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ARTICLE

Estimation of exposure durations for vitamin D production and sunburn risk in Switzerland

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Abstract

Although overexposure to solar ultraviolet radiation (UVR) is responsible for cutaneous melanoma and epithelial skin cancer and can cause negative health effects such as sunburn, a “little and often” exposure regime is often suggested to produce naturally recommended vitamin D levels, being essential for skeletal health. This study aimed to quantify solar UV doses needed to trigger 1000 International Units (IU) vitamin D doses and, at the same time, producing sunburn in Switzerland. Solar UV erythema irradiance (in mW/m^2) measured at four meteorological stations in Switzerland for the period 2005–2017 were used to evaluate effective solar UV radiation producing 1000 IU vitamin D doses in skin phototype II and III individuals. Daily solar UV exposure durations (in minutes) needed to produce vitamin D with limited sunburn risk were estimated while considering mean vitamin D food intake of the Swiss population and seasonal skin coverage. In summer and spring, with 22% of uncovered skin, 1000 IU vitamin D doses are synthesized in 10–15 min of sun exposure for adults. Exposure durations between erythema risk and 1000 IU vitamin D production vary between 9 and 46 min. In winter and autumn, the recommended vitamin D production without sunburn risks often unachievable, since up to 6.5 h of sun exposure might be necessary considering 8–10% of uncovered skin surface. The vitamin D food intake only represented 10% of the recommended vitamin D production and remained unchanged throughout the year. These findings might clarify why vitamin D deficiency is common in Switzerland. Moreover, exposure durations between recommended vitamin D and increased sunburn risk might only differ by few minutes. Without additional oral vitamin D supplementation, daily doses of vitamin D (1000 IU) are not reachable in autumn and winter months in Switzerland.

Introduction

Vitamin D is essential for skeletal health. It may decrease the risk of a number of solid cancers (especially stomach, colorectal, liver and gallbladder, pancreas, lung, female breast, prostate, bladder, and kidney cancers) [1], reduce skin inflammations [2, 3], prevent respiratory tract infections [4] and some autoimmune diseases [5]. Vitamin D deficiency is a potential cause for generalized muscle weakness, bone aches, osteomalacia and intensification of osteoporosis [6]. Ultraviolet (UV) doses exceeding a certain minimum threshold are recognized as the main natural source of vitamin D_3 (cholecalciferol) [7–10]. Unfortunately, overexposure to solar UV radiation can also cause adverse health effects such as skin cancer, cataract, sunburn (also known as erythema), skin ageing, and immunosuppression [11].

Recommended daily dose of vitamin D is between 400 and 1000 International Units (IU), where the biological activity of 40 IU equals 1 microgram (µg) of vitamin D_2 (ergocalciferol, provided by plant-based foods) or vitamin D_3 (provided by animal-based food or synthesized from pre-vitamin D_3 in the skin) [5, 6, 12, 13]. Calciferol (vitamin D_2 and D_3) enters the blood circulation and is hydroxylated in

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the liver to form 25-hydroxyvitamin D (25(OH)D, i.e., calcidiol). The latter is used to determine the vitamin D status in the serum [6]. A second conversion step occurs primarily in the kidney to generate the biologically active form of 1,25$(OH)_2$ vitamin D (calcitriol), but also extrarenal conversion are important for its activation [14].

To support optimal prevention messages, it is crucial to quantify simultaneously the effect of the solar UV doses on both the amount of natural vitamin D_3 synthesized and the risk of erythema [15–17]. Although vitamin D_3 synthesis and skin diseases result from exposing unprotected skin zones to UV radiation, the two dose-response relationships are different. The vitamin D_3 synthesis is mostly reactive to UV-B radiation (280–315 nm). Skin damages such as sunburn are caused by both UV-B and UV-A (315–400 nm) radiations, although UV-B is much more effective than UV-A [18–20] since shorter wavelengths are more energetic than longer wavelengths.

Erythema occurs when the minimal erythema dose (MED), which is dependent on the individual skin phototype, is exceeded. The pre-vitamin D_3 synthesized in all exposed skin zones contributes to the 25(OH)D serum concentration, whose production is regulated by instable reactants produced by photochemical reactions [21]. Thus, short exposure durations of large skin zones are more favorable than long exposure durations of small skin zones to increase the vitamin D_3 levels while reducing the risk of erythema. An exposure regime to prevent vitamin D deficiency is, therefore, “little and often” [17], but the exposure of anatomical zones is not the only factor to take into account. In addition to individual factors such as age, gender, body mass index and skin complexion, understanding the influence of environmental factors towards the natural vitamin D_3 synthesis is essential [22, 23]. Large seasonal differences exist in the vitamin D_3 production, linked to the presence of clouds and the variation of the solar zenith angle (SZA), which is the angle between the local vertical and a line from the observer to the sun. Several studies show that deficiencies can occur during wintertime (“vitamin D winter”), from October to March for northern mid-latitudes [10, 22, 24, 25], because of the combined effect of low UV doses and the need to cover most of the body to stay warm.

