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UV Radiation, Vitamin D and Human Health: An Unfolding Controversy

Daily Duration of Vitamin D Synthesis in Human Skin with Relation to Latitude, Total Ozone, Altitude, Ground Cover, Aerosols and Cloud Thickness

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ABSTRACT

Vitamin D production in human skin occurs only when incident UV radiation exceeds a certain threshold. From simulations of UV irradiances worldwide and throughout the year, we have studied the dependency of the extent and duration of cutaneous vitamin D production in terms of latitude, time, total ozone, clouds, aerosols, surface reflectivity and altitude. For clear atmospheric conditions, no cutaneous vitamin D production occurs at 51 degrees latitude and higher during some periods of the year. At 70 degrees latitude, vitamin D synthesis can be absent for 5 months. Clouds, aerosols and thick ozone events reduce the duration of vitamin D synthesis considerably, and can suppress vitamin D synthesis completely even at the equator. A web page allowing the computation of the duration of cutaneous vitamin D production worldwide throughout the year, for various atmospheric and surface conditions, is available on the Internet at http://zardoz.nilu.no/~olaeng/fastrt/VitD.html and http://zardoz.nilu.no/~olaeng/fastrt/VitD-ez.html. The computational methodology is outlined here.

INTRODUCTION

Vitamin D is essential for natural bone metabolism and for the calcium and phosphorus homeostasis. In addition, a protective effect of vitamin D on cancer in colon, prostate, and breast has been suggested on the basis of both epidemiological (1–4) and experimental studies (5). Vitamin D is obtained either from the skin when exposed to UV radiation or through a few dietary sources; primarily fatty fish, cod-liver oil, and fortified margarine and butter. A dramatic effect of seasonal and latitudinal changes of solar UV radiation on vitamin D synthesis was revealed by Webb *et al.* (6). They found that below a certain threshold of UV radiation, corresponding to cloudless conditions in Boston, MA (42°N) in mid-February near solar noon, no photoconversion of provitamin D to previtamin D was detected. Models (7) and experiments (8,9) describing photoconversion of provitamin D to previtamin D exist, but are not well validated or associated with critically low vitamin D–weighted irradiances at which vitamin D production in human skin is initiated under natural daylight conditions. The period when there is not sufficient UV radiation outdoors for a person to produce vitamin D is termed the "vitamin D winter." The potential health risk due to the presence of "vitamin D winter" is real: moderate hypovitaminosis D was found in one-quarter of the northern Norwegian population (blood serum circulating 25-hydroxyvitamin D [25(OH)D] <37.5 nmol $\cdot$ L^{-1}). Two thirds had blood plasma concentrations below the recommended level (25(OH)D <50 nmol $\cdot$ L^{-1}) (10).

From simulations of UV irradiances worldwide and throughout the year, we estimated the daily time period when UV radiation exceeds the required threshold (6,10). The duration of vitamin D production depends not only on latitude and time, but also on several other parameters, most importantly total ozone, clouds, aerosols, surface reflectivity and altitude. To our knowledge we are first to investigate cutaneous synthesis of vitamin D in terms of all these other parameters that describe the major optical properties of the terrestrial surface and atmosphere in the UV spectral region.

This paper presents a novel method for estimating the maximum daily duration of vitamin D synthesis in human skin at any location worldwide throughout the year. The estimates are available through a web browser, or from a computer script available free from the author. The manuscript constitutes a re-evaluation of the extent of the vitamin D winter (*i.e.* the period when no cutaneous vitamin D

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Abbreviations: BED, biologically effective dose; DU, Dobson unit (1 DU = 1 matm-cm, equivalent to the thickness of 0.01 mm of pure ozone at standard conditions of temperature [273.15 K] and pressure [1 013.25 Pa]); FWHM, full-width half-maximum of a spectrometer's spectral response function; TOMS, Total Ozone Mapping Spectrometer; UV-B, ultraviolet radiation of wavelengths in the 280–315 nm range; 25(OH)D, blood serum circulating 25-hydroxyvitamin D; 7-DHC, 7-dehydrocholesterol = provitamin D.

Table 1. Duration of vitamin D winter

Vitamin D winter	Minimum latitude [°N] (solar zenith angle [°]) of incidence	Period at 70°N	Cloud liquid water column threshold at 70°N ($g \cdot m^{-2}$)*
Clear atmosphere	51 (74.3)	5 October–10 March	1 500
Low ozone (100 DU)	63 (85.8)	6 November–6 February	>3 000
High ozone (500 DU)	42 (64.7)	10 September–4 April	500
Low visibility (5 km)	49 (72.0)	29 September–16 March	1 500
High altitude (3 km)	52 (75.0)	7 October–8 March	1 500
Snow-covered ground	53 (76.0)	9 October–6 March	>3 000

*Threshold of perpetual vitamin D winter.

synthesis exists). Its findings may have implications for future general public advice on nutrition and UV exposure.

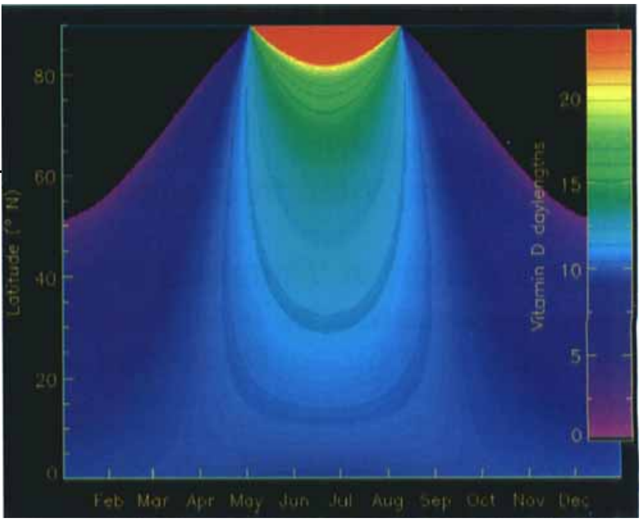

Figure 1. Daily period (in hours) of vitamin D production in terms of time and latitude for a clear atmosphere and no surface reflection and for a typical level of total ozone (300 DU). The austral vitamin D winter is identical to the vitamin D winter at northern latitudes.

MATERIALS AND METHODS

Based on information outlined by Webb *et al.* (6), we established a biologically effective UV dose (BED) rate for photoconversion of 7-dehydrocholesterol (7-DHC, Aldrich Chemical Co., Milwaukee, WI) to previtamin D in skin (10). Webb *et al.* (6) found no detectable photoconversion of 7-DHC to previtamin D in mid-February, and only a small production of previtamin D in mid-March in Boston. In mid-February, within a half-hour of solar noon at the maximum intensity of the day, Webb *et al.* measured surface irradiances of 0.024, 1.0 and 10 $mW \cdot m^{-2} \cdot nm^{-1}$ with an Optronics 742 spectroradiometer (Optronic Laboratories Inc., Orlando, FL) at wavelengths of 300, 306 and 316 nm, respectively. The BED was established by adding the measured surface irradiances weighted by the relative efficiencies for converting 7-DHC to previtamin D. The weighting factors are 0.92, 0.45 and 0 for 300, 306 and 316 nm, respectively (6). Below the threshold $BED_{threshold} = 0.024 \cdot 0.92 + 1.0 \cdot 0.45 = 0.472$, we assumed that no photoconversion to previtamin D took place.

