A Novel Method to Calculate Solar UV Exposure Relevant to Vitamin D Production in Humans

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ABSTRACT

We present a novel method to calculate vitamin D3-weighted exposure by integrating the incident solar spectral radiance over all relevant parts of the human body. Earlier investigations are based on the irradiance on surfaces, whereas our calculated exposure of a voxel model of a human takes into account the complex geometry of the radiation field. Assuming that sufficient vitamin D3 (1000 international units) can be produced within the human body in one minute for a completely uncovered body in vertical posture in summer at midlatitudes (e.g. Rome, June 21, noon, UV index of 10), we calculate the exposure times needed in other situations or seasons to gain enough vitamin D3. Our calculations show that the UV index is not a good indicator for the exposure which depends on the orientation of the body (e.g. vertical (standing) or horizontal (lying down) posture). Without clothing the exposure is dominated by diffuse sky radiation and it is nearly irrelevant how the body in vertical posture is oriented toward the sun. At the winter solstice (December 21, noon, cloudy) at least in central Europe sufficient vitamin D3 cannot be obtained with realistic clothing, even if the exposure were extended to all daylight hours.

INTRODUCTION

Ultraviolet radiation from the sun (1) causes a considerable global disease burden including acute and chronic health effects on the skin, eye and immune system. Worldwide up to 60 000 deaths per year are estimated to be caused by ultraviolet radiation, most of which are due to malignant melanoma (2). On the other hand, UV is essential for the vitamin D3 production of humans. (1,3) In the following vitamin D is used as a general term, whereas we use the expression vitamin D3 to describe UV-related issues. Emerging evidence suggests an association between vitamin D levels as an indicator of health risk (3) relating to some cancers, cardiovascular disease and multiple sclerosis among others, along with the established link with musculoskeletal health. Vitamin D is essential for regulating the calcium metabolism and is important for various intracellular processes and bone health. Prospective observational and cohort studies have shown that the cardiovascular morbidity and mortality risk is around 50% lower with a higher vitamin D supply (4–8). There is also consistent epidemiological evidence that there is an association between a lack of vitamin D and some kinds of cancer (3).

Vitamin D synthesis in the human skin due to solar UVB (280–315 nm) radiation is the main source of vitamin D for humans, whereas dietary intake contributes only a small percentage (10%) to the necessary supply (9), at least according to the present knowledge. Although vitamin D can be effectively produced by UVB radiation, there are large seasonal differences in its production (10,11), mainly caused by the varying solar altitude and the different proportion of skin that is exposed to solar radiation. As a result more than 50% of the German population has an insufficient vitamin D supply, especially during wintertime (12). Even in summertime the available UVB irradiance is much smaller than at comparable latitudes in the southern hemisphere (13).

Many investigations have been performed including modeling, calculating and measuring the vitamin D3-weighted exposure according to percentage of exposed skin and their seasonal and latitudinal variation (12,14–21). Several studies indicated the so-called “vitamin D winter” which is the time when it is not possible to gain an adequate vitamin D status by solar exposure. Often the vitamin D winter for midnorthern latitudes is stated to range from October to March (12,14,19,20,22), whereas other authors suggested that if the commonly assumed action spectrum for vitamin D production is correct, then it should be possible to synthesize vitamin D even in winter (16). However, it would be difficult to gain optimal vitamin D3-weighted UV exposure without a risk of sunburn (16,18). A common “rule of thumb” is that below UV indices (UVI) of 1 to 3 it is impossible to reach an adequate vitamin D status (12,16,18). To ameliorate this problem short exposure times (up to 20 min) are suggested with as much exposed skin as possible (12,16). Some investigations state that the vitamin D status will not be as low as assumed in winter time due to the long lifetime of vitamin D, and the possibility of human body to store vitamin D in body fat (15).

Most of the publications used to date have related the irradiance on surfaces to the UVI and then calculated the time to

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reach a threshold for an optimal vitamin D. This threshold varies from low values (400 IU, international units) to values up to 4000 IU (21). Although there is not yet an agreed minimum, a consensus opinion could be 1000 IU (15,16,23–26) which is equivalent to 25 μg (12) per day. The mean daily vitamin D intake by food varies from 1 μg (40 IU) to 4 μg (120 IU) in Germany (12).

For the calculation of optimal exposure times of human bodies it is insufficient to assume horizontal or singly tilted surfaces. By a geometric conversion factor Godar and Pope (27 and H) visualized the UV exposure of a human body by combining the measured UV irradiance of inclined surfaces with a virtual human surface model. Their visualization shows a distribution of erythemally weighted irradiance on the human body. Similar calculations were performed by Vernaz et al. (32,33) who calculated the dose and distribution of UV exposure of a 3D human model using radiative transfer models.