A small percentage, approximately 10%, of the necessary daily vitamin D intake is provided by foods or oral supplements [26]. As a lipophilic substance, vitamin D can be stored in fatty tissues during times of abundant presence, which assures regular replenishment. However, in geographical locations with long winter months, individuals may present insufficient storages resulting in low vitamin D status. In Switzerland, a prevalence of 76% vitamin D deficiency or insufficiency has been reported, with highest prevalence in the winter months [22]. Different algorithms have been developed in order to relate vitamin D production to UV radiation [6, 27], considering the percentage of exposed skin zones and the seasonal and latitudinal variation of solar UV radiation [6, 16, 17, 21, 28, 29]. These algorithms are based on transfer models and cylinder geometry for the human skin surface [16]. They calculate vitamin D weighted exposure by integrating the incident solar spectral radiance overall relevant parts of the human body [28, 29].

The aim of this study is to estimate daily solar UV exposure duration (in minutes) needed in Switzerland to produce the vitamin D doses of 1000 IU)with limited sunburn risk and considering mean vitamin D food intake of the Swiss population.

Materials and methods

Erythemally-weighted UV measurements

Erythemally weighted global (sum of direct and diffuse) UV irradiances are measured at four MeteoSwiss stations: Payerne (46.8°N, 6.9°E, altitude 491 m), Davos (46.8°N, 9.8°E, altitude 1590 m), Jungfraujoch (46.6°N, 8.0°E, altitude 3582 m) and Locarno-Monti (46.2°N, 8.8°E, altitude 366 m). The four sites represent the variability of the Swiss topography: Payerne is situated in the Swiss lowlands, Davos is set in an alpine valley in the eastern part of Switzerland, Jungfraujoch is located in a high alpine site and Locarno-Monti represents the climate conditions in the lowlands, southern alpine foothills. The erythema UV radiation is measured using the broadband UV SolarLight SL501A radiometers with filters mimicking the erythema response. The measurement period is from 01 January 2005 to 31 December 2017 and erythema UV data have been averaged over 1 h. The radiometers measuring the global erythema UV irradiance are mounted on benches at 2 m height at locations so that shading by manmade structures is minimized. Irradiance data quality control procedures are conducted daily by using plausibility criteria on individual data components (equivalent UV direct and diffuse components are also measured at the stations) and by comparing the sum of the direct and diffuse components to the global UV irradiance. UV radiometers are replaced every year with radiometers that went through a calibration check. This calibration check includes a 4-months comparison (March to June, when ozone column is most variable) at Payerne with reference radiometers of the same type (SL501A). The reference radiometers are calibrated yearly at the World Radiation Center at Davos (PMOD/WRC). During the calibration check, the calibration constants and dependency matrices on ozone column and solar zenith angle-accounting for differences between the spectral response of the instruments and the theoretical erythema action spectrum—are updated for each tested radiometer. Then, the UV irradiances measured by each tested radiometer with the updated calibration values are compared to those measured by the reference instruments, and radiometers are rejected and not used for the network if more than 5% irradiance data dissent by more than 5% from the corresponding irradiance of the reference radiometers. These quality assurance procedures ensure that the overall uncertainty of the measurements is below 10%.

Total ozone measurements

Satellite overpass data for all the stations considered are derived from the ozone monitoring instrument (OMI), on board NASA EOS-Aura spacecraft launched in July 2004. The OMI instrument is a nadir viewing spectrometer measuring solar reflected and backscattered light from the Earth atmosphere and surface in the wavelength range from 270 nm to 500 nm, providing global daily coverage with a spatial resolution of $13 \times 24\,\mathrm{km}^2$ in nadir. Two algorithms, OMI-TOMS (total ozone mapping spectrometer) and OMI-DOAS (differential optical absorption spectroscopy) are used to produce OMI daily total ozone datasets. In our study, OMI-TOMS ozone overpass data (based on TOMS V8.5 algorithm) over the period 01 January 2005 to 31 December 2017 were downloaded from the NASA–AURA validation data center platform (https://www.esrl.noaa.gov/gmd/grad/neubrew/SatO3DataTimeSeries.jsp). Total ozone values are reported in Dobson Units (DU).

Relationship between UV_{ery} and UV_{vitD}

The relationship between the erythemally-weighted UV radiation (UV_{ery}) and vitamin D-production-rate weighted UV radiation (UV_{vitD}) has been investigated in various studies [15, 27]. There is a close proportionality between the two quantities, with UV_{vitD} being approximately twice as large as UV_{ery}, except for lower values during winter months [27]. Therefore, it is possible to derive UV_{vitD} from UV_{ery} if the ozone total content in the atmosphere (ozone column) and the solar zenith angle are known:

$$\mathrm{UV}_{\mathrm{vitD}} = R(\mathrm{ozone}, \mathrm{SZA}) \cdot \mathrm{UV}_{\mathrm{ery}} \quad (1)$$

where R is the ratio between erythemal and vitamin D action spectrum weighted UV. Assuming the extended CIE action spectrum, the calculated R factors to convert from UV_{ery} to UV_{vitD} can be found in the Appendix of ref. [27].

In this study, we used the daily recommended vitamin D dose of 1000 IU as referenced in the technical report of the International Commission on Illumination entitled: Rationalizing nomenclature for UV doses and effects on humans [30]. This report highlights the controversial definition of an optimal vitamin D status and refers that most health agencies recommend a 25(OH)D serum level of at least 50 nmol/l, which is approximately equivalent to a daily intake of 1000 IU of vitamin D. It has been previously demonstrated that a full body exposure of fair skin phototype II produces 1000 IU in less than 1 min under high sun condition (UV Index = 10) [6, 27, 31]. Considering a set of reference conditions, it is possible to estimate the time necessary to produce 1000 IU vitamin D using the following formula (adapted from ref. [27]):

$$t_{\mathrm{UV_{vitD}}}(\mathrm{min}) = t_0(\mathrm{min}) \frac{\mathrm{UV}_{\mathrm{ery}0}(\mathrm{W/m^2}) \cdot R_0 \cdot \mathrm{MED}(\mathrm{J/m^2})}{\mathrm{BE} \cdot \mathrm{AF} \cdot \mathrm{UV}_{\mathrm{vitD}}(\mathrm{W/m^2}) \cdot \mathrm{MED}_0(\mathrm{J/m^2})} \quad (2)$$

where MED (minimal erythema dose) is defined as the minimal amount of energy required to produce a qualifying erythema response, usually after 24 h, for a specific skin phototype; BE (body exposure) is the fractional area of skin surface exposed (Table 1); AF is an age factor that reflects the ability of an adult to produce vitamin D, which decreases with increasing age due to epidermal thinning [31]. The factors marked with 0 refer to a set of standard conditions: $UV_{ery0} = 250\,\mathrm{mW/m^2}$, $t_0 = 1$ min and $R_0 = 2$ for UVI = 10 (peak for mid-latitudes in the northern hemisphere), $MED_0 = 250\,\mathrm{J/m^2}$ (skin type II).

In this study, we considered no sunscreen and skin type II and III, being the most common phototype among the Swiss population. The skin zone exposed to UV radiation is extremely important in determining the resulting effect on vitamin D status. BE was estimated during each season on the basis of epidemiological references [32]. For winter, we used a BE of 0.08 considering the face and the back of hands as exposed. For summer and spring, we used a BE of 0.22 considering the face, the neck, the back of hands, and the arms. Finally, for autumn, the face, the neck, the back of hands and the lower (half) arms were considered as uncovered (BE = 0.1).

The time to induce erythema, taking into account the conversion from seconds to minutes, was calculated as follows:

$$t_{\mathrm{ery}}(\mathrm{min}) = \frac{1}{60} \frac{\mathrm{MED}(\mathrm{J/m^2})}{\mathrm{UV}_{\mathrm{ery}}(\mathrm{W/m^2})} \quad (3)$$

Table 1 Body exposure (BE) and age factor (AF) definition used for eq. (2)

Season	Months	BE	Age	AF
Winter	Dec–Jan–Feb	0.08	0–22	1
Spring	Mar–Apr–May	0.22	22–40	0.83
Summer	Jun–Jul–Aug	0.22	41–59	0.66
Autumn	Sep–Oct–Nov	0.10	60+	0.49

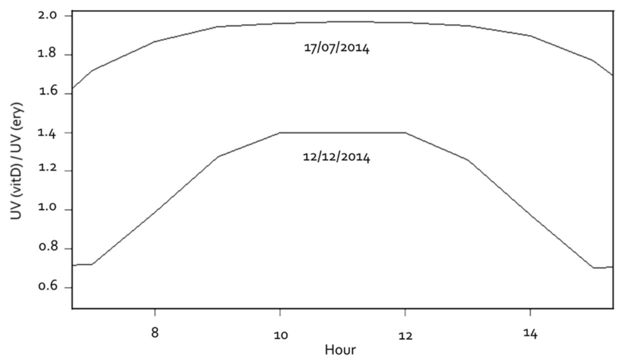

Fig. 1 UV_{vitD}/UV_{ery} ratio by solar time for a winter and summer day in Payerne, Switzerland

The diurnal variation of the UV_{vitD} / UV_{ery} ratio in summer and winter for Payerne during two cloudless days is shown in Fig. 1.

The total column ozone was quite similar during both days: 331 DU for summer (17 July 2014) and 336 DU for winter (12 December 2014). The figure confirms that most of the variation of the ratio is due to the difference in SZA and Earth-Sun separation. In summer, the ratio is stable throughout the day (around 2) and in winter, it is lower varying between 0.7 and 1.3.

Dietary vitamin D_2 and D_3 intake of the Swiss population

Dietary intake of calciferol (vitamin D_2 and D_3) was estimated using data from the Swiss Nutrition Survey, menuCH [33]. Food consumption was based on a mean of two 24-hour dietary recalls (24HDR) in 2085 Swiss residents aged 18–75 years representative of the Swiss population. Foods reported by survey participants were linked to calciferol content using the Swiss Food Composition Database (SFCD). Daily mean vitamin D intake for each month of the year was converted into solar exposure duration (min) "shortened" by food intake to reach 1000 IU Vitamin D status following eq. (2) and on the fact that 1 IU of vitamin D is equivalent to 0.025 micrograms (abbreviated as either mcg or µg) of cholecalciferol or ergocalciferol.

Results

UV_{ery} and UV_{vitD} in Switzerland

Mean irradiances around noon of daily UV_{vitD} and UV_{ery} were calculated from 11:30 CET to 12:30 CET (sun at its highest) for each month of the year and represented in Fig. 2 for skin phototype II. The mean seasonal average UV_{vitD} irradiances (in mW/m^2) for every hour between 9:30 am and 4:30 pm were shown in Table 2.

As shown in Fig. 2, highest values were found in June for Jungfraujoch (210 mW/m^2 for UV_{ery} and 409.4 mW/m^2 for UV_{vitD}) while, for the other stations, the values were quite similar ranging from 139.8 mW/m^2 to 145.3 mW/m^2 for UV_{ery} and from 270.0 mW/m^2 to 282.0 mW/m^2 for UV_{vitD}. Lowest values were found in December for the Payerne station (13.9 mW/m^2 for UV_{ery}, 18.9 mW/m^2 for the UV_{vitD}), while Jungfraujoch reported almost twice the values (26.5 W/m^2 for UV_{ery}, 37.9 mW/m^2 for the UV_{vitD}). Indeed, similarly to UV_{ery} radiation, maximum values of the climatological mean of UV_{vitD} are found during summer (June-July-August), while minimum values are found during winter (December–January–February). As previously pointed out, the UV_{vitD} irradiance for summer spectrum is nearly twice as large as for erythema mainly due to its increased contributions between 295 and 315 nm (Fig. 3) and about 1.4 for winter months [34]. Largest values for both irradiances have been found for the highest measurement station, Jungfraujoch, which is situated at a high-altitude alpine site.

On an hourly basis, represented in Table 2, the four stations follow the same pattern and the differences are not remarkable, except for Jungfraujoch. Especially in summertime, hourly values may be higher than 100 mW/m^2 with respect to the other stations.

Exposure durations (min) for sunburn risk and vitamin D status of 1000 IU

The exposure duration needed to induce erythema and to produce 1000 IU for a person of skin type II and III were calculated for the period 2005–2017 from 11:30 CET to 12:30 CET for all the MeteoSwiss stations and for different age groups (22–40 years, 41–59 years, 60+ years) (Supplementary Table 1a+2a). In June, without any sun protection, a skin phototype II person should not stay more than 20 min (at Jungfraujoch) or 28–29 min (for the other stations) under the sun to avoid erythema. For the same month, in order to get 1000 IU vitamin D it would take only 7–10 min for a person between 22 and 40 years (between 8 and 13 min for 41–59 years, 11–17 min over 60 years). Compared to skin phototype II, a skin phototype III has an up to 12 min prolonged solar UV exposure duration until sunburn (except for Jungfraujoch with duration to erythema only prolonged by 8 min), and a prolonged exposure duration (up to 68 min) in wintertime. For a person between 22 and 40 years, skin phototype III exposure duration estimated, for the 1000 IU vitamin D doses production, were about 4 min longer compared to skin phototype II (about 5 min for 41–59 years, about 7 min over 60 years). Table 3 compares exposure duration responsible for sunburn and needed for a vitamin D status of 1000 IU of skin phototype II. Between March and August, optimal vitamin D statuses

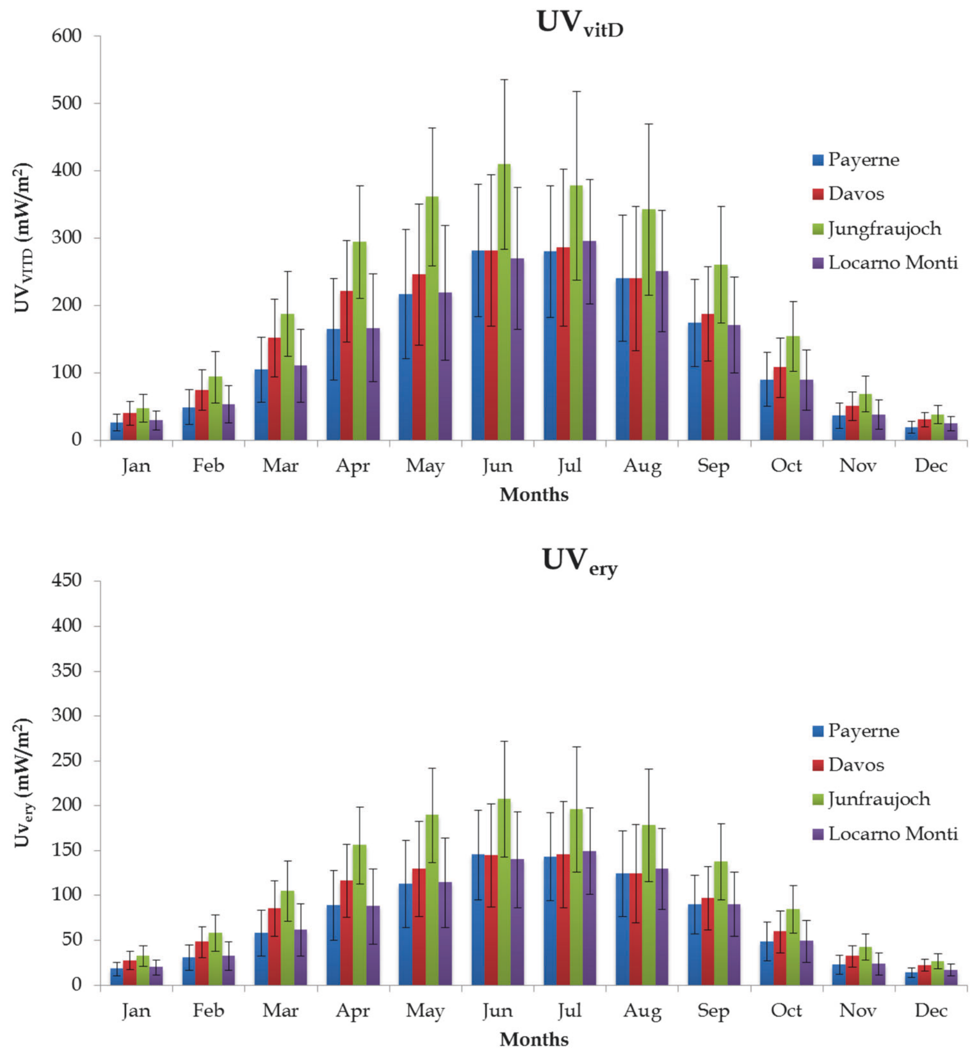

Fig. 2 Mean values of daily UV_{vitD} and UV_{ery} from 11:30 CET to 12:30 CET for each month, at 4 Swiss stations (Payerne, Davos, Jungfraujoch and Locarno-Monti)

are reached by sun exposure independently of geolocation and age category considered.

Exposure windows are defined as UV exposure durations with a reduced sunburn risk and at the same time long enough to produce 1000 IU vitamin D doses. Within these months they vary between 9 12 and 46 min, leaving most tolerant exposure setting to the 22–40 year age category (range: 19–46 min; versus 60+ year age category: 9–28 min). Compared to skin phototype III, the exposure durations are shortened up to 150 min (Payerne, age 60 +) and prolonged up to 24 min in September (Davos, age 22–40) (Supplementary Table 3a).

In winter, the situation is different and producing 1000 IU vitamin D by sun exposure without sunburn is often unachievable. In December, one should expose oneself no more than 157.3 min for Jungfraujoch (297.7 min for Payerne, 190.7 min for Davos, 248.4 min for Locarno-Monti) to avoid erythema, but it would take 198.0 min (over 3 h) of solar exposure to produce 1000 IU daily dose of vitamin D at Jungfraujoch for persons aged between 22 and 40 years. Between September and November, the exposure window of the 20–40 year age category varies between 7 and 20 min, except for September exposure time, when sunburn occurs 9 min before doses of 1000 IU vitamin D can be reached.

Exposure durations (min) "shortened" by food intake to produce 1000 IU vitamin status

All estimated exposure durations are summarized in Fig. 4 for the age category of 22–40 years, including the exposure duration "shortened" in minutes by dietary vitamin D intake and thus minutes left to reach 1000 IU vitamin doses.

For this estimation, a yearly mean vitamin D intake of 2.48 µg (Supplementary Table 4a) was used and which corresponds to about 100 IU. At all stations included in this study, the time (min) saved by food intake was very low (range: 0.9–37.0 min in Payerne) and is proportional to the monthly duration needed for optimal vitamin D status (range: 8.8–360.3 min for Payerne). While exposure time

Table 2 Seasonal average UV_{vitD} irradiances (in mW/m^2) for every hour between 9:30 am and 4:30 pm for skin phototype II

Station	Season	Seasonal average irradiance [mW/m^2]						
		9.30 am–10.30 am	10.30 am–11.30 am	11.30 am–12.30 pm	12.30 pm–01.30 pm	1.30 pm–2.30 pm	2.30 pm–3.30 pm	3.30 pm–4.30 pm
Payerne	Winter	21 (10–30)	29 (16–42)	31 (15–85)	25 (10–40)	14 (4–25)	5.5 (0.3–11)	1.2 (0.2–2.7)
	Spring	140 (80–190)	160 (100–220)	160 (110–220)	140 (90–190)	110 (60–141)	58 (30–88)	26 (10–42)
	Summer	230 (200–250)	270 (240–290)	270 (240–290)	240 (210–260)	180 (160–200)	110 (96–130)	60 (45–70)
	Fall	82 (25–140)	100 (33–160)	100 (31–170)	80 (20–140)	50 (7.2–94)	24 (5–45)	7.5 (1–15)
Davos	Winter	36 (19–53)	48 (26–70)	48 (25–72)	35 (15–56)	19 (5.2–32)	6.5 (0.6–12)	1.3 (0.8–2.7)
	Spring	186 (130–240)	210 (160–270)	210 (160–250)	170 (130–210)	120 (80–150)	62 (37–85)	25 (11–38)
	Summer	254 (220–280)	280 (250–310)	270 (240–290)	230 (200–250)	160 (140–190)	100 (80–120)	47 (36–59)
	Fall	110 (47–170)	120 (54–190)	110 (46–180)	85 (29–140)	49 (10–90)	21 (1–42)	5.9 (1.4–12)
Jungfraujoch	Winter	41 (21–61)	58 (31–85)	59 (30–90)	46 (18–44)	25 (6–45)	9.1 (1–18)	1.8 (0.5–4.1)
	Spring	250 (150–330)	280 (190–370)	280 (190–370)	240 (160–310)	160 (110–220)	92 (52–130)	39 (16–61)
	Summer	350 (310–390)	390 (350–420)	380 (340–410)	320 (280–350)	230 (200–260)	140 (110–160)	68 (52–84)
	Fall	140 (58–230)	170 (72–260)	160 (65–260)	120 (40–210)	74 (15–130)	32 (5–55)	9.4 (2.7–21)
Locarno-Monti	Winter	25 (15–36)	35 (21–49)	36 (20–52)	27 (13–41)	15 (4.9–25)	5.4 (0.5–10)	1.1 (0.1–2.4)
	Spring	150 (88–200)	170 (110–220)	170 (110–220)	140 (92–190)	100 (59–140)	50 (28–80)	22 (8.2–36)
	Summer	240 (220–270)	280 (250–300)	270 (250–290)	230 (210–260)	170 (150–190)	100 (90–120)	51 (40–60)
	Fall	88 (30–145)	110 (36–170)	99 (32–170)	77 (20–130)	46 (6.7–86)	20 (0.8–42)	5.9 (1.7–14)

The data express the median and, given in brackets, the 25–75 percentiles

left for optimal vitamin D is quite low in summer and spring months (April until August in Payerne, range: 8.8–15.1 min), the exposure duration needed in winter months (December until February 140.4–360.3 min) are impracticable, especially considering the cold weather conditions.

We found no significant seasonal variation in dietary vitamin D intake in data from the Swiss National Nutrition survey (P-value for the likelihood ratio test for month effect = 0.40 and for season effect = 0.62) (Supplementary Table 5a and Fig. 3a).

Discussion

This study estimated the exposure durations of seasonal daily UV exposure for 1000 IU vitamin D doses with reduced sunburn risk in Switzerland, while taking dietary vitamin D intake into account. In summer and spring, with 22% of uncovered skin, 10–15 min of sun exposure appear sufficient to synthesize 1000 IU of vitamin D for adults between 22 and 40 years. In winter and autumn, with 8–10% of uncovered skin surface, 1.5–6.5 h might be necessary, depending on the geolocation and calendar day considered. The estimated exposure durations needed to reach 1000 IU vitamin D production substantially increases with age, and exposure windows balancing sunburn risk with vitamin D status differ across seasons. While in summer and spring, the vitamin D status of 1000 IU could be reached before developing erythema, in autumn and winter, the situation is reversed.

The asymmetry of the exposure duration curves of Fig. 4 is striking. While in March the exposure windows raise dramatically, suggesting that sun exposure is sufficient to trigger 1000 IU vitamin D status in spring, the contrary is observed in autumn. These differences are explained both by the lesser body exposure in autumn than in spring (10% vs 22% uncovered skin) and the lower position of the sun (SZA) in autumn, and thus less effective for vitamin D production [27, 32]. Hence, directly after the summer period, both erythema and vitamin D duration estimates are very close. It should also be noted that exposure duration between vitamin D production and getting sunburnt might only differ by a few minutes. Thus, exposure window may difficult to put into practice. Our results concur with those from a Spanish study [35] performed for skin type III individuals. In summer, vitamin D status of 1000 IU needs at least 7 min of UV exposure and no more than 29 min to avoid sunburn, while, in winter, it takes between 100 and 180 min to reach the vitamin D status.

This study considered the seasonal vitamin D intake from food, by comparing the seasonal estimated exposure duration with dietary habits of the Swiss population. Diet contributes only between 10 and 20% to serum 25(OH)D level

[22, 36]. In Switzerland, using data from the Swiss National Nutrition Survey, menuCH [33], daily mean intake of calciferol from food was estimated at about 2.5 ug (≈100 IU; ≈ 10% of optimal vitamin D level), which does not "shortened" much exposure time as highlighted in Fig. 4. The food intake analysis showed no relevant seasonal differences in calciferol intake, in line with data from the French Nutrition Survey [37]. A substantial amount of vitamin D may also come from dietary supplements or treatment. menuCH data showed that about 18% of the Swiss adults take any vitamin supplements, without specification [38]. Another study in a similar population found that only 4% are taking specific vitamin D supplements [22]. Overall, our findings might explain why vitamin D deficiency is common in Switzerland [22]. However, no conclusion should be drawn suggesting higher solar UV exposures as already recommended elsewhere [39].

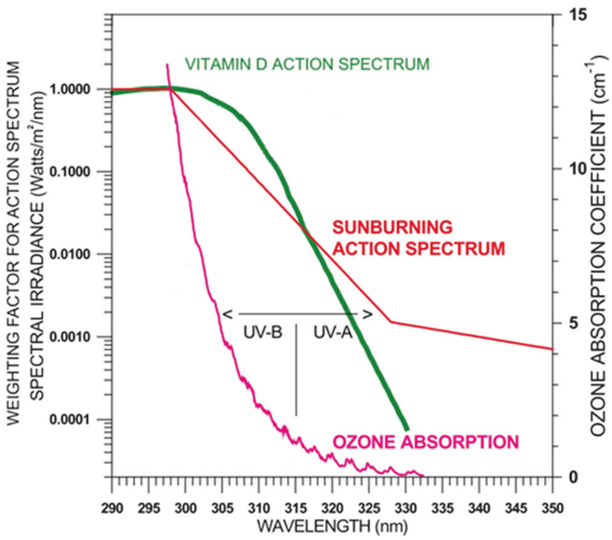

Fig. 3 Vitamin D (green) and erythema (red) action spectra. Absorption by stratospheric ozone (magenta) is the main cause for the decrease by several orders of magnitude with decreasing wavelength (Fioletov et al., [15])

The hourly UV_{vitD} irradiances highly depend on the season and the measurement station considered, and, to a lesser extent, on the time of the day. All irradiances at solar noon were above the threshold value of 3.46 mW/m^2 needed for the initiation of vitamin D photoproduction [7, 22]. However, the UV_{vitD} irradiances after 2:30 PM for wintertime did not exceed the defined value, meaning that no sufficient UV radiation to trigger the vitamin D production exists for these hours.

