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Solar Simulators for Healthy Vitamin D Synthesis

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Abstract. *Background/Aim: The angular distribution of solar radiance and its spectral characteristics is required for the determination of vitamin D_3 production in humans. Materials and Methods: The vitamin D_3 weighted exposure can be calculated by integrating the incident solar spectral radiance over all relevant parts of the human body. A novel instrument allowing simultaneous measurements of spectral radiance from more than 100 directions has been developed. A large solar simulator for controlled experiments is described. Results: In summer it is relatively easy to obtain sufficient vitamin D because sun exposure times are short. In winter solstice vitamin D_3 cannot be obtained with realistic clothing even if the exposure were extended to all daylight hours. Conclusion: Improved and controlled experiments to determine vitamin D_3 production are required to assess the positive effects of solar UV radiation and to assess its natural variability.*

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. On the other hand, UV is essential for vitamin D_3 production in humans (1, 2). Emerging evidence suggests an association between vitamin D levels as an indicator of health risk (2) related to some cancers, multiple sclerosis among others, along with the established link with musculoskeletal health. The causal relationship between numerous diseases and vitamin D_3 has been shown in a recent study (3). In the following vitamin D is used as a general term whereas we use the expression vitamin D_3 to describe UV related issues.

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 (4), at least according to current knowledge. Although vitamin D can be effectively produced by UVB radiation, there are large seasonal differences in its production (5, 6). As a result more than 50% of the German population has an insufficient vitamin D supply, especially during winter (7). This finding has been recently re-confirmed in a large group of patients (8).

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The diffuse irradiance on a horizontal surface, that is used in most studies to date, does not take into account the complex geometry of the radiation field of the sky for different meteorological conditions. Therefore, our goal was to calculate the vitamin D_3 weighted exposure of a human, represented by a 3D voxel model (9), using radiative transfer models of the sky radiance. In addition sky radiance can now be measured sufficiently fast by a newly-developed multi-directional spectroradiometer (MUDIS) (10). In combination with well-designed solar simulators (11) which have been developed for plant research already 30 years ago, these measurements and calculations are capable to trigger new insights into the production of vitamin D of humans.

Materials and Methods

Controlled environmental chambers had been developed and constructed already since 25 years ago for plant research (11). The major achievements were:

- Irradiance up to 1,100 W/m^2
- Spectral distribution similar to sunlight
- Diurnal variation of sunlight
- Spatial inhomogeneity <10%
- Reasonable operational costs

A comparison of the natural and simulated irradiance can be found in Figure 1.

In contrast to the simplification to using just irradiance to describe solar radiation, in reality, outdoor radiation is more complex and best described by the physical quantity "spectral radiance" (9). The spectral radiance is a complex function that depends on time of the day, day of the year, latitude, longitude, height above sea level, wavelength, ozone column and ozone profile, aeresols, clouds cover, cloud type, cloud distribution in the sky, air pressure, humidity and is a function of the zenith as well as the azimuth angles. Typical distributions of the sky radiance for cloudless skies are shown in Figure 2.

Clouds complicate the picture significantly, as can be concluded from Figure 3. In recent decades spectral sky radiance has been measured by scanning instruments (12). For accurate measurements both the wavelength spectrum and the sky distribution need to be measured. Since the necessary time to complete one wavelength scan

Table I. *UV index (UVI) and estimated times to gain 1,000 IU vitamin D for five different cases (for the cities Rome and Hannover) and exposure areas. The overcast cases represent a very thick and dark cloud. The method is described in more detail in (9).*

