The Solar Exposure Time Required for Vitamin D₃ Synthesis in the Human Body Estimated by Numerical Simulation and Observation in Japan

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(Received September 19, 2012)

Summary Although the importance of solar radiation for vitamin D₃ synthesis in the human body is well known, the solar exposure time required to prevent vitamin D deficiency has not been determined in Japan. This study attempted to identify the time of solar exposure required for vitamin D₃ synthesis in the body by season, time of day, and geographic location (Sapporo, Tsukuba, and Naha) using both numerical simulations and observations. According to the numerical simulation for Tsukuba at noon in July under a cloudless sky, 3.5 min of solar exposure are required to produce 5.5 μg vitamin D₃ per 600 cm² skin corresponding to the area of a face and the back of a pair of hands without ingestion from foods. In contrast, it took 76.4 min to produce the same quantity of vitamin D₃ at Sapporo in December, at noon under a cloudless sky. The necessary exposure time varied considerably with the time of the day. For Tsukuba at noon in December, 22.4 min were required, but 106.0 min were required at 09:00 and 271.3 min were required at 15:00 for the same meteorological conditions. Naha receives high levels of ultraviolet radiation allowing vitamin D₃ synthesis almost throughout the year.

Key Words vitamin D₃, solar exposure time, UV-B, vitamin D deficiency, vitamin D₃ synthesis

Fifteen cases of vitamin D-dependent rickets were reported in the national survey of calcium metabolism disorders of children by a study group of the Ministry of Health, Labour and Welfare, Government of Japan during 1971–1980 (1). The study investigated more than 300 medical facilities and 10 of the 15 cases were identified in the Hokkaido and Niigata districts in the northern part of Japan. Seven of the affected children were breast-fed and the study suggested that the condition was possibly caused by insufficient exposure to ultraviolet (UV) radiation in winter. Fujii et al. (2) investigated 34 cases of vitamin D deficiency in various parts of Japan for the period 1995–2005. It was found that 17 cases were speculated and 3 cases were suspected to be due to low solar exposure time (2). According to Yorifuji et al. (3) the incidence of craniotabes in Kyoto, Japan, was present at a high rate in neonates, and that of the birth month had obvious seasonal variations, highest in April–May and lowest in November, which correlates with daylight hours of the month. Ono et al. (4) reported that the mean serum 25-hydroxyvitamin D level of the month was lowest at the end of winter and highest at the end of summer. Corrective countermeasures for vitamin D deficiency include ingesting vitamin D from food, taking medication containing activated vitamin D, and increasing exposure to solar radiation. Among them, everyone can increase their exposure to solar radiation

easily, although there is a limitation by location, season, and the time of day. After the discovery of ozone layer depletion, it became well known that excessive exposure to solar radiation can increase the risk of skin cancer and photo-aging (5) and therefore many people avoid exposure to solar radiation for health and cosmetic reasons. Erythematous UV is defined as the component of UV that reddens the human skin, and is known as UV Index to cause skin cancer, eye cataracts, etc. through excessive exposure. Infant sun baths were originally recommended in the Maternity and Child Health Handbook published by the Ministry of Health, Labour and Welfare, Government of Japan, but newer versions suggest avoiding the potential harm of UV exposure and replace the term “sun bath” with “air bath.” Accurate information on UV exposure is important to prevent the adverse health effects of excessive UV exposure, but it is also important to receive the UV necessary to generate vitamin D₃ in the body (hereafter, UV for vitamin D₃ synthesis). Even slight UV exposure produces adequate vitamin D₃ in the body although both erythematous UV and UV for vitamin D₃ synthesis are virtually identical on the UV spectrum. Therefore, UV for vitamin D₃ synthesis can be equivalent to harmful erythematous UV, which raises questions of how much UV is effective for producing vitamin D₃ and how much UV is detrimental to health (6).

As UV reaching the ground surface varies depending on the season, the time of day, and geographic location, information regarding an appropriate exposure time to

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solar radiation for vitamin D₃ synthesis should be disseminated to the public according to these factors. UV levels are determined by parameters such as solar position, atmospheric pressure, total ozone, atmospheric aerosol, surface albedo, and cloud cover. Although it is difficult to estimate UV levels on the ground, they can be calculated by numerical simulation, except under cloudy conditions that make UV transfer too complicated to simulate. Here, we have processed a calculating system of the UV for vitamin D₃ synthesis under a cloudless sky, and adapted it to determine seasonal, hourly, and locational variation at three geographically representative locations in Japan (Sapporo, Tsukuba, and Naha).