The individual exposure setting considered clothes' coverage, however, neither the effects of shade or sunscreen nor factors influencing vitamin D levels, (e.g., body mass index, drug intake, wine consumption and physical activity) were included in the reported estimates [22, 31]. Mean UV irradiance was used as input data, where estimated summer midday exposure allowed recommended vitamin D production without sunburn risk. However, in case of extremely high UV conditions, this estimated exposure duration would imply major shortenings.

The recommended daily dose on vitamin D is debated and is thought to range between 400 and 1000 IU [40–43]. The Institute of Medicine (IOM) suggested in 2011 that consuming 400–800 IU of vitamin D should meet the needs of 97–98% of all healthy people [44] and this recommendation is also effective in Switzerland [22]. However, many experts believe these recommendations are insufficient to reach an optimal vitamin D status. Indeed, studies showed that higher 25(OH)D concentrations were associated with a dose-response decrease in breast cancer risk, with

Table 3 Daily exposure windows (in minutes) comparing erythema risk and vitamin D (1000 IU) status for skin phototype II individuals. Negative numbers highlight an increased erythema risk before 1000 IU vitamin D status is reached (Raw data in Annexe: Table 1a)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Location	Age												
Payerne	22–40	−59	−18	46	30	24	21	19	23	12	20	18	−99
	41–59	−135	−58	39	26	21	17	17	20	3	3	−25	−202
	60+	−263	−126	28	19	16	12	12	15	−12	−26	−97	−375
Davos	22–40	−39	−14	31	24	21	21	19	23	−9	14	10	−57
	41–59	−89	−40	26	20	18	17	17	20	−17	0	−21	−121
	60+	−172	−84	18	15	13	12	13	15	−31	−25	−73	−229
Jungfraujoch	22–40	−30	−9	25	18	14	13	14	15	7	10	10	−41
	41–59	−71	−29	22	15	12	11	12	13	1	0	−13	−93
	60+	−141	−64	15	11	9	9	9	9	−9	−17	−52	−179
Locarno-Monti	22–40	−46	−12	43	30	23	20	19	21	11	17	19	−62
	41–59	−113	−48	37	26	20	17	16	18	2	0	−22	−142
	60+	−225	−110	26	19	15	13	12	13	−14	−29	−92	−277

Negative numbers highlight an increased erythema risk before 1000 IU vitamin D status is reached (Raw data in Annexe: Table 1a)

