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Adequate vitamin D_3 skin synthesis versus erythema risk in the Northern Hemisphere midlatitudes

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ABSTRACT

Health-optimum-exposure index (HOEI) is proposed to assess if the prescribed amount of vitamin D_3 (target value) could be synthesized in the human skin without erythema appearance. It is defined as the ratio between the vitamin D_3 quantity received during the maximum allowed outdoor exposure without erythema risk and the target value. Sunbathing is safe for HOEI > 1 and 1/HOEI represents a part of minimal erythema dose (MED) necessary to obtain the target value. We examine the following targets: a vitamin D_3 quantity equivalent to 1000 IU vitamin D_3 taken orally, and an optimal vitamin D_3 quantity defined by Krzyścin et al. (2016). The biologically weighted (previtamin D_3 and erythemal) doses from the Northern Hemisphere midlatitudinal stations are analyzed to find HOEI dependence on personal and meteorological factors. HOEI depends mostly on the exposed skin area, person's age, and sun elevation at noon but not on the Fitzpatrick skin phototype. We found that only young adults (< 21 yr) could safely obtain vitamin D_3 quantity, which is equivalent to 1000 IU taken orally, almost throughout the whole year. Duration of such exposures appears < 1 h only in the warm subperiods of the year (April–September) for a person with minimal erythema dose of 330 J m^{-2}. Exposing larger part of the body (~30%) enables the oldest persons (> 59 yr) to reach 1000 IU target during warm days in spring and summer. The optimal daily vitamin D_3 quantity could only be synthesized only by young adults for about 40–60% of days in the May–August period if they expose at least 1/3 part of their body surface area. Vitamin D_3 supplementation seems to be necessary over the whole year for the oldest persons with daily dosage of ~2000 IU but reduced to ~1000 IU in summer for sunseekers exposing significant part of the body.

1. Introduction

UV radiation from the Sun can have detrimental health effects (such as skin cancer, photoaging, eye diseases, DNA damage and erythema), but also has potentially positive impact (psoriasis clearance, synthesis of the vitamin D) e.g. [1–2]. In the recent years, the researchers have found that vitamin D deficiency is related to the cardio-vascular, digestive and nervous system diseases, not only to rickets and osteoporosis [3–5]. There is also research conducted to evaluate the relationship between cancer mortality and vitamin D deficiency [6–7]. Baggerly et al. [8] discussed that there is a need to find a method that could help to balance negative and positive effects of UV radiation. Recent studies show that oral vitamin D could lessen inflammation after excessive exposure and also prevents sunburn [9–10].

Duration of the exposure required to gain the recommended UV dose depends on: geographic conditions (latitude and elevation), meteorological conditions (such as total ozone amount, cloudiness, aerosol/cloud optical thickness), e.g. [11–13], and individual personal characteristics (age, skin phototype, lifestyle) [14–15]. An additional essential factor is the exposed skin surface area, which for some people depends on the wind chill temperature [16]. Recently, the public awareness regarding vitamin D deficiency has been increased. Present vitamin D guidelines state much higher daily intake than that recommended towards the end of 1990s [17]. Moon et al. [18] proved, that among Google users, the searches for the term "vitamin D" increased rapidly between years 2004–2010 with peaks in late winter. This suggests that people are aware of possible health problems that may be connected with the vitamin D deficiency.

Various adequate daily quantities of vitamin D_3 due to solar exposure were recommended: 400 IU [2], 600 IU [16], 1000 IU [19–20], and 1500–2000 IU [21]. The followed recommendations should be based on individual state of health, age, body weight, dietary and cultural habits, and climate conditions at dwelling site [22]. Krzyścin et al. [23] proposed to measure daily vitamin D_3 synthesis in optimal vitamin D_3 (OVD_3) unit. 1 OVD_3 unit keeps serum 25(OH)D concentration at a high level (~100 nmol l^{-1}), i.e. the level which black-

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skinned human ancestors living in East Africa gained during the evolution process lasting many millennia.

Exposures providing the adequate vitamin D level should be undertaken without erythema risk, i.e., the erythemal dose received during optimal outdoor activity cannot exceed minimal erythema dose (MED). Several studies provided rules to balance risk and benefits of solar UV. For example, the sufficient vitamin D_3 dose was received after exposure of: 1/4 of the body to 1/4 MED [19], 1/3 of the body to 1/3 MED during warm-sub period of the year in low- and mid-latitudes regions [23], full body during one minute with UV Index of 10 [24]. Chubarova and Zhdanova [16] introduced a classification of UV resources over Northern Eurasia using following categories: UV deficiency, UV optimum, and UV excess, which are based on the relation between vitamin D effective dose and the erythemal dose received at noon.

In this study, previtamin D_3-weighted (PD_3W) and erythemal doses are calculated from spectral measurements in the period 2005–2014 at the Northern Hemisphere (NH) midlatitude stations representing different climate conditions, Aosta (Italy), Belsk (Poland), Reading (U.K.), and Toronto (Canada). The biologically weighted doses are used to build a metric, health-optimum-exposure index (HOEI), that states if a target daily amount of vitamin D_3 could be synthetized safely, i.e. without the erythema appearance. The statistical properties of the index are analyzed for the period 2005–2014 to infer its dependence on personal and meteorological factors.

2. Materials and Methods

2.1. UV Observations

The UV spectra measured by the four UV spectrometers operating in the NH midlatitudes were examined. Stations' names, pertaining geographical coordinates, the site elevation, instrument type, and data period are shown in Table 1. The spectra for three stations, excluding Belsk, are available at the web site of World Ozone Ultraviolet Data Center, Toronto, Canada: http://woudc.org/archive/Archive-NewFormat/Spectral_1.0_1/. The Belsk's data is stored at the Institute Geophysics Polish Academy of Sciences Data Base (https://github.com/BelskSpectraUV/brewer). The spectrometer' sensitivity to UV radiation should be calibrated frequently (few times per year) by 50 W lamps supplied by the instrument manufacturer (Sci-Tec, Canada; or Kipp& Zonen, the Netherlands) for monitoring the instrument stability especially during initial years of operations when the instrument's aging rate was usually highest. For three stations (Aosta, Belsk and Toronto) using the Brewer spectrophotometer (BS), the quality control of the instrument performance was also assessed by almost yearly calibration against the traveling world standard BS, serial number 17 (BS017) provided by the International Ozone Service Inc. (http://www.io3.ca/Calibrations). BS017 itself has been regularly calibrated against a set of three Brewer instruments, the so-called “Brewer reference triad” [25]. Calibration details of the Bentham DM150 spectroradiometer are described by Kazantzidis et al. [26]

2.2. Previtamin D_3 Versus Erythema Weighted Dose

Erythemal ambient irradiance could be provided by many ground-based stations using relatively low-cost broad-band biometers, however this is not the case for PD_3W irradiance. In this paper, spectral UV data are used to obtain both PD_3W and erythemal doses directly from spectral observations. Measured UV spectra around noon are weighted by PD_3W and erythema action spectrum [27–28]. Next, the weighted spectra are integrated over wavelengths to obtain biologically weighted irradiances. Such option is possible for a limited number of sites due to high cost of UV spectrometers and their calibrations. Thus, an approximation formula of the ratio between these biologically weighted doses is needed.

Here we search for an empirical formula based on the Brewer measurements (Aosta, Belsk, and Toronto) which will be verified using the Bentham DM150 spectra taken in Reading. The proposed formula will be used in Section 3 to assess if an adequate quantity of vitamin D_3 could be synthesized in the skin without a dangerous erythema appearing after prolonged exposure to the solar UV radiation.

