SimUVEx v2: a numeric model to predict anatomical solar ultraviolet exposure

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***Abstract*— Solar ultraviolet (UV) radiation has a dual effect on human health. Low UV doses promote the photosynthesis of vitamin D and regulate calcium and phosphorus metabolism, while an excessive UV exposure is the main cause of skin cancer, along with eye diseases and premature skin ageing. Nevertheless, the link between UV radiation levels and UV exposure is not fully understood since exposure data are limited and individual anatomical variations in UV doses are significant. For these reasons, a numeric simulation tool (SimUVEx) has been developed and validated in order to predict the dose and distribution of UV exposure received taking into account postural information and ambient irradiation data. SimUVEx is based on 3D graphics techniques usually used to render virtual environments to estimate the exposure of a 3D virtual manikin characterised as a triangular mesh surface. Each triangle receives a certain quantity of solar energy depending on the direct, diffuse and reflected radiation, the body surface orientation to the sun and the shadows from other parts of the body. The goals of the second version of SimUVEx are to move from individual-based to population-based (e.g., Switzerland and, eventually, Europe) exposure assessment, expanding temporal, spatial and morphological simulation capabilities. Outputs from SimUVEx version 2 will allow building exposure scenarios, identifying high-risk situations and producing reference dose ranges for typical outdoor occupational and leisure activities.**

Keywords—3D graphics, 3D rendering, modelling, anatomical exposure, ambient UV, skin cancer, solar UV

I. INTRODUCTION

Solar radiation is a crucial factor for both the development and subsistence of life on Earth. The observable biological effects on human health are due almost exclusively to ultraviolet radiation and are circumscribed to skin and eyes because of the low penetration of ultraviolet radiation (UVR) in human tissues. Depending on the length of the exposure, two types of responses can be distinguished: acute and chronic effects. The former is characterised by a rapid onset and short duration (sunburn, tanning, vitamin D production); the latter is generally of gradual onset and long duration (photo-ageing, skin cancer, cataract) [1]. It means that while small amounts of UV could be favourable for people and essential in the production of vitamin D, prolonged exposure may cause acute and chronic effects on skin, eyes and immune system. In particular, cutaneous malignant melanoma (MM) is associated with intermittent sun exposure and usually occurs on occasionally exposed anatomical zones [2], basal cell carcinoma (BCC) is mostly related to cumulative and acute exposure [3] and squamous cell carcinoma (SCC) is predominantly induced by cumulative sun exposure [4]. Furthermore, more and more people, over the past decades, have developed skin cancer compared with all other cancers combined [5] as a result of the progressive increase in outdoor leisure activities, vacations in sunny regions and change in clothing habits [6] [7]. A deeper understanding of the dose-response relationship between UV exposure and skin cancer occurrence is becoming more decisive to establish threshold values. This is not yet possible, however, because of the heterogeneity of anatomical UV exposure distribution, poorly correlated to ground irradiance (amount of energy received by a surface per unit area) and depending on many factors such as posture, time of exposure, skin complexion, orientation to the sun and clothing [8] [9].

Photoelectrical captors and photosensitive dosimeters are valid instruments to quantify the amount of individual UV exposure, but their measurements are strongly related to the specific position and occasionally affected by epidemiological biases. It is, therefore, necessary to develop tools to predict individual exposure without the employment of personal dosimetry in order to generalise the results. An accurate simulation of the UV irradiation phenomenon is still unrealistic. Nonetheless, a reasonable approximation can be achieved by using real data measurements combined with simple numerical simulation techniques used in 3D computer

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graphics for 3D rendering. Within this framework, the first version of SimUVEx (Simulating UV Exposure) has been developed to predict individual UV exposure on the basis of current methods of 3D rendering and 3D human modelling [10]. The objective was to model daily solar UV exposure patterns, taking into account measurements of direct, diffuse and reflected UV irradiances by broadband detectors for inferring doses on various body parts for different postures and morphologies. In order to obtain more and more realistic scenarios, we are currently working on the second version of SimUVEx with the purpose of improving temporal, spatial and morphological simulation capabilities.

In this article a general description of the model is firstly given, then an introduction and comparison of the two versions of SimUVEx are presented along with a discussion of our perspectives in sun prevention messages regarding outdoor activities.

II. Materials And Method

SimUVEx is a prediction model of individual UV exposure based on the adaptation of 3D rendering techniques and 3D human modelling that uses continuous datasets of ambient ground irradiance. The amount of energy received is displayed on a 3D human manikin and a .csv file provides the dose-responses (J/m^2), one-minute step, for each anatomical zone. During the development of the first version, the results of the rendering engine have been validated by comparison with dosimetric measurements [10].

A. Implementation

The application is based on VCG (Visualization and Computer Graphics Library) [11], an open source C++ library for handling and processing triangle meshes, and implemented as a plug-in in MESHLAB [12], an open source system for computing and editing 3D triangular meshes. The purpose of the application is to read the irradiation datasets of one-minute time resolution and sets the 3D manikins in various postures to simulate outdoor occupational and leisure activities, with the possibility to rotate each position of 360° every 15 minutes.