Rome 21. June Clear Sky	Han. 21. June Clear Sky	Han. 21. June Overcast	Han. 21. March Clear Sky	Han. 21. March Overcast	Han. 21. Dec Clear Sky	Han. 21. Dec Overcast
			UVI			
10	8	1	3	0.5	0..4	0.04
			Unclothed, upright posture			
1.0 min	1.1 min	6.6 min	2.3 min	19 min	39 min	2.1 d
			Winter clothing, upright posture			
17 min	18 min	1.,9 h	37 min	9.6 h	3.0 d	35 d

could be up to 30 min with (fast) scanning instruments, it takes a day or more to complete one measurement of spectral sky radiance. Clouds, however, can move quite quickly and therefore can change the radiation field within seconds (13). Therefore we developed a novel instrument that is capable of measuring sky radiance in different directions simultaneously (10). With such an instrument (Figure 4) it is possible to acquire a spectrum from more than 100 directions (Figure 5) within one second. It is, therefore, well-suited to provide the necessary information on spectral sky radiance, that is required to measure the Vitamin D3 weighted exposure of humans.

To calculate a biologically-weighted exposure, the weighted radiance distribution of the sky and the geometry of the human are needed as input. The radiance distribution can be simulated with a radiative transfer model (Figure 1) or it is measured with a spectroradiometer like MUDIS mentioned before and seen in Figures 4 and 5. The procedure of weighting can be recognized in Figure 7. The geometry of a human is taken into account by using projectionareas (projections) of a 3D-Modell of a human as can be seen in Figures 6 and 8. With different clothing the projections of the human can vary and therefore can represent different atmospheric conditions and human behavior (Figure 6).

The weighted exposure of a human is calculated by multiplying the weighted radiance distribution with the projections of the human (Figure 7) and integrating over the whole hemisphere (9).

Results

With the assumption that an unclothed human can produce 1,000 IU Vitamin within just 1 min for an UV index of 10 and assuming linearity it has been possible to estimate the following exposure times for a healthy Vitamin status (1,000 IU per day).

Difficulties and uncertainties

To estimate required exposure times for synthesizing vitamin D several assumptions were made. In reality none of these assumptions are probably strictly fulfilled and at least the following assumptions need to be checked:

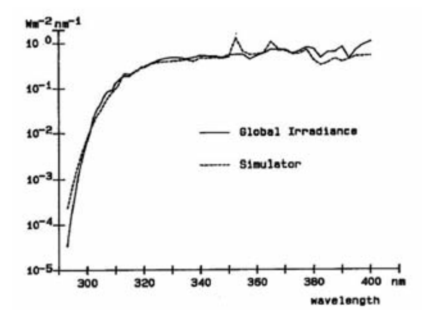

Figure 1. *Spectral global irradiance measured at 30° solar zenith angle (summer) in Neuherberg, Germany and artificial global irradiance in the wavelength range 280-400 nm. The agreement between natural and simulated irradiance is satisfying (11).*

- The exposure from solar radiation of a human in vertical posture experiencing a UVI of 10 is equivalent to 1,000 IU per minute.
- Different parts of the human skin may have a different spectral transmission and a different sensitivity towards the incoming energy.
- The weighting function for vitamin D production is correctly described by the CIE weighting function.
- The accumulated vitamin D increases linearly with exposure.
- The impact of reflected radiation from the ground due to higher albedo is negligible.

Further difficulties are the inclusion of specific obstructions (*e.g.* houses, trees) for a realistic outdoor exposure.

Conclusion

We were able to estimate the time required to achieve 1,000 IU per day (16), the assumptions that lead to these exposure times are still quite uncertain.