The empirical analytical formula for the erythema → previtamin D_3 conversion has been constructed using the Brewer biologically effective irradiances for the considered midlatitudinal stations (Table 1). The observed conversion factor, $CF_{\text{eryt}\rightarrow\text{previtD3}}$, was regressed on solar zenith angle (SZA) and total ozone (TO_3) measured by the Brewers, i.e. $\cos(SZA)$ and $TO_3/300$ DU represent the explaining variables. Following analytical formula is found, for three SZA ranges:

$$CF_{eryt\rightarrow previtD3}(SZA, TO_3) = \begin{cases} 2.028(\cos(SZA))^{0.2285}(TO_3/300DU)^{-0.504} & SZA \le 40^{\circ} \\ 2.209(\cos(SZA))^{0.4690}(TO_3/300DU)^{-0.5298} & 40^{\circ} < SZA \le 60^{\circ} \\ 1.702(\cos(SZA))^{0.2780}(TO_3/300DU)^{-0.9961} & SZA > 60^{\circ} \end{cases} \quad (1)$$

Fig. 1a shows the results of a comparison between the observed and modeled conversion factor by Eq. (1). There is an overall correspondence between the ratios with the mean value 1.00 ± 0.10 (2σ) and the correlation coefficient 0.965. The linear regression line based on the scattered points is $y = 1.00\ x + 0.0046$, where y and x are observed and modeled ratio, respectively. Most of the data points gather around the diagonal line representing the 1–1 (perfect) agreement line. Eq. (1) is verified using independent (not used in the regression calculation) irradiances measured in Reading by Bentham 150DM spectroradiometer. It appears (Fig. 1b) that the formula (1) reproduces the observed values of the conversion coefficient.

Fig. 2 shows $CF_{\text{eryt}\rightarrow\text{previtD3}}$ variability in the period 2005–2014 based on Eq. (1) applied to total ozone measured in Reading and noon SZA values. $CF_{\text{eryt}\rightarrow\text{previtD3}}$ varies only slightly around 1.85 in spring and summer season but for noon SZA > 60° (between mid-October and next year late February) it strongly depends (inversely) on total ozone. In this period $CF_{\text{eryt}\rightarrow\text{previtD3}}$ variations are also in much larger range due to ozone fluctuations.

2.3. Vitamin D_3 Model

The quantity of vitamin D_3 synthesized in the human skin during

Table 1
The characteristics of midlatitudinal sites with the spectrophotometer data.

Location	Place coordinates	Noon SZA		Altitude (m)	Data period	Type
		Min	Max			
Aosta	7.36°E, 45.74°N	22.30°	69.22°	570	01/2007–12/2014	Brewer MKIV°
Belsk	20.79°E, 51.84°N	28.40°	75.12°	180	04/2004–09/2014	Brewer MK II
Reading	0.94°E, 51.14°N	27.70°	74.52°	66	02/2004–12/2014	Bentham DM150
Toronto	79.40°W, 43.66°N	20.22°	67.06°	40	01/2005–12/2014	Brewer MK II

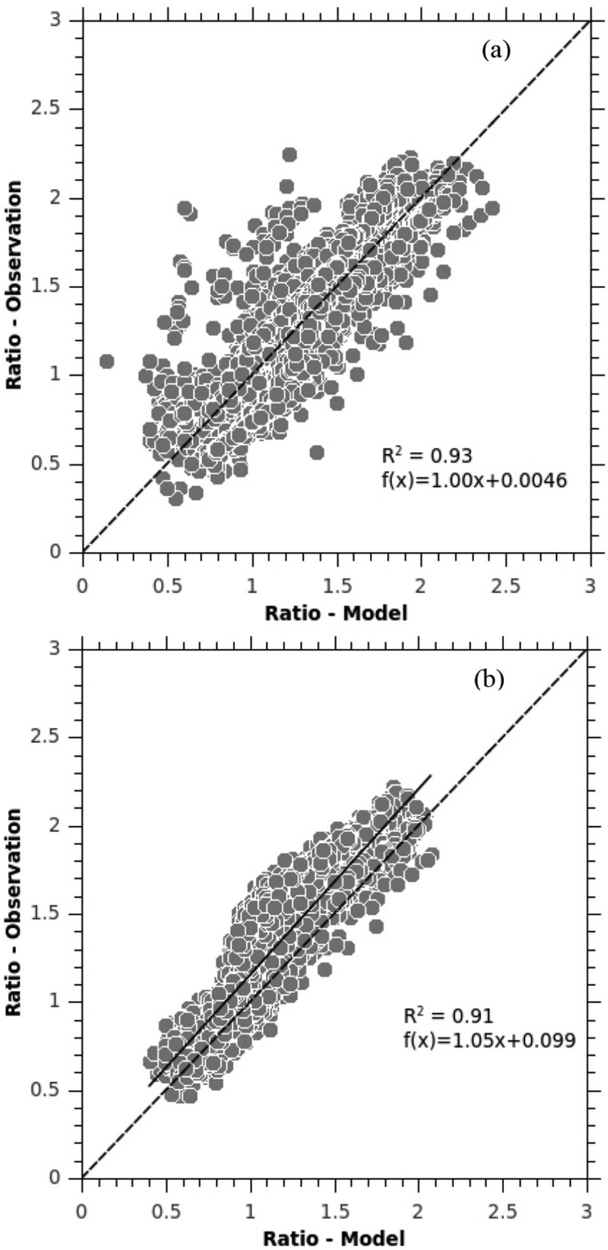

Fig. 1. Ratio between the vitamin D_3 effective and erythemal 1 h midday doses taken from the Brewers' spectra measured in Aosta, Belsk, and Toronto versus pertaining ratio from the regression model of the ratio on noon solar zenith angle and total ozone – (a), Ratio between the vitamin D_3 effective and erythemal 1 h midday dose taken from the Bentham spectra measured in Reading versus pertaining ratio from the regression model taken into account noon solar zenith angle and total ozone in Reading – (b). Straight line shows linear fit by ordinary least-squares method.

outdoor activities starting at the moment t_o and lasting Δt by a person with I-th Fitzpatrick phototype [29], $Q_{VitD3,\ I}$, is as follows:

$$Q_{VitD3,I}(t_o, \Delta t) = Rate_I \times VitD_{3,P}(t_o, \Delta t) \times ESA \times AF \tag{2}$$

$Rate_I$ is amount of vitamin D_3 dose synthesized per 1 J of PVD_3 radiation received by a person (with I-th phototype), $VitD_{3,P}(t_o, \Delta t)$ is the personal PVD_3 dose per 1 m^2 area of uncovered parts of the body received in the period $\{t_o, t_o + \Delta t\}$, *ESA* is geometrical area of exposed skin (m^2), *AF* is age factor as the vitamin D_3 synthesis weakens almost linearly with age, e.g. $AF = 1$ for young adults < 21 yr but $AF \sim 0.5$ for the oldest persons > 59 yr [30]. However in some sunny countries, it is possible that older people could stay outdoors for longer than the younger ones. Thus, the vitamin D level decreases only slightly with age [31].

Usually $VitD_{3,\ P}(t_o, \Delta t)$ is derived from the ambient PVD_3 weighted dose, $VitD_{3,\ A}(t_o, \Delta t)$, which comes from measurements or simulations of the PVD_3 weighted solar irradiance on a horizontal surface. The relation between ambient and personal PVD_3 weighted doses depends on many factors including body posture, solar elevation, ground reflectivity, etc. Here we use simplified approximation, which is based on the so-called geometrical conversion factor, *GCF*, introduced by Pope and Godar (2010) [32],

$$VitD_{3,P}(t_o, \Delta t) = GCF \times VitD_{3,A}(t_o, \Delta t) \tag{3}$$

$GCF = 0.46$ is taken in further calculations that pertains a person in upright positions under moderate SZA (20°–50°) for all-sky conditions (clear or cloudy sky). Such a person receives roughly half of the ambient dose. Similar estimate was obtained by other authors for a standing person randomly oriented towards the Sun during outdoor activities [33–34].