METHODS

Concentration of 25-hydroxyvitamin D₃ synthesized by UV in the body. The provitamin D₃ has a structure similar to cholesterol and is converted from squalene metabolized in the liver and the skin. It is reserved in the epidermis, especially in the basal layer portion of the outer skin. There it is converted into the previtamin D₃ following UV exposure and finally 1,25-dihydroxyvitamin D₃ (1,25-(OH)₂-D₃) is synthesized through 25-hydroxyvitamin D₃ (25-(OH)-D₃) by the action of the kidneys and liver (7). Davie and Lawson (8) and Davie et al. (9) attempted to estimate cholecalciferol synthesis in skin exposed to a mercury lamp whose energy spectrum was known. They studied the concentration of plasma 25-hydroxyvitamin D₃ synthesis in the body of Europeans of various ages without sex discrimination. The study included 51 individuals who were white skinned and had no clinical or biochemical features of osteomalacia. They were divided into six groups, and three of them (25 individuals) were exposed to UV-B emitted by a lamp placed 50 cm from a section (600/900 cm²) of their dorsal skin for 3 min a day, 3 d a week, over a 10-wk period. They used a mercury lamp (Hanovia, 7A prescription lamp) that emits a line spectrum mainly in the UV-B with a small portion of UV-C. Following exposure, they measured the concentration of plasma 25-hydroxyvitamin D₃ synthesis in the subjects. We applied their results to our calculations of UV exposure time required to generate enough vitamin D₃ synthesis in the body and adopted a cholecalciferol synthesis level of 0.0015 ± 0.0008 nmol/mJ that leads to a 25-hydroxyvitamin D₃ level of 0.0006 ± 0.00032 μg/mJ. The unit μg/mJ denotes the production rate of 25-hydroxyvitamin D₃ for the energy of UV emitted by the lamp used for vitamin D₃ synthesis (8, 9).

Definition of UV for vitamin D₃ synthesis in epidermis. We referred to a model by Gueymard, SMARTS2 (10), that made it possible to calculate the spectrum of solar radiation on the ground surface for wavelengths of 280–4,000 nm. In particular for wavelengths from 280 to 1,700 nm, calculations can be made at 1 nm intervals. The component of UV for vitamin D₃ synthesis can be estimated from the Commission Internationale de l'Éclairage (CIE) action spectrum for vitamin D₃ synthesis (11, 12) (hereafter, CIE action spectrum). UV for vitamin D₃ synthesis can be expressed by multiplying

each wavelength of the UV spectrum by the CIE action spectrum and by accumulating the wavelengths of a UV flux density as follows:

$$I_{\text{CIE}} = \int_{\lambda} E(\lambda) \cdot S_{\text{vd}} d\lambda, \quad (1)$$

where

$E(\lambda)$: UV flux density of the wavelength, λ,

S_{vd} : CIE action spectrum for vitamin D₃ synthesis.

Calculation system of UV for vitamin D₃ synthesis. The UV spectrum of the wavelength λ at the horizontal plane surface is expressed as follows;

$$E(\lambda) = E_{\text{bn}}(\lambda) \cos \theta_z + I_{\text{d}}(\lambda), \quad (2)$$

where

$E_{\text{bn}}(\lambda)$: UV spectrum of the direct component of solar radiation

θ_z : solar zenith angle

$I_{\text{d}}(\lambda)$: UV spectrum of the diffusive component of solar radiation.

The calculation system used in this study was processed along Eqs. (1) and (2) referring to the SMARTS2 model. This model enables to calculate the UV spectrum $E_{\text{bn}}(\lambda)$, and $I_{\text{d}}(\lambda)$ at the ground surface for a given season, time, and place under a cloudless sky. We applied this calculation to the three sites of Sapporo, Tsukuba, and Naha in Japan. The UV flux reaching the top of the atmosphere from the sun is corrected for the distance between the Earth and the sun for each day of the year. Total ozone and the atmospheric pressure by air molecules and aerosols in the atmosphere were considered in the calculations, because they reduce UV in the atmosphere. Total ozone was also measured on a daily basis at the three locations, using a Dobson spectrophotometer operated by the Japan Meteorological Agency, who have published the data (13). The optical thickness of aerosols was observed under a cloudless sky at the Tsukuba station, Japan Meteorological Agency, using a sun-photometer that split the direct solar radiation into 368, 500, 675, 778, and 862 nm portions, which yield the Ångström's parameters, α and β. Because there were no data for aerosols at Sapporo and Naha, the data for aerosols for Tsukuba were used, assuming that Sapporo and Naha were cloudless. Rayleigh scattering is related to the amount of air molecules that may generate atmospheric pressure. Here, we assumed that standard pressure (1,013.25 hPa) conditions persisted for all days of the year. In reality, the changes in atmospheric pressure throughout the year are not significant enough to affect UV levels on the ground. Multiple reflections between the Earth's surface and the atmosphere were also considered. The other parameters necessary for the calculation were incorporated from the SMARTS2 model.

UV spectra have been observed by the Japan Meteorological Agency, every hour on a daily basis with Brewer spectrophotometers (MARK III) for the wavelengths 290–340 nm. Within the 290–325 nm region (mainly UV-B), spectra are available for every 0.5 nm interval. Seventy-one wavelengths are available (14) at the stations in Sapporo, located in the most northern part of the Japanese Archipelago (43°04' N, 141°20' E, 26.3 m above sea level), Tsukuba, in the central region (36°03' N, 140°08' E, 31.0 m), and Naha, in the southwest

Table 1. Recalculated power for UV for vitamin D₃ synthesis using the CIE action spectrum (12).

Wavelength (nm)	UV-B spectrum ($\mu\text{W}/\text{cm}^2$)	CIE action spectrum	Amount of the UV for vitamin D ₃ synthesis ($\mu\text{W}/\text{cm}^2$)	Amount of the UV for vitamin D ₃ synthesis used by Davie et al. (8) ($\mu\text{W}/\text{cm}^2$)
254	40	0.043	1.72	10.88
265	75	0.122	9.15	23.40
297	55	0.996	54.78	52.80
303	90	0.771	69.39	82.80
313	120	0.083	9.96	75.36
380			145.0	245.24

The second column gives the spectrum emitted by the lamp used by Davie and Lawson (8). Multiplying UV-B spectrum by CIE action spectrum and accumulating at each wavelength yields the UV for vitamin D₃ synthesis, 145.0 $\mu\text{W}/\text{cm}^2$.

(26°12' N, 127°41' E, 27.5 m). Therefore, the UV for vitamin D₃ synthesis could also be obtained by observations as well as using Eq. (1).

Parameters concerning the quantity of vitamin D₃ synthesis. The quantity of vitamin D₃ synthesis in the epidermis, Q_D can be expressed as follows:

$$Q_D = q_e \cdot S_{\text{type}} \cdot S_{\text{der}} \cdot t_{\text{ex}} \cdot I_{\text{CIE}}, \quad (3)$$

where q_e , S_{type} , S_{der} , and t_{ex} denote the production rate for UV for vitamin D₃ synthesis, the effect of skin type, exposed skin area, and the solar exposure time, respectively, and it should be marked that Q_D is proportional to S_{der} and t_{ex} as well as I_{CIE} . Power at 50 cm from the lamp used by Davie and Lawson (8) that produces the plasma 25-hydroxyvitamin D₃ in the epidermis was recalculated by multiplying by the CIE action spectrum and accumulating at each wavelength that yields UV for vitamin D₃ synthesis, 145.0 $\mu\text{W}/\text{cm}^2$ from 245.24 $\mu\text{W}/\text{cm}^2$ which was derived from an action spectrum of Kobayashi and Yasumura (15), as shown in Table 1. It means that the production rate q_e , $0.0006 \pm 0.00032 \mu\text{g}/\text{mJ}$ could be re-estimated to be $0.00101 \pm 0.00054 \mu\text{g}/\text{mJ}$ for vitamin D₃ synthesis for the CIE action spectrum. The skin type of the subjects who were investigated by Davie et al. (9) was assumed to be II. Skin type refers to the amount of melanin pigment in the epidermis that reduces the ability of UV to penetrate into the skin. The efficiency of vitamin D₃ synthesis in the epidermis depends on skin type (16). Because skin types are not always the same among the people, the efficiency of vitamin D₃ synthesis varies between different individuals. Davie and Lawson (8) analyzed vitamin D₃ synthesis in the human skin for Europeans with generally white skin. The skin types of Japanese people are generally considered to skin types II, III, and IV although most Japanese people have skin type III as defined internationally (17). To consider the effect of skin type on UV for vitamin D₃ synthesis we referred to Webb and Engelsen (18). S_{type} was inferred to be 0.83, resulting from the ratio of UV energy for one minimal erythemal dose (MED) depending on the difference between skin types II and III. S_{der} is the area of bare skin. I_{CIE} is the UV for vitamin D₃ synthesis defined by the flux density on a unit area of horizontal plane as in Eq. (1) in mW/cm^2 that is equivalent to a unit, $\text{mJ}/\text{s}/\text{cm}^2$. In this case S_{der} corresponds to the exposed skin

Fig. 1. Calculated UV for vitamin D₃ synthesis compared to that observed at 12:00 in 2007 at Tsukuba, where the symbol $\times$ denotes the calculated UV for vitamin D₃ synthesis on 51 cloudless days and the dotted lines show that observed for all days (including cloudy days) of the year.

area in cm^2 and t_{ex} corresponds to the solar exposure time in seconds. If UV for vitamin D₃ synthesis (I_{CIE}) and the exposure time (t_{ex}) are given, a quantity of vitamin D₃ synthesis (Q_D) can be calculated using Eq. (3) under the conditions of q_e , S_{type} , and S_{der} .

RESULTS

Evaluations of the numerical simulation

To evaluate the calculation system, the calculated UVs for vitamin D₃ synthesis were compared to those observed at Tsukuba station, where data for the optical thickness of aerosols were available and the days of cloudless sky were determined by the direct solar radiometer (51 d were recognized for 2007). Data were used at 12:00 when UV levels were generally highest. Cloudless sky conditions were defined by direct solar radiation being constant 30 min before and after 12:00. The results are shown in Fig. 1. It is clear that the calculated values for cloudless days are equivalent to the maximum observed values for each day. Figure 2 shows the relationship between the observed UV for vitamin D₃ synthesis and the calculated values at Tsukuba at 12:00 for the 3 y of 2005 (43 data points), 2006 (30 data points), and 2007 (51 data points), giving a total of 124 data points. The observations have inevitable instrument errors (14) and the calculation system is based on

Fig. 2. Relationship between the observed and calculated UV for vitamin D₃ synthesis at 12:00 for 124 cloudless days during 2005–2007 at Tsukuba.

several assumptions. Despite this, the correlation coefficient between observed and calculated values is very high (0.989) although the calculated UV for vitamin D₃ synthesis is slightly larger than the observed values. The calculation system for UV for vitamin D₃ synthesis used in the study could be adapted to observations at any place and time under cloudless sky when there is no UV observation data, if the parameters necessary for the calculation are available (e.g., total ozone and atmospheric aerosols).

Calculation of UV for vitamin D₃ synthesis at representative locations in Japan

The calculations of UV for vitamin D₃ synthesis were performed at the three sites, Sapporo, Tsukuba, and Naha, on the same days for the comparison among them only when observations were made at Tsukuba under cloudless skies during 2005–2007. Sapporo and Naha did not always experience cloudless skies when Tsukuba was cloudless, but cloudless conditions were assumed in the calculations. Because there were no data for aerosols or sky conditions at Sapporo and Naha, the calculations were performed using the same data as that used at Tsukuba, except total ozone as these data were available for Sapporo and Naha. This assumption generated some discrepancies in the results but could be generally applied. Figure 3 shows the seasonal variation in monthly mean vitamin D₃ synthesis (μg) for human skin (600 cm^2) in 1 min as calculated from Eq. (3) at each site at 09:00, 12:00, and 15:00. The 09:00 and 15:00 periods were used to represent typical morning and afternoon conditions. The parameters used in the calculation for 09:00 and 15:00, such as total ozone and Ångström's parameters of aerosols, were the same as those used for 12:00. The area of 600 cm^2 is considered to correspond to the area of a face and the back of a pair of hands for an adult weighing 70 kg, according to Davie et al. (9). Usually the face and hands are exposed to solar radiation without the cover of clothing. There were strong seasonal variations at all three sites for each hour, caused mainly by differences in the solar zenith angle, total ozone, and the optical thickness of aerosols. Comparing the seasonal variations at each site for 12:00 when the maximum vitamin D₃ synthesis

(a) Sapporo

(b) Tsukuba

(c) Naha

Fig. 3. Seasonal variation of vitamin D₃ synthesis in human skin ($\mu\text{g}/600\text{ cm}^2/\text{min}$) under the cloudless conditions. Values are monthly means based on calculations for the period of 2005–2007 at 09:00, 12:00, and 15:00 at (a) Sapporo, (b) Tsukuba, and (c) Naha.

occurs, in every month, vitamin D₃ synthesis at the site located at the higher latitude (Sapporo) was less than the two more southern sites (Tsukuba and Naha). Maximum vitamin D₃ synthesis occurred in July: $1.9\text{ }\mu\text{g}$ at Naha, $1.6\text{ }\mu\text{g}$ at Tsukuba, and $1.2\text{ }\mu\text{g}$ at Sapporo. There were rapid decreases from summer to winter at all sites, particularly at Sapporo, where a substantial decrease was clear from September to December. In January, vitamin D₃ synthesis declined to $0.8\text{ }\mu\text{g}$ at Naha, $0.3\text{ }\mu\text{g}$ at Tsukuba, and less than $0.1\text{ }\mu\text{g}$ at Sapporo. It should be noted that at Sapporo it was very low in winter, all day long.

Fig. 4. Seasonal variation of solar exposure time (min) required to produce 5.5 μg vitamin D₃ over 600 cm² human skin under the cloudless conditions. Values are monthly means based on calculations for the period of 2005–2007 at 09:00, 12:00, and 15:00 at (a) Sapporo, (b) Tsukuba, and (c) Naha.

The time dependency of calculated vitamin D₃ synthesis

In Fig. 3, at all sites, vitamin D₃ synthesis at 09:00 and 15:00 was much less than at 12:00 in all months, and especially at Sapporo through October to March, being almost zero in winter. At 09:00 at Sapporo in June, July, and August, and at Tsukuba in May, June, July, and August more than 0.5 μg vitamin D₃ could be produced in 1 min; however, at 15:00 less than 0.5 μg was produced throughout the year, as well as in most seasons at Tsukuba but for June and July. Much more vitamin D₃ could be produced at Naha than the other sites except for in winter at 09:00. Because Naha is

located in the western part of the Japanese Archipelago, solar altitude is not high enough at 09:00 to produce sufficient UV levels for vitamin D₃ synthesis. The differences in vitamin D₃ synthesis at different times of the day are caused largely by variation in the solar zenith angle with the season related to the true solar time at the location of the site.

Exposure time required for the synthesis of 5.5 μg vitamin D₃

If the quantity of vitamin D₃ synthesis required in the body corresponding to Q_D and I_{CIE} are given, an exposure time, t_{ex} , can be calculated in opposite way as calculating Q_D from Eq. (3). According to the Ministry of Health, Labour and Welfare (19), for adequate nutrition an intake of 5.5 μg a day of vitamin D₃ is necessary for Japanese people older than 18 y. Figure 4 shows the solar radiation exposure time if all of this vitamin D₃ requirement were to be produced by UV exposure. To produce 5.5 μg vitamin D₃ at Sapporo, a solar exposure time of less than 15 min is required in midsummer at 09:00, 12:00, and 15:00 but for the other seasons much more time is required (Fig. 4 (a)). At 09:00 in October through March and at 15:00 in October through April it is very difficult to obtain enough UV for vitamin D₃ synthesis. At Tsukuba less than 10 min was required to achieve the production of 5.5 μg vitamin D₃ at 12:00 in most seasons (Fig. 4 (b)) except for winter, but at 09:00 and 15:00 much more time was required except for in midsummer. It is difficult to generate the required vitamin D₃ in short time periods given the weaker UV radiation intensity generally in the morning and afternoon. However, the required vitamin D₃ synthesis was possible at Naha in less than 10 min at 12:00 during all seasons, as well as during most of seasons at 15:00 except for winter (Fig. 4 (c)). Table 2 summarizes the required exposure time at each site for at 09:00, 12:00, and 15:00 in Fig. 4, which reflects the seasonal variation in solar exposure time for the production of 5.5 μg vitamin D₃. As shown in Table 2, the calculated exposure time was 4.6 min at Sapporo, 3.5 min at Tsukuba, and 2.9 min at Naha at 12:00 in July. However, at 12:00 in December, the calculated exposure time required drastically increases to 76.4 min at Sapporo, 22.4 min at Tsukuba, and slightly to, 7.5 min at Naha in which much difference can be seen among the each site.

Vitamin D₃ synthesis under all weather conditions by observation

Cloud cover generally lessens UV radiation greatly on the ground surface. The calculation system developed in the study could not be carried out for cloudy conditions because of its complexity. UV observation data at each site were applied for taking into account the cloud effect in the vitamin D₃ synthesis in the seasonal variations and the differences among each site. Figure 5 shows the vitamin D₃ produced in 1 min at 12:00 at each site as observed monthly means for the period of 2005–2007 and covering all weather conditions. The data include all days of the year, including both cloudless and cloud cover conditions. When compared to those at 12:00 in Fig. 3, it can be seen that the vitamin D₃ synthesis was much less than that calculated for a cloudless day

Table 2. Monthly means of the solar exposure time (min) required to produce 5.5 μg vitamin D₃ at 09:00, 12:00 and 15:00 in July and December, i.e., the representative summer and winter seasons.

		July			December		
		9 o'clock	12 o'clock	15 o'clock	9 o'clock	12 o'clock	15 o'clock
Sapporo	Cloudless	7.4	4.6	13.3	497.4	76.4	2,741.7
(min)	All weather	—	7.0	—	—	94.7	—
Tsukuba	Cloudless	5.9	3.5	10.1	106.0	22.4	271.3
(min)	All weather	—	7.9	—	—	30.5	—
Naha	Cloudless	8.8	2.9	5.3	78.0	7.5	17.0
(min)	All weather	—	3.9	—	—	13.4	—

Upper: cloudless conditions determined by calculations, lower: all weather conditions of the month determined by observations.

Fig. 5. Seasonal variation of vitamin D₃ synthesis in human skin ($\mu\text{g}/600\text{ cm}^2/\text{min}$) for all weather conditions. Values are monthly means based on observations via Brewer Spectrophotometer for the period of 2005–2007 at 12:00, at Sapporo, Tsukuba, and Naha.

at each site and at any season, because actual weather conditions were not always cloudless. Vitamin D₃ was produced in the order of Sapporo<Tsukuba<Naha, except for the month of July. It can be seen that vitamin D₃ synthesis at Tsukuba was less than that at Sapporo in July and decreased from May to July. This is due to the rainy season at Tsukuba at this time. A large increase in vitamin D₃ synthesis from June to July was observed at Naha, which might be due to the earlier end of the rainy season at that location. The exposure time required to produce 5.5 μg vitamin D₃ at 12:00 at the three sites is shown in Table 2. In July, 7.0 min were required at Sapporo (4.6 min for cloudless conditions), 7.9 min were required at Tsukuba (3.5 min for cloudless conditions), and 3.9 min were required at Naha (2.9 min for cloudless conditions). The vitamin D₃ produced each day varied considerably. Cloud generally decreases UV on the ground surface depending on the species and the thickness of cloud, as well as cloud cover. When the sky is covered with thick clouds, vitamin D₃ might not be produced at all.

DISCUSSION

We estimated the quantity of vitamin D₃ produced in the epidermis under cloudless sky conditions using the SMARTS2 model with the CIE action spectrum at Sap-

poro, Tsukuba, and Naha in all seasons at 09:00, 12:00, and 15:00. This study revealed the locational characteristics of expected vitamin D₃ synthesis in the body so that there were considerable differences in vitamin D₃ synthesis among the three sites, the season, and the time of day. It is difficult to produce enough vitamin D₃ at Sapporo in the northern part of the Japanese Archipelago compared to the other sites to meet nutritional needs from UV exposure alone, except for the midsummer period. The inhabitants of Naha might not be concerned about vitamin D₃ synthesis by increasing their UV exposure. Inhabitants of the central part of Japan (e.g., Tsukuba) have the opportunity to produce vitamin D₃ through UV exposure around noon under cloudless sky conditions, but during the morning and afternoon it would be difficult to produce vitamin D₃ during short UV exposures, except for the midsummer period. Depending on the cases a sufficient quantity of vitamin D₃ required cannot be produced by exposure to solar radiation. On the other hand, the Ministry of the Environment, Japan, advises that enough vitamin D₃ can be produced by exposing an area of skin corresponding to the back of a pair of hands to solar radiation only for 15 min in sunshine and 30 min in a shaