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Quantifying UV exposure, vitamin D status and their relationship in a group of high school students in an alpine environment

Matthias Gröbner,[a,†] **Julian Gröbner**[*b] **and Gregor Hülsen**[b]

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The relationship between personal UV exposure and vitamin D status was studied among 7 high school students from Davos, Switzerland from March to August 2013. The personal UV exposure was monitored using electronic dosimeters, while blood samples were taken at monthly intervals to determine the serum concentration of 25-hydroxyvitamin D3 (25(OH)D3). During school days students were exposed to 1.7% of the ambient UV irradiance, while 85% of the cumulative UV dose was obtained on weekends and holidays. Insufficient vitamin D levels in March (9 ng/ml 25(OH)D3) rose to 25(OH)D3 concentrations of over 40 ng/ml, meeting sufficient levels in August. The increase in vitamin D levels among 5 high school students correlated well (r=0.89) with their measured personal UV exposure, yielding a mean increase in serum 25(OH)D3 concentration of 0.38 ± 0.22 ng/ml per 100 J/m^2 of vitamin D-weighted UV exposure, a value consistent with other studies. During certain periods of the study, increases in vitamin D status and UV doses differed from the average of the whole study, implying that other factors must influence vitamin D metabolism.

1 Introduction

There is consensus that for most people the body's primary source of vitamin D results from cutaneous exposure to sunlight. UVB-Photons penetrating the skin induce the conversion of provitamin D3 to previtamin D3. Once formed, due to the body temperature vitamin D3 is rapidly converted to the active form of vitamin D (1,25-dihydroxyvitamin D), followed by a hydroxylation resulting in its circulating form, 25-hydroxyvitamin D3 (25(OH)D3).[1,2]

Vitamin D regulates calcium and phosphorus metabolism and its essential role in bone health has long been recognized.[3] In addition, there is now evidence that vitamin D may benefit a variety of other important functions, *e.g.* in modulating immune functions or reducing the risk of several cancers.[4,5] On the other hand, vitamin D deficiency is associated with rickets in children;[6] latest epidemiologic studies have linked insufficient vitamin D levels with an increasing risk of cancers, type II diabetes, autoimmmune diseases and infections.[7] Although it is assumed that just a relatively small amount of UV irradiation is capable to maintain sufficient vitamin D,[8] insufficient and deficient vitamin D levels are worldwide common.[9]

The quantitative relationship between the cutaneous synthesis of vitamin D and UV exposure is difficult to estimate due to geographical, behavioural and genetical differences from individual to individual.[10] Despite its importance, few studies have reported quantitative values. Moreover, all studies characterizing this relation have been performed in urban environments; by now no comparable research has been done in an alpine climate where the solar irradiance differs significantly from metropolitan sides.[11] To pursue clarification, a study among students was conducted at Davos (Switzerland), situated 1650 meter above sea level. The main study objectives were to observe the students' both personal UV exposure and vitamin D status and, consequently, to determine the relationship between their UV exposure and vitamin D status.

2 Methods

2.1 Study design and participants

This study was conduced in the alpine environment around Davos, located 1650 meter above sea level. The participants of the study were 7 male, same-aged (17-18 yr) high school students, all attending the same class of the Schweizerische Alpine Mittelschule at Davos (SAMD). The study was performed in compliance with the relevant Swiss laws and institutional guidelines and under the supervision of Dr. C. Eschenmoser of the Hochgebirgsklinik Davos Wolfgang. Informed consent was obtained from the participants to the study; all were willing to have blood samples taken at a monthly basis, to wear a UV dosimeter, and to keep a logbook. Due to the

[a] *Schweizerische Alpine Mittelschule Davos, Guggerbachstrasse 2, CH-7270 Davos Platz, Switzerland*
[b] *Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland. E-mail: julian.groebner@pmodwrc.ch*
† Currently M. Gröbner is student at ETH Zürich, CH-8092 Zürich, Switzerland.

size of the school class (17 students), these represented nearly the complete male fraction of the school class. We refrained from including female participants to try to reduce the number of free variables.

