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Location and Vitamin D synthesis: Is the hypothesis validated by geophysical data?

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Abstract

The literature reports strong correlations between UV exposure and latitude gradients of diseases. Evidence is emerging about the protective effects of UV exposure for cancer (breast, colo-rectal, prostate), autoimmune diseases (multiple sclerosis, type II diabetes) and even mental disorders, such as schizophrenia. For the first time, the available levels of vitamin D producing UV or "vitamin D UV" (determined from the previtamin D action spectrum) and erythemal (sunburning) UV from throughout the USA are measured and compared, using measurements from seven locations in the USA are measured and compared, using measurements from seven locations in the US EPA's high accuracy Brewer Spectrophotometer network. The data contest longstanding beliefs on the location-dependence and latitude gradients of vitamin D UV. During eight months of the year centered around summer (March–October), for all sites (from 18°N to 44°N latitude) the level of vitamin D UV relative to erythemal UV was equal (within the 95% confidence interval of the mean level). Therefore, there was no measured latitude gradient of vitamin D UV during the majority of the year across the USA. During the four cooler months (November–February), latitude strongly determines vitamin D UV. As latitude increases, the amount of vitamin D UV decreases dramatically, which may inhibit vitamin D synthesis in humans. Therefore, a larger dose of UV relative to erythemal UV is required to produce the same amount of vitamin D in a high latitude location. However, the data shows that at lower latitude locations (<25°N), wintertime vitamin D UV levels are equal to summertime levels, and the message of increasing UV exposure during winter is irrelevant and may lead to excessive exposure. All results were confirmed by computer modeling, which was also used to generalize the conclusions for latitudes from 0° to 70°N. The results of this paper will impact on research into latitudinal gradients of diseases. In particular, it may no longer be correct to assume vitamin D levels in populations follow significant latitude gradients for a large proportion of the year.

Keywords: Vitamin D; Ultraviolet radiation

1. Introduction

Ultraviolet (UV) radiation is a carcinogen. Excessive exposure causes at least 20% of melanoma and 99% of non-melanoma skin cancer [1]. The numerous deleterious effects of UV exposure also include cataracts, photokeratitis, aging of the skin and sunburn [2]. Together, the global burden of diseases (BOD) due to excessive UV exposure accounts for the loss of 1.7 million disability-adjusted life-years (DALYs) annually [3].

Paradoxically, adequate sun exposure is essential for human health. Practically, our entire requirement of vitamin D is satisfied by exposing ourselves to UV radiation, causing its synthesis in our skin [4]. Vitamin D regulates calcium absorption and, in conjunction with the parathyroid hormone, bone mineralization. Vitamin D insufficiency leads to reduced bone mass, which can be manifested as the debilitating diseases of osteoporosis and osteomalacia in adults and rickets in children [5].

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Recently, the global burden of these UV deficient diseases was estimated for the WHO at 3.3 billion life-years annually, almost 2000 times greater than the BOD of excessive UV exposure [3,6]. Vitamin D insufficiency is widespread, highlighted by the recent claim by Prof Roger Bouillon of University of Leuven that one billion people worldwide are vitamin D insufficient. Vitamin D insufficiency occurs in up to half of free-living adults in New Zealand [7], one-quarter of Australians [8], 14% of French [9], 36% of US young adults and 57% of US general medicine inpatients [10], and particularly in the elderly, including up to 90% in UK [11] and 86% in Switzerland [12]. Dietary intake and artificial fortification of foods is a trivial and ineffectual proportion of vitamin D intake for most populations. Adequate UV exposure would alleviate the sizeable burden of vitamin D deficiency [4,13–15].

However, it is critical to measure levels and trends of UV radiation before healthy sun exposure is to be advocated. So far, the most important determinant for vitamin D levels is said to be where you live, due to the dependence on geographical location of the availability of UV radiation for vitamin D synthesis determined from the previtamin D action spectrum (“vitamin D UV”). Hence, it has been assumed that vitamin D levels in populations follow latitude gradients (increasing with closer proximity to the equator). Latitude gradients of cancer (breast, colo-rectal, prostate), autoimmune diseases (multiple sclerosis, type II diabetes), coronary heart disease and mental disorders correlate with these hypothetical vitamin D latitude gradients. Such correlations have been used as evidence to assert the protective nature of UV exposure for these diseases [6,16–19]. Ad hoc increases in sun exposure are now being hastily promoted by media and in the literature [20–24].

