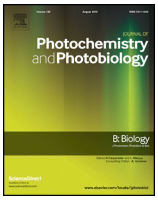
Journal of Photochemistry & Photobiology, B: Biology 159 (2016) 101–105

Contents lists available at ScienceDirect

Journal of Photochemistry & Photobiology, B: Biology

journal homepage: www.elsevier.com/locate/jphotobiol



Optimal vitamin D_3 daily intake of 2000 IU inferred from modeled solar exposure of ancestral humans in Northern Tanzania

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ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form 4 March 2016
Accepted 21 March 2016
Available online 29 March 2016

Keywords:
UV radiation
Personal exposure
Vitamin D
Oral supplementation

ABSTRACT

Recently, high serum 25-hydroxyvitamin D concentration (~110 nmol/L) was found in the Hadza tribe still keeping ancient hunter-gather life style. This level could serve as optimal vitamin D level that was built during millennia of human evolution. The personal vitamin D_3 effective solar exposures of the Hadza adults are estimated using radiative model simulations with input from the satellite observations over lake Eyasi (3.7°S, 35.0°E). The calculations are carried out assuming the Hadza typical clothing habits and specific scenarios of the out-door activity comprising early morning and late afternoon working time in sun and prolonged midday siesta in the shade. The modeled doses received by the Hadza are converted to the vitamin D_3 effective daily doses pertaining to the lighter skinned persons. We propose a novel formula to get adequate vitamin D level — exposure of 1/3 MED around local noon to 1/3 part of the whole body during warm sub-period of the year in the low- and mid-latitude regions. Such daily solar exposure is equivalent to ~2000 IU of vitamin D_3 taken orally. For many contemporary humans with limited out-door activity habit achieving such daily norm requires vitamin D_3 supplementation of 2000 IU throughout the whole year.

1. Introduction

The growing interest in vitamin D in recent years stems from its importance for health. Low vitamin D status appears to be correlated with higher risks of various diseases [1–3]. There are three basic sources of vitamin D: skin insolation by UV-B radiation, food, and dietary supplementation. Most of vitamin D comes from casual exposure to sunlight [4]. The current style of life, limiting out-door activity plus sun-protective recommendation to avoid skin cancer lead to an inadequate worldwide vitamin D status [5]. The serum concentration of 25-hydroxyvitamin D (25(OH)D) represents an index of vitamin D status.

There is an ongoing debate concerning the 25(OH)D level needed for optimal health. The serum concentration of 25(OH)D below 25 nmol/L is widely accepted as the deficient level related to high risk of rickets and osteomalacia [6]. The sufficient level of 50 nmol/L, which is based on bone health conditions, is recommended by some authors [7,8]. The optimal vitamin D status of ~75–80 nmol/L is deduced from the osteoporosis studies [9]. Much larger optimum of 115–120 nmol/L is proposed by very recent studies [10,11]. The level of about 100–120 nmol/L is supported by various studies dealing with a relation between cancer risks and vitamin D_3 status [12–15].

The mean serum 25(OH)D concentration of 115 nmol/L was found in human ancestral, Massai and Hadza tribes, still practicing traditional way of life in the equatorial Africa [16]. This level could serve as a target of optimal vitamin D status that was built during millennia of human evolution, controlled by natural selection rules. It seems that such optimal level was fixed during human migration out of the equatorial Africa (since ~100,000 years ago) that forced loss of skin pigmentation in populations living out of the tropics. Thus, lighter skin is a result of adaptation to low UV-B intensity that allows the same vitamin D synthesis which previously occurred in the tropics.

We would like to estimate a daily mean vitamin D_3 effective (VD_3E) personal dose received by the Hadza adults during their normal out-door activities. Using a radiative transfer model we calculate the cloud-free ambient irradiance on a horizontal surface, which is multiplied by the action spectrum pertaining pre-vitamin D_3 skin synthesis. The personal dose is obtained multiplying ambient VD_3E dose by weights related to the Hadza's habits of clothing and out-door activity. Taking MED values for unexposed skin according the Fitzpatrick photo-types [17] and MED value for VI photo-type (typical for the Hadza) after photo-adaptation, we convert the daily mean VD_3E personal dose received by the Hadza to an optimal VD_3E personal dose to be received by other lighter skinned populations to keep healthy vitamin D level.

