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The climatology of Vitamin D producing ultraviolet radiation over the United States☆

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Abstract

The US population is located in a wide range of latitudes, longitudes, and altitudes over mainland United States. Subsequently, high UV irradiants are found at southern locales, whilst in some northern areas, particularly at high latitudes, insufficient levels of ambient UV radiation to synthesize pre Vitamin D in humans are reported. This fact, coupled with the cold northern climates (resulting in high amounts of skin covered in clothing), some people may be susceptible to hypovitaminosis D. Surprisingly, hypovitaminosis D is still relatively common in developed countries such as the USA and the UK. In a large epidemiologically based study of 15,778 noninstitutionalized adult men and women living in the US, 9% had low serum 25-hydroxyvitamin D levels (15 ng/ml) [N. Engl. J. Med. 339 (1998) 12]. Further evidence of this came from recent research by McGrath [Med. Hypertens. 56 (2001) 367] who found that adults living in South East Queensland (with Queensland known as having the highest rates of skin cancer in the world) have surprisingly high rates of Vitamin D deficiency and insufficiency (8 and 23%, respectively). Therefore, hypovitaminosis D represents a serious issue for public health in both sunny and cold climates. This paper will present data on the distribution of Vitamin D forming UV over the USA using collected spectrally resolved ambient UV data from the US EPA Brewer spectrometer UV Monitoring Network. This data is obtained from the network of 21 Brewer spectrometers deployed throughout the USA, allowing for investigation of changes in Vitamin D producing UV with season and location.

Keywords: Ultraviolet; Vitamin D; USA; Climatology

1. Introduction

High ambient UV irradiants are found at southern and tropical locales and in high, northern latitudes, there may be insufficient levels of UV radiation to synthesize pre Vitamin D in humans. Coupled with the cold climates in the northern region (resulting in high amounts of skin covered in clothing) some people living in these northern locations may be susceptible to hypovitaminosis D. On the other hand, populations based at a southern locale are exposed to a much higher ambient UV irradiances and are, subsequently, at risk of development of skin cancer as a result of overexposure to UV. However, living in sunny climates does not necessarily assure the population of enough sunlight exposure to synthesize Vitamin D. Recent research by McGrath [2] found that adults living in South East Queensland (with Queensland known as having the highest rates of skin cancer in the world) have surprisingly high rates of Vitamin D deficiency and insufficiency (8 and 23%, respectively). Hypovitaminosis D is still common in developed countries such as the USA and the UK. The US and other developed countries are finding mounting evidence that a sizeable portion of the population is Vitamin D deficient. For example, a US survey of women aged 20–29 (the peak years for child-bearing) reported that 12% had serum 1,25 hydroxyvitamin D_3 levels below the generally accepted threshold for deficiency [1]. In a more extensive study, Nesby-O'Dell et al. [3] found that of 1546 African-American women studied, 42.4% had Vitamin D levels in the deficient range, while 4.2% of white women ($n = 1426$) were deficient. The ethnic difference may be due to the increased exposure to UV radiation that is needed by persons with dark pigmentation to produce appropriate amounts of Vitamin D [4].

The role of Vitamin D has been traditionally thought to be limited to calcium and phosphate homeostasis, and to bone formation and maintenance, however, low Vitamin D has been linked to the development of a surprisingly wide range of diseases in addition to bone disorders. Epidemiological data and animal studies indicate that low Vitamin D is also

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linked to rickets, bone mass loss, multiple sclerosis, breast cancer, prostate cancer, colorectal cancer, insulin dependent diabetes, and schizophrenia [2,5].

Garland et al. [5] suggests that underexposure to UV radiation (hence Vitamin D production) is associated with premature cancer mortality in the American population. More recent evidence suggests Vitamin D is also involved in the development and functioning of the nervous system [6]. There is also growing evidence that low maternal Vitamin D levels disrupt fetal brain maturation. Eyles et al. [7] point out that the plausibility of this hypothesis rests on data showing Vitamin D receptors are present in the developing brain, Vitamin D induces neuronal growth factor (NGF), and Vitamin D has a strong effect on neuronal cell differentiation. In a study of rat pups born from Vitamin D depleted versus control dams, the brains from Vitamin D depleted neonates had proportionally thinner cortices and larger lateral ventricles. This paper investigates the erythemal, or sun-burning UV (which is the basis of the UV index forecast) and its relationship to Vitamin D producing UV over various latitudes and climatologies.

2. Methodology

The data presented in this paper is based on ground-based ultraviolet (UV) irradiance measurements, utilizing the US Environmental Protection Agency (EPA) network of Mk IV Brewer spectrophotometer instruments. These instruments, which are permanently located outdoors, undertake spectral solar UV measurements throughout the course of the day with a wavelength range of 286.5–363 nm in 0.5 nm steps. Instruments undergo an UV irradiance calibration (to take into account fluctuations and degradation of the optical components of the instrument), using a standard UV lamp traceable to a US National Institute of Standards and Technology (NIST) 1000 W UV lamp. This work is performed by staff of the University of Georgia’s (UGA) National UV Monitoring Center (NUVMC) approximately once per year. In addition to these annual calibrations by the NUVMC, independent quality assurance audits of the instruments take place by staff of the National Oceanic and Atmospheric Administration (NOAA) to ensure accurate measurements.

2.1. Corrections to brewer UV data

Careful UV measurements require a full understanding of instrument performance in all conditions. Subsequently, UV data used in this paper were corrected for dark count, dead time, and stray light using the algorithms of SCI-TEC [8]. The UV data uses an estimated daily instrument response based on an annual UV irradiance calibration, using a secondary standard lamp traceable to the NIST 1000 W lamp. The instrument response function is calculated for each day based on a linear interpolation between the two temporally closest response functions. The data is then corrected for the instrument’s angular (cosine) response and temperature dependence. The cosine correction leads to an increase in the UV irradiance relative to that of the uncorrected data since the full sky collector operates at a reduced throughput for rays at large angles from zenith, the angle for which the instrument is calibrated. The temperature response function of each instrument in the EPA/UGA network has its own wavelength dependent characteristic temperature dependence of about 1% per degree centigrade [9].

2.2. Biologically effective UV-Vitamin D and erythema

The biologically effective solar UV, UV_{BIO}, can be assessed using the following equation:

$$UV_D = T \int_{uv} S(\lambda) A(\lambda) d\lambda \tag{1}$$

where $S(\lambda)$ is the solar spectral irradiance, $A(\lambda)$ is the action spectrum for human Vitamin D production [10] or erythemal action spectrum [11] and T is the exposure time interval. The measured irradiance is weighted according to the erythema and Vitamin D biological action spectra. The Vitamin D spectra is based on the conversion of 7-dehydrocholesterol to pre-Vitamin D_3 as measured described previously in [10]. For this study, four sites were utilized Atlanta, GA (latitude = 33.74, longitude = 84.42, altitude = 147 m); Chicago, IL (latitude = 41.79, longitude = 87.60, altitude = 156 m); Denali National Park, AK (latitude = 63.73, longitude = 148.97, altitude = 839 m); and the US Virgin Islands (latitude = 18.33, longitude = 64.79, altitude = 0 m). These locales represent a wide latitude variation in addition to differing climatology.

3. Results

Measured solar noon (∼noon local time) Vitamin D and erythemal (‘sun-burning’ UV) spectral UV data, expressed for the year 2000 only, is presented in Fig. 1. UV irradiances listed are expressed relative to 215 J/m^2 of the effective biological exposure, which for erythema, approximates 1 minimal erythemal dose (MED). An MED is the amount of UV required to produce erythema (reddening) of type 1 (fair) human skin. Fig. 1 plots UV as a function of solar zenith angle (SZA). The SZA is the angle between zenith sky (directly overhead) and the position of the sun, and is expressed as a value between 0 and 90°. Simply, the larger the SZA, the lower the sun is in the sky and the opposite for smaller SZA.

This data in Fig. 1 shows the maximum capability of the sun to produce erythema at solar noon (which is the maximum UV irradiance for that day) at these locales. For the more southern sites (Atlanta and Virgin Islands), the SZA at solar noon becomes smallest in summer, with values of 12 and 6° for the Atlanta and Virgin Islands sites, respectively.

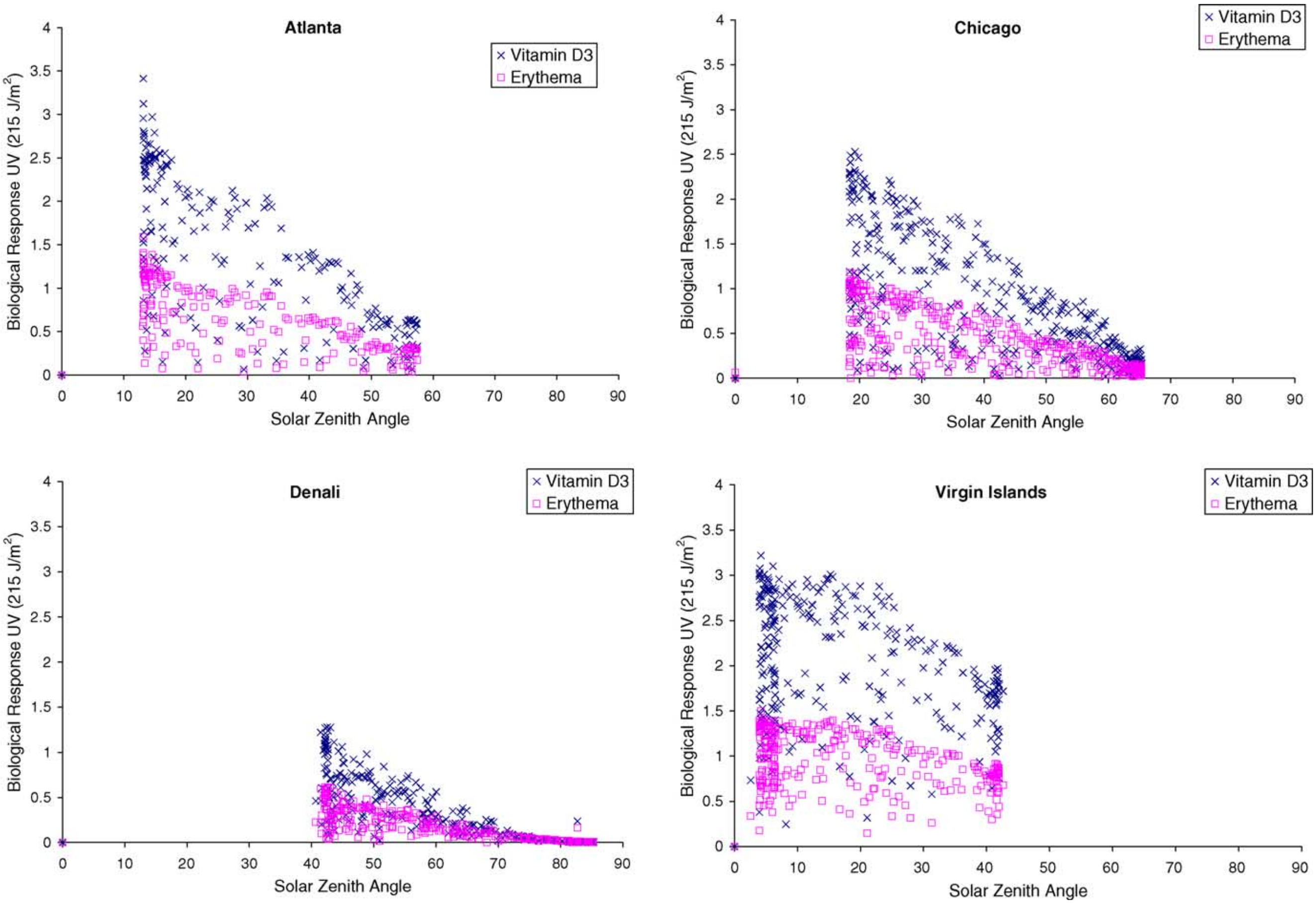

Fig. 1. Biologically effective UV for Atlanta, Chicago, Denali, and Virgin Islands.

The northern locations (Chicago and Denali) during summer have a smallest SZA of 19 and 41° for the Chicago and Denali sites, respectively. The larger SZA at these northern locales means that the UV radiation has to travel a longer optical pathlength through the atmosphere, hence the UV radiation is reduced. In addition, the northern locales typically have higher ozone that is recorded in the southern locales, this, when combined with the Vitamin D action spectrum being highly sensitive to the region of the UV spectrum that is influenced by ozone (UVB 280–320 nm),

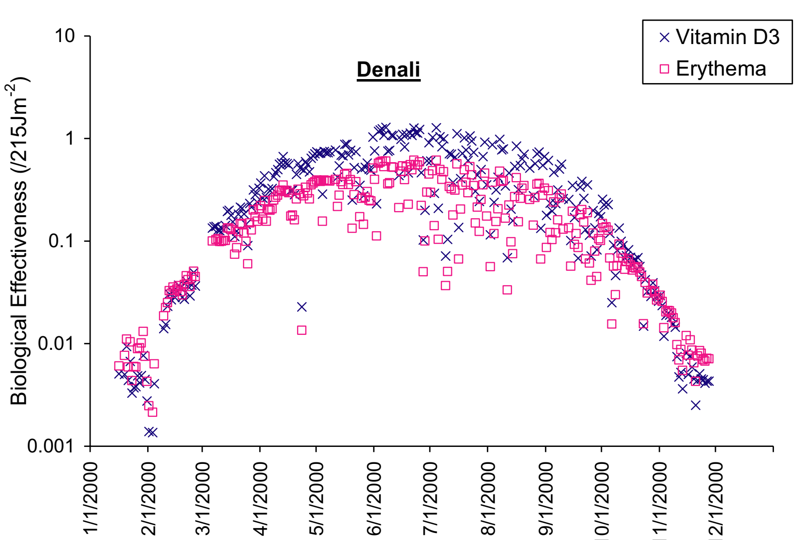

Fig. 2. Denali Vitamin D and erythemal UV irradiances for the year 2000.

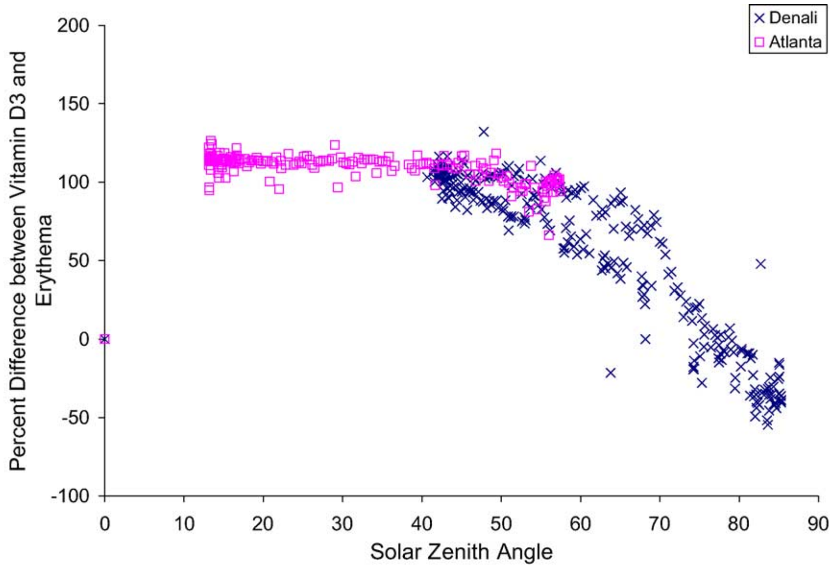

Fig. 3. Percent difference between Vitamin D producing UV and erythemal UV for Atlanta and Denali.

makes the capability of the sun to produce Vitamin D at these northern locals difficult, even in summer. This is highlighted in Fig. 2, where the erythemal UV and Vitamin D producing UV are presented. In the winter months (November through to March), Denali experiences a "cross-over" whereby the effective erythemal exposure exceeds the biologically effective Vitamin D exposure. This clearly demonstrates that erythemal ('sun-burning') UV irradiances (which are the basis for UV index values) should not be used as a proxy guide for Vitamin D production of the sun, especially at large solar zenith angles (found at high latitudes).

To highlight this fact, the percent difference between the data between erythemal UV irradiances and Vitamin D irradiances is shown for Denali (northern site) and Atlanta (southern site) as a function of SZA in Fig. 3. For Atlanta, the percent variability remains relatively constant over a wide range of SZAs. However, the data from the Denali from approximately 75° SZA the difference becomes much greater, clearly indicating that at these large solar noon SZAs the differences between the sun's capability of erythemal UV and Vitamin D producing UV.

4. Conclusions

The data presented in this paper (for the year 2000 only) highlights the potential health concerns associated with the sun's capability to produce Vitamin D. For example, the incidences of diseases such as rickets are more likely to develop in locations where solar UV levels are low for much of the year. Recent research also suggests that at latitudes above 37°, the UV climatology, air pollution, ozone and human behavior reduce the dermal synthesis of Vitamin D to zero during the winter months [10]. The data collected from this research supports this statement, however, further analysis needs to be conducted into this topic. At high locales, in the morning and afternoon (when there are larger SZAs than at solar noon) the capability of the sun to produce Vitamin D is reduced by a even greater value than those presented in this paper. The data presented in this paper was the maximum daily UV irradiance values.

To understand the lower relative production of Vitamin D for the winter months at high latitudes one must consider the weighting of the Vitamin D action spectrum. This occurs as the effective production of Vitamin D becomes more dependent on the shorter UV wavelengths more so than the effective erythemal response. The large SZAs and subsequently increased path through the atmosphere result in increased absorption and scattering of the shorter wavelengths. The relative proportions of absorption and scattering are both more pronounced at the shorter wavelengths due to increased absorption by ozone and increased Rayleigh scattering at the shorter wavelengths. At more southern locations, at smaller SZAs, the relative production of Vitamin D tends to be higher, due to reduced scattering and absorption of the more effective shorter wavelengths that produce Vitamin D.

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