This report uses actual data of ground-level UV measurements across the USA from year 2000, in conjunction with computer modeling, to challenge current perceptions on vitamin D latitude gradients. We will investigate latitude gradients of vitamin D relative to erythemal UV, and discuss implications for healthy sun exposure. We then highlight the need to monitor and report on levels of UV for vitamin D photoproduction (not just erythemal UV), especially for high latitude locations.

2. Methodology

2.1. Action spectrum for previtamin D synthesis

An action spectrum $A(\lambda)$ describes the wavelength-dependence of a biological effect arising from exposure to UV radiation. Convoluting an action spectrum with the measured solar spectrum $S(\lambda)$ on each day gives the weighted “effective irradiance” $E_{\text{eff}} = \int_{\lambda} S(\lambda)A(\lambda)\,\mathrm{d}\lambda$ for inducing that effect. The paradoxical effects of sun exposure are erythema (reddening of the skin after sun exposure) and the positive impact of vitamin D synthesis. The erythemal action spectrum was established by CIE [25] (Fig. 1) showing the wavelength dependency of UV for the development of erythema, with the shorter UVB (280–320 nm) wavelengths causing the greatest response. However, there is an impact on erythema due also to the UVA (320–400 nm) wavebands.

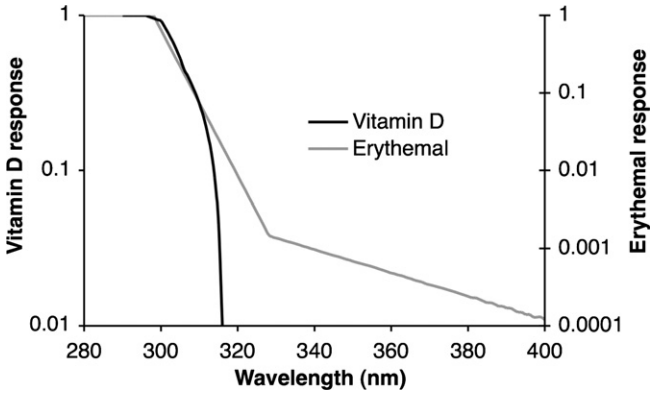

Fig. 1. Action spectra for vitamin D production and erythema.

To date, the most accepted vitamin D action spectrum is that of Webb and Holick [26], which was obtained by irradiating neonatal foreskins with UV then quantifying the conversion of the cutaneous vitamin D precursor, 7-dehydrocholesterol (7-DHC), to previtamin D_3 (Fig. 1). Subsequent isomerization by thermal reaction produces vitamin D_3. In the human body, hydroxylations in the liver and kidneys would then produce the active circulating vitamin (1,25-dihydroxyvitamin D) [27]. When discussing vitamin D in this paper, we refer to the photoconversion of 7-dehydrocholesterol to previtamin D_3 only, which is the standard marker of circulating vitamin D levels. We are not relating this term to circulating levels of 1,25-dihydroxyvitamin D.

Both the erythemal and vitamin D effects respond strongly in the UVB region. However, the erythemal action spectrum extends through the UVA region to 400 nm. UVA radiation accounts for up to 97% of solar UV on earth and causes up to ~40% of an erythemal effect. Vitamin D synthesis is strictly confined to the UVB region [28] and cannot occur in the UVA region (above $\lambda = 315$ nm). UVB levels and hence vitamin D synthesis are more strongly affected by ozone and scattering from aerosols and pollution, whereas UVA and erythema are less strongly affected. Vitamin D synthesis and erythema may hence occur at different rates, varying with time of day, season and latitude.

2.2. UV data from USA EPA Brewer spectroradiometer network

The data used in this paper was collected by the US EPA-funded UV monitoring network of high resolution (0.5 nm) Mk IV Brewer UV Spectrophotometers. For this research we present data from seven sites that have the widest possible latitude gradient between the locations. The data were taken for the year 2000 since maximum data collection occurred that year. These instruments undertake typically 25–30 measurements of the ultraviolet spectrum $S(\lambda)$ during the course of a day. For this report, the UV

scans on each day closest to local solar noon (one of the highest UV irradiances during the day) were averaged over a month. The raw UV data were then convoluted with the action spectra to give vitamin D and erythemally weighted UV irradiances.