From March to August 2013 the students were wearing electronic UV dosimeters during their everyday lives to record their personal UV exposure. Blood samples to determine serum 25(OH)D3 concentration were taken monthly in this halfyear. We collected external factors influencing vitamin D status to subsequential clarify the relation between the increase in 25(OH)D3 and the UV exposure related to the vitamin D production. The observation of the vitamin D levels was extended to February 2014 with the aim of getting a full annual variation of the 25(OH)D3 concentrations.

2.2 UV dosimetry

Personal UV exposure was measured by using state-of-the-art electronic UV dosimeters (Scienterra Ltd, New Zealand).[12,13] In comparison to polysulfone films, they have been specifically designed to record UV datasets with high temporal resolution. Throughout the study the dosimeters sampled UV irradiance from 7 am to 10 pm in 5-second intervals. With these settings the daily number of gathered UV data points per participant exceeded 10,000, *i.e.* the whole study consisted of over 10 million UV data points. During school holidays or during periods where the dosimeters could not be readout weekly, the sampling rate was reduced to 10 seconds in order to avoid potential data losses by cause of battery failure. The effects of this sampling rate decline extrapolated to the entire study are negligible ($<2‰$). Previous investigations have shown that the wrist is a representative side for UV body monitoring.[14,15] On these grounds participants wore their dosimeters like wristwatches on their wrist anytime they were outside.

Several problems led to data gaps which, as complete data series of all participants were required, had to be diagnosed and subsequently filled. Missing data was reconstructed based on approximation procedures. Missing UV exposures during school hours were deduced from 3 different, approximated sums: (1) the average UV exposure of all the participant's prior UV exposures from the missing time period, (2) the average UV exposure of the other participants' UV exposures of this particular period and (3) the average ratio of all ratios between the school exposure relative to the ambient UV irradiance. These assumptions were justifiable as all students were in the same class and behaved similarly in school periods. As for missing data during holidays, all participants had enough usable data from their holiday destination to extrapolate the missing UV exposures. The measurement series of 2 participants consisted of more than 60% unreliable data due to unexpected failure of the dosimeters, and in view of the high reconstruction uncertainty, those time series were not analysed any further. In the remaining 5 data series, approximately 20% of all data points had to be reconstructed.

Absolute calibrations of the dosimeters were performed on clear-sky days at the Physikalisch-Meteorologisches Obervatorium Davos, World Radiation Center (PMOD/WRC), which since January 2013 has been recognized as World Calibration Center for UV radiation (WCC-UV) for the World Meteorological Organization (WMO). Prior to the first absolute calibration all dosimeters passed through an aging process in order to minimize temporal variations. For this, the dosimeters were irradiated over 12 hours by a 1 kW Xenon lamp. Absolute calibrations were performed several times during the study relative to an erythemally-weighted broadband radiometer, which was directly calibrated against the travelling reference spectroradiometer QASUME (traceable to primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB), Germany).[16] To assure high data quality, the dosimeters were calibrated approximately every 6 weeks.

The calibration factor for vitamin D-weighted irradiances was obtained by comparison to the same UV broadband radiometer using vitamin D-weighted solar UV irradiances as reference. The latter were calculated using a conversion matrix to convert from detector-weighted to vitamin D-weighted irradiances based on the currently accepted CIE action spectrum for the vitamin D production,[17] following the methodology described in Hülsen and Gröbner[18]. In addition, the personal vitamin D-weighted UV exposure was corrected for exposed body area and sunscreen use, as described in section 2.3.

Ambient UV irradiances were derived from the reference radiometer at PMOD/WRC used for absolute calibration, and were accordingly comprised of UV irradiance incident on a horizontal surface. Only measurements taken within the region of Davos, representing a 10 km radius from the reference radiometer, were used for the determination of relative UV exposure between the dosimeters and the ambient UV irradiances.