2. The Hadza Tribe

The Hadza are the Bushmen tribe, living in a wild and remote surrounding of Lake Eyasi (3.7°S, 35.0°E, 1027 m a.s.l., north-central Tanzania). Their skin is highly pigmented (deeply black) and belongs

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http://dx.doi.org/10.1016/j.jphotobiol.2016.03.029
1011-1344/

to type VI of the Fitzpatrick's classification of the skin sensitivity to erythemal irradiation. The Hadza are the last true nomades of the world, still practicing hunter-gather life style as their ancestors did ~10,000 years ago.

Their food is a poor source of vitamin D, so all of their vitamin D is due to the solar exposure. They have a mean 25(OH)D concentration of 109 nmol/L regardless of age, sex or BMI [16]. It is much more than the present 25(OH)D level in populations worldwide [5]. The Hadza spend most of their days in the sun but they avoid direct exposure to the midday sun staying in the shade. Most of the daily activities are organized in the early morning and late afternoon while middle part of the days is reserved for a prolonged siesta. The duration of an active part of the day for adults is around 6 h, regardless of sex and season, i.e. about half of the day duration [18].

In calculation of VD_3E daily doses we assume the following scenario of their out-door activity: staying in sun is symmetrical around local noon with equal duration of the morning and afternoon exposure. We examine various durations of the resting time in the shade, 4 h, 5 h, 6 h (the most probable), and 7 h. Fig. 1 shows the modeled ambient erythemal irradiance on September 1, 2007 for 6 h of siesta. It is practically impossible to calculate precisely the ambient UV irradiance in a shady place without on-site measurements of UV irradiance. We assume that during the midday siesta in the shade, the level of UV irradiance is the same as that at the moment of going for a rest in the late morning. In the afternoon they go back to work in sunny places as the UV irradiance falls to the same late morning value.

There are number of factors important for the radiation attenuation due to trees including foliage density, height of the canopy, solar elevation, and surrounding ground albedo. Previous studies showed that the exposure in the tree shade varied in the wide range between 5% and 50% of that measured in full sun [19,20]. For the assumed 6 h midday siesta the Hadza adults stop working when the ambient erythemal irradiance is equal about 5 UV index (UVI) ~40% of the UVI maximum on September 1, 2007 (Fig. 1). Thus, it seems that the Hadza's resting sites were under not so dense tree canopy.

Uncovered part of body surface area (BSA) is necessary for a calculation of personal VD_3E doses. The Hadza clothing covers mainly their upper body and upper legs. Frequently men wear only short trousers. It is worth mentioning that the Hadza do not use sunscreens. The revised Lund and Browder diagram suggests that uncovered BSA in this case is ~33% including: hairless head anterior (~3%), arms (18.8%), and shanks (13.8%) [21]. Uncovered BSA for men dressed only in short trousers (covering thighs) is about 60% but they have the same 25(OH)D serum concentration as women [16]. It suggests that increasing uncovered BSA above 33% does not improve vitamin D_3 and the selection of 33% uncovered BSA is the optimal choice for vitamin D_3 synthesis. This finding agrees with a hypothesis that the skin synthesis of vitamin D_3 reaches a plateau when uncovered BSA is larger than 33% [22]. Moreover 35% of irradiated skin area was selected in model studies and recommended for solar exposure to improve vitamin D status [23,24].

Surface temperature (Table 1) of Northern Tanzania allows one to use thin clothing throughout the whole day. The Hadza stay in shelters, built from local wood, leaves, and grass, only during rain and night. Cloudiness and rain are rare in the dry and sunny period starting in June up till the end of October. Sunshine duration is ~80% of the day length, whereas ~65% in the wet season culminating in February and March (Table 1).

3. The Personal Dose Calculation

The daily estimates of ambient VD_3E doses over the Hadza territory for cloud-free conditions are calculated for the period 2005–2014 using the UV spectra (290 nm–400 nm) derived by the Tropospheric Ultra Violet and Visible (TUV) radiative transfer model conditions [25]. Model input consists of daily means of total ozone, aerosol characteristics at 388 nm (optical depth and single scattering albedo), and the radiative cloud fraction taken by the ozone monitoring instrument (OMI) on board of the Aura spacecraft launched 15 July 2004.

The erythemal irradiances for all-sky conditions are obtained by multiplying the cloud-free irradiances by the so-called cloud modification factor (CMF) equal to 1 for cloud cover up to 2 octas [26]. For larger cloud cover, *CC* in percent, the empirical relationship derived for near equatorial region, $CMF = 1–0.0056 \times CC$ is used [27]. Table 1 shows that UVI is almost constant throughout the whole year as it varies ~1.5 UVI around the yearly mean. Moreover, it is found that the UVI yearly mean (11.5) agrees with the UVI mean (11.6) calculated for the dry period. The cloud-free model can be used for the period June–October as the cloud fraction is around 20% (Table 1) and corresponds with the sunshine duration measured at Dodoma airport (6°S, 36°N) as the sum of both values is ~100%. The monthly mean total ozone shows only a small seasonal variation within the range ~20DU.

We use web based data exploring tool — GIOVANI, http://giovanni.sci.gsfc.nasa.gov/giovanni/, to collect the model input data: total ozone amounts, aerosol optical depth at 388 nm, single scattering albedo at 388 nm, and radiative cloud fraction. The data were averaged over the domain {4.7°–2.7°S, 34°E–36°E} with Lake Eyasi in the centre.

The modeled spectral UV irradiance is weighted using the action spectrum of pre-vitamin D_3 formation from 7-dehydrocholesterol in

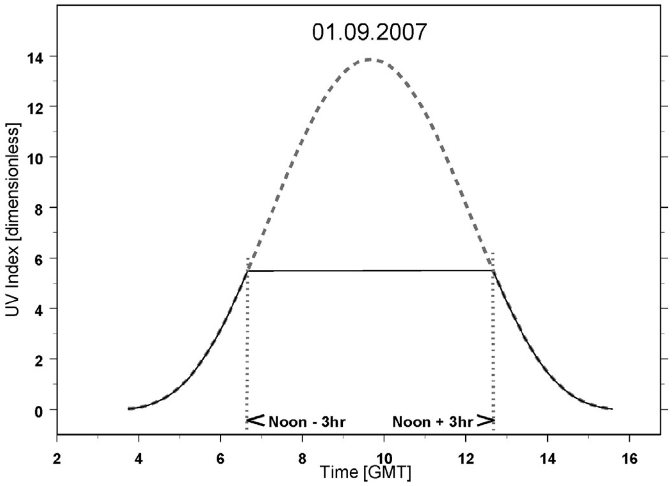

Fig. 1. The modeled ambient erythemal irradiance on September 1, 2007 over Lake Eyasi for the proposed schedule of the Hadza out-door activity with midday 6 h siesta (solid curve) superposed on the cloud-free daily irradiance (dashed curve).

Table 1
The long-term (2005–2014) monthly mean values and the yearly mean measured at Dodoma airport (the maximum and minimum temperature at 2 m level, sunshine duration in percent of the whole day) and calculated from satellite observations averaged over 2°×°2 domain centered on Lake Eyasi (radiative cloud fraction, total ozone, and UV index for cloud-free and all-sky conditions).

Month	Temp. max °C	Temp. min °C	Sunshine duration (%)	Cloud fraction(%)	Total ozone (DU)	UV index clear	UV index all
Jan	29.9	19.3	68	27	246	13.5	11.5
Feb	29.8	18.9	63	26	249	14.3	12.2
Mar	29.5	19.0	64	28	254	14.2	12.0
Apr	28.8	18.3	71	26	257	13.0	11.1
May	28.3	16.9	76	24	256	11.3	11.3
June	27.4	15.7	82	16	257	10.1	10.1
July	26.8	14.4	86	16	260	10.2	10.2
Aug	27.5	15.2	83	20	263	11.6	11.6
Sep	29.3	16.2	82	21	265	12.8	12.8
Oct	30.9	17.6	83	21	262	13.2	13.2
Nov	31.6	18.9	72	33	257	13.1	10.7
Dec	30.4	19.4	68	37	249	13.1	10.4
Year	29.2	17.5	75	25	256	12.5	11.4

the human epidermis [28]. The VD$_3$E irradiance is obtained by integration over the whole UV spectral range. The ambient daily mean VD$_3$E doses, i.e. the sum of the partly daily doses measured on a horizontal plane in places of the Hadza out-door activity or siesta, is obtained by time integration of daily course of the modeled vitamin D effective irradiance (with 5-min step) similar to that shown in Fig. 1 with a midday plateau during the siesta.

Fig. 2 shows the long-term (2005–2014) daily mean VD$_3$E doses for the scenario of 6 h midday siesta. The maximum values of modeled VD$_3$E doses of ~8000 J/m^2 are found in February whereas the minimum value in June of about 5000 J/m^2. The yearly mean daily doses is about 6600 J/m^2 and it corresponds to mean value (5970 J/m^2) for dry sub-period of the year (June–October) when the cloud-free conditions prevail, and the modeled values seem to be realistic.