We run model (2) using following two options for $Rate_I$ term based on:

a) classical Holick's approach [19], i.e. a person will synthesize vitamin D_3 quantity being equivalent of 16,000 IU taken orally after receiving his personal MED, MED_I, during whole body exposure by fluorescent tubes in a medical cabinet. Taking into account Dowdy et al. [35] correction factor *n*, which was proposed to convert erythemal doses obtained in the medical cabinet to PVD_3 effective doses, we obtain,

$$Rate_{I,1} = 16{,}000\ \text{IU}/(n \times MED_I \times ESA_o) \tag{4}$$

where $n = 1.32$, ESA_o of about $= 1.97\ m^2$ is estimated using Mosteller formula [36] for a typical US adult (weight = 82.6 kg, height = 1.69 m, being the mean value for male and female aged over 20 yr, respectively, [37]). Finally, we have:

$$Rate_{I,1} = 6153\ \text{IU}/MED_I \tag{5}$$

b) Krzyścin et al. [23] approach to quantify daily personal vitamin D_3 exposure in the optimal vitamin D_3 quantity unit, $Opt_{VitD3,\ I}$,

$$Opt_{VitD3,I} = 298.5\ \text{J} \times \text{MED}_I/\text{MED}_6 \tag{6}$$

This value was inferred for adults belonging to Hadza tribe living in the Northern Tanzania and still continuing the lifestyle of the human ancestors before the migration out of Africa (~100,000 years ago) [23]. They have high level of serum $25(OH)D_3$ concentration of 115 nmol l^{-1} [38]. There are suggestions that this level could be treated as the target for contemporary humans [8]. In this case:

$$Rate_{I,2} = 1/(VitD_{3,P,Hadza} \times ESA_{Hadza} \times Ratio_I) \tag{7}$$

where $VitD_{3,P,Hadza}$ is the personal PVD_3 weighted dose equal to 597 J m^{-2} derived from the daily outdoor activity scenario of Hadza adults and climatological conditions in Tanzania, $Ratio_I = MED_I/MED_6$, ESA_{Hadza} is the exposed skin area estimated to be 1/3 of the whole body, [23]. According Mosteller formula, the whole skin area of typical Hadza adult (male & female) is equal to 1.49 m^2, which is derived assuming 1.56 m and 51 kg as height and weight, respectively [39]. Taking $MED_6 = 900\ J\ m^{-2}$, and $ESA_{Hadza} = 0.5\ m^2$, formula (7) is simplified to:

$$Rate_{I,2} = 3.015/MED_I \tag{8}$$

Using Eqs. (2) and (5) with following values: MED value for VI Fitzpatrick phototype i.e. $MED_6 = 900\ J\ m^{-2}$, $ESA_{Hadza} = 0.5\ m^2$ (1/3 of the Hadza whole body area), and $VitD_{3,\ P,\ Hadza} = 597\ J\ m^{-2}$, we obtain that $Opt\ Q_{VitD3,\ 6}$ is equivalent to 2041 IU taken orally. The same optimal daily vitamin D_3 quantity unit could be obtained for all Fitzpatrick phototypes.

Assuming $MED_2 = 330\ J\ m^{-2}$, which roughly represents the mean MED value for Fitzpatrick phototype II with MED in the range

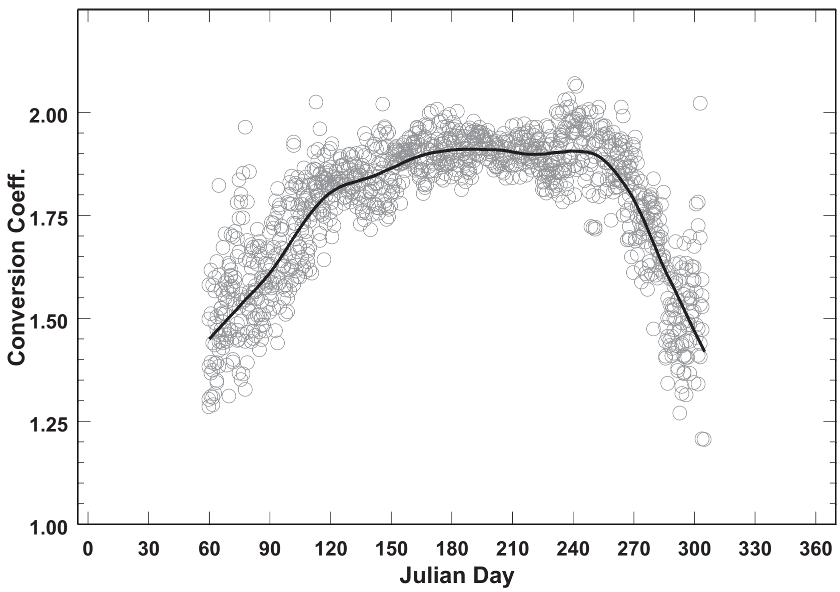

Fig. 2. Ratio between the vitamin D_3 effective and erythemal 1 h midday dose in Reading for the period 2005–2014 taken from the regression model using noon solar zenith angle and total ozone measured by Bentham DM150.

250–400 J m^{-2}, we obtain $Rate_{2,\ 1}$ = 18.645 IU J^{-1}. For UV index (UVI) equals to 8 (i.e. 0.2 W m^{-2} and ~0.4 W m^{-2} for erythemal and PVD_3 weighted irradiance, respectively), which is the typical noon value in sunny late spring in NH midlatitudes, it could be found that ~15-min exposition of 1/3 of the whole body (i.e. ESA = 0.66 m^2 for a typical US adult) during outdoor activity in the upright body position (GCF = 0.46) is equivalent to 2038 IU. The erythema in such person appears on the horizontally oriented parts of the body (e.g. arms, top of head) after solar exposure of ~28-min. During that time, he/she receives vitamin D_3 quantity equivalent of ~3700 IU taken orally. Thus, large quantity of vitamin D_3 could be obtained without the erythema risk. Safety of the sunbathing required to receive adequate vitamin D_3 dose will be discussed in Section 3 using time series of ambient UV measurements at midlatitudinal sites.

2.4. Health-optimum-exposure Index

Dimensionless health-optimum-exposure index, $HOEI_{\text{Target, I}}\ (t_o)$ is proposed to estimate if the prescribed amount of the vitamin D_3, *Target*, could be reach without the erythema risk by a person with I-th phototype. It is defined as the personal vitamin D_3 quantity received during the maximum allowed outdoor exposure without erythema risk divided by the selected target value:

$$HOEI_{\text{Target,I}}\ (t_o) = Q_{\text{VitD3,I}}\ (t_{o,}\ \Delta t_{\max})/Target \quad (9)$$

where $Q_{\text{VitD3, I}}\ (t_{o,}\ \Delta t_{\max})$ is vitamin D_3 effective personal daily dose received during skin synthesis starting at moment t_0 and lasting $\Delta t_{\max}$, i.e. up to the moment when ambient erythemal doses reaches individual person MED_I. *Target* could be, for example, 1000 IU or 1 unit of optimal quantity of vitamin D_3. For sunbathing providing maximum vitamin D_3 benefit without the erythemal risk, $HOEI_{\text{Target, I}}\ (t_o)$ should be larger than 1. Whereas the value below 1 suggests that the assumed vitamin D_3 target value could not be reached safely.