Measurement uncertainty. The calibration factor of each dosimeter was obtained from measurements during a single clear-sky day, up to five times during the study. The uncertainty for each calibration was then estimated from the diurnal variation of the calibration factor, $\pm$ 4%, and the uncertainty of the reference radiometer, $\pm$ 3.5%, resulting in an average uncertainty of $\pm$ 5.3% for the calibration factor of each dosimeter. The variability of the calibration factor results mainly from the mismatch between the spectral sensitivity of the dosimeters and the CIE erythema action spectrum and their poor angular response function. While these factors can be corrected on horizontally operated UV radiometers,[18] the operational use of the dosimeters on the wrist preclude the application of these methodologies. The calibration factor for

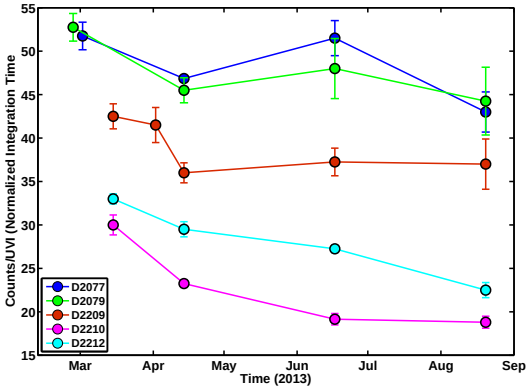

Fig. 1 Illustrating calibration factors and measurement uncertainties within the calibration process. Each point stands for a calibration day, the errorbars show the diurnal variance of the calibration factor.

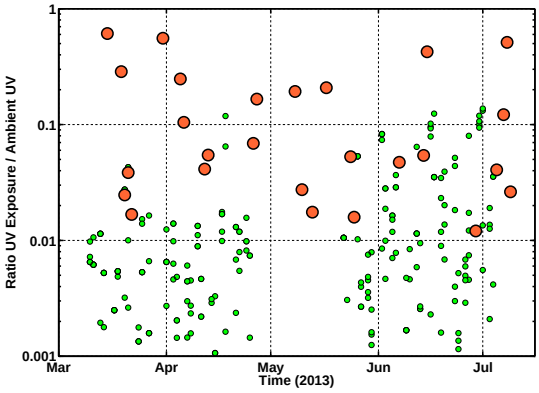

Fig. 2 Ratio between the personal UV exposure and the ambient UV irradiance. The green dots represent the fractional UV exposure of all students from all school days. The large (orange) dots stand for the UV exposure on weekends and holidays of one participant, being an representative individual for intense outdoor activity. Note that in this plot UV exposures outside the region Davos are neglected, since no reference data of ambient UV doses was available for other locations. Also days spent indoors (where the ratio was 0) were removed for reasons of clarity.

a particular day was calculated from a linear interpolation between the calibrations performed before and after this day, see Figure 1. The uncertainty of this interpolation was estimated from the observed changes in the calibrations, resulting in an additional uncertainty of $\pm$ 3%.

The resulting expanded measurement uncertainty of $\pm$ 12% is stated as the standard uncertainty of the calibration, multiplied by a coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%.

2.3 Logbooks

All participants kept a diary logbook in which they provided information on their attire, sunscreen use, outdoor activity and location. The skin area exposed to UV radiation was estimated based on the 'Rules of nine'.[19] As previous studies have suggested that in normal life sunscreen is applied inadequately,[20,21] an effective rather than the declared SPF was assumed[22] and used for data analysis. The fractional body area as well as the effective sunscreen factor were incorporated in the UV exposure relevant for vitamin D production.

