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Report

Daily, seasonal, and latitudinal variations in solar ultraviolet A and B radiation in relation to vitamin D production and risk for skin cancer

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Abstract

Background Solar ultraviolet (UV) radiation varies with latitude, time of day, and season. Both spectral UV composition and ambient UV dose lead to different health outcomes at different latitudes. Finding the optimal time for sun exposure, whereby the positive effects of UV exposure (vitamin D) are facilitated and the negative effects (skin cancer, photoimmunosuppression) avoided are the most important consideration in modern skin cancer prevention programs.

Objectives This paper focuses on the latitude dependency of UVB, UVA, vitamin D production, and skin cancer risk in Caucasians.

Methods Biologically effective UVB (280–315 nm) and UVA (315–400 nm) doses were calculated using radiative transfer models with appropriate climatologic data for selected locations. Incidences of squamous cell carcinoma (SCC) and cutaneous melanoma (CM) were retrieved from cancer registries and published articles.

Results Annual doses of UVA radiation decrease much less with increasing latitude than annual doses of UVB. Incidences of CM also decrease less steeply with increasing latitude than incidences of SCC. As SCC is caused mainly by UVB, these observations support the assumption that UVA plays an important role in the development of CM. The variations in UVA (relevant to CM) and UVB (relevant to vitamin D production) over 1 day differ: the UVB : UVA ratio is maximal at noon.

Conclusions The best way to obtain a given dose of vitamin D with minimal carcinogenic risk is through a non-burning exposure in the middle of the day, rather than in the afternoon or morning.

Introduction

Exposure to solar ultraviolet (UV) radiation is the most important environmental risk factor for the development of skin cancer.[1] Exposure to UVB (280–315 nm) is mainly responsible for the induction of basal cell carcinoma (BCC) and squamous cell carcinoma (SCC).[1] Cutaneous melanoma (CM) is also associated with UV exposure,[1] but the mechanisms and even the wavelengths responsible are unclear. The newest experiments in cells and in mice suggest that both UVB and UVA (315–400 nm) are involved in the development of CM.[2,3]

More than 75% of SCC and BCC in humans occur on sun-exposed skin (head, neck, and hands).[4] The incidence of SCC on the nose is more than 200 times higher than that on the trunk, whereas the anatomical location of CM is not well correlated with exposure.[4] Chronic UV exposure is strongly associated with an increased risk for SCC, whereas BCC and CM are related to chronic and intermittent UV exposure.[1]

Skin cancer is the most common cancer affecting white-skinned persons, and its incidence rates, including those of CM, the deadliest of the skin cancers, are increasing worldwide.[1] Family history, multiple moles, red hair, fair skin, lack of tanning ability, tendency to burn, and tendency to freckle have been identified as genetic risk factors for both melanoma and non-melanoma skin cancers.[5] The low risk for skin cancers in dark-skinned people is partly attributable to the photoprotection provided by the epidermal melanin barrier, which halves the penetration of UVB through the epidermis in Black people compared with that in those of White European ethnicity (Caucasians).[6] The transmission of Caucasian epidermis increases from 27% at 315 nm to

47% at 400 nm, whereas transmission rates through heavily pigmented skin are about 4% and 14% at 315 nm and 400 nm, respectively.[7] Thus, a significant fluence rate of UVA will reach the dermis and induce oxidative DNA damage, which is strongly implicated in both cell death and malignant transformation of skin cells.[3] Therefore, epidermal damage is mainly caused by solar UVB, whereas the role of UVA in carcinogenesis may refer to its additional direct and indirect actions in deeper layers of the skin.

UVA exposure leads to high levels of expression of heme oxygenase-1 (HO-1),[8] which catalyzes the degradation of heme to iron, biliverdin, and carbon monoxide, all of which offer immunoprotective potentials.[9] In this way, UVA can modulate UVB-induced photoimmunosuppression. Furthermore, UVA generates nitric oxide, which reduces blood pressure, improves cardiovascular status, may act as a neurotransmitter, and even stimulates HO-1 expression.[8,10] UVB is also essential for vitamin D production.[11] Thus, the positive effects of solar radiation are mediated through both UVA and UVB.