The personal daily mean VD$_3$E dose for day *t*, $Dose_{\text{HADZA}}(t)$ received by a typical Hadza adult exposing 33% of his body area is a part of ambient dose, $Dose_{\text{AMBIENT}}(t)$, as it is multiplied by weight, $Weight_{\text{POSTURE}}$, related to the body orientation towards the sun:

$$Dose_{HADZA}(t) = Weight_{\text{POSTURE}} Dose_{\text{AMBIENT}}(t). \tag{1}$$

We calculate $Dose_{\text{AMBIENT}}(t)$ based on cloud-free simulations of the daily course similar to that shown in Fig. 1 with specific duration of the midday siesta. $Weight_{\text{POSTURE}}$ of 0.5 is selected as the value typical for a person randomly oriented towards the sun during all sky conditions for SZA larger 50° [29]. This SZA range corresponds to the Hadza working periods, i.e. about 3 h before and after local noon. Theoretical calculations of the erythemal and vitamin D$_3$ doses measured on a cylinder with different orientations relative to horizontal plain support also that for SZA > 50° human body receives about half of the dose measured on a horizontal surface [30]. For a person exposing smaller part of his body, Eq. (1) needs to be multiplied by actual uncovered BSA and divided by 33% (the typical Hadza's BSA). Irradiation of larger part body (more than 33%) is not effective in producing vitamin D$_3$ [22].

4. Results

The mean personal daily VD$_3$E dose for the Hadza under different scenarios of the midday siesta is calculated assuming $Weight_{\text{POSTURE}} = 0.5$ and averaging all modeled cloud-free personal daily doses during the sunny part of the year (June–October) in the period 2005–2014. The cloud-free doses are larger from December up to May but cloudiness makes the all-sky doses approximately equal to those found in the sunny season (Table 1).

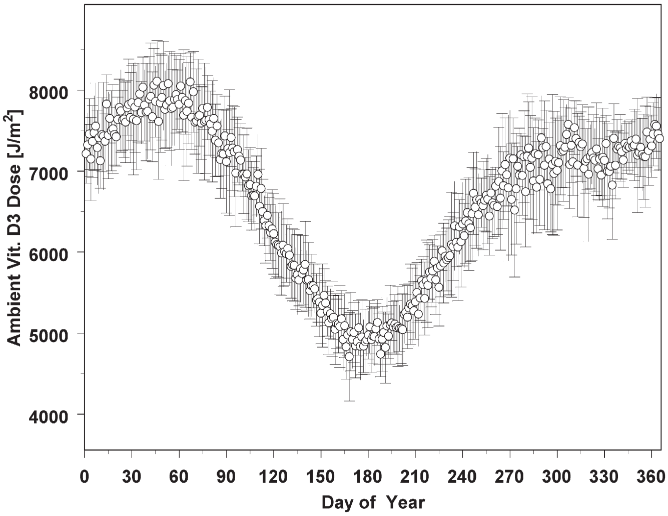

Fig. 2. Long-term (2005–2014) means of modeled ambient vitamin D$_3$ effective daily dose for cloud-free days over lake Eyasi for the scenario of 6 h midday break. The vertical lines show ±1 standard deviations.

Our objective is to calculate standard daily VD$_3$E doses for various photo-types based on the minimum erythemal dose (MED) causing redness of unexposed skin (Table 2). After numerous sunlight exposures, a person adapts to the doses exceeding his own MED for unexposed skin because of the natural sun protective effects such as tanning and skin thickening. MED value for the natural black skin adapted to high solar intensity is approximately 5 times larger than the unexposed (prior photo-adaptation) MED value [31]. For lighter skin (II and III photo-type) such as the MED increase is smaller ~4 [32].

The mean VD$_3$E personal dose of the Hadza adapted to high UV radiation is converted to the minimum vitamin D$_3$ dose (MVD$_3$D) necessary to keep adequate vitamin D status (~110 nl/L) for a person with the *m*-th skin photo-type prior photo-adaptation:

$$MVD_3D_m(t) = MED_m / MED_6 \times Dose_{HADZA}(t) / PHOTO\_ADAPT_6 \tag{2}$$

where $MVD_3D_{\text{m}}(t)$ is the minimum vitamin D$_3$ dose for unexposed *m*-th skin photo-type, MED_{m} is pertaining MED value ($m = 6$ for photo-type VI) and $PHOTO\_ADAPT_6 = 5$ is the photo-adaptation ratio for photo-type VI.

Holick's rule states that exposing ¼ of the body to ¼ MED of sunlight will produce VD$_3$E dose equivalent to 1000 IU taken orally, i.e., adequate daily amount to keep healthy status of vitamin D. Dowdy et al. noticed that the whole body exposure during Holick's experiment was due to fluorescent tubes not due to noon sunlight [33]. Thus, the MED value was multiplied by conversion coefficient of 1.33 to obtain corresponding VD$_3$E doses (see Table 2 for column with "Holick's rule" header). Such exposures appear to be 2 times less than those calculated for the most probable scenario of 6 h midday resting time.

The conversion coefficient MED → MVD$_3$D depends on the spectrum of the light source. Fig. 3 shows values of the conversion coefficient for different combinations of total ozone and solar zenith angle (SZA) during solar exposure. Bars illustrate the variability range of the conversion coefficient caused by changes of the aerosol properties: aerosol optical thickness at 320 nm from 0.05 up to 1.0, and single scattering albedo from 0.85 up to 0.95. In case of northern Tanzania, the mean conversion coefficient (for the whole year) is about 2. In the tropics and midlatitudinal regions the conversion coefficient is between 1.6 and 2 for typical noon values of SZA and total ozone in late spring up to mid-autumn.

We propose an alternative to Holick's rule: ⅓ of the body (i.e. typical for the Hadza adult) is exposed to ⅓ MED to get adequate vitamin D level. The results based on this rule perfectly agree with those obtained for the most probable out-door scenario (6 h siesta, Table 2). The conversion coefficient of 2 is used in this calculation. Slightly lower values of the coefficient should be applied for near noon exposures at other low or midlatitudinal sites during warm sub-period of the year. Thus, slightly larger erythemal exposure will be necessary to obtain the threshold values for the VD$_3$E doses shown in Table 2.

Table 2
Personal vitamin D$_3$ effective doses for unexposed skin to keep optimal vitamin D level for various photo-types and duration of the Hadza midday siesta. The doses based on the Holick's rule and on the proposed rule (1/3 of body exposed to 1/3 MED) are shown for a comparison.

Phototype	MED [J/m^2]	Minimum vitamin D$_3$ effective dose [J/m^2]					
		Holick's rule	Our rule	Duration of midday siesta			
				4 h	5 h	6 h	7 h
1	150	50	100	152	128	99	69
2	250	83	167	253	214	166	115
3	300	100	200	304	256	199	138
4	400	133	267	405	342	265	184
5	600	200	400	608	513	398	276
6	900	299	600	911	769	597	414

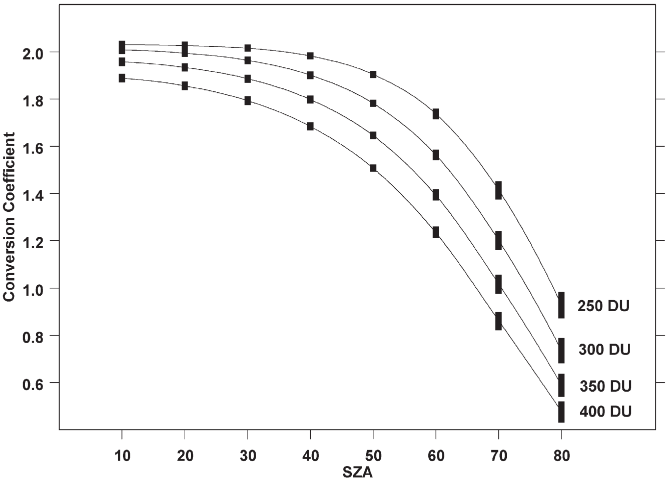

Fig. 3. Dependence of the conversion coefficient of MED to vitamin D effective dose on total ozone and solar zenith angle. Bars represent the range of the coefficient changes due to the aerosol characteristic changes.

Fig. 4 shows an example of the annual series of the sunbathing duration for a person with photo-type III exposing 33% BSA in standing posture in San Diego, USA (33°N, 117°W) and at Belsk, Poland (52°N, 21°E). The exposure starts at local noon and lasts up to the moment of receiving dose of 199 J/m^2 (Table 2 for III photo-type), which is based on the scenario of 6 h midday siesta. The all-sky UV spectra measured in San Diego by the SUV-100 spectrophotometer (manufacturer, Biospherical Instrument Inc.) and at Belsk by the Brewer spectrophotometer (manufacturer, Kipp &Zonen) are used in the calculations. It is seen that the duration of the noon sunbathing in cloud-free summer days is about 12–15 min (San Diego) and 20–30 min (Belsk). These values should be enlarged by a factor of 3 for a person exposing only face, neck, and palms (option for a colder season of the year). Thus, only in summer vacation or during weekends it seems possible that an in-door worker stays out-door long enough to get the adequate solar exposure.

5. Conclusions

The rule of thumb for vitamin D_3 production due to sunlight says that just a few minutes of out-door activities around noon in summer is enough to get an adequate vitamin D level. Our results show that it is difficult to reach the target level of the serum 25(OH)D concentration which the human ancestors had in Africa before starting the migration to other continents. We propose the rule for getting optimal vitamin D level, i.e. ⅓ MED of near noon solar exposure of ⅓ of our body during warm subperiods of the year. It means that ~1 MED exposure is necessary for those exposing only face and palms. This is rather health risk option as the MED barrier could be easily broken during outdoor activities. Thus exposing larger part of body and then avoiding doses close to MED is safe solution but not possible in midlatitudinal regions during cold part of the year. Our rule provides approximately twice higher minimum vitamin D_3 effective dose to keep healthy level of vitamin D_3 than those provided by standard Holick's rule. The proposed daily exposure is then equivalent to ~2000 IU vitamin D_3 taken orally.

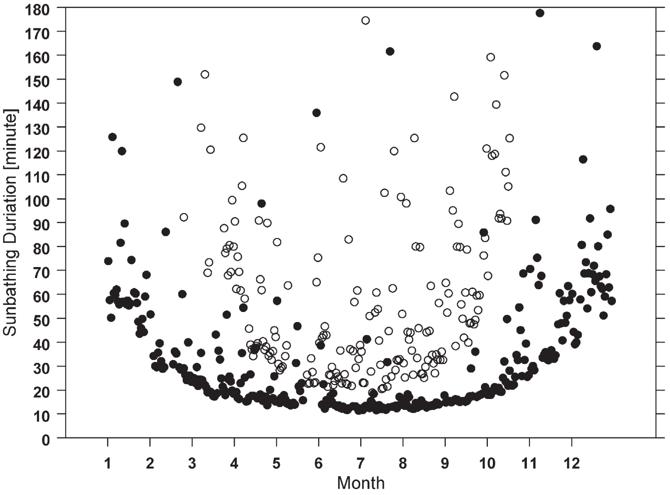

Fig. 4. Sunbathing duration in 2005 to get minimum vitamin D_3 dose for photo-type III person exposing 1/3 of his body in San Diego (33°N, 117°W) — full circles and at Belsk (52°N, 21°) — open circles. Only results with the duration less than 3 h are presented.

Similarly, the oral equivalent was inferred from the model study with simulated (by fluorescent tubes) typical UK summer's exposures of 1/3 skin area [24]. The Endocrine Society recommends 1500–2000 IU/d vitamin D intake for all adults, even for the category 70+ yr, to raise the serum 25(OH)D concentration above 75 nmol/L [34]. Experimental studies revealed that the 2000 IU/d supplementation during winter months led to ~30–45 nmol/L increase of the serum 25(OH)D concentration and it reached ~100 nmol/L in the end of the supplementation [35,36]. Such intake level is also supported by our calculations based on life style of the human ancestors and the solar exposure over their dwelling environment. Our finding gives an additional argument to the recent recommendations of vitamin D oral supplementation. Thus 2000 IU/d of vitamin D_3 supplementation throughout the whole year is necessary for many contemporary humans with limited out-door activity.

The rule of 1/3 MED solar exposure on uncovered 1/3 part of body is rather for young healthy persons (~20 yr) as the efficiency of vitamin D_3 synthesis decreases significantly with age, e.g. the senior adults must double their solar exposure to meet the effects of solar exposure by young adults [37]. Oral supplementation of at least 2000 IU vitamin D per day is then only a possible option for elder persons to keep optimal vitamin D level. The recommended daily supplementation of 2000 IU is much below tolerable upper intake level for vitamin D equal to 10,000 IU per day [34,38].

Acknowledgments

This work was partially supported within statutory activities No. 3841/E-41/S/2015 of the Ministry of Science and Higher Education of Poland. We appreciate UV spectra for San Diego taken from the NSF UV Monitoring Network database.

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