We applied the fast, yet accurate UV simulation tool FastRT (11) to simulate surface irradiances at 300 and 306 nm as would be measured by an Optronics 742 spectroradiometer similar to the one used by Webb *et al.* (6). For each day throughout the year we simulated the amount of time the BED exceeded the UV radiation threshold for vitamin D production described above for the entire globe for various atmospheric and surface conditions. We assumed a very clear "base case" atmosphere over a nonreflecting surface with an ozone layer thickness fixed at a typical level (300 Dobson units; DU) and a rural aerosol optical depth, given by $\tau = \beta \cdot \lambda^{-\alpha}$, where the Ångström coefficients α and β were set to 1.3 and 0.02, respectively, and the wavelengths (λ) are in micrometers. The Ångström coefficient β was related to visibility $R_m[km]$ using the parameterization contained in (12); that is, $\beta = 0.55^{1.3}\,(3.912/R[km] - 0.01162)[0.02472 \cdot (R_m[km] - 5) + 1.132]$.

For cloudy, overcast conditions we assumed homogeneous alto-stratus type clouds (13) of variable densities at 2–7 km above ground. For snow-covered ground, we assumed an albedo of 0.9, which pertains to fresh, new snow. Otherwise, for all simulations we assumed a U.S. standard atmosphere (14).

RESULTS

In clear atmospheric conditions, a vitamin D winter occurs at 51 degrees latitude and higher (Table 1, Fig. 1). At 70 degrees latitude, cutaneous vitamin D synthesis can be absent from 5 October through 10 March. The main parameters influencing UV radiation (ozone, aerosols, clouds, albedo and altitude), roughly speaking, shifts the extent of the dark field (*i.e.* the vitamin D winter in Fig. 1) up or down while the essential shape is preserved.

Ozone strongly absorbs UV-B radiation. Extremely high/low ozone levels (500 DU/100 DU) can decrease/increase the latitude of vitamin D winter incidence by about 10 degrees, and extend/shorten its period of duration by about 2 months.

Atmospheric aerosols attenuate surface UV-B radiation. On the other hand, reflection of UV radiation from the Earth's surface enhances UV-B radiation. Snow cover or a turbid atmosphere (5 km visibility; *i.e.* Ångström $\beta = 0.4$) can change the lower latitude of occurrence for the vitamin D winter by a couple of degrees and alter the duration of cutaneous vitamin D synthesis by about 1–2 weeks. Increasing the surface elevation to 3000 m has about the same effect as covering the ground with snow at sea level.

Clouds generally attenuate UV-B radiation. Thick clouds can reduce surface UV-B radiation to as much as 1% of clear sky levels. Even scattered clouds on the horizon may significantly lower the UV radiation. Cutaneous vitamin D synthesis can halt completely at the equator for a very thick overcast cloud with a liquid water column of 2 700 $g \cdot m^{-2}$ or greater (not shown in Table 1). At 70 degrees latitude the vitamin D production in skin can disappear even at midsummer for a medium-thick cloud cover with a liquid water column of 1 500 $g \cdot m^{-2}$.

DISCUSSION

Uncertainties

As mentioned before, we used a threshold pertaining to cloudless conditions in Boston, MA (42°N) within a half-hour of the solar noon for the closest cloudless day to 15 February 1986, for which spectral UV irradiances are available (6). Those measured irradiances are somewhat lower than those we would normally obtain for corresponding cloudless sky simulations at that time and location. Using the FastRT simulation tool, we could reproduce the measurements in (6) only in mid-February 1986 by assuming an extremely high ozone column (~600 DU) and a very turbid atmosphere (visibility of ~5 km). According to the Total Ozone

Table 2. Duration of vitamin D winter using a simulated weekly mean BED radiation threshold centered at 12 February 1986 ($BED_{threshold} = 3.46$)*

Vitamin D winter	Minimum latitude [°N] (solar zenith angle [°]) of incidence	Period at 70°N	Cloud liquid water column threshold at 70°N ($g \cdot m^{-2}$)
Clear atmosphere	40 (63.3)	6 September–8 April	300
Low ozone (100 DU)	55 (78.5)	16 October–28 February	1 400
High ozone (500 DU)	27 (49.8)	22 July–23 May	<100
Low visibility (5 km)	36 (58.9)	25 August–19 April	300
High altitude (3 km)	42 (64.7)	10 September–4 April	300
Snow-covered ground	43 (66.1)	13 September–31 March	900

* Cloudless sky conditions at solar noon in Boston with a visibility of 25 km and total ozone obtained from the TOMS satellite instrument. The weekly mean ozone column at this time was 388 DU (for reference only). The weekly mean BED was computed to reduce the effect of inexact dates of exposure for the 7-DHC solutions described in (6).