One of the main results of this simulation is that the diffuse part of radiation is quite important for calculations of human exposure and should not be underestimated. They stated that about 80% of annual UV exposure is caused by diffuse radiation and that the direct irradiance is only responsible for UV irradiance peaks around noon, especially in summer and for horizontally oriented parts of the human body. The diffuse irradiance on a horizontal surface, however, does not take into account the complex geometry of the radiation field of the sky for different meteorological conditions. Even if measured UVI values on tilted surfaces are taken into account it is difficult to parameterize the influence by reflections from the ground to sufficient accuracy. Therefore, our goal has been to calculate the vitamin Dweighted exposure of a human, represented by a 3D voxel model, using estimates of the sky radiance and the direct radiance.

**MATERIALS AND METHODS**

The spectral exposure $E_{x}$ [J] may be defined as the spectral radiant energy $Q_{\lambda}$ [J] falling on a human body which stands on an imaginary horizontal plane.

$Q_{\lambda}$ can be calculated by integrating the spectral radiance (34)

$$L_{\lambda}(e, \varphi, t, \lambda) = \frac{d^{2}Q_{\lambda}}{d\Omega \cdot d\varphi \cdot \cos \varphi} \cdot \frac{W}{m^{2} \cdot sr}$$

(1)

which depends on the wavelength $\lambda$, the time $t$, the azimuth angle $\varphi$ and the incident angle $e$; $d\Omega$ is the infinitesimal area and $d\Omega$ is infinitesimal solid angle. We define the incident angle $e$ as the angle between incident light beam and the horizontal plane mentioned above (see Fig. 1), also denoted as elevation angle. $x$ is defined as the angle between the normal vector of the area $dA$ and the incident radiation. $E_{x}(\lambda)$ may be weighted with a biological action spectrum $S_{\lambda}(\lambda, dA, x, \varphi)$, which may depend on the skin area under consideration as well as on the azimuth angle $\varphi$ and the angle $x$. To assess its biological impact, the exposure is integrated over all relevant wavelengths. In this case, the exposure is no longer a function of wavelength and has the unit Joule (times an arbitrary factor that depends on the normalization of the action spectrum which may be applied).

If different areas of the human body have different biological weightings, $E_{x\text{weighted}}$ may therefore be calculated by the following formula:

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$$E_{x\text{weighted}} = \int_{t_1}^{t_2} \int_{x_1}^{x_2} \int_{\varphi_1}^{\varphi_2} \int_{\lambda_1}^{\lambda_2} L_{\lambda}(e, \varphi, t, \lambda) \cdot dA_{\lambda} \cdot S(\lambda, dA_{\lambda}, x, \varphi) \cdot \cos(x) \sin(\varphi) \cdot dC \cdot d\varphi \cdot dt$$

(3)

where $t_1$ is the start of the exposure period, $t_2$ the end of the exposure period, $e$ the incident angle and $S(\lambda, dA_{\lambda}, x, \varphi)$ is the weighting function which may depend on wavelength $\lambda$, area $dA_{\lambda}$ (different skin surfaces, noted by the subscript $\lambda$), may have a different sensitivity), incident angle to the surface area normal $x$, surface area $dA_{\lambda}$, and azimuth angle $\varphi$ (1). The deviation of the ideal cosine behavior of lambertian surfaces can be described by the latter three dependencies of $S(\lambda, dA_{\lambda}, x, \varphi)$. $L_{\lambda}$ denotes the scalar product between the spectral radiances and the unit area of the human body. To compute the vitamin Dweighted exposure, the radiance from each sky coordinate is weighted with the action spectrum of a determined biological response to vitamin D and integrated over all relevant wavelengths to assess its biological impact. For the weighting function we use the action spectrum for synthesis of previtamin D in human skin of the International Commission on Illumination (35), denoted as $S_{\text{vit}}$. The calculation of the exposure by the formula given above can be quite demanding and the following simplifying assumptions have been made: In reality not all radiation is absorbed by the relevant skin layers, but is partly reflected or absorbed by inactive material. The dependence of the incident radiation could be quite complex and may not be well represented by the dependence of a Lambertian surface. Therefore, the first assumption is that the areas considered can be treated as a Lambertian surface, i.e., the energy falling onto any surface under consideration has an angular dependence that follows the cosine of the incident angle. In addition, it is assumed that all areas of the human body have the same sensitivity. In this case the integration over the wavelength can be separated from the calculation of the spectral exposure $E_{x}$.