Strict UV irradiance calibrations are essential since ambient levels of UVB are relatively very low. These were performed annually on site by staff of the National UV Monitoring Center (NUVMC), located at the University of Georgia, USA, using a secondary standard lamp traceable to a National Institute of Standards and Technology (NIST) 1000 W primary standard lamp. Calibration creates an instrument response function for each Brewer, which is used to translate UV photon count from a photomultiplier tube into UV irradiance measurements. For maximum accuracy, daily response functions were used, which were obtained by a linear interpolation between the two temporally closest response functions. In addition, regular independent quality assurance audits of the instruments are performed by the National Oceanic and Atmospheric Administration (NOAA). The data were corrected for dark count, dead time and stray light using the algorithms of Sci-Tec [29]. The cosine (sun angle-dependent) response of each Brewer was measured using a standard 1000 W lamp in the NUVMC laboratory. The equations of Bias et al. [30] were used to calculate the total cosine correction assuming a diffuse isotropic clear-sky. The ratio of the direct/global irradiance was based on the clear-sky model of Rundel [31].

Temperature fluctuations affect the instruments' response and must be corrected for. Internal temperatures of the Brewer Mk IV instruments may vary from approximately 5° to 45 °C during the course of a year. Temperature response functions of each instrument in the EPA/UGA network were determined as a function of wavelength. The temperature dependence can be as large as 1% per degree centigrade [32]. This can result in a correction of up to 25% relative to the response at 20 °C. The instrument's temperature corrections can be positive or negative depending on the relative temperature of a UV scan to that of the temperature when the calibrations were performed. The overall uncertainty of the UV irradiance measurements of the Brewers, including the relative change of the instruments, was estimated to be ±6% [33].

2.3. Computer model data

To confirm the measurements and generalize the conclusions of this report to extreme latitudes, computer modeling was performed. The UV model is a hybrid of a number of established semi-empirical UV transmittance equations [34,35] and was run for latitudes from 0°N to 80°N (in 10° steps) to obtain monthly UV irradiance data for one year. Fixed model input parameters were aerosol optical depth = 0.2, constant total column ozone concentration of 300 DU, and altitude = 0 km (sea level). The UV spectral data from the model was weighted with the erythemal and the vitamin D action spectra and compared with the Brewer data. The UV model used in this research calculates the horizontal plane irradiance. Field measurements of daily erythemally effective exposure at the Queensland University of Technology (UV-Biometer, Solar Light Co. model 501) confirmed that the accuracy of the model is ±10%.

3. Results

UV data will be reported as ratios of vitamin D UV to erythemal UV. Normalizing vitamin D UV in this way is physiologically appropriate because exposing different skin types to the same amount of UV, relative to the skin type's particular MED (the minimal erythemal dose of UV required to produce erythema), will produce the same quantity of vitamin D [36].

The distribution of the data is shown in Fig. 2, in which all the ratios of vitamin D UV to erythemal UV are plotted from the seven locations. For 8 months of the year (March to October, centered around summer) the ratio of the vitamin D UV to erythemal UV is practically constant for all sites (lying within 2 standard deviations/95% confidence interval of the mean of 2.1). This startling result indicates that there is practically no relative vitamin D UV latitude gradient during 8 months of the year. However, during the four cooler months (November–February), the vitamin D UV irradiance is strongly determined by latitude and hence large distribution of vitamin D UV irradiances between each of the locales is seen in the figure, which is most pronounced in the middle of winter.

3.1. Summer versus winter availability of vitamin D UV

To elucidate this result, the relative vitamin D UV levels were plotted as a function of site latitude for summer (June, July and August) and winter (December, January and February) in Fig. 3. During the summer months, the relative level of vitamin D UV is indeed independent of latitude and stays consistent at approximately 2.1. During winter months, a strong latitude gradient is evident, indicating

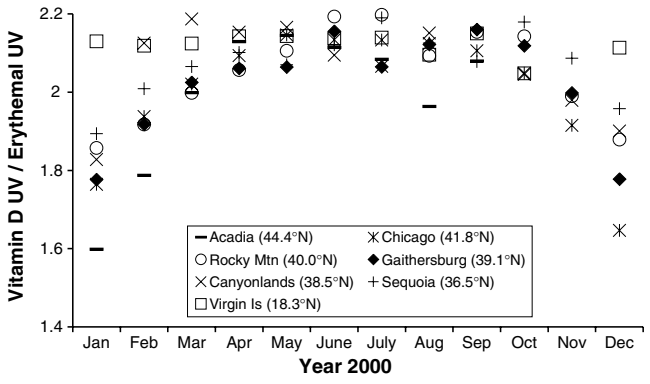

Fig. 2. Vitamin D UV (vitamin D UV) to erythemal UV ratio throughout the year 2000.

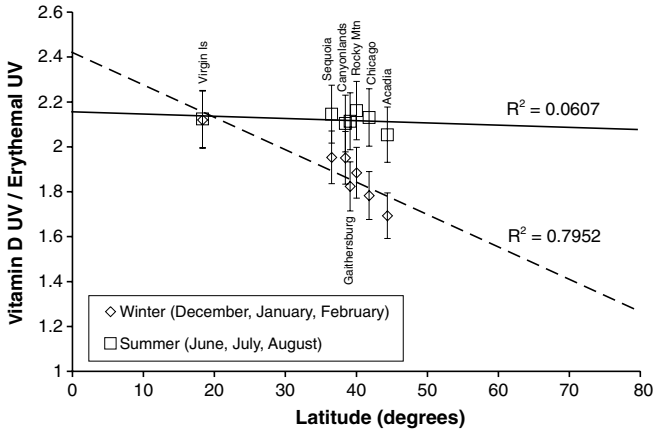

Fig. 3. Ratio of vitamin D UV to erythemal UV versus latitude for summer and winter.

that latitude is a major predictor of the sun's capability to synthesize vitamin D. The seasonal difference is most pronounced at high latitudes such as Acadia National Park (44.4°N). In summer in this locale, the ratio of vitamin D UV to erythemal UV is approximately 2.1, whilst in winter, this ratio drops to 1.6. Therefore, considerably more UV is required to maintain vitamin D sufficiency in winter when compared to summer. In these high latitude locations (e.g. >35°N), monitoring vitamin D UV levels is essential; summer and winter vitamin D UV levels differ dramatically and sun exposure should be varied accordingly for the aim of maintaining vitamin D sufficiency. However, the data suggest that it is unnecessary to increase one's wintertime sun exposure for latitudes < 25°N, since Fig. 2 shows only little difference between relative summertime and wintertime vitamin D UV levels.

3.2. Confirmation and extrapolation by computer modeling

In Fig. 4, the shapes of the model (■) and data (□) wintertime curves are in very close agreement. Therefore, the model data clearly confirms the strong latitude gradient of winter vitamin D UV levels. The offset of the data with respect to the model is accounted for by the assumptions in the computer model (constant 300 DU ozone concentration, 0 km altitude, 0.2 aerosol density). We kept these model input values constant, as we wanted to assess the impact of changing latitude only. In reality, the actual values of these parameters would be different to the model values, and would vary continuously, giving rise to the offset. Computer modeling also allowed us to extrapolate the graphs for latitudes less than 18.3°N and greater than 44.4°N. (The 70°N and 80°N data points are situated at zero because the model reported negligibly small erythemal and vitamin D UV irradiances.)

Temperature data were obtained for each location from a weather Internet site (wunderground.com) averaged over daily averages during the three months of each season. The wintertime gradient of vitamin D UV clearly extends across all latitudes but does not follow the trend of temperature variability with location (Fig. 4). At high latitudes the temperature decreases rapidly while the ratio of vitamin D UV to erythemal UV decreases at a slower rate clearly showing that site temperature is not a good indicator of vitamin D UV.

Likewise, in summer, excellent agreement is found between the model (■) and data (□) curves (Fig. 5). The offset is again inconsequential and due to the aforementioned modeling conditions. The computer model also allows us to extrapolate our conclusions; it seems that relative UV levels during summer are practically identical up to very high latitudes (~60°N) and for average summertime temperatures. The temperature variation between the sites is less than in winter, but again confirms that temperature trends do not correspond to vitamin D UV levels.

3.3. Wintertime availability of vitamin D UV at high latitudes

Previous landmark research suggested that latitudes above 42°N north in winter do not have sufficient UV irradiance to synthesize vitamin D [37]. Yet, these calibrated, high-accuracy, spectrally resolved instruments have mea-

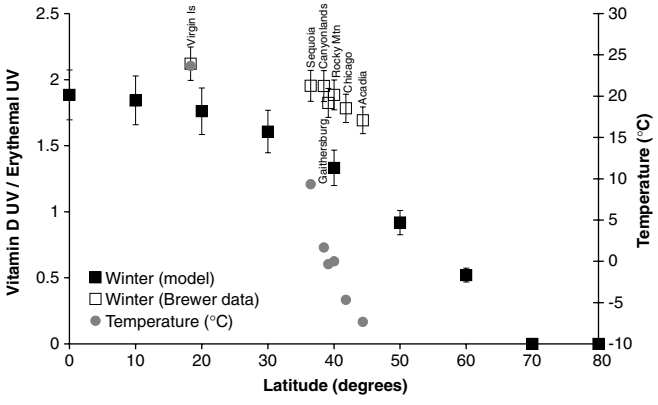

Fig. 4. Ratio of vitamin D UV to erythemal UV, and temperature, versus latitude for measured and modeled wintertime data.