Mapping Spectrometer (TOMS) satellite instrument, Boston had ozone columns ranging from 280 to 450 DU in February 1986. These ozone values would not attenuate cloudless sky UV radiation as much as observed by Webb *et al.* in (6) except during extreme, low visibility events (*e.g.* volcanic eruptions or haze). According to our calculations, the period of vitamin D winter seems thus somewhat overestimated in (6). It is important to note, however, that completely cloudless days are rare. There are almost always some scattered clouds in the sky dome, even on days that most people would consider cloudless. Because most UV radiation is diffuse, scattered clouds, even those near the horizon and not occluding the sun, influence the surface irradiance. Likewise, nearby building structures and other surroundings can block and thus abate radiation. Unfortunately, no relevant sky dome images are available for Boston in February 1986, so it is not possible to verify whether conditions were truly cloudless.

The FastRT UV simulation tool is by no means perfect. The program is designed to have uncertainties better than current high-quality UV measurements when all input parameters are known (11).

Another source of uncertainty is the lack of a confirmed spectral response function for the Optronics 742 instrument used in Boston in 1986. We have assumed the spectral response function measured for another Optronics 742 instrument currently located in Reading, England. Assuming instead a triangular spectral response function with a full-width half-maximum (FWHM) of 1.5 nm (*i.e.* the nominal FWHM of the Optronics 742 instrument) reduces the threshold solar zenith angle for a clear atmosphere by 0.7° (compare with Table 1, column 1). The uncertainty caused by the missing spectral response functions is somewhat reduced by the construction of the BED. This problem would have been reduced further if other irradiances from the vitamin D effective spectral range were available. Furthermore, this would have provided a better BED and a more accurate threshold for vitamin D synthesis.

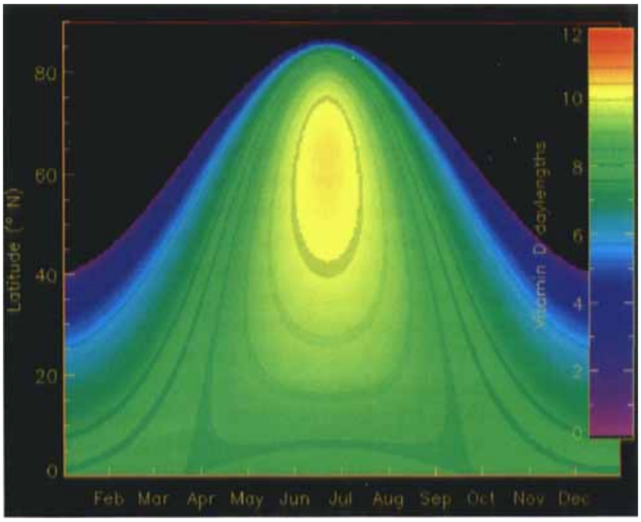

Figure 2. Similar to Figure 1, but using the higher simulated radiation threshold as described in Table 2 ($BED_{threshold} = 3.46$).

Measurement uncertainties for UV radiation always exist and may have influenced the BED threshold. Even high-quality UV-B measurements have uncertainties ($\pm 2\sigma$) of about 13% (300 nm wavelength at 60° solar zenith angle) (15). The spectral UV measurements made in Boston in 1986 may not have been subject to the same advanced quality controls as one would expect today, and consequently, may have even higher uncertainties. To further evaluate the measurements forming the basis for the BED threshold, we simulated irradiances corresponding to those measured by the Optronics 742 instrument in (6) throughout 1986 in Boston for cloudless atmospheres but assuming a global average visibility of 25 km and taking ozone columns from the TOMS. The ratios of the measured irradiances with respect to simulations revealed no systematic bias neither for the 300 nm channel (0.70 ± 2.48) nor for the 306 nm band (0.57 ± 1.21).