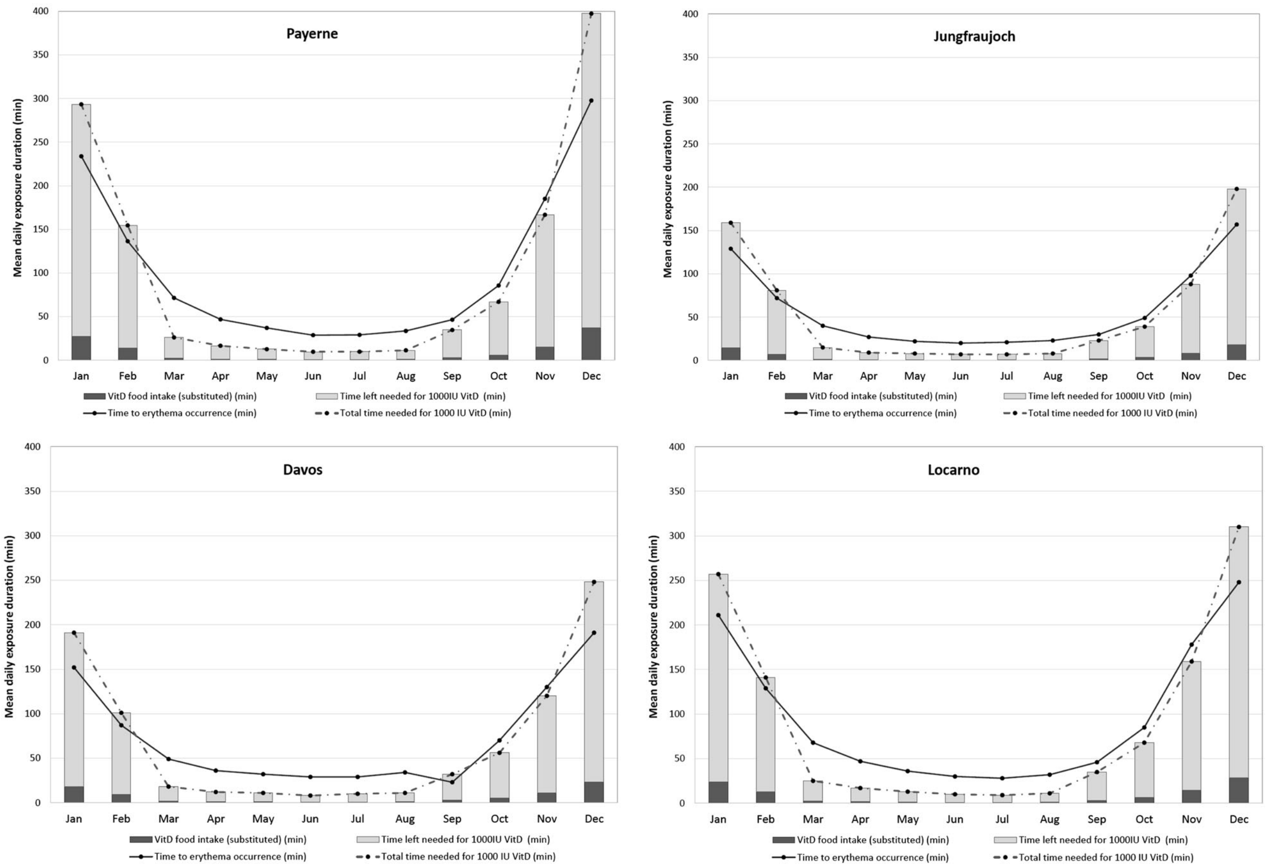

Fig. 4 Mean daily solar UVR exposure (min) for optimal vitamin D status (1000 IU), for sunburn (erythema) occurrence, substituted by food intake or left after food intake to reach optimal Vitamin D status. Values are estimated at 4 Swiss stations for a population age between 22 and 40 years

concentrations ≥60 ng/ml being most protective [45]; maternal 25(OH)D concentrations ≥40 ng/mL were associated with substantial reduction in preterm birth risk [46] and 25(OH)D concentrations ≥40 ng/ml were associated with substantial reduction in risk of all invasive cancers combined [47]. All results in our study are estimated for a vitamin D recommendation of 1000 IU, which was considered as a likely threshold to reach optimal vitamin D status at the population level. Our exposure durations might be overestimated, if an intake of 400 IU is sufficient, as some have suggested [27]. Under these circumstances, the exposure durations to achieve the desired UV dose would be decreased by a factor of 2.5 from those calculated.

All shown estimates are defined for a skin phototype II and III and for being older than 22 years. Even if the skin phototype II and III represents a common phototype in the Swiss population, further estimations are needed to cover the entire population. No conclusion can be drawn for children or teenagers who are more sun-sensitive compared to adults [22, 31]. The algorithm (2) we used is based on the MED, a factor that expresses the number of SED required to induce erythema according to Fitzpatrick skin classification [48–50]. Nevertheless, some papers suggest that Fitzpatrick skin type is a subjective expression of ultraviolet sensitivity based on erythema and tanning reactivity after a single exposure and suggest using objective factors, such as the pigmentation protection factor [51, 52]. Others stated that there is a very considerable overlap of MED between skin types which shows that MED is a very poor indicator of skin type.

Noteworthy, the side effect of a regular sun exposure intended to promote vitamin D production is also to produce tanning. When repeatedly exposed to UV radiation, the skin tans, producing melanogenesis and stratum corneum thickening, resulting in an increased photoprotection. Tanning tends to increase the MED, especially in fair-skinned individuals, thus artificially shifting their skin type. Previous studies suggest that the photoprotective effect of tanning is however limited. A moderate photoprotection, ranging from 1.4 to 2.3 has been observed after repeated exposures to solar UV [53]. Tanning through UVA exposure, such as exposure to sunlamps, fails however to provide a minimal photoprotection of 1.5 [54]. Arguably, tanning, which affects both vitamin D production time and erythemal time, could change the yearly pattern of the exposure window. In order to assess the effect of tanning, daily solar exposure for optimal vitamin D and sunburn was computed for phototype skin III and IV. A shift from skin type II to skin type II and IV correspond respectively to an increase of about 1.4–1.8 in MED. While both erythemal and vitamin D duration increased, the overall pattern of the exposure window remains the same (results shown for Payerne in Supplementary Figs 2a and 3a). While in summer and spring, the vitamin D status of 1000 IU could be reached before developing erythema, in autumn and winter, the situation is reversed. Overall, the tanning effect tends to narrow the exposure window, increasing the difficulty to reach the vitamin D status of 1000 IU in autumn and winter.

Many people cannot get enough sunlight for various reasons, thus foods and supplements that are high in vitamin D can help. There is evidence that carotenoids, micronutrients present mainly in fruits and vegetables, protect the skin against sunburn by increasing the basal defense against UV light-mediated damage [55–57], and that omega-3 fatty acids prevent non-melanoma skin cancer [58], markedly increasing the MED when compared with diets containing other polyunsaturated fatty acids. Alcohol, on the other hand, seems to decrease the protection efficiency of the antioxidant network and increases thus the risk of sunburn in human skin.

Our vitamin D dietary intake results might have been underestimated for two reasons. First, the SFCD lacks completeness. For 13% of foods reported by survey participants, mostly uncommon and branded foods, no calciferol value could be found. Second, the fraction originating from the 25(OH)D in animal-based foods or fortified foods, such as milk and branded breakfast cereals, was practically not considered, mostly due to lack of data in the SFCT and lack of information from survey participants (e.g., no brand name reported). This leads to an underestimation of the total vitamin D activity because 25(OH)D is about five times more active than vitamin D3 [59]. Moreover, it is likely that some branded products specifically fortified in vitamin D (e.g., breakfast cereals) were not considered as such due to lack of information (e.g., brand name) from survey participants or in the SFCD [60].

In conclusion, sun exposure durations for 1000 IU vitamin D doses only were estimated in spring and summer months. Surprisingly, early autumn months had very small exposure windows, leaving very few minutes between recommended vitamin D production and risk of sunburn. Thus, exposure windows are difficult to put into practice. Without additional oral vitamin D supplementation, daily doses of vitamin D (1000 IU) are not reachable in autumn and winter months in Switzerland.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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