Taking into account the conversion factor between erythemal and pre-vitamin ambient D_3 weighted doses, $CF_{\text{eryt}\to\text{previtD3}}$, we obtain that

$$VitD_{3,A}\ (t_{o,}\ \Delta t_{\max}) = CF_{\text{eryt}\to\text{previtD3}}\,(SZA^{*}TO_3^{*}) \times MED_I \quad (10)$$

where SZA^* and TO_3^* are mean SZA and TO_3 values for the period {t_o, $t_o + \Delta t_{\max}$}. In this case $HOEI_{\text{Target, I}}(t_o)$ is expressed by the following formulas:

$$HOEI_{\text{Target 1,I}}\ (t_o) = 6153/Target_1 \times Coeff \quad (11)$$

$$HOEI_{\text{Target 2,I}}\ (t_o) = 3.015/Target_2 \times Coeff \quad (12)$$

where Eqs. (11) and (12) are for *Target* expressed in IU of vitamin D_3 ($Target_{\ 1}$) and in $Opt_{\text{ VitD3, I}}$ unit ($Target_{\ 2}$), respectively, and.

$$Coeff = CF_{\text{eryt}\to\text{previtD3}}\,(SZA^*, TO_3^*) \times GCF \times ESA \times AF \quad (13)$$

Usually the vitamin D_3 dose due to UV radiation is modeled using dimensionless area of uncovered part of the body, *UPB*, which is expressed in percent of the whole-body area. Thus, assuming the whole-body area for typical US person of 1.97 m^2 (see Section 2.3), we have $ESA = 0.0197 \times UPB$ (m^2) and $Coeff = 0.0168 \times UPB \times AF$ for sunbathing in upright position (GCF = 0.46) at noon in spring/summer season ($CF_{\text{eryt}\to\text{previtD3}}(SZA^*,\ TO_3^*) \approx 1.85$, see Fig. 2). Finally, for $Target_1$ = 1000 IU and $Target_2 = Opt_{\text{ VitD3,I}}$, respectively, we obtain:

$$HOEI_{\text{1000 IU,I}}\ (t_o) = 0.103 \times UPB \times AF \quad (14)$$

$$HOEI_{\text{Opt.VitD3,I}}\ (t_o) = 0.051 \times UPB \times AF \quad (15)$$

Eqs. (14) and (15), which do not depend on MED_I, show that percent of the uncovered body area and age are essential for estimation of conditions of pro-health sunbathing. Young adult (< 21 yr) (AF = 1.0), regardless of the Fitzpatrick prototype, receives vitamin D_3 quantity equivalent to 1000 IU taken orally without erythema after exposing 10% part of his/her body in late spring/early summer. However, for such person > 20% uncovered body is necessary to reach optimal vitamin D_3 quantity. For the oldest persons (> 59 yr, AF~0.5), it is practically impossible to obtain optimal vitamin D_3 quantity without erythema.

2.5. Dependence of Uncovered Part of the Body on Temperature

Area of uncovered part of the body depends on many factors including meteorological variables and religious/cultural determinants. For many people, outdoor temperature is the only decisive factor determining their clothing style. Wind chill (feels like) temperature, i.e. temperature felt by a person, is usually used to assess a personal way of clothing. Sometimes wind chill temperature is much lower than the measured temperature at 2 m level because of wind chilling effect. For example, *UPB* of 9.5% and 33.5% were found for young adults during winter and summer, respectively, in the United States according to Godar et al. [40] estimates based on data from Lund and Browder diagram [41].

We carried out half-year (February–August 2013) observations of clothing style of Londoners during their near noon outdoor activities. The number of examined people was about 100. Examined Londoners belonged to the category of working people (including students) who spent their lunchtime on outdoor activities. Using corresponding midday wind chill temperature retrieved from the ERA-Interim reanalysis we found a dependence of *UPB* on the wind chill temperature at 2 m level, T_{2m}, as follows:

$$UPB(T_{2m}) = 9.8 - 0.105\,T_{2m} + 0.0012\,(T_{2m})^2 + 0.00186(T_{2m})^3 \quad (16)$$

where T_{2m} is in Celsius degrees, for $T_{2m} < 5\,^{\circ}C$ constant $UPB(T_{2m})$ value of 9% is assumed. It is worth mentioning that typical summer clothing with *UPB* ~33% corresponds T_{2m} of about 23 °C.

Fig. 3 illustrates $UPB(T_{2m})$ dependence of the wind chill (feels like) temperature together with Chubarova et al. [16] formula. The differences between the curves are especially pronounced for mild temperature (T_{2m} ~15 °C). It seems that it will be difficult to find a universal formula to link *UPB* with temperature as sometimes local habits are decisive for the clothing style. To support our formula, we carried out a statistical analysis of 10-year (2005–2014) daily *UPB* values based on Eq. (16) and the wind chill temperature over London, U.K., taken from the ERA-Interim reanalysis. The seasonal mean values are calculated as 10%, 12%, 16%, and 10%, for winter, spring, summer, and autumn, respectively, that corresponds with the exposed body area of 7%, 11%, 14%, and 8% for the white cohort data taken in Manchester by Webb et al. [42]. The climatic conditions in U.K. disallow solar exposure of larger parts of body that implies high rates of hypovitaminosis D in British adults [42–43].

Further in the paper, we will calculate the vitamin D_3 daily quantity received throughout the year taking into account formula (16), and assuming *UPB* = 10% (only face, neck, and palms are exposed) or *UPB* = 33% (casual summer clothing: T-shirt and knee-length shorts).

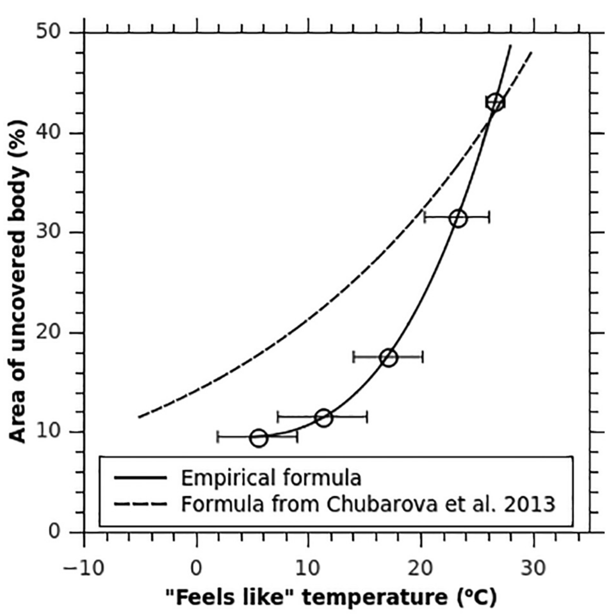

Fig. 3. Exposed skin area (percent of the uncovered part of the whole body) dependence on "feels like" temperature from February–August 2013 observations of clothing style of Londoners and ERA-Interim "feels like" temperature at local noon. Chubarova et al. [16] formula is attached for a comparison. Bar represents standard deviation of "feels like" temperature for selected exposed skin area.

3. Results

3.1. Health Optimum Exposure Index Dependence on Latitude

Figs. 4 and 5 show daily $HOEI_{1000\ IU,\ I}(t_{noon})$ and $HOEI_{Opt.VitD3,\ I}(t_{noon})$ by Eqs. (11) and (12), respectively for the period 2005–2014 in two sites close to the NH midlatitude lower and upper boundary, El Arenossilo (Spain, 37.1°N, 6.73°W) and Oslo (Norway, 59.91°N, 10.72°E). Noon value of SZA is calculated from standard astronomical formula and TO_3 is taken from measurements during the stations' overpasses by the Ozone Monitoring Instrument (OMI) on board of the Aura platform (data available at web site: https://avdec.gsfc.nasa.gov/pub/most_popular/overpassess/OMI/OMUVB).

Figs. 4a and 5a show that the quantity of vitamin D_3 equivalent 1000 IU taken orally and 1 unit of optimal vitamin D_3 quantity, respectively, could not be obtain without erythema risks in Oslo if weather conditions or other reasons permit only exposition of 10% of the whole-body area. Such exposition could provide 1000 IU at El Arenossilo almost throughout the whole year.