Regular use of sunscreen prevents the development of actinic keratosis, SCC, and photoaging, although there is still insufficient evidence to conclude that sunscreens are beneficial in preventing BCC development.[12] Sunscreens that absorb both UVB and UVA radiation reduce the risk for CM by approximately 50%.[13] The recent study by Viros *et al.*[14] in mice provides experimental evidence that sunscreen can delay but not completely block UV-induced melanoma, a finding in line with human epidemiologic data.

However, the correct use of sunscreen blocks the production of vitamin D,[15] which plays an important role in maintaining skeletal health and in preventing autoimmune diseases, cardiovascular diseases, and cancers, seemingly including CM.[11] As solar UV radiation is an unavoidable natural irritant, the use of optimal sun protection is a key principle of skin cancer prevention, especially in groups at particular risk. This paper aims to evaluate the optimal time for sun exposure.

Materials and methods

Ultraviolet fluence rates at minimal solar zenith angles in Oslo (60.0 °N), London (51.5 °N), Barcelona (41.4 °N), the Canary Islands (28.1 °N), and at the equator (0 °N) were calculated using a Coupled Ocean and Atmosphere Radiative Transfer (COART) simulation tool established on the Coupled DIScrete Ordinate Radiative Transfer (CDISORT) code (http://cloudsgate2.larc.nasa.gov/jin/coart.html, cloud-free conditions). Solar zenith angles at midsummer were established using a SOLPOS calculator (http://www.nrel.gov/midc/solpos/solpos.html). Ozone values measured by the ozone monitoring instrument on the Aura satellite (2005–2014) were used as inputs to a solar spectrum simulator.

A multiple scattering radiative transfer model containing the radiative transfer equation solver DISORT was used to calculate daily and latitudinal variations in UVA and UVB. Calculations were based on daily zonal ozone values from the total ozone mapping spectrometer (TOMS) on the Nimbus 7 satellite (1979–1992). Atmospheric vertical ozone column, pressure, and temperature profiles were taken from the US1976 standard atmosphere model. The effect of the seasonal variable earth–sun distance was taken into account in these calculations.

Calculations of immunosuppressive and erythema-effective irradiances were made using the action spectrum for UV radiation-induced immunosuppression in humans and the International Commission on Illumination (CIE) proposed action spectrum for human erythema, respectively.[16,17]

Age-standardized incidence rates (1997–2007) according to the world standard population (ASIR-W) of CM in Norway, Sweden, and Denmark were retrieved from cancer registries in those countries (NORDCAN; http://www-dep.iarc.fr/nordcan.htm). Data for CM in Australia, New Zealand, Germany, and Scotland were obtained from the Australian Institute of Health and Welfare, the New Zealand Cancer Registry, the Association of Population-based Cancer Registries in Germany, and the Scottish Cancer Registry, respectively. Data for SCC and additional data for ASIR-W for CM were taken from published articles.[18–27] Incidence rates of SCC in Norway and Scotland were obtained from the Cancer Registry of Norway and the Scottish Cancer Registry, respectively.

Results

The relative impact of solar UVB radiation on the immune response increases with decreasing latitude (Fig. 1). However, UVA contributes to approximately 57% and 62% of sunlight-induced immunosuppression at noon at the equator and in the Canary Islands, respectively. UVA contributions of 66%, 69%, and 73% were obtained for Barcelona, London, and Oslo, respectively.

Daily UVA doses at the equator show seasonal variation similar to that of UVB doses, although with a smaller amplitude (Fig. 2). The variations in UVB and UVA are significantly larger at higher latitudes (Oslo, 60 °N), where UVB is almost absent during winter months. However, the longer periods of daylight at higher latitudes (Oslo) during the summer explain why daily UVA doses in the north are as high as those at the equator.

The wavelengths of 305 nm and 370 nm were chosen for calculating the impacts of UVB and UVA, respectively, on UV-inducible responses in human skin because the efficiency spectra of vitamin D formation and erythema induction reach a maximum at about 305 nm,[28]

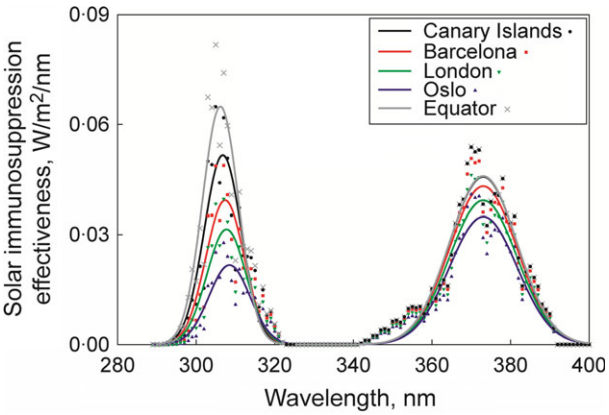

Figure 1 Efficiency spectra for immunosuppression in human skin in Oslo, London, Barcelona, the Canary Islands and at the equator at the highest solar elevation. Data are fitted to a Gaussian distribution