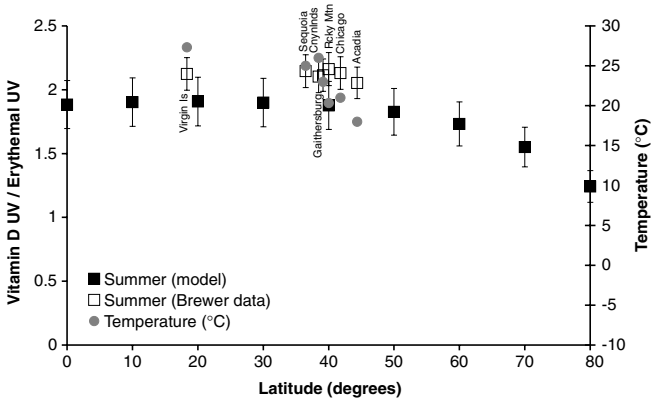

Fig. 5. Ratio of vitamin D UV to erythemal UV, and temperature, versus latitude for measured and modeled summertime data.

sured vitamin D UV in winter in Acadia (44.4°N, Fig. 2). Computer modeling also indicated the availability of vitamin D UV at much high latitudes. Why no vitamin D was synthesized at this latitude remains unanswered.

4. Discussion and conclusions

Using data from the US EPA Brewer network and computer modeling, we have investigated the seasonal dependence of vitamin D UV levels relative to erythemal UV levels. The results can be confirmed by computer modeling and generalized to latitudes from 0°N to 70°N. During the 8 warmer months of the year (March–October), relative vitamin D UV levels are practically independent of latitude. We conclude that there is practically no latitude gradient of relative vitamin D UV for the entire USA during summer, and indeed during most of the year. This result has important implications for epidemiologic studies of gradients of disease. Namely, it may no longer be accurate to assume vitamin D levels in populations follow considerable latitude gradients for a large proportion of the year.

During 4 months of the year (November–February), the ratio decreases dramatically with increasing latitude and strong latitude gradients appear in the data. However, increased sun exposure is not important for lower latitude locations (<25°N) since the measured summertime and wintertime vitamin D UV irradiances are practically identical. Indeed, at the Virgin Islands (18.3°N) the summertime and wintertime levels were almost equal. Increasing sun-time for low latitude locations could needlessly increase the risk of UV overexposure and skin cancer. For high latitude locations >35°N, the data obviates the need for increased sun exposure for maintaining vitamin D sufficiency during winter. This means it is necessary to measure high latitude (>35°N) vitamin D UV irradiances to understand appropriate wintertime sun exposure for high latitude populations. Measurements must be performed with spectrally resolved, calibrated, high performance UV monitoring equipment (such as Brewer spectroradiometers) to provide weighted vitamin D UV and erythemal UV data for comparison. For lower latitude (<25°N) locations, measuring relative vitamin D UV irradiances seems unnecessary.

This data also highlight that erythemally weighted UV data (which is the basis of the internationally recognized UV Index) cannot measure levels and fluctuations in vitamin D-synthesizing UV radiation. For example, summertime vitamin D UV irradiances were generally two times greater than erythemal irradiance measurements (Fig. 3). Basing sun exposure requirements for vitamin D synthesis on erythemal UV measurements may result in UV overexposure and increased skin cancer risk. The relative variations of vitamin D UV and erythemal irradiances arise from the discussed physical differences of the action spectra, because of the different biological weighting as a function of wavelength. Both action spectra are highly responsive in the UVB (280–320 nm) component of the solar spectra, however the erythemal action spectrum extends into the UVA while the vitamin D action spectrum ends abruptly at around 315 nm.

Therefore, vitamin D UV is more strongly influenced by ozone fluctuations and pollution than the erythemal UV that is currently measured, further suggesting that wide scale vitamin D UV, ozone, aerosol and pollution monitoring is necessary in the pursuit of vitamin D sufficiency. The effect of the difference in the action spectra is evident in the above data. During the colder months (November–February), the ratio of vitamin D UV to erythemal UV changes, causing a latitude gradient, indicating that more sun exposure is required relative to erythemal UV (or equivalently the particular person's MED) for vitamin D synthesis. This was particularly noticeable at high latitudes, where an understanding of adequate sun exposure time is critical for vitamin D sufficiency. During warmer months, the ratio is constant since erythemal UV and vitamin D UV are proportional. Hence, erythemal UV and the UV Index could be used as a simple indicator of the relative level of vitamin D UV.

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