With the assumptions described above the vitamin Dweighted exposure $E_{x\text{D}}$ is then given by

$$E_{x\text{D}} = \int_{t_1}^{t_2} \int_{x_1}^{x_2} \int_{\varphi_1}^{\varphi_2} \int_{\lambda_1}^{\lambda_2} L_{\lambda}(e, \varphi, t, \lambda) \cdot dA_{\lambda} \cdot S(\lambda, dA_{\lambda}, x, \varphi) \cdot \cos(x) \sin(\varphi) \cdot dC \cdot d\varphi \cdot dt$$

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(3)

where $t_1$ is the start of the exposure period, $t_2$ the end of the exposure period, $e$ the incident angle and $S(\lambda, dA_{\lambda}, x, \varphi)$ is the weighting function which may depend on wavelength $\lambda$, area $dA_{\lambda}$ (different skin surfaces, noted by the subscript $\lambda$), may have a different sensitivity), incident angle to the surface area normal $x$, surface area $dA_{\lambda}$, and azimuth angle $\varphi$ (1). The deviation of the ideal cosine behavior of lambertian surfaces can be described by the latter three dependencies of $S(\lambda, dA_{\lambda}, x, \varphi)$. $L_{\lambda}$ denotes the scalar product between the spectral radiances and the unit area of the human body. To compute the vitamin Dweighted exposure, the radiance from each sky coordinate is weighted with the action spectrum of a determined biological response to vitamin D and integrated over all relevant wavelengths to assess its biological impact. For the weighting function we use the action spectrum for synthesis of previtamin D in human skin of the International Commission on Illumination (35), denoted as $S_{\text{vit}}$. The calculation of the exposure by the formula given above can be quite demanding and the following simplifying assumptions have been made: In reality not all radiation is absorbed by the relevant skin layers, but is partly reflected or absorbed by inactive material. The dependence of the incident radiation could be quite complex and may not be well represented by the dependence of a Lambertian surface. Therefore, the first assumption is that the areas considered can be treated as a Lambertian surface, i.e., the energy falling onto any surface under consideration has an angular dependence that follows the cosine of the incident angle. In addition, it is assumed that all areas of the human body have the same sensitivity. In this case the integration over the wavelength can be separated from the calculation of the spectral exposure $E_{x}$.

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(3)
where the radiance is integrated over the relevant areas \( dA \) of the human body, integrated over all solid angles \( \Omega \) and integrated over the time of exposure. In this context the radiance \( L \) and the surface area \( dA \) are shown as a result of the scalar product \( L \cdot dA \cdot \cos \alpha \). As already mentioned above, \( \alpha \) is the angle between the vector \( \mathbf{L} \) and the normal of the surface area \( dA \) as shown in Fig. 1. In this context relevant areas \( dA \) are those where the angle \( \alpha \) is \( 90^\circ \leq \alpha \leq 270^\circ \) and which are not covered by clothing (assuming that clothing has a negligible UV transmission).

Due to the interval \([90, 270]\) of the angle \( \alpha \) and the definition of the scalar product, the results of the calculated projections are always negative (see Fig. 1), and absolute values of the projections are used.

As the spectral radiance \( L \) is constant for a given time and solid angle, it can be separated from the calculation of the geometric factor \( dA \) which is obtained by inquiring for the following of all uncovered surface areas \( dA \) (see Fig. 1). The vitamin D-weighted exposure \( Ex_{D} \) is then given by the equation:

\[
Ex_{D} = \int_{\Omega} \int_{\frac{330}{252} \text{nm}} L_{\lambda}(\omega, \varphi, t, \lambda) \cdot S_{\text{ex}_{D}}(\lambda) \cdot dA \cdot \cos \alpha \cdot d\Omega
\]

(4)

Figure 2. 3D voxel model with typical clothing for winter, visualized by the dark gray color. Only hands and face are exposed to UV radiation and shown in white color. The projection of the visualized 3D voxel model is displayed for incident angles 30°, 60° and 90° with the front turned by 30° in azimuth. The projection areas of a person in vertical posture become smaller with an increasing incident angle.

\[
1000 \text{ IU in less than } 1 \text{ min.} \]

This statement is based on values of Holick (41) and Holick (15). It has been stated in Holick (41) that “Exposure of 6% of the body to minimal erythemal dose is equivalent to taking between 600 and 1,000 IU of vitamin D\(^3\).” One MED equals to 250 \( \frac{\text{IU}}{\text{min}} \) for skin type 2 according to Fitzpatrick (42). A UVI of 10 corresponds to an erythemally weighted irradiance \( E_{\text{eye}} \) of 250 \( \frac{\text{mW cm}^{-2}}{\text{nm}} \) according to the definition of the UVI. The required exposure time for receiving one MED can thus be calculated by:

\[
\text{exposure time [min]} = \frac{\text{MED}}{E_{\text{eye}}} \cdot 1/60. \quad (6)
\]