For the case of 33% body exposition, the target of 1000 IU could be reached safely in El Arenossilo (Fig. 4b) even by the oldest persons (> 59 yr, $AF = 0.5$). It is possible also for the oldest persons in Oslo but not in the period November - next year February. However, 33% uncovered body area is only an option for warm late spring/summer days at Oslo. Here 10% option is more realistic assumption for the whole year. The optimal vitamin D_3 quantity could be reached only by young adults exposing 33% of the whole-body area (Fig. 5b) but appropriate weather conditions for such sunbathing are rarely met at Oslo. For example, wind chill temperature over 20 °C appears only in 13% of days in July in Oslo but in 99.6% of days at El Arenossilo.

3.2. Characteristics of Cutaneous Vitamin D_3 Synthesis Based on Spectral UV Measurements

The biologically effective spectra (erythemal and previtamin D) calculated from the measured UV spectra by Bentham 150DM (Reading, U.K.) and Brewer Mark II (Toronto, Canada) in the period 2005–2014 are examined to find quantity of vitamin D_3 synthesized during maximally 1 h exposure around local noon, i.e. in the period of the highest UV intensity and usual lunch break (or weekend outdoor activities). Thus, there is a hope that personal vitamin D status could be easily improved by increasing the time spent outdoor and/or area of the uncovered part of the body.

Fig. 6a shows the duration of exposure at Reading to get MED_2 equal to 330 J m^{-2} (i.e. the mean MED value for II phototype). It is calculated in minutes as $MED_2/(0.025 \times UVI \times 60)$, where constant =0.025 is applied to convert UVI given in dimensionless units to W m^{-2}, and 60 is used to calculate time in minutes. The duration of maximally safe exposure (without erythemal risk) is about 30 min in late spring/summer but could be extent to 2–3 h in case of very low UVI (1.2–1.8 UVI) that may be found even in summer during heavy cloudiness. The uncovered part of the whole body, based on the wind chill temperature, is about 10% and 15% in the cold and warm period of the year, respectively, and rarely is larger than 20% (Fig. 6b).

Averaged time spent outdoor near noon by people living in Great Manchester was found only about 10 min [44]. Fig. 6c and d show the daily values of vitamin D_3 quantity synthesized during 10-min outdoor activities in upright posture at noon for the period 2005–2014. Formula (2) with the production rate by Eqs. (5) and (8) are taking into account to express the skin synthesized D_3 in IU (Fig. 6c) and in optimal vitamin D_3 unit (Fig. 6d) by a young adult whose way of clothing depends on the wind chill temperature as defined by Eq. (16). The values larger

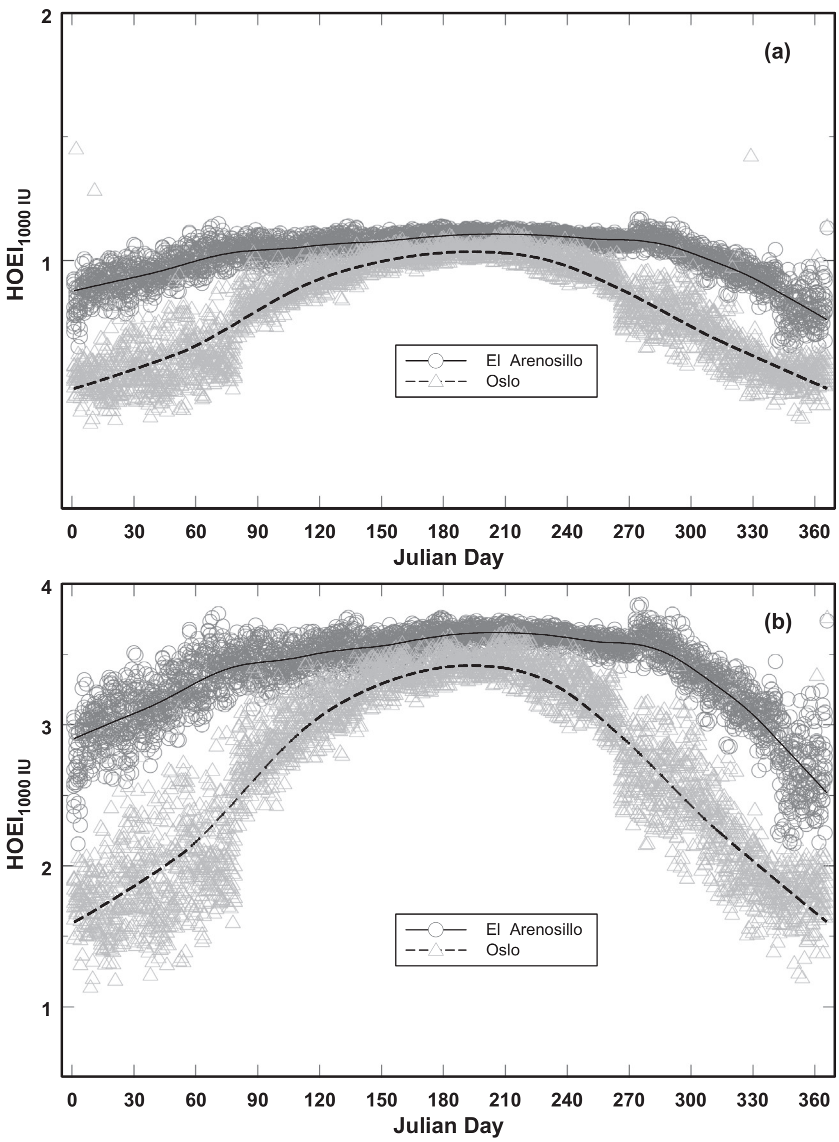

Fig. 4. Health-optimum-exposure index for young adults (< 21 yr) and 1000 IU target value at noon in El Arenossilo and in Oslo for the period 2005–2014 based on formula (11) with the satellite (OMI) total ozone from the sites' overpasses: 10% of the uncovered total skin area –(a), 33% of the uncovered total skin area –(b). Curves show the smoothed values by LOWES filter [45].

than the 1000 IU target were found only for 30 days but optimal vitamin D_3 quantity level was never reached. Evidently 10-min outdoor activity period is too short to provide enough vitamin D_3.

Fig. 7a and b illustrate the $HOEI_{(\dots)}$ values based on near noon exposures (local noon ± ½ h) in Reading for all days with the measured UV spectra in the period 2005–2014 for the case of 1000 IU target and the optimal vitamin D_3 quantity target, respectively. The smoothed pattern (by the locally weighted smoothing, LOWES, smoother, [45]) of $HOEI_{1000\ IU,\ 2}$ values allows to conclude that 1000 IU level could be reached safely from April 1st up to October 31th, but the level of optimal vitamin D_3 quantity ($HOEI_{Opt.VitD3,\ 2}$) is difficult to reach if the uncovered part of the whole body depends on the wind chill temperature. Exposure of the larger skin area seems to be necessary to improve the vitamin D status. Less effective vitamin D_3 synthesis by the oldest persons ($AF = 0.5$) will result in less frequent appearance of $HOEI_{(\dots)}$ values over 1. The mean $HOEI_{1000\ IU,\ 2}$ seasonal pattern, derived by the LOWES smoothing, will be in this case below 1 throughout the whole year suggesting that 1000 IU target could not be reached safely.

Percent of days with optimal conditions for vitamin D_3 synthesis in young adults and the oldest persons, i.e. $HOEI_{1000\ IU,\ I}(t_{noon}) > 1$ or $HOEI_{Opt.VitD3,\ I}(t_{noon}) > 1$, for each calendar month in the period 2005–2014 are shown in Table 2 (Reading) and Table 3 (Toronto). The vitamin D_3 amount (in IU and in optimal vitamin quantity) synthesized during 10 min near noon outdoor activities are also shown in Tables. It is found that young adults could safely obtain vitamin D_3 quantity equivalent to 1000 IU taken orally in the period April–October (Reading) and in February–November (Toronto) if the uncovered part of the body is determined by the wind chill temperature. For 33% body exposure, the optimal conditions to reach 1000 IU appear throughout the whole year for all adults but this option is not possible in cold days.