B. Input data

The model uses three ambient irradiance datasets of one-minute resolution for direct, diffuse and reflected radiation (W/m^2). It derives radiances (amount of energy received by a surface, per unit solid angle and unit projected area) from these inputs, using simplifying assumptions. The datasets are obtained using biometers (multiple broadband radiometers) located in various meteorological stations. Specifically, we used measurements made in Switzerland (at the stations of Payerne, Davos, Jungfraujoch and Locarno Monti), where broadband radiometers measure the erythemal UV radiation.

Erythemal UV radiation can also be modelled using a Radiative Transfer Model (RTM), such as libRadtran, a library for radiative transfer calculations [13]. In this case, the simulation can be performed just for clear sky conditions, an unrealistic situation which precludes the complexity of the clouds. Total ozone, solar zenith angle (SZA), albedo, altitude and aerosol composition are the main variable parameters used as input to the RTM. In cloudless sky conditions, the radiative model provides a better estimate of the irradiance and its accuracy is mostly due to the uncertainty of the input values. [14].

The 3D virtual manikin is produced using 3D human modelling and animation approaches [15] [16]. The surface of the manikin is represented as a series of 3D triangular meshes whose size depends on the resolution (the low resolution corresponds to a smaller number of triangles while the high resolution to a larger one). Various postures of the virtual manikin, corresponding to characteristic working positions, were produced. The amount of solar energy received by each triangle took into account the three components of the radiation and shading from other body parts, depending on the posture and the orientation to the sun.

C. Radiation – body interaction modelling

UV exposure is calculated in different ways for the direct, diffuse and reflected radiation. The former is the sunlight travelling on a straight line varying in intensity with time and direction with the sun, whereas the diffuse and reflected radiation are considered hemispherical and isotropic sources with intensities depending on the time. This assumption can be solved by deriving the isotropic radiance in a hemisphere from a measured irradiance. If we consider, for example, the diffuse radiation and take into account a perfect Lambertian response for broadband detectors:

$$I_D(t) = \int_{\varphi=0}^{2\pi} d\varphi \int_{\theta=0}^{\frac{\pi}{2}} d\theta\, u_D(\theta,\varphi,t) cos\theta sin\theta$$
$$= 2\pi u_D(t) \int_{\theta=0}^{\pi/2} d\theta cos\theta sin\theta = 2\pi u_D(t)\frac{1}{2}$$

where $I_D(t)$ is the measured diffuse irradiance, $u_D(t)$ the diffuse radiance. Discretizing both hemispheres into several sub-areas and considering $A_s/_{2\pi}$ as the ratio between the solid angle of the sub-area and the hemisphere, we obtain the diffuse radiance as:

$$D(t) = u_D(t) \int d\varphi \int d\theta sin\theta = u_D(t) A_s = 2 I_D(t) \frac{A_S}{2\pi}$$

Due to the anisotropy of the diffuse radiation especially near the ground [17], the model takes into account a linear decrease between 25° and 0° (horizontal plane). On the contrary, an equal amount of energy is associated with each subsurfaces element of the bottom half-sphere for the reflected radiation which is assumed isotropic.

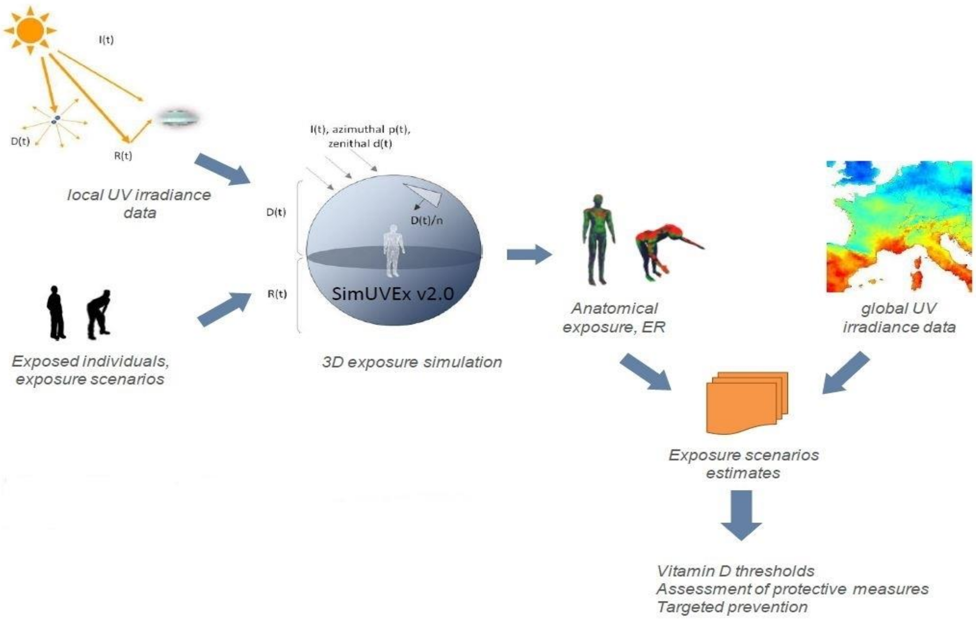

Fig. 1. Schematic view of the project and use of SimUVEx version 2.

In the manikin, exposure depends not solely on radiation intensity, but also on triangles orientations and shadows from other body parts. The direct radiation (I(t)) is considered a parallel light source and the energy (E_v) received, for each time step, by the vertices visible from the directional light source can be written as:

$$E_v = \int_{t_0}^{t} I(t)\, cos\vartheta\; dt \qquad [\frac{J}{m^2}]$$

where ϑ is the angle between the incident light and the vertex normal $\overrightarrow{N_v}$, which represents the average of all the normals of the meshes contiguous to the vertex. For the diffuse and reflected radiation, a "visibility map" which represents the number of surfaces of each hemisphere visible from the vertex, has been created [18]. The energy from each visible surface is computed in a similar way to the direct radiation, but, in this case, ϑ is the angle between the vertex normal and the normal to the diffuse or reflected subsurface in consideration each time.

D. Visualization

The surface of the 3D human manikin is coloured according to the exposure distribution allowing a direct visualisation of the results. A three colour scale was used to distinguish low (blue), intermediate (green) and high (red) values.

III. SimUVEx version 1: Main Achievements

The main features about the 3D human modelling of the first version of SimUVEx are the following:

- One morphology: adult man;
- Manikin resolution of about 2500 vertices;
- 45 anatomical zones;
- 6 working postures (seated, kneeling, standing-arms-down, standing-arms-up, standing-bowing, lying on the ground on the back);
- Basic representation of clothes as sunscreen with a specific protection index for different anatomical zones.

As discussed more in detailed in [10], SimUVEx model provides an accurate prediction of the exposure distribution for the whole body. Moreover, the components of UV radiation were computed for anatomical exposure patterns, emphasising the importance of diffuse UV radiation usually underestimated in prevention messages [19]. The simulations also estimated the contribution of occupational UV exposure to SCC, qualifying SCC as an occupational disease [20], and confirmed daily doses exceeding recommended exposure for outdoor workers (for most body sites).

IV. SimUVEx version 2: Developments and Perspectives

The improvements of the 3D human modelling in the second version have been made to achieve more and more realistic situations (Fig. 1):

- Integration of four gender- and age-related morphologies: adult man, adult woman, heavy man, child;
- Accurate face modelling in 3 different versions: unprotected head, head with hat, head with cap;
- Two resolutions: Low resolution (837 vertices, 1800 for the heavy man) – High resolution (13476 vertices, 14444 for the heavy man, 4333 for the face);

- 45 anatomical zones for the body low resolution, 46 for the body high resolution;
- 36 anatomical zones for the face;
- Added three leisure time postures (seated position, lying on the ground on the belly, seated position stretched legs);
- Incorporation of realistic values regarding sun protective factors (clothing, hair, sun creams, etc.);
- Development of the model simulation capabilities to cover long exposure periods (e.g., year-round simulations) and different scenarios (involving different body postures and orientations to the sun).

The simulation engine has been optimised to handle long exposure periods in order to shift from individual to population predictions. The outputs obtained from the second version will help us to identify over-exposures, associated with skin cancer, as well as under-exposures, associated with short-term vitamin D deficiency (particularly during periods of low UV radiation and high skin coverage by clothes, as is the case in winter). Secondly, we will be able to produce reference dose ranges for common outdoor occupational and leisure activities in order for it to be possible to assess most effective sun protection strategies.

It must be pointed out that the tool is inexpensive and uses 3D computer graphics techniques to compute UV doses based only on postural information and ambient UV measurements available from meteorological stations, satellites, radiation transfer modelling and semi-empirical UV reconstruction methods. It means that no individual exposure data are required.

V. Conclusion

In this paper, we described how 3D computer graphics and rendering techniques are integrated and adapted with simplifying hypothesis about UV irradiance. It results in a UV rendering model that estimates the UV exposure distribution over the human body shape from ambient irradiance datasets obtained from broadband radiometers available at meteorological stations. It is important to note that 3D rendering is not used to visualise the exposure data but to compute them. The first release of SimUVEx contributed to improve our understanding of exposure patterns and identify 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. These elements will enable to identify and quantify active sun protection strategies, in order to elaborate targeted prevention messages for high-risk populations or situations, including risks of overexposure as well as of underexposure. The visualisation tool could also be useful for the general public to illustrate on a coloured human body the impact of UV exposure. This project also opens further perspectives in skin cancer research by providing quantitative exposure estimates at a population level. Reference doses should be, effectively, analysed concomitantly with skin cancer registries to support epidemiological research.

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