The international unit (vitamin D) per minute for a full-body exposure is estimated by the following equation:

\[
\frac{\text{IU}}{\text{min}} = \frac{\text{IU}_{\text{literature}}}{\text{exposure time}} \cdot \frac{100\%}{\text{skin area} [\%]} \quad (7)
\]

With the literature values from (41) and an exposure time of 16.7 min (see Eq. 7) the statement of McKenzie (16) is confirmed. In Holick (15), it is stated in Table 1 that “Exposure to sunlight (ultraviolet B radiation, 0.5 minimal erythemal dose) equals about 3000 IU of vitamin D\(^3\).” In the subscripts of this table it is further specified “About 0.5 minimal erythemal dose of ultraviolet B radiation would be absorbed after an average of 5–10 min of exposure (depending on the time of day, season, latitude, and skin sensitivity) of the arms and legs to direct sunlight.” Unfortunately, it is not stated whether these numbers are derived by outdoor or indoor experiments, and no details on the spatial distribution of the spectral radiation are provided. Adams et. al. (43) provide more details on the experimental setup and a quite uniform radiation can be assumed. Similar to Holick who applied the values he derived by artificial radiation to outdoor exposure (15), we assume for the following calculations that the estimated value of 1000 IU per minute (Eq. 7) is valid for a human outdoors in vertical posture and an UVI of 10. In any case it appears reasonable that the numbers given above will be in range 10 000–25 000 IU for full-body exposure and 1 MED as stated by Holick (15,41). We therefore believe that current knowledge suggests the maximum
Table 1. Parameters for case 5, $R_{eff}$ is the effective radius of the cloud droplet size distributions in μm, LWC is the liquid water content in g m$^{-2}$ and $z$ is the height of the basis and top of the homogeneous cloudiness in m. Stratocumulus (Sc) ranges from 1300 to 1800 m and Altocumulus (Ac) from 4200 to 4500 m.

<table>
<thead>
<tr>
<th>$z$ [km]</th>
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<tr>
<td>4.500</td>
<td>0.100</td>
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<td>0.100</td>
<td>5.77</td>
</tr>
<tr>
<td>1.800</td>
<td>0.092</td>
<td>4.00</td>
</tr>
<tr>
<td>1.300</td>
<td>0.092</td>
<td>4.00</td>
</tr>
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The different cases and parameters used are listed in Table 2. The components direct, diffuse and "global" of vitamin D$_3$–weighted exposure per second in Rome on June 21 at solar noon are shown in Fig. 6 as a function of orientation of the 3D voxel model to the sun. Although both the direct and the diffuse component depend on the orientation of the 3D voxel model with respect to the sun, the dominating diffuse component remains relatively constant. Therefore, the maximum variation in the exposure is less than ±4%. This is probably negligible compared with other uncertainties in determining the exposure. However, the variation with orientation of a human in vertical posture must be taken into account in the case of the chosen clothing, which covered 93% of the total skin area. For all following results the front side of the 3D voxel model was orientated with respect to the sun over the day.

Assuming that a human in upright position would be able to produce 1000 IU vitamin D by the exposure as described for case 1 and assuming a linear dose effect relationship, the exposure may also be expressed in IU. For this purpose the conversion factor was determined by setting the calculated vitamin D$_3$–weighted exposure as optimal (R. Scragg, personal communication). In central Europe (e.g. Hannover), the UVI is always lower than 10 for cloudless skies.

As mentioned above, the spectral radiance may be determined by measurements or calculated by radiative transfer models. For this study the radiance was calculated by the DISORT code of the UVSPEC model in the LibRadTran package (44). The solution of the simulated radiance is 5° for both incident and azimuth angles. This resolution results in 1297 different directions and is sufficient for the calculation of the exposure. The different cases and parameters used are listed in Table 2. Common parameters are as follows: radiative solver DISORT, pressure = 1013.0 hPa, ozone dense column = 300 DU and an albedo of 0.02 for Hannover and 0.05 for Rome.

For an albedo of 0.02, which is typical for many surfaces (e.g. grass) in the UV (45) in summer, the influence of the reflected spectral upwelling radiance can be neglected. This can be shown by calculating the extra exposure from an isotropic surface reflection, which was found to be smaller than 3% of the exposure from the downwelling radiance for cases 2–5 and 7% for case 1. Compared with the other uncertainties described in the discussion, omitting the reflection from the ground will therefore be a negligible effect, provided the albedo is low. It should be noted that for some artificial surfaces, white sand or snow (46,47), a significant amount of UV exposure originates from the upwelling radiance. For these cases the exposure can be calculated by our method as well if the upwelling radiance is known. However, such cases are not elaborated for this study.