In the event that the measured irradiances were incorrect and our cloudless sky simulations for mid-February represent the real radiation threshold, duration of vitamin synthesis in human skin would be far less extensive (Table 2, Fig. 2), and more in line with the vitamin D winter extent found for Boston and Edmonton (52°N, vitamin D winter about 2 months longer than Boston) in (6). Nonetheless, the vitamin D solutions at the center of the experiments in (6) give the best indication of whether any previtamin D was formed at that time and those conditions, and not whatever the UV measurements or the FastRT model predict.

Note that the measured UV radiation thresholds determined by (6) were determined on the basis of in vitro samples. The effect of clothes and skin were ignored. The spectral effectiveness of conversion from 7-DHC to previtamin D in human skin and *in vitro* solutions may also deviate somewhat. Furthermore, the radiation threshold pertained to the last monthly measurement when no photoconversion to previtamin D was detected in spring. The initiation of photoproduction of vitamin D actually took place sometime during the following month. In addition, the figures and tables in this paper present results for very clear, pristine atmospheres, which rarely occur. In summary, the real UV radiation threshold for cutaneous vitamin D synthesis may be expected to be higher, but because we selected a conservative value in this manuscript, the real vitamin D winter is thus likely to be longer than shown here. Tests on excised human skin samples (6), and with a more sensitive high-performance liquid chromatography system to detect previtamin D (A. Webb, personal communication), indicated an extension and reduction, respectively, of a couple of weeks for the vitamin D winter in Boston.

Public health implications

Vitamin D status is determined by the sum of exposure to UV radiation and dietary intake. When considering vitamin D status in a population, lifestyle, culture and behavioral parameters need to be addressed. Studies have found intake of vitamin D to increase with increased latitude (16), and that traditional diets, with increased intake of vitamin D–rich food items during winter, can compensate for lack of sun-induced vitamin D (17). The total contribution of UV radiation on vitamin D levels in blood is affected both by clothing and sun-exposure behavior. An illustrative example is that a high prevalence of vitamin D deficiency has been found among women and neonates in Saudi Arabia due to clothing traditions (18).

To further investigate the role of vitamin D in health and diseases in humans, methodological approaches need to be improved in which both the quantitative and qualitative aspects of UV radiation are included in addition to actual skin exposure and diet in populations living in different geographical and cultural settings. Most epidemiological studies on vitamin D and health lack information either on UV exposure or dietary intake data. The data obtained by the method described in this present paper could, in combination with questionnaire data on diet and sun-exposure behavior, contribute to a methodological improvement for prospective epidemiological investigations into vitamin D and different health outcomes.

CONCLUSION

We have described a method for estimating the duration of vitamin D synthesis in terms of time and location as well as surface and atmospheric conditions. The quality and availability of information on the relevant surface and atmospheric parameters such as total ozone, clouds, aerosols and snow cover has now greatly improved from recent advances in computer science, meteorological models and satellite data.

Our studies show that cutaneous vitamin D production cannot be sustained throughout the year for latitudes of about 50 degrees and higher. In the Arctic, vitamin D production can be absent for several months. Our conclusions are somewhat less dramatic than previous studies. The vitamin D winter seems not as extensive as that described by Webb *et al.* (6). Conversely, clouds, aerosols and thick ozone events reduce the duration of vitamin D synthesis considerably, and can force a "vitamin D winter" even at the equator.

We have reexamined the irradiance measurements presented by Webb *et al.* (6) and found that they may not pertain to perfectly cloudless conditions as stated. If the measurements presented in (6) were incorrect, and the *in vitro* samples were exposed to sunlight under idealized cloudless conditions as we simulated, the vitamin D winter is indeed very extensive (Table 2, Fig. 2). The real vitamin D winter period probably lies somewhere between those indicated in Tables 1 and 2 (A. Webb, personal communication).

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