The percentage of days with optimal conditions for vitamin D_3 synthesis needs to be calculated for all-sky conditions. It means that duration of save sunbathing could sometimes last many hours for heavy overcast days. In practice, average outdoor activities last about 1 h [44]. When setting a limit of 1 h of outdoor activity, the optimal conditions appear in months when averaged 10-min exposure provides

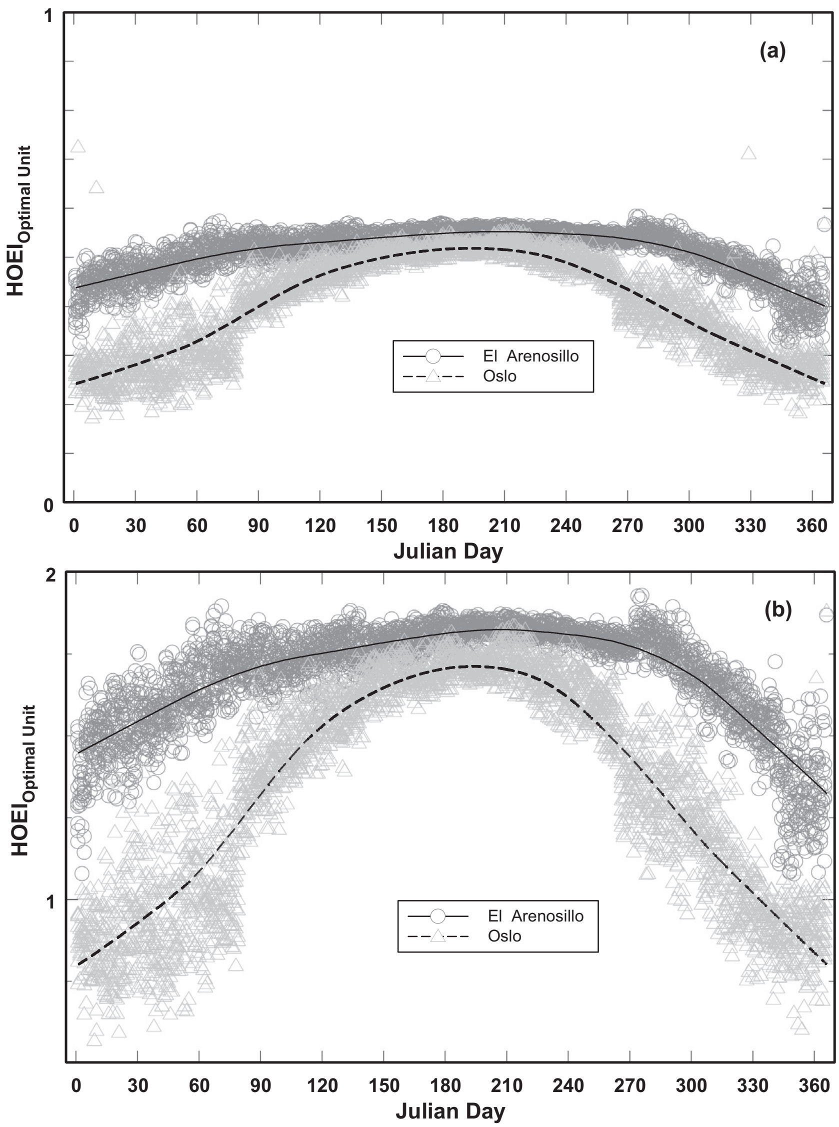

Fig. 5. The same as Fig. 4 but for the target value of 1 optimal vitamin D_3 quantity (Eq. (6)) and pertaining formula (12).

vitamin D_3 quantity above 160 IU and above 0.16 of optimal unit for a young adult (MED = 330 J m^{-2}) in upright position. Tables 2 and 3 show that these values are found in the April–September period (for 1000 IU target) and May–August (for the optimal vitamin D_3 quantity target) for both sites when the uncovered part of the body depends on the wind chill temperature.

Exposing larger part of the body (see results in Tables 2 and 3 for the case of 33% body exposure) enables the oldest persons to reach 1000 IU target during warm days in spring and summer. The optimal vitamin D_3 quantity could be synthesized only by young adults for about 40–60% of days in May–August period if they expose at least 1/3 part of their body. Vitamin D_3 supplementation seems to be necessary over the whole year for the oldest persons with daily dosage of ~2000 IU but reduced to ~1000 IU in summer for sunseekers exposing significant part of the body. In this recommendation, an approximate relation, 2000 IU of vitamin D_3 taken orally per 1 unit of the optimal vitamin D_3 quantity (Section 2.3), is taken into account.

4. Discussion and Conclusion

We focus on midday exposure as it corresponds to the lunch break time in many NH countries. During weekdays at that time, for indoor workers and school children, there is only one chance per day to get enough amount of vitamin D_3. During weekends, it is important not to miss a period of high UV intensity at midday and plan outdoor activities to get as much of vitamin D_3 due to solar radiation as possible. Health-optimum-exposure index is proposed to assess if prescribed amount of vitamin D_3 (target value) could be synthesized in the human skin without erythema appearance. The results are presented for two selected target values: vitamin D_3 quantity equivalent to 1000 IU vitamin D_3 taken orally, and 1 unit of the optimal vitamin D_3 dose defined by Krzyścin et al. [23]. The latter target value was inferred from the Hadza outdoor activities leading to high serum concentration of 25(OH) D = 115 nmol l^{-1}.

It is worth noting that daily quantity of vitamin D_3 is expressed in IU when Eqs. (2) and (5) are applied, but in dimensionless unit (number of