2.4 Serum vitamin D

11 blood samples per participant were obtained at roughly monthly intervals starting with the beginning of March 2013 and ending in February 2014. Blood tests were taken at Davos and were delivered the same day to Labormedizinisches Institut Dr Risch (LI), accredited to ISO 17025 by SAS and certified to ISO 9001/2008 by SQS. Vitamin D status, reported as the serum concentration of 25(OH)D3, was determined using Ultra High Performance Liquid Chromatography (CV 10%).[23]

3 Results and discussion

3.1 Erythemal UV exposures

For the major part of the study, the participants were at school. As in buildings solar UV radiation is blocked by walls and windows, students were only exposed to sunlight on their ways to and from school and occasionally during school breaks. Thus, during days spent at school the students gathered just a small fraction of the available ambient UV irradiance. On average, this daily UV exposure represented only 1.7% of the ambient daily UV dose with a standard deviation of 2.4%. The daily UV exposure at school never exceeded 15%. As expected, this fraction slightly increased towards summer and higher ambient temperatures (2.7%). In summertime sport lessons were held outdoors which accounted on average for 58% of the weekly cumulated UV school exposure.

On the other hand, more than 85% of the cumulative UV exposure from March to August 2013 was acquired outside school days. At times, during *e.g.* skiing in Davos, more than 65% of the ambient daily UV dose was gathered. Especially during school holidays, the personal UV exposure increased significantly. Depending on the student's activity the total erythemal UV dose over the study period varied between

Table 1 Overview of absolute vitamin D levels and cumulative UV exposures for 5 participants. 25(OH)D3 concentrations (VitD) are stated in ng/ml, the cumulative UV doses are given as 100 J/m^2 exposures of erythemally- and vitamin D-weighted UV irradiance (uv_{ery}, resp. uv_{vitd}), thus as SED, resp. SDD. The cumulative ambient UV dose (CUV) is indicated in SED

		P_1			P_2			P_3			P_4			P_5		
	CUV	VitD	uv_{ery}	uv_{vitd}	VitD	uv_{ery}	uv_{vitd}	VitD	uv_{ery}	uv_{vitd}	VitD	uv_{ery}	uv_{vitd}	VitD	uv_{ery}	uv_{vitd}
05-Mar-13	-	16	-	-	9	-	-	12	-	-	5	-	-	3	-	-
27-Mar-13	373	18	41.1	2.4	10	8.3	1.2	16	17.9	1.5	9	8.3	1.4	3	2.6	0.4
17-Apr-13	874	28	112.4	8.7	9	16.9	2.7	12	41.8	4.4	13	19.9	3.7	10	9.0	2.3
28-May-13	2002	44	175.9	54.2	57	74.8	38.7	28	94.2	56.3	16	45.3	17.5	29	33.7	11.0
18-Jun-13	2734	46	227.7	94.4	34	97.9	50.0	27	117.9	86.8	21	61.5	35.9	19	43.9	15.3
11-Jul-13	3537	31	300.2	181.6	42	144.0	85.9	-	-	-	29	105.0	96.4	39	69.6	28.9
20-Aug-13	4947	57	404.8	292.4	46	217.5	155.7	70	209.9	201.5	15	129.7	121.8	38	102.2	50.8
24-Sep-13	5675	45			28			30			42			35		
05-Nov-13	6017	48			35			29			8			13		
17-Dec-13	6247	31			8			22			13			12		
12-Feb-14	6504	22			14			17			15			11		

102 SED and 405 SED.

Fig. 2 illustrates the personal UV exposures at school and in spare time relative to the ambient UV dose. As mentioned above, during school periods this ratio was small, whereas in spare time students were exposed to significant higher levels of UV radiation. Spending one day outside school could represent a up to 20 times higher UV exposure that spent one entire week at school. This infers that UV doses gathered at school contribute insufficiently to the UV dose and might not be high enough without additional activity outside school.

3.2 Vitamin D status†

At the beginning of March 2013 all 7 participants were insufficiently supplied with vitamin D; their mean 25(OH)D3 concentration was 8.7 ng/ml. The largest increase in vitamin D resulted in the spring and summer holidays, where the status increased by 53% on average. For half of the students, vitamin D levels declined again by an average of 25% between spring and summer holidays, probably due to reduced UV exposure during school. Vitamin D status was highest in mid-August when the average 25(OH)D3 concentration reached 42.6 ng/ml. From this annul maximum in summer, vitamin D levels declined towards winter by monthly 29%, to an average minimum concentration of 18.4 ng/ml by February 2014.