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<td>0.092</td>
<td>4.00</td>
</tr>
</tbody>
</table>

uncertainty of our assumption (adapted from McKenzie et. al. (16)) to be less than a factor of 2.

RESULTS

All projection areas are plotted in Fig. 3 as a polar plot in dependence of the azimuth and the elevation angles of incident radiation. The size of the elemental projection areas ranges between 0.09 and 0.55 m$^2$. The upper plots show the model with skin not covered by clothing and the lower plots refer to clothing typical for colder days (see Fig. 2). The calculated percentage of covered skin area to the total skin area is 93%.

Radiance simulations

Five different cases were chosen (see Table 2), including one for Rome (June 21) and four for Hannover (June 21, March 21 and two simulations for December 21). The summer and winter solstice dates were selected because the sun’s noon solar incident angle at solstice is maximal in June and minimal in December. Except for case 5 which was simulated for December 21 in Hannover for homogeneous cloudiness, all cases were simulated for cloudless sky. Rome was selected because simulations have shown that the UVI on June 21 can reach the value 10. A UVI of 10 represents the maximum UVI for northern midlatitudes.

It has been stated that if the UVI is equal to 10, a person can produce 1000 IU vitamin D in one minute, which would result in a sufficient vitamin D status (15,16,41). Some scientists consider even higher values of up to 3000 IU vitamin D concentrations as optimal (R. Scragg, personal communication). In central Europe (e.g. Hannover), the UVI is always lower than 10 for cloudless skies.

As mentioned above, the spectral radiance may be determined by measurements or calculated by radiative transfer models. For this study the radiance was calculated by the DISORT code of the UVSPEC model in the LibRadTran package (44). The resolution of the simulated radiance is 5° for both incident and azimuth angles. This resolution results in 1297 different directions and is sufficient for the calculation of the exposure. The different cases and parameters used are listed in Table 2. Common parameters are as follows: radiative solver DISORT, pressure = 1013.0 hPa, ozone dense column = 300 DU and an albedo of 0.02 for Hannover and 0.05 for Rome.

For an albedo of 0.02, which is typical for many surfaces (e.g. grass) in the UV (45) in summer, the influence of the reflected spectral upwelling radiance can be neglected. This can be shown by calculating the extra exposure from an isotropic surface reflection, which was found to be smaller than 3% of the exposure from the downwelling radiance for cases 2–5 and 7% for case 1. Compared with the other uncertainties described in the discussion, omitting the reflection from the ground will therefore be a negligible effect, provided the albedo is low. It should be noted that for some artificial surfaces, white sand or snow (46,47), a significant amount of UV exposure originates from the upwelling radiance. For these cases the exposure can be calculated by our method as well if the upwelling radiance is known. However, such cases are not elaborated for this study.

Case 5 represents the great majority of meteorological situations in winter in Germany (48). The radiance for this case has been calculated with the radiative transfer model for homogeneous cloudiness with the parameters given in Table 1. The resulting irradiance on a horizontal surface deviates by less than 15% from measurements of the spectral irradiance performed by the NDACC mobile reference instrument (49) for wavelengths between 310 and 400 nm and for solar zenith angles of 75°±1°.

The vitamin D$_3$–weighted sky radiance for the downwelling radiance has been calculated for summer conditions in Rome (case 1) and is shown in Fig. 4. In this case the highest values of sky radiance can be recognized around the solar disk.

The weighted radiance and the projection surfaces were multiplied for all incident and azimuth angles. The direct beam contributes to the exposure as well. For the calculation of this contribution the projection areas (determined for the sky radiance resolution of 5°) were interpolated to a resolution of 0.1°. A typical result for case 1 and the 3D voxel model in vertical posture is shown in Fig. 5.

The components direct, diffuse and "global" of vitamin D$_3$–weighted exposure per second in Rome on June 21 at solar noon are shown in Fig. 6 as a function of orientation of the 3D voxel model to the sun. Although both the direct and the diffuse component depend on the orientation of the 3D voxel model with respect to the sun, the dominating diffuse component remains relatively constant. Therefore, the maximum variation in the exposure is less than ±4%. This is probably negligible compared with other uncertainties in determining the exposure. However, the variation with orientation of a human in vertical posture must be taken into account in the case of the chosen clothing, which covered 93% of the total skin area. For all following results the front side of the 3D voxel model was orientated with respect to the sun over the day.