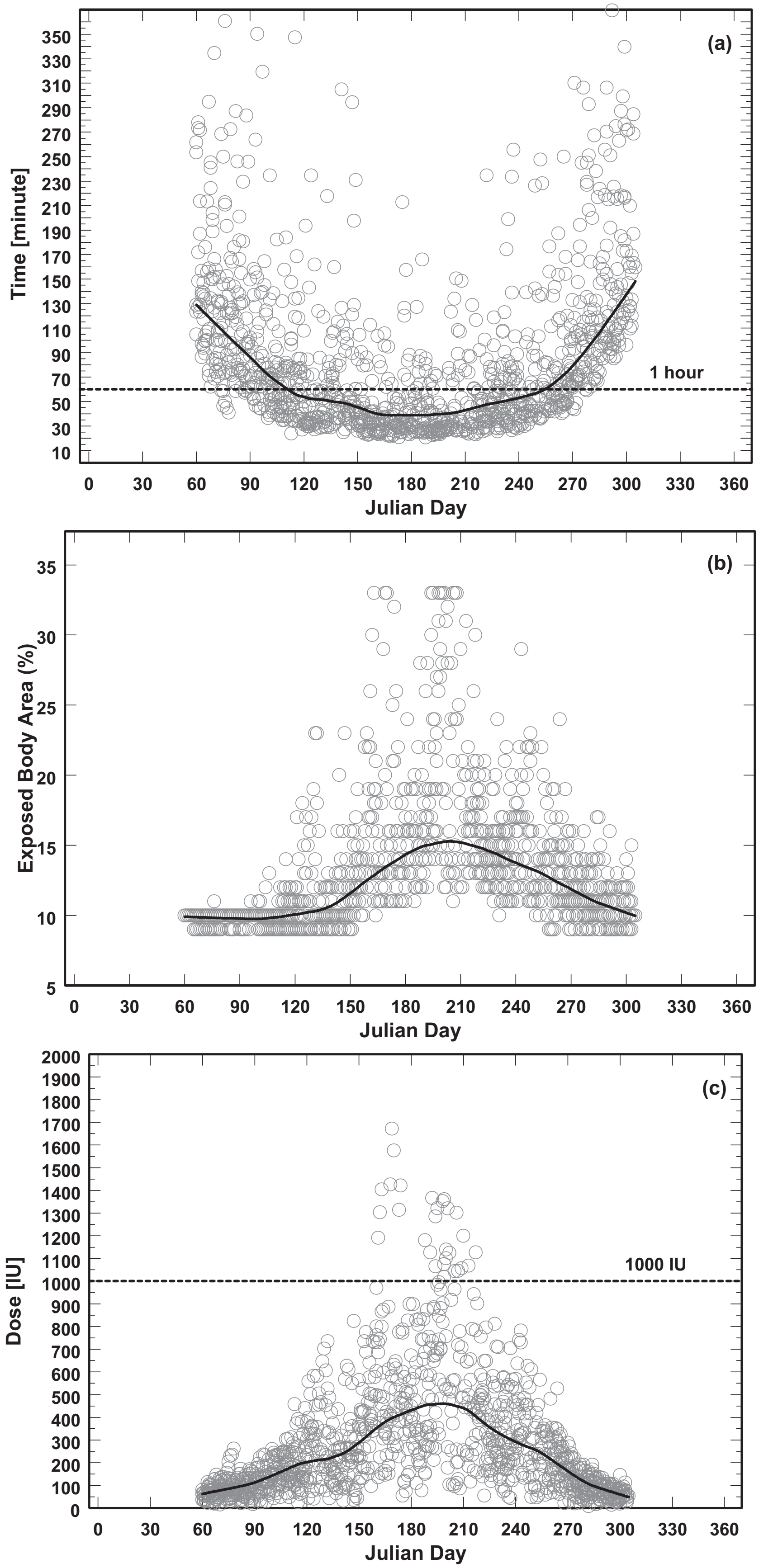

Fig. 6. Daily characteristics (2004–2015) of the "safe" (without erythema risk) solar UV exposure in Reading for white young adults with II phototype (MED = 330 J m^{-2}) derived from the Bentham DM150 spectra and wind chill temperature: the maximum duration of safe exposure –(a), percent of uncovered part of the body based on the wind chill temperature – (b), the vitamin D_3 quantity derived during 10 min exposure near noon in upright position calculated in IU of vitamin D_3 – (c), the same as Fig. 6c but in units of the optimal vitamin D_3 quantity (Eq. (6)) – (d). Solid curves show the smoothed values by LOWES filter [45].

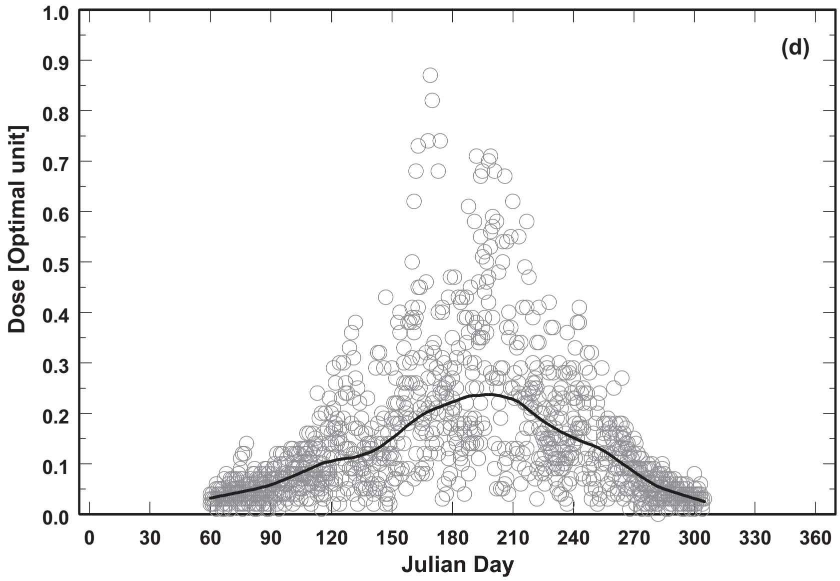

Fig. 6. (*continued*)

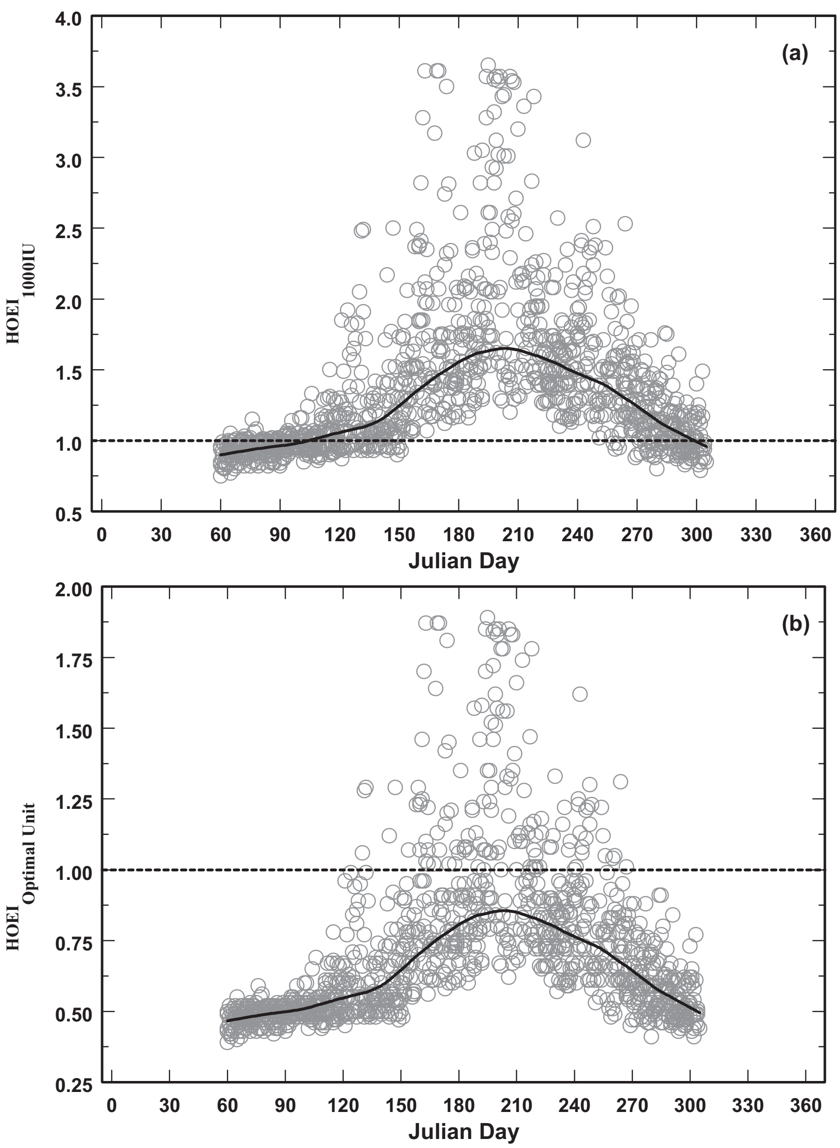

Fig. 7. Health-optimum-exposure index (HOEI) for near noon exposures (local noon ± ½ h) in the period 2005–2014 for young adults derived from the previtamin D_3 and erythema weighted spectra by the Bentham DM150 spectrophotometer in Reading, U.K., and percent of uncovered skin area depending on the wind chill temperature: HOEI calculated for 1000 IU target value – (a), HOEI calculated for the target of 1 unit of the optimal vitamin D_3 quantity – (b). Solid curves show the smoothed values by LOWES filter [45].