3.3 Relationship between UV exposure and vitamin D status.

Fig. 3 shows the weekly UV exposure of participant P_1 both erythemally- and vitamin D-weighted, while Table 1 summarises those UV exposures and vitamin D levels for all five participants wearing UV dosimeters. As can be seen in the figure, especially in wintertime there exist large differences between those two UV weightings . Even though the erythemal dose was high due to the high albedo from the surrounding snow covered area, only about 6% of this dose was effectively used for vitamin D synthesis in the skin. This was mainly due to the cold temperatures in winter and spring, so that students covered their major body area with clothes resulting in a minimal skin exposure to solar radiation. For participant P_1, the mean factor taking into account skin coverage from attire and sunscreen use was 0.08 between 5th March and 12th April, 0.32 until 5th June and 0.59 for the remaining part of the study. Note that for instance by skiing beside the whole body, hands and even the face were covered.

Although under those conditions vitamin D synthesis theoretically might be possible,[8] we believe that in practise this vitamin D production is too little for maintaining sufficient levels. Hence, under natural circumstances even in an alpine climate where in wintertime the cutaneous UV exposures are low, insufficient vitamin D levels seem likely.

The interdependence between the personal UV exposure and the vitamin D synthesis was quantified for the period from March to August 2013, where the overall vitamin D levels increased. In Fig. 4 the increase in serum 25(OH)D3 of this period is shown as a function of the cumulative vitamin D-weighted UV exposure for 5 participants. The mean increase in serum 25(OH)D3 was 0.38 ng/ml per 1 SDD¶with a standard deviation of 0.22 ng/ml, which was derived for cumulative doses less than 100 SDD. The median daily vitamin D-weighted dose of the participants varied from 6 J/m^2 to 29 J/m^2, supporting the assumption of a linear relationship between 25(OH)D3 concentration and sun exposure within this range.

This value stands in very good agreement with the cor-

† In this study, circulating levels of serum 25(OH)D3 concentration are taken as: $<$5 ng/ml as deficient, $<$32 ng/ml as insufficient and $\geqslant$32 ng/ml as optimal.[24,25] The conversion factor from ng/ml to nmol/l is 2.50.

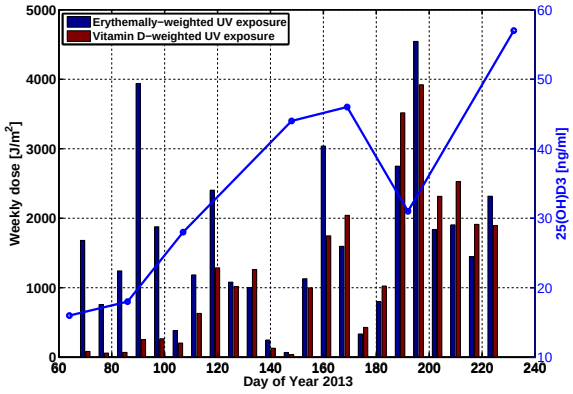

Fig. 3 Summary of the weekly averaged UV exposure of participant P_1 (erythemally-weighted in blue and vitamin D-weighted in red). The blue line represents the 25(OH)D3 concentration. Note that the vitamin D-weighted UV exposure was corrected for exposed skin area and sunscreen factor.

responding value derived from a similar study recently performed in New Zealand,[26] which showed that an exposure of 2 SED over 2 weeks increased the 25(OH)D3 concentration in the European subset by 0.38 ng/ml per SDD. In our study we detected no significant differences in correlation between the erythemally-weighted UV exposure (r=0.88) and the vitamin D-weighted UV exposure (r=0.89) in terms of the increase in vitamin D levels.