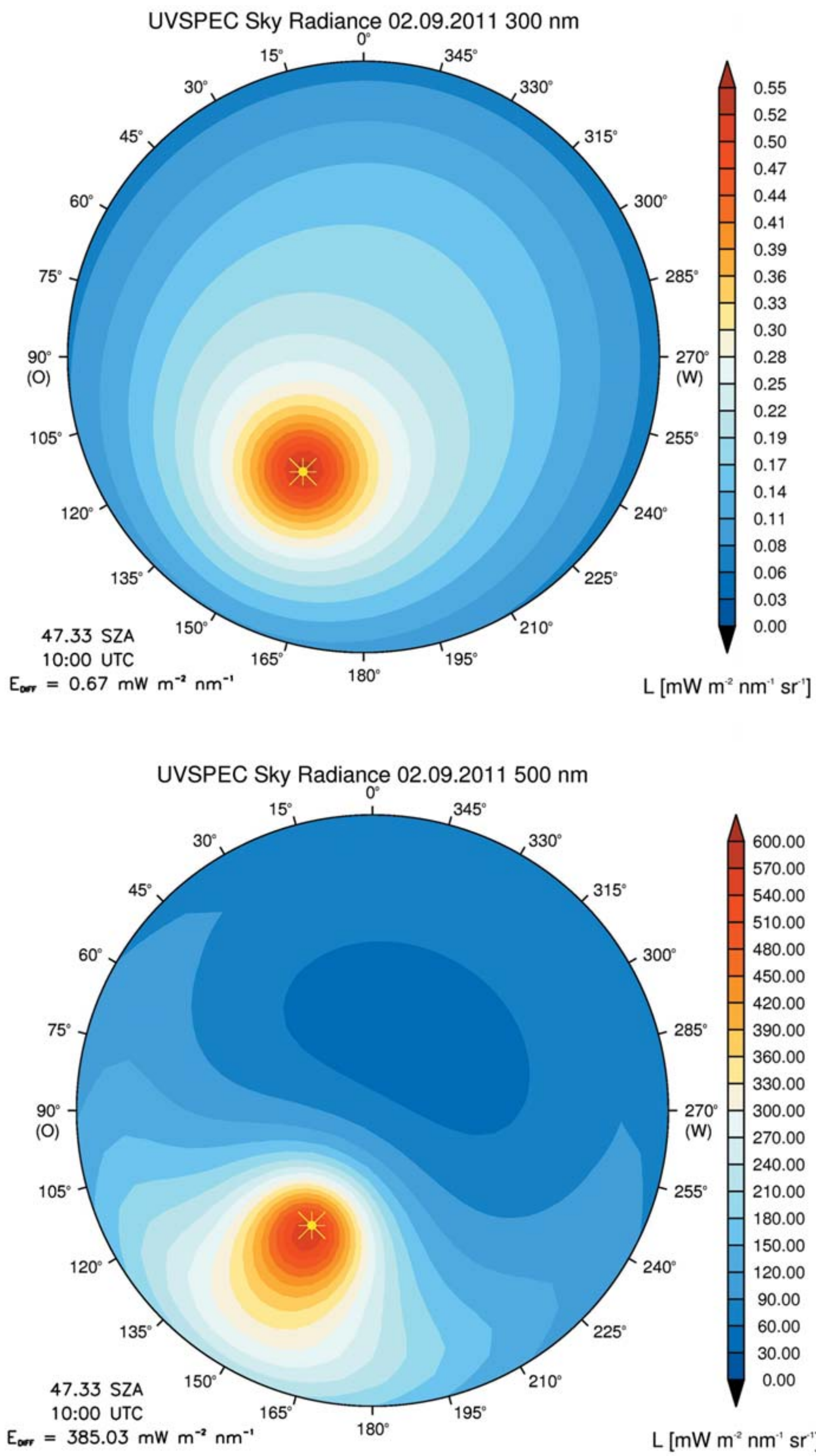

Figure 2. *Calculated spectral sky radiance for UVB and in the visible for cloudless sky in Hannover. The position of the sun is marked with an asterisk. The sky region around the sun is the brightest, whereas the horizon is relatively dark. There are remarkable differences between the spatial distribution in the UV and in the visible. The latter shows a minimum 90 degrees away from the sun, whereas this minimum disappears at 300 nm. Near the horizon the spectral radiance is pretty low in the UV, whereas in the visible it is bright in the direction of the sun, but low opposite the sun.*