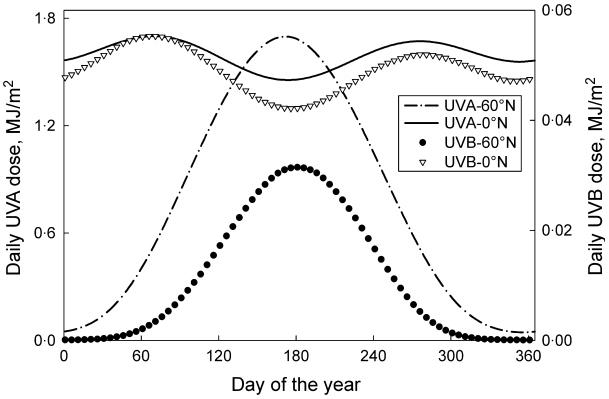

Figure 2 Seasonal variations in doses of ultraviolet (UV) A and UVB at the equator (0 °N) and in Oslo (60 °N). Doses of UV at the equator are normalized to 1; doses in Oslo are given relative to those at the equator

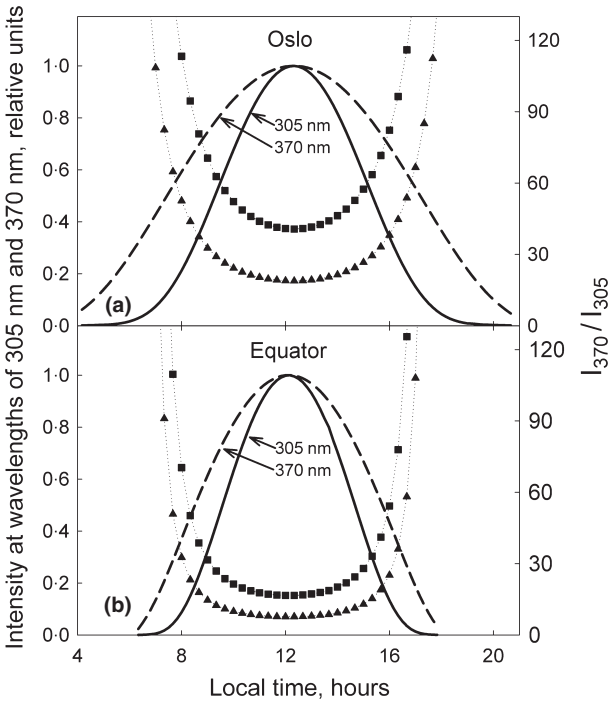

Figure 3 Solid and dashed lines represent solar irradiances at 305 nm (ultraviolet [UV] B) and 370 nm (UVA); stippled parabolas represent the corresponding UVA : UVB ratio (370 nm : 305 nm) for midsummer day (a) in Oslo (60 °N) and (b) at the equator (0 °N). Curves for irradiances are normalized to the same height at noon. Stippled curves with squares in both panels show the UVA : UVB ratio below the epidermis, using a penetration spectrum of the epidermis.[7] Curves with triangles represent the UVA : UVB ratio above the epidermis

and the efficiency spectrum of photoimmunosuppression is maximal at about 305 nm and 370 nm[16] (Fig. 1). The variations in UVA (370 nm) and UVB (305 nm) (both normalized to the same value at maximal solar elevation at midsummer) in Oslo (60 °N) at the skin surface and below the epidermis are shown in Figure 3a. Curves for UVB are much sharper than those for UVA, with half-value widths at 6.1 hours and 9.7 hours, respectively. Similar data for the equator with the sun in the zenith at noon are shown in Figure 3b. Half-value widths for 305 nm and 370 nm are 5.1 hours and 7.2 hours, respectively.