The results cannot be generalised because of the large variability from student to student and the non-linearity in vitamin D increase between different times for the same person. In Table 1 we see that high UV doses don't necessarily imply high vitamin D production; for example for participant P_1, 25(OH)D3 levels increased from 18 to 28 ng/ml between 27th March and 17th April for a UV exposure dose of 6.3 SDD, whereas between 28th May and 18th June the measured UV dose of 40.2 SDD resulted in an increase of only 2 ng/ml 25(OH)D3. This observation is consistent with a non-linear relationship between UV exposure and serum 25(OH)D3 concentration as suggested by McKenzie *et al.* [28], which applied a logarithmic model of the type $a \cdot \log(SDD) + b$. The resulting fit to the data shown in Figure 4, with $a = 4.1$ and $b = 18.0$, approximates the data better at large cumulative UV doses.

In some cases we observed that despite significant high UV exposures serum 25(OH)D3 concentrations actually decreased. Particularly in summer high vitamin D levels quickly declined although the absolute UV doses were comparably high as in wintertime, where those exposures significantly increased the vitamin D status. More melanin as a more endogenous skin protection in summer might explain why in summer months less vitamin D is produced under same UV doses. Nonetheless, more complex factors and mechanisms must play an important role in vitamin D synthesis and body storage which yet we don't understand.

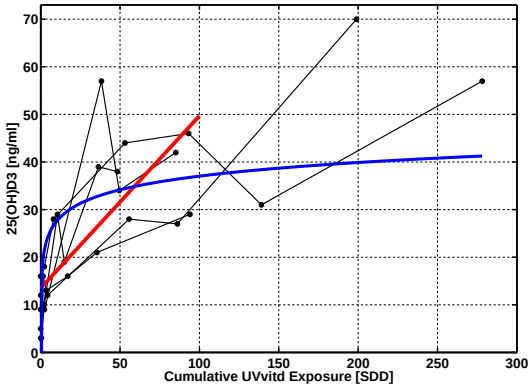

Fig. 4 Vitamin D status as a function of the cumulative vitamin D-weighted UV exposure starting on 27th March 2013. The black lines represent the sensitivities for the 5 participants, the red line shows the mean 25(OH)D3 increase per SDD. The blue line is a logarithmic fit to the data following the procedure outlined in another study[28].

4 Conclusions

The UV exposure and vitamin D status in a group of 5 high school students at Davos, Switzerland (1560 m.a.s.l.) was monitored from March to August 2013. The personal UV exposure during school was only a small fraction of the accessible ambient UV dose, with a mean exposure ratio of less than 2%. During the study period, the vitamin D status increased significantly, from initially insufficient concentrations to more than 40 ng/ml 25(OH)D3, reaching sufficient levels. Even in an alpine environment the decline in vitamin D status during winter months seems inevitable due to both geographical circumstances and little skin exposure to solar radiation. Moreover, due to reduced UV exposure at school, students with limited outdoor activities are at risk of becoming inadequately supplied with vitamin D.

The main aim of this study was to determine the relationship between personal UV exposure and induced 25(OH)D3 production. The average sensitivity of the study group, derived

¶ Here 1 SDD (standard pre-vitamin D-weighted dose) is defined as an exposure of 100 J/m^2 vitamin D-weighted UV irradiance, analogous to the definition of 1 SED (standard erythemal dose) for 100 J/m^2 of erythemally-weighted UV exposure.[27] Note that in this study the vitamin D-weighted UV exposure includes the CIE action spectrum for the synthesis of previtamin D, the fractional body area exposed to sunlight and the sun protection factor.

from the CIE action spectrum for the vitamin D production, was 0.38 $\pm$ 0.22 ng/ml per 1 SDD for cumulative doses less than 100 SDD. However, we noticed large variability among the students in their UV doses, vitamin D levels and corresponding sensitivities, implying that more factors must be important in the vitamin D metabolism.

As the sample size and study period of this study were limited, a follow-up investigation with a larger group of participants over a longer period is suggested.

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