Table 2

Statistical characteristics of near noon exposures lasting maximally 1 h in Reading for the period 2004–2015 derived from the spectral measurements by the Bentham DM150. Monthly frequency (percent of all days in month) of health-optimum-exposure index > 1 for the target values: 1000 IU and 1 unit of optimal vitamin D_3. The results are for young adults (< 21 yr) and the oldest persons (> 59 yr) for hypothetical 10% and 33% of uncovered skin area, and for skin area inferred from the wind chill temperature. The amount of vitamin D_3 (in IU and in optimal vitamin D_3 quantity) synthesized in 10 min during near noon exposure by white young adult (MED = 330 J m^{-2}) in upright posture randomly related to the Sun.

Month	$HOEI_{1000\ IU} > 1$ (% all days)		$HOEI_{Opt\ VitD3} > 1$ (% of all days)		Exposure 10 min. vit. D_3 amount < 21 yr	
	< 21 yr	> 59 yr	< 21 yr	> 59 yr	IU	Opt Unit
Uncovered 10% of the whole body						
January	0	0	0	0	23(11)	0.01(0.01)
February	3	0	0	0	34(18)	0.02(0.01)
March	37	0	0	0	82(40)	0.04(0.02)
April	90	0	0	0	180(90)	0.09(0.05)
May	100	0	0	0	270(110)	0.14(0.05)
June	100	0	0	0	320(120)	0.16(0.06)
July	100	0	0	0	320(140)	0.16(0.07)
August	100	0	0	0	260(100)	0.13(0.05)
September	100	0	0	0	170(70)	0.08(0.04)
October	76	0	0	0	70(31)	0.04(0.02)
November	0	0	0	0	23(9)	0.01(0.00)
December	0	0	0	0	18(5)	0.01(0.00)
Uncovered 33% of the whole body						
January	100	100	0	0	79(37)	0.04(0.02)
February	100	100	0	0	110(60)	0.06(0.03)
March	100	100	0	0	270(130)	0.14(0.07)
April	100	100	12	0	600(300)	0.30(0.15)
May	100	100	64	0	910(350)	0.45(0.18)
June	100	100	62	0	1100(400)	0.54(0.20)
July	100	100	53	0	1100(470)	0.53(0.24)
August	100	100	35	0	850(340)	0.42(0.17)
September	100	100	1	0	560(230)	0.28(0.12)
October	100	100	0	0	230(100)	0.12(0.05)
November	100	100	0	0	76(29)	0.04(0.01)
December	100	100	0	0	60(17)	0.03(0.00)
Uncovered part of the whole body from the wind chill temperature						
January	0	0	0	0	24(11)	0.01(0.01)
February	3	0	0	0	34(18)	0.02(0.01)
March	37	0	0	0	82(40)	0.04(0.01)
April	90	0	0	0	190(100)	0.09(0.02)
May	100	0	0	0	320(150)	0.16(0.05)
June	100	26	7	0	530(330)	0.27(0.08)
July	100	42	16	0	620(370)	0.31(0.16)
August	100	25	1	0	420(230)	0.21(0.19)
September	100	8	0	0	230(120)	0.11(0.11)
October	85	0	0	0	75(33)	0.04(0.06)
November	0	0	0	0	23(9)	0.01(0.00)
December	0	0	0	0	18(5)	0.01(0.00)

optimal vitamin D_3 units) in case of using Eqs. (2) and (8). The former vitamin D_3 quantity is based on indoor experiments and recommendation of medical societies. The latter quantity is derived from numerical simulation of the outdoor radiation over the Hadza's territory and their life style providing high serum 25(OH)D concentration. During migration of the human ancestors to other continents adaptation to different climatic conditions caused skin whitening depending on the radiation level and available food at dwelling places to provide the same vitamin D_3 photoproduction as it was at the beginning of migration out of East Africa.

It is found that the optimal daily vitamin D_3 quantity is in some cases (e.g. for selected skin area, body posture analyzed in this study) equivalent to ~2000 IU vitamin D_3 taken orally. This relationship is derived assuming 16,000 IU per MED exposure in medical cabinet and 597 J m^{-2} as personal dose received by Hadza adults during 6-h outdoor activity. Taking into account uncertainties of these value, i.e. 10,000–20,000 IU [19] and 414–769 J m^{-2} [23] it could be obtained that 1 unit of optimal vitamin D_3 quantity is somewhere in the wide range of 900–3200 IU vitamin D_3 taken orally. Thus, both measures of the vitamin D_3 amount synthesized in skin by solar UV should be treated separately. The duration of exposures needed to reach 1000 IU target could be approximately converted as half of that to get 1 unit of optimal vitamin D_3 quantity.

A high potential of solar radiation to synthesize vitamin D_3 at noon in the NH midlatitudes and its latitudinal variability have been discussed by many authors using real and modeled UV radiation, e.g. [16, 20, 46]. However, it appears that surprisingly high percentage of people exhibit vitamin D deficiency, e.g. [44, 47–49]. Thus, it means that people are unable to effectively manage their UV exposure, perhaps due to being overwhelmed with information about the harmful effects of UV provided through mass media. The proposed health-optimum-exposure index allows, in a simple manner, to balance the risks and benefits of UV solar radiation in order to optimize outdoor activities. Personal vitamin D status could be improved by catching sunny moments around noon and searching for sunny and warm places which would allow for an exposure of larger part of the body. Such places sometimes could be found even if the wind chill temperature forbids lighter clothing.

Table 3
The same as Table 2 but for Toronto and the Brewer spectra.

Month	$HOEI_{1000\ IU} > 1$ (% all days)		$HOEI_{Opt\ VitD3} > 1$ (% of all days)		Exposure 10 min. vit. D_3 amount < 21 yr	
	< 21 yr	> 59 yr	< 21 yr	> 59 yr	IU	Opt Unit
Uncovered 10% of the whole body						
January	65	0	0	0	28(13)	0.01(0.01)
February	94	0	0	0	56(26)	0.03(0.01)
March	100	0	0	0	120(60)	0.06(0.03)
April	100	0	0	0	180(96)	0.09(0.05)
May	100	0	0	0	250(110)	0.13(0.05)
June	100	0	0	0	290(120)	0.15(0.06)
July	100	0	0	0	290(110)	0.15(0.05)
August	100	0	0	0	250(91)	0.13(0.05)
September	100	0	0	0	190(78)	0.09(0.04)
October	100	0	0	0	92(51)	0.05(0.03)
November	99	0	0	0	46(22)	0.02(0.01)
December	71	0	0	0	22(11)	0.01(0.01)
Uncovered 33% of the whole body						
January	100	100	0	0	91(44)	0.05(0.02)
February	100	100	0	0	180(84)	0.09(0.04)
March	100	100	0	0	380(190)	0.19(0.10)
April	100	100	13	0	590(320)	0.29(0.16)
May	100	100	41	0	830(350)	0.42(0.17)
June	100	100	57	0	960(400)	0.48(0.20)
July	100	100	57	0	970(360)	0.48(0.18)
August	100	100	37	0	840(300)	0.42(0.15)
September	100	100	5	0	620(260)	0.31(0.13)
October	100	100	0	0	300(170)	0.15(0.08)
November	100	100	0	0	150(73)	0.08(0.04)
December	100	100	0	0	74(38)	0.04(0.02)
Uncovered part of the whole body from the wind chill temperature						
January	65	0	0	0	28(13)	0.01(0.01)
February	94	0	0	0	56(26)	0.03(0.01)
March	100	0	0	0	120(60)	0.06(0.03)
April	100	1	0	0	180(100)	0.09(0.05)
May	100	10	1	0	300(170)	0.15(0.09)
June	100	42	5	0	480(280)	0.24(0.14)
July	100	77	13	0	610(310)	0.31(0.16)
August	100	67	3	0	460(220)	0.23(0.11)
September	100	22	1	0	260(170)	0.13(0.08)
October	85	4	0	0	99(60)	0.05(0.03)
November	99	0	0	0	46(22)	0.02(0.01)
December	71	0	0	0	22(12)	0.01(0.01)

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