The corresponding UVA : UVB ratio changes by a factor of 2.2 after passing through the epidermis and increases strongly with decreasing solar elevation (Fig. 3). At the equator, at the time when solar UVA intensity is half of the zenith value, the UVA : UVB ratio is 2.6 times larger than it is when the sun is in the zenith. The corresponding ratio for Oslo is 4.0 (i.e. about 1.5 times larger than at the equator).

Both raw (physical, or unweighted) and biologically effective UV doses have sigmoidal dependence on latitude (Fig. 4). The influence of UVA or UVB on effective UV doses can be determined from latitudinal gradient, whereby stronger UVA impact causes a lesser gradient. The latitudinal gradient is much steeper for SCC than for CM (Fig. 5).

Discussion

The efficiency spectrum for the interaction of solar radiation with the immune system has two peaks, at 305 and at 370 nm (Fig. 1). This indicates that few types of cutaneous chromophore are involved in the initiation of UV-induced immunosuppression. DNA, trans-urocanic acid, membrane phospholipids, 7-dehydrocholesterol, and tryp-

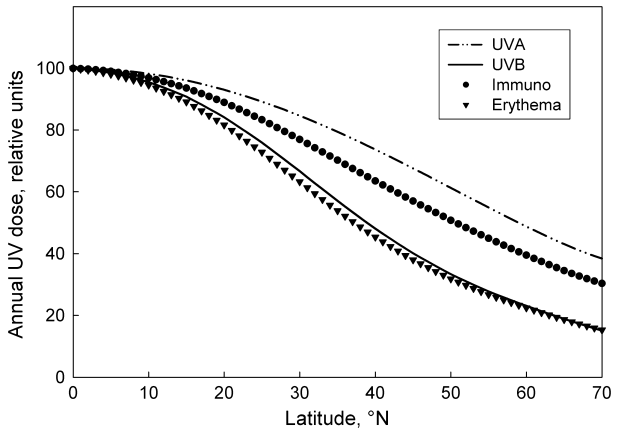

Figure 4 Latitude dependency of annual ultraviolet (UV) A and UVB doses together with erythema and immunosuppression effective doses. Curves are normalized to the same height at latitude of 0 °N

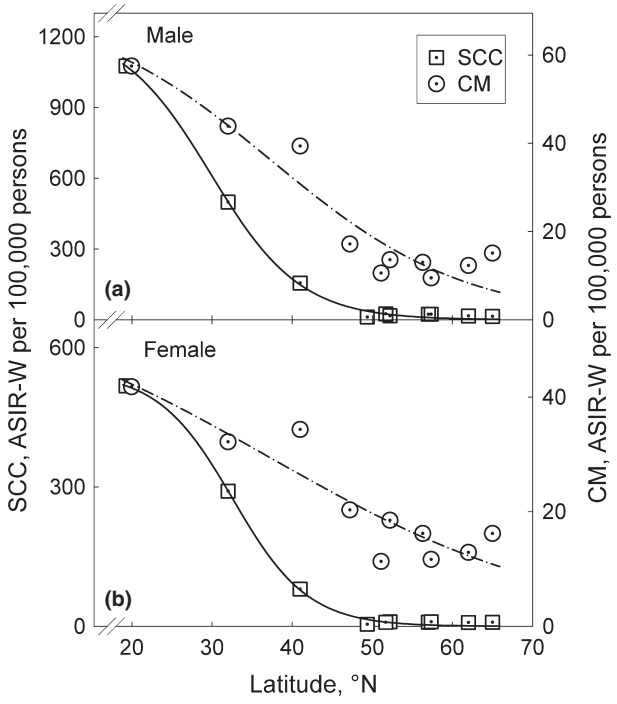

Figure 5 Annual incidences of squamous cell carcinoma (SCC) and cutaneous melanoma (CM) in (a) men and (b) women. Curves are sigmoidal lines adjusted to the same heights for SCC and CM at latitude of 20 °N. ASIR-W, age-standardized incidence rates according to the world standard population

tophan may act as chromophores.[29] These chromophores are excited directly by UVB and can probably act independently of oxygenation level, whereas UVA radiation acts through oxygen-dependent processes.[3] Thus, UVA radiation is strong in well-oxygenated skin, notably at the bottom of the epidermis. UVA penetrates much deeper into human tissue than UVB.[6] The main reason for the difference in UVA : UVB ratios at the geographic locations considered (Fig. 1) is that the relative contribution of UVB increases with decreasing latitude as a result of the absorption of UVB by ozone in the stratosphere. Absorption by ozone is weak in the UVA band but strong in the UVB band. If solar elevation decreases, UVB absorption will increase as a result of the longer path lengths through the ozone layer. Other important factors are the strong wavelength dependence of Rayleigh scattering and the differences in total ozone column amounts. Thus, contributions to sunlight-induced immunosuppression of greater than 57% and 73% are expected at the equator and in Oslo, respectively, when solar elevation is less than it is at noon.