Assuming that a human in upright position would be able to produce 1000 IU vitamin D by the exposure as described for case 1 and assuming a linear dose effect relationship, the exposure may also be expressed in IU. For this purpose the conversion factor was determined by setting the calculated vitamin D$_3$–weighted exposure of 1 min for solar noon of case 1 (14.09 J) equivalent to 1000 IU, which results in a conversion factor of 70.97 [IU J$^{-1}$ (i.e. IU per Joule of vitamin D–weighted UV)] for case 1 for example. With the assumption that the vitamin D$_3$–weighted irradiance at solar noon corresponds to 1000 IU per minute, the corresponding conversion factor is 33.51 [IU m$^{-2}$ W$^{-1}$]. Diurnal variations are illustrated by showing vitamin D$_3$–weighted power versus time, e.g. exposure per minute versus time of day. The resulting seasonal and diurnal variations are so large that it was necessary to use a logarithmic ordinate scale.

Figure 7 shows diurnal variation in the vitamin D$_3$–weighted irradiance and the vitamin D$_3$–weighted exposure for a vertical and horizontal posture for case 1 (Rome, noon, June 21,
cloudless, UVI = 10, unclothed). In this case the horizontal posture will synthesize more IU per minute than the vertical posture at almost all times of the day. At noon the exposure of the human body in horizontal posture is 35% larger than the human body in vertical posture. The increase is not caused by the direct component of the sun. For case 2 (June 21, noon, Hannover, 

Figure 3. 3a (left upper plot): Projection areas of the 3D voxel model in vertical posture, oriented toward 0°/North, as a function of elevation and azimuthal angles. The minimal projection area is located in the middle of this picture, representing the zenith at an elevation angle of 90°. The front and back of this model with a maximum projection area of 0.55 m² can be recognized at azimuth angles of 0° and 180° respectively (elevation angle = 0°), whereas the side projections are smaller (90° and 270°). 3b (right upper plot): Distribution of projection area of the 3D voxel model in horizontal posture (sole of foot is directed to 0°/North). As expected the largest projection area occurs in the middle of the plot, at an elevation angle of 90°. 3c (left lower plot): Projection areas for the 3D voxel model in vertical posture oriented toward 0°/North with only face and hands exposed. As expected the projection areas become much smaller. 3d (right lower plot): Projection areas for the 3D voxel model in horizontal posture (sole of foot is directed to 0°/North) with only face and hands exposed.

Table 2. Exposure and estimated times to gain 1000 IU vitamin D for five different cases and exposure areas. For all realistic conditions there is not enough daily vitamin D production at the beginning of winter in central Europe even if the exposure times are extended to all daylight hours.

<table>
<thead>
<tr>
<th>Case</th>
<th>Place</th>
<th>Latitude</th>
<th>Date</th>
<th>SZA at solar noon</th>
<th>Cloudiness</th>
<th>UVI</th>
<th>Daily production in IU, human in vertical posture with full-body exposure</th>
<th>Exposure in J per minute at noon, human in vertical posture with full-body exposure</th>
<th>Required Exposure time with full-body exposure</th>
<th>Required exposure time with clothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rome</td>
<td>41.8833</td>
<td>June 21</td>
<td>18.4385</td>
<td>None</td>
<td>10</td>
<td>440000</td>
<td>14.09</td>
<td>Vertical posture</td>
<td>Vertical posture</td>
</tr>
<tr>
<td>2</td>
<td>Hannover</td>
<td>52.3914</td>
<td>June 21</td>
<td>28.9465</td>
<td>None</td>
<td>8</td>
<td>398000</td>
<td>12.62</td>
<td>Vertical posture</td>
<td>Vertical posture</td>
</tr>
<tr>
<td>3</td>
<td>Hannover</td>
<td>52.3914</td>
<td>March 21</td>
<td>52.2699</td>
<td>None</td>
<td>3.3</td>
<td>134000</td>
<td>6.11</td>
<td>Vertical posture</td>
<td>Vertical posture</td>
</tr>
<tr>
<td>4</td>
<td>Hannover</td>
<td>52.3914</td>
<td>December 21</td>
<td>75.8086</td>
<td>Homogeneous</td>
<td>0.4</td>
<td>5400</td>
<td>0.36</td>
<td>Vertical posture</td>
<td>Vertical posture</td>
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<tr>
<td>5</td>
<td>Hannover</td>
<td>52.3914</td>
<td>December 21</td>
<td>75.8086</td>
<td>Homogeneous</td>
<td>0.04</td>
<td>470</td>
<td>0.03</td>
<td>Vertical posture</td>
<td>Vertical posture</td>
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</tbody>
</table>

...
UVI = 8), the person in horizontal posture has a higher exposure than the person in vertical posture as well. However, in this case the increase is only 19%. The differences between a person in vertical and horizontal posture depend strongly on season even without taking account of seasonal differences in attire: In March a person in horizontal posture receives a lower exposure than a person in vertical posture (case 3), and in December at noon there is no remarkable difference in exposure times between a person in vertical and horizontal posture. The main parameters for the different cases and the resulting exposure times are summarized in Table 2. For short exposure times (e.g. 1 min) the times refer to local noon. For longer exposure times, the integral under the graph with its center at solar noon has been calculated with limits chosen so that 1000 IU are reached. If more than all daylight hours are necessary, it can be concluded that a sufficient vitamin D status can no longer be reached because the requirement has been for 1000 IU on each day. The extreme case occurs for December 21 under cloudy conditions with clothing, when less than 3% of the daily requirement can be synthesized. It is thus impractical to obtain the required UV exposure at the winter solstice (December 21).

