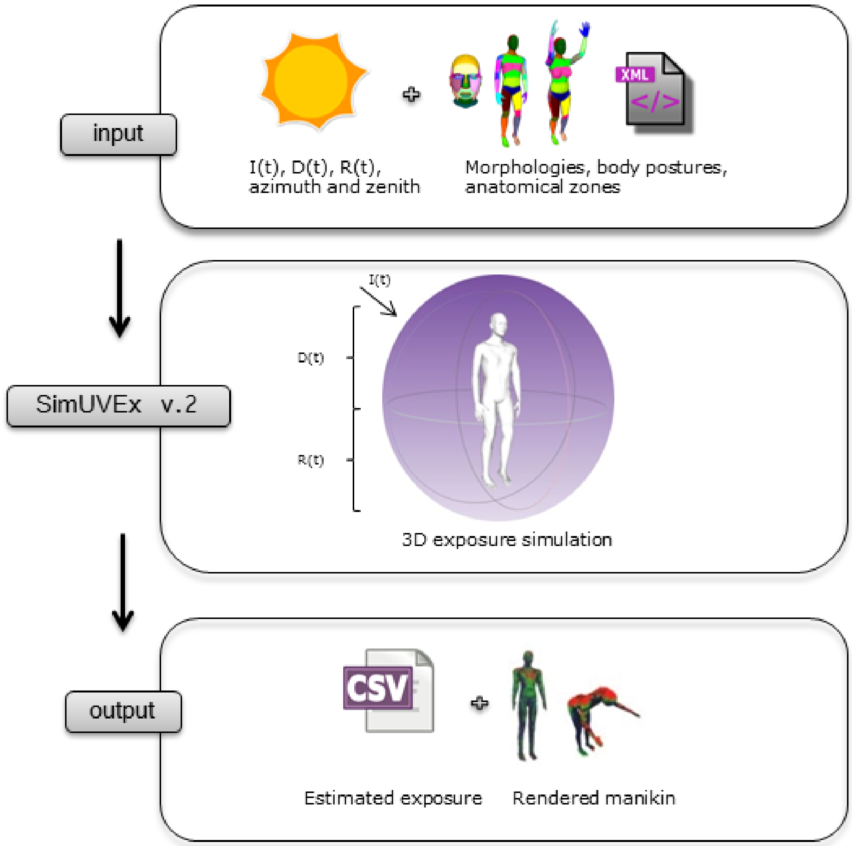

Figure 1. Schema view of SimUVEx v2.

that can be applied directly to the mesh. It reduces the amount of UV radiation received by protected vertices, choosing an appropriate protection factor depending on the textile or material considered in order to simulate garments. The protection factor in SimUVEx v2 is defined as the ratio between the received radiation without protection and the received radiation after protection, similarly to the ultraviolet protection factor (UPF) described in [29].

E. SimUVEx Algorithm

Body posture and orientation to the sun play a key role in skin exposure to UV. In real situations, individuals hardly stay static, so it has been necessary to consider postural and orientation changes over the exposure period. Thus, depending on the type of the simulation chosen, the position can either be fixed for every time iteration or change on a given time and angle step in order to obtain an average orientation. The amount of solar UV energy received by each triangle of the 3D manikin is calculated considering the three radiation components and shading from other body parts. Each triangle has a precise orientation in the space, defined by the triangle's surface-normal vector. The direct component I(t) is described as a parallel source of radiation varying in intensity, with time, and in direction, with the sun position. Its estimation is possible by calculating the vector dot-product between the surface-normal and the incoming light ray if the vertex is visible. To check if a vertex is visible, a bounding box optimization has been used. In case of intersection between the ray and the bounding box, it has been checked, for each side, if the ray directed from the source to the target vertex crosses the face first. If it does, then the vertex is visible, otherwise it is not.

Calculation of the diffuse (D(t)) and reflected (R(t)) UV components depend on the surface orientation facing the sun position, as well as on the sky view factor. In our model their UV exposure is derived from the assumption that diffuse and reflected irradiance are hemispherical isotropic sources with time-dependent intensities, as represented in Fig.1. Both hemispheres are discretised into regular sub-surfaces. The diffuse radiation is assumed to decrease linearly from an elevation angle of 25° and the horizontal layer, while the reflection radiation is assumed to be isotropic so that an equal amount of energy is assigned to each subsurface element to the bottom half-sphere. For each posture SimUVEx produces a "visibility" map which contains the number of sub-surfaces of each hemisphere visible from the vertex, for the diffuse