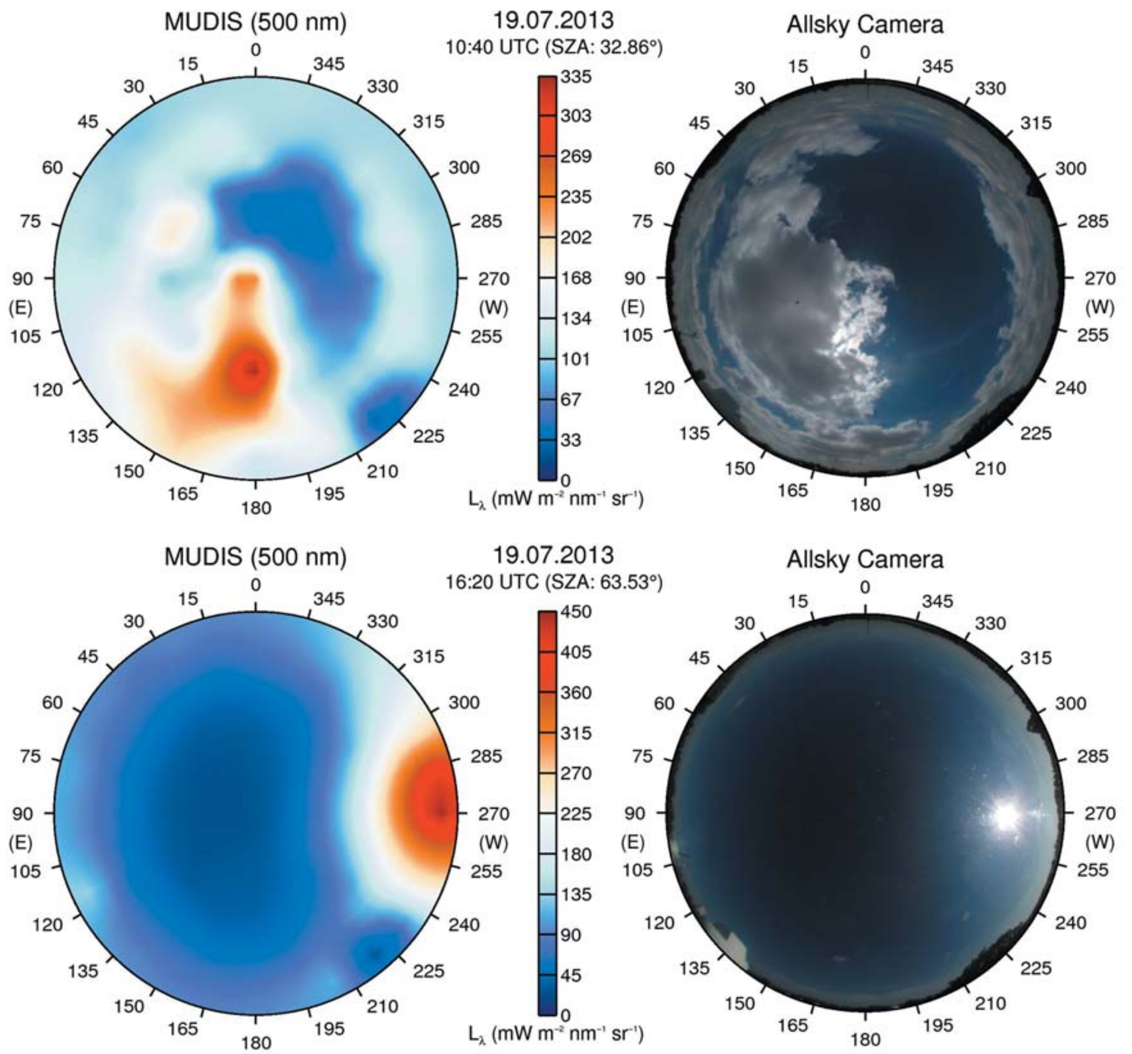

Figure 3. *Influence of clouds on the sky radiance. The images show that the sky radiance is significantly altered by clouds. (a) Upper left: Spectral radiance at a visible wavelength (500 nm) measured by the MUDIS system. 500 nm has been taken as one example from the wavelength range 300-550 nm. (b) Upper right: same scenery as in (a); the image taken the hemispherical sky imager system (14-15) at the roof institute building . Lower left: Spectral sky radiance measured with MUDIS at cloudless conditions. (c) Lower right: same scenery as seen by the hemispherical sky imager.*

This is particularly true for the statement that a person can synthesize 1,000 IU in one minute with an UVI of 10 (16-18). Therefore our exposure times should be treated with caution.