Often it is argued that the vitamin D$_{3}$–weighted exposure can be estimated from the UVI (16,18). However, we found that the UVI is not a good indicator to represent the real exposure. This is demonstrated by the example shown in Fig. 9, which illustrates the ratio of exposure per minute over UVI as a function of UVI for the person in vertical and horizontal posture. For comparison the ratio between vitamin D$_{3}$–weighted irradiance and UVI is plotted as well, assuming that 1000 IU will result from the vitamin D$_{3}$–weighted irradiance with an UVI of 10. We consider the variation in exposure with respect to UVI as too large to derive the exposure from the UVI. Even if the body in horizontal posture is scaled to the irradiance on horizontal planes there would be a difference between vertical and horizontal postures.

**DISCUSSION**

We have calculated the exposure by integrating the spectral radiance weighted with the projection areas of a 3D voxel model of their human form. The following assumptions were made:

1. The exposure from solar radiation of a human in vertical posture experiencing a UVI of 10 is equivalent to 1000 IU per minute
2. 1000 IU per day are sufficient for a healthy vitamin D status
3. The radiation reflected from the ground can be neglected (e.g. no white sand or snow at the ground)
4. The calculated spectral radiance represents the radiation field of the downwelling radiance sufficiently. This may not be the case as the radiative transfer models calculating radiance have not yet been rigorously validated.
5. Aerosols have no significant impact on the exposure
6. No shading by obstruction of the horizon occurs (e.g. no buildings)
7. The production of vitamin D is proportional to the cosine of the incident angle on all skin areas
8. Different parts of the human skin have the same spectral transmission and the same sensitivity toward the incoming energy
9. The weighting function for vitamin D production is correctly described by the CIE weighting function
10. The accumulated vitamin D increases linearly with exposure (a linear dose effect relationship is assumed)
11. The investigation was done for skin type II person. Differentpigmentations of the skin do not need to be considered
12. Aging effects of the human skin do not need to be considered
13. The chosen 3D voxel model represents the human body well
14. The front-side 3D voxel model is (except in the calculations of Fig. 6) oriented to the sun

In reality none of these assumptions are probably strictly fulfilled. Therefore, our exposure times should be treated with caution. Some of the assumptions can easily be adjusted if new knowledge is gained. This is particularly true for the statement that a person can synthesize 1000 IU in one minute with an UVI of 10 (15,16,41). The posture of the person has not been specified in these publications. However, it appears reasonable to assume that persons are mostly in vertical posture outdoors. Some scientists consider 1000 IU as not sufficient, but request about 3000 IU per day (R. Scragg, personal communication); in this case, the necessary exposure times would be three times greater. Other assumptions impose greater difficulties, such as a nonlinear dose effect relationship; an example for such a nonlinear effect is that an intoxication of vitamin D cannot be caused by excessive exposure to sunlight because any excess of vitamin D is destroyed within the human body (15,50). Concerning the spectral transmission of human skin Meinhardt-Wollweber and Krebs (51) calculated different sensitivities at different parts of the human body. This is, for example, demonstrated by the optical properties of thick horny layer of thumbs compared with the inner side of the forearm. Especially on colder days the pigmentation of (sun-exposed) skin might lead to an elevated risk of vitamin D deficiency (21) because the needed exposure time could increase by a factor 6 (12). Fig. 8.

Previous studies estimated the exposure to UV radiation by use of the spectral or weighted irradiance on a horizontal surface (12,14–21). However, even if the measured irradiance on tilted surfaces is considered (30,32,33), there is always the difficulty that the effects of reflections from the ground are difficult to parameterize and will influence the measured irradiance of the tilted surfaces. According to Diffey (14) important dependences of vitamin D–weighted exposure are the posture, the orientation with respect to the sun and the influence of nearby shade. Our results confirm the importance of posture, but we found that for a human body in vertical posture the importance of orientation toward the sun depends on clothing, whereas for an unclothed person it is nearly irrelevant. Although we did not consider any shading obstructions, we agree on the importance of this factor for the calculation of a realistic exposure. There is also concern about the correctness of the CIE weighting function for previtamin D₃ production (52). As our investigations consider spectral radiance, rather than weighted irradiance (e.g. with erythema), the calculations can easily be repeated for other vitamin D action spectra.

In the following we compare the exposure times needed to gain an adequate vitamin D status with some results found in literature. Compared with the exposure calculated on the basis of vitamin D–weighted horizontal irradiance (see asterisks in Fig. 9), we find an exposure that is about 40% higher for an UVI of 2, both for the human body in vertical and horizontal posture. As the analysis of McKenzie et al. (16) is based on
irradiance on horizontal surfaces, we conclude that the real exposure will be underestimated in cases of low UVI when only irradiance is taken into account. This result is in accordance with the results of Hoppé et al. (31) that assessed an underestimation of the UV exposure for horizontal planes. McKenzie et al. (16) stated a ratio of vitamin D–weighted irradiance between winter and summer of approximately 5% at 45°S. Our results (for 50°N) indicate a ratio of 1% between winter and summer for a person in horizontal posture. It should be noted that this ratio corresponds to a low UVI, which is quite typical for the European midwinter. Our results cannot confirm statements that the "vitamin D winter" lasts from October to March (12,14,19,20,22). Instead the exposure times required at the end of winter (March 21) are only about half an hour for cloudless skies, even if just face and hands are exposed.

Webb et al. (19) estimated the time to gain an adequate vitamin D status during midsummer sunlight for a person in vertical posture, with 35% skin exposed, to be 22 min and for a person in horizontal posture to be 13 min at 53.5°N on a cloudless day. With 13 min exposure time for the same location on June 21, Rhodes et al. (17) obtained similar results, assuming a 35% skin exposure. In contrast we calculated

Figure 8. Diurnal variation in exposure (left ordinate), for different postures, compared with vitamin D₃–weighted irradiance (right ordinate) for Rome with cloudless sky on June 21. Under these conditions the vertical posture has a lower exposure than the horizontal posture.

Figure 9. Ratio of exposure per time interval and UVI (left ordinate) and ratio of vitamin D₃–weighted irradiance and UVI (right ordinate) for midsummer conditions in Rome (case 1). It can be concluded that the UVI is not a good indicator for the vitamin D₃–weighted exposure of a human.
exposure times of about 4 min for a person in vertical posture and about 3 min for a person in horizontal posture with minor differences in skin area (32%) and latitude of 52.4°N. We conclude that at least in summer there are significant differences in the estimated exposure times. It must be emphasized, however, that the method to determine the exposure times is quite different from our approach. In addition, Webb et al. (19) assume 2000 IU ± 600 IU to be sufficient for an adequate vitamin D status, whereas we assume 1000 IU to be sufficient in accordance with Holick (15,41) and McKenzie et al. (16). Summarizing the exposure times calculated by McKenzie et al. (16) are found to be in better agreement with our calculations than the results of Rhodes et al. (17). Nevertheless, there remains a remarkable difference in the estimated exposure times required to obtain a sufficient Vitamin D level.

CONCLUSION

Our new method to estimate the UV exposure for humans enables, in principle, to calculate the necessary exposure times to gain a healthy vitamin D status for various conditions taking into account the complex geometry of both the human body and the sky radiance. Although it is easy in summer under cloudless skies to obtain a sufficient exposure, the situation is quite different in winter. If the assumptions of the model are correct, the results show that in December in central Europe it is theoretically possible to gain enough UV radiation to produce 1000 IU under clear sky conditions in approximately one hour. This specific situation requires, however, that the whole human body would be fully exposed, which is extremely unlikely or at least inconvenient during winter time. However, for realistic winter time skin exposures it is not possible to get enough exposure for vitamin D production at the beginning of the winter. Under cloudy conditions on December 21 in Hannover even exposing the whole body for the whole day, it would not be possible to gain enough vitamin D. If only hands and face are exposed, the situation becomes even worse. Less than 3% of the daily dose required can be attained. Under these circumstances a person would have to wait more than 35 days before the sufficient daily exposure would be reached – in other words, the winter would have nearly passed by before a sufficient vitamin D status could be reached. These calculations confirm the earlier findings that it is not possible to gain enough vitamin D in winter (20) and the statement in the analysis from McKenzie et al. (16) that sufficient vitamin D may be gained in winter are not realistic for the European winter. In this context the role of gaining vitamin D requirements from diet should be reconsidered because the earlier findings that only 10% of vitamin D is gained by food are probably not correct in winter. The mean daily vitamin D intake of German adults ranges between 40 and 120 IU (12). These amounts are not available from solar exposure for a clothed human on a cloudy winter day. We also conclude that for northern midlatitudes the “vitamin D wintertime” does not cover all months between October and March. However, more work is needed to assess the exposure on humans and to determine the exposure times necessary for a healthy vitamin D status as a function of season, time of day, clothing, shading and location.

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