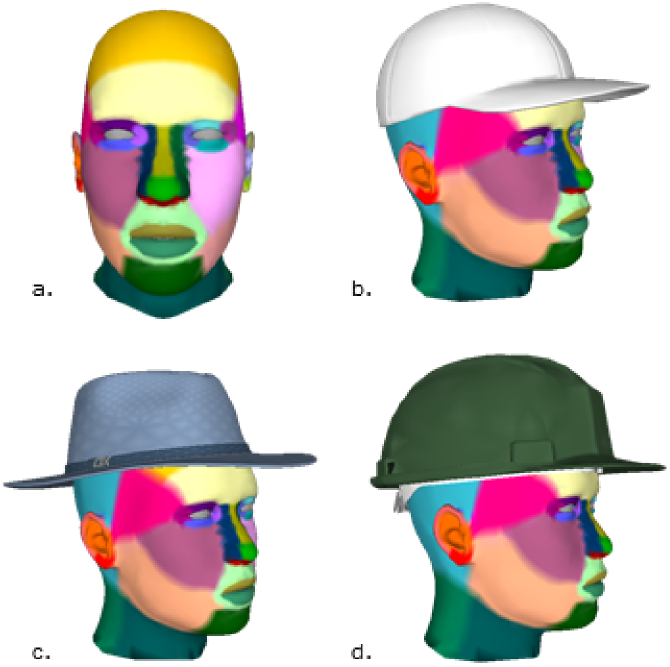

Figure 2. Different models of the head: a) head without protection, b) head with cap, c) head with wide-brimmed hat and d) head with helmet.

and reflected radiation. The energy contribution for each visible subsurface to exposure of a given vertex was computed similarly to the direct radiation, taking in consideration, this time, the angle between the vertex normal and the normal to the diffuse/reflected subsurface.

F. Output and Visualisation

The output of SimUVEx v2 consists in .csv files containing radiance data one-minute resolution for each anatomical zone. UV intensities received by each anatomical zone are evaluated iterating through all of the zone vertices and adding all the received intensities together. Then, the received intensity is divided by the area of the zone. If a zone contains sub-zones, then first evaluate the sub-zones as above and then aggregate the sub-zones results in the zone. Moreover, a 3D visualisation of UV exposure in the manikin is also provided to enhance understanding. A three colour scale is used to identify low (blue), intermediate (green) and high (red) doses.

G. Data Field: Irradiance ground-based dataset

The measurements used in this study were performed at the MeteoSwiss Payerne Station (44.815° N, 6.994° E, altitude 491 m). Ambient direct, diffuse and reflected UV erythemally weighted irradiance are measured simultaneously at this facility using broadband UV radiometers. The overall uncertainty of the measurements is estimated at 10%. Only data collected between 10 AM and 2 PM on July 16, 2009 were used in the analysis, in order to take in consideration the sun at its highest in the sky during a typical summer day.

III. RESULTS

Case study: Head

The performance of the SimUVEx v.2 in the prediction of solar exposure was first evaluated using the head form. Three styles of hats were selected to evaluate the degree of sun protection at different anatomical sites on the head. For leisure time we used the cap (about 10 cm frontal brim) and the wide-brimmed hat (about 6 cm brim), the helmet for working situations (about 7 cm frontal brim, 4 cm lateral brim) (see Fig. 2). It must be pointed out that we created a 3D model head with three different styles of hats instead of using a general attenuation factor in order have a more realistic simulation and take into account the shade from other head parts (e.g. ear exposure). The protection factor has been used for the top of the head solely, the only zone directly in contact with the material of the hat. Overall, the UPF depends on many factors (weave density, composition of the fabric, weight per unit area, fabric thickness, colour, additives, tension, condition, moisture content), so according to the literature [30] [31] we chose a low UPF for the cap, usually made in cotton (5), a medium value for the wide brimmed hat (30) and the highest UPF for the helmet, usually made in plastic (50+).

We report our results for the anatomical regions in solar protection cases, in a specific exposure situation, with the purpose to investigate further these situations. As shown in Fig.2, each anatomical zone is characterized by a different colour and the facial anatomical regions are constituted as following:

- Top of the head: forehead, top;
- Back head;
- Face: cheek (left/right), jaw (left/right), chin;
- Temple: left, right;
- Eye (left/right): tear-duct, upper, lower, lateral;
- Ear (left/right): auricula, earlobe, earlobule front, earlobule back;
- Nose: columnella, external nose right, external nose left, tip of the nose, dorum nasale;
- Oral region: upper lip, lower lip, orbicularis oris;
- Neck: front, back

The comparison between the head with and without protection was evaluated in terms of Predicted Protective Factor (PPF):

$$PPF(\%) = \frac{H_{withoutprotection} - H_{withprotection}}{H_{withoutprotection}} \times 100 \quad (2)$$

A positive PPF means that the dose without protection is greater than the one with protection, as expected. The greater the difference, the more effective the protection.