Achieving a higher accuracy experiments under controlled conditions would be desirable. The phytochambers described above are still operational. However, they would need to be characterized with respect to spectral radiance. In addition new technologies that did not exist in the 1980s could be applied, such as radiation from LEDs. Meanwhile, there are several UV LED commercially available from different manufacturers (*e.g.* 19). With a combination of different LEDs it may be even possible to develop an improved solar simulator.

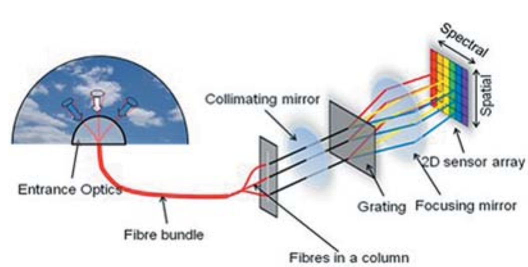

Figure 4. *Measurement principle of the recently developed MUulti-DIrectional Spectroradio-meter (MUDIS). Older technology required up to a complete day to measure the spectral radiance distribution, whereas this recently developed instrument requires not more than a second. This enables the investigation of the fast changing radiation field.*

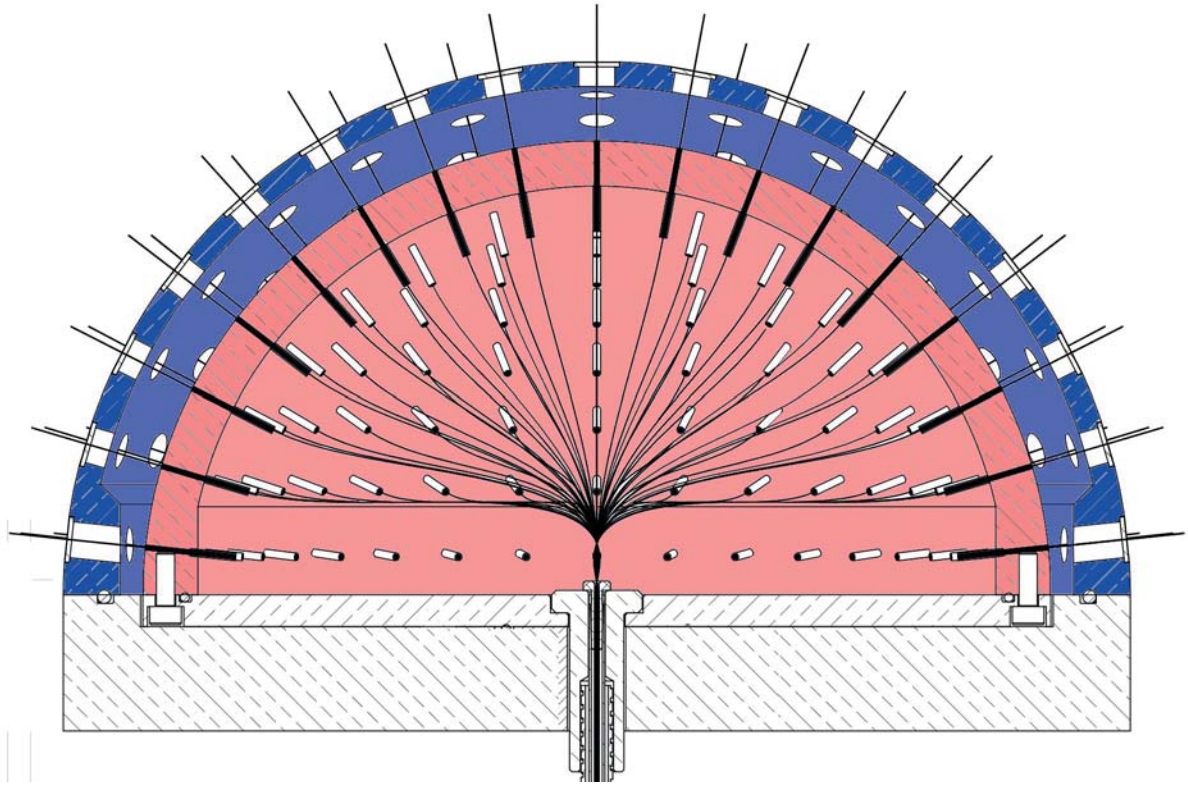

Figure 5. *Entrance optics of the MUDIS instrument. The different fibres are attached to ferules (long white tubes), and the weather protection is shown in blue colour. The radiation from each direction enters the input optics by a quartz plate.*