Seasonal variations in both UVB and UVA are small at the equator, where the minimal solar elevation is 66.5°. Thus, vitamin D, for instance, is generated with similar daily yields in all seasons, and levels of vitamin D are likely to be almost constant throughout the year.

The half-value times of both UVB and UVA are shorter at the equator than in Oslo (5.1 hours and 7.2 hours versus 6.1 hours and 9.7 hours for UVB and UVA, respectively) (Fig. 3). The reason for this is that at the equator, the sun is in the zenith at noon, whereas in Oslo its maximal elevation at noon at midsummer is 53.5°. Furthermore, the UVA curves are much wider than the UVB curves, by 3 hours in Oslo and by 2 hours at the equator (Fig. 3). Thus, UVA has greater impact in Oslo than it does at the equator. The reason why the curves are sharper for the equator than for Oslo and, in both cases, sharper for UVB than for UVA in part refers to the fact that Rayleigh scattering, which has a scattering cross-section with wavelength dependency inversely proportional to the fourth power of the wavelength, has greater impact on UVB than on UVA. The scattering cross-section is about 2.2 times larger at 305 nm than at 370 nm. Another factor contributing to the greater sharpness of the curves is the difference in ozone amounts, which also explains the elevation dependency of the UVA : UVB ratio.

A comparison of the latitudinal gradients of incidence rates of CM with those of SCC offers an opportunity to evaluate the role of UVA in melanomagenesis because the action spectrum for SCC is strongly UVB-dependent and similar to that for erythema,[30] whereas that of CM is probably more UVA-dependent, although unfortunately the action spectrum for CM induction in humans is not known. The north–south gradients of incidence rates for SCC are steeper than those for CM, just as was found earlier for Scandinavia. UVB latitudinal gradients are also steeper than UVA gradients (Fig. 4). However, several contributing factors may be

important. Firstly, sun exposure patterns may play different roles in the development of SCC and CM. It is likely that SCC is related to total, integrated exposures, whereas CM is related to intermittent and burning exposures more than it is to integrated exposures. Secondly, there may be genetic differences among populations. However, the demographic development of Australia has been remarkably influenced by immigrants from the British Isles during the last two centuries, and several North Atlantic regions, including British Isles as a core area, were colonized by Norse Vikings about a millennium earlier. The relationship in skin pigmentation among Norwegian, British, and Australian people is augmented through the highly polymorphic pigmentation gene *MC1R*, and the three main red hair color variants *R151C*, *R160W*, and *D294H*, which are associated with poor tanning response and risk for melanoma, are most common among these populations.[31]

Thirdly, there is certainly a latitudinal gradient in ambient temperatures which, in turn, influence skin temperatures. The role of skin temperature on skin cancer induction and progression has been discussed.[32] Essentially, a high skin temperature will influence skin oxygenation through increased blood flow. This is likely to make photosensitized UVA processes more efficient and thus to make melanomagenesis more efficient. However, the opposite is observed: CM rates are higher than expected in the cold north, at least in comparison with SCC rates (Fig. 5).

In conclusion, UVA and UVB variations with season are greater at higher latitudes than they are at the equator and thus the health effects of solar radiation are very similar in all seasons at the equator. During the summer the daily dose of UVA in Oslo (60 °N) is as strong as the maximal dose at the equator, whereas the daily dose of UVB is 1.3–3.1 times lower. At a constant level of risk for CM (UVA-related), noon is the time of maximal vitamin D generation. The annual UVA radiation dose decreases much less with increasing latitude than does the annual dose of UVB (Fig. 4). Incidences of CM also decrease less steeply with increasing latitude than those of SCC (Fig. 5). As SCC is caused mainly by UVB, the present observations support the assumption that UVA plays an important role in the development of CM. If this is correct, people who lack vitamin D should be encouraged to obtain non-sunburn exposure in the middle of the day rather than in the afternoon when UVB intensity is low and that of UVA is high.

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