Tab. I summarizes the various exposure scenarios investigated with the static head orientation. It must be noted that most of the total UV exposure comes from diffuse and direct radiation [9], whereas the reflected radiation has a really small contribute. Slight differences for the PPF for the same region but different sides (right-left) can also be due to the precision of the manual selection of each anatomical zone. Generally, the results underline the importance of the brim for the sun

Table I
PPF (%) BETWEEN ERYTHEMALLY WEIGHTED DOSE WITH AND WITHOUT PROTECTION CATEGORISED BY FACIAL SITE AND COMPONENT OF UV RADIATION.

	Head with Cap				**Head with Hat**				**Head with Helmet**			
Regions	*Total*	*Diffuse*	*Direct*	*Reflected*	*Total*	*Diffuse*	*Direct*	*Reflected*	*Total*	*Diffuse*	*Direct*	*Reflected*
Top of the head	50.13	51.71	47.81	27.33	58.83	59.72	57.77	26.15	62.09	64.35	58.80	28.85
Back Head	0.30	0.30	0.44	0.14	8.89	9.31	5.34	1.71	14.90	12.47	52.54	6.67
Temple	1.82	2.26	0.34	2.65	11.18	12.93	5.34	0.01	18.54	17.41	26.01	6.10
Ear Left	8.41	7.12	-	0.57	32.18	25.99	-	-0.92	38.14	32.06	-	0.13
Ear Right	7.47	6.52	-	0.67	32.29	25.20	-	-0.90	37.24	33.54	-	0.89
Eye Left	29.04	29.91	33.25	2.70	13.55	17.75	1.15	-2.63	26.93	26.49	38.86	-1.41
Eye Right	27.76	31.42	21.74	2.70	11.73	16.12	0.49	-2.45	24.98	28.81	21.57	-1.62
Nose	63.45	44.38	93.73	0.30	45.47	26.57	75.31	-1.54	56.16	37.38	85.97	-0.87
Face	24.16	14.36	67.50	0.06	24.44	10.21	83.42	-0.47	26.56	14.74	78.12	-0.09
Oral Region	41.22	18.07	82.45	-0.20	38.21	11.69	85.36	-1.19	43.49	15.22	94.02	-0.68
Neck	1.42	1.39	-	-0.07	10.75	7.99	-	-1.06	8.51	8.59	-	-0.32

protection, confirming that a hat with a large brim is necessary to provide reasonable protection around nose and cheeks. More precisely, the hat with a large frontal brim (cap) provides high protection to the nose (about 64%) and eye regions (about 28%), but negligible protections to the ears which are evidently exposed. On the other side, the wide brimmed hat offers good protection in several anatomical zones because of its larger brim all around the circumference of the head. The protection on the eyes zone in this case is smaller (13.55% for the left side, 11.73% for the right one) because the brim is smaller in comparison to the one of the cap. The helmet provides a better protection for all zones, as it can be readily imagined, because of its bigger dimensions, on average. In each case the neck is the most exposed part because the brim's shadow does not reach this area, whereas the nose and the oral region are the most protected for all the situations, even before eye regions and face region (chin, cheeks). Ear regions are covered only in the case of the helmet and hat. Regarding the top of the head, for whom we used three different UPF depending on the texture of the hat, it turns out to be the most protected zone because its protection is clearly proportional to the level protection provided. The brim seems effective only to body parts immediately close to the hat, while its protection for the other body parts is limited (e.g. neck). This fully justify the fact that caps are not sufficient in high exposure situation and that legionnaire caps (with a cover on the neck) have to be used instead.

IV. Conclusions

SimUVEx v2 is an inexpensive tool that estimates individual UV exposure distribution over the human body and head. It combines numerical modelling and ground irradiance data for the direct diffuse and reflected radiation. The first release contributed to improve our understanding of exposure patterns and identify some potential shortcomings in current sun protection recommendations. SimUVEx v2, for its part, has been extended and optimised to achieve new levels of results by moving from individual to population-based exposure assessments, adding protection measurements, detailed situations, new resolutions, postures and morphologies. In this first study based on the version 2, we compared UV exposure of the anatomical zones of the head with and without protection, taking into account direct, diffuse and reflected radiation. Overall, the site-specific PPF was really heterogeneous, ranging from 2% to 63%. The highest values were found for the top of the head (from 50.13% to 62.09%), the zone of the nose (63.45% for the cap, 45.47% for the hat, 56.16% for the helmet), followed by the oral region, the eye regions and the face. Our estimates were in line with epidemiological studies on protection with hats that used time-consuming individual dosimetry, such as ultraviolet-sensitive film badges on model human forms. Our purpose is to go deeply in these results, expanding analysis in order to identify and quantify active sun protection strategies to elaborate targeted prevention messages for high-risk populations or situations, including risks of overexposure as well as of underexposure for typical outdoor occupational and leisure activities. Reference doses should be, effectively, analysed concomitantly with skin cancer registries' data to support epidemiological research.

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