Figure 6. *Projections of the human model for incident angles 30°, 60° and 90° with the front turned by 30° in azimuth. Left: Example for winter clothing, 7% skin exposed. Right: Example for summer clothing, 32% skin exposed.*

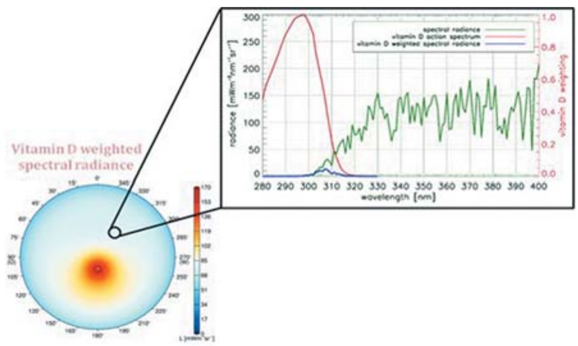

Figure 7. *Calculated Vitamin D weighted sky radiance for 21 June, noon in Rome. This condition corresponds to a UV index of 10. The maximum of the sky radiance is centered around the direct sun, which is the marked by an yellow asterisk.*

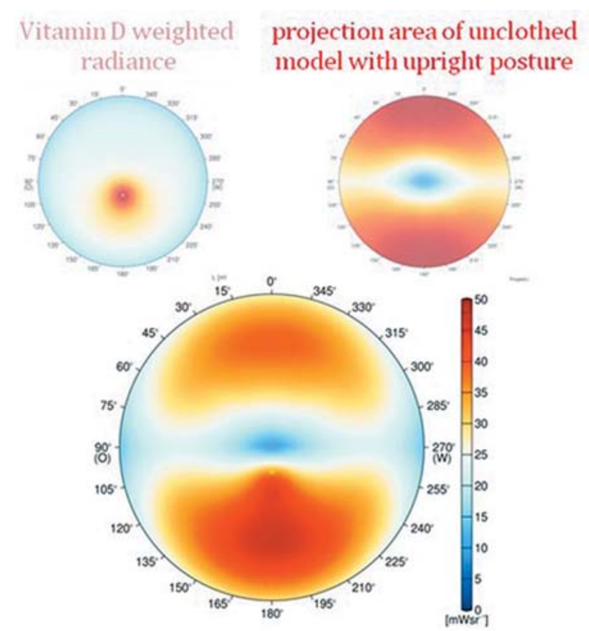

Figure 8. *Upper left: Vitamin D weighted radiance as shown in figure 4. Upper right: Projection area of a model human as a function of zenith and azimuth angle. Lower panel: Multiplication of Vitamin D weighted radiance and projection area as a function of zenith and azimuth angle. The minimum in the zenith is a consequence of the small projection area of the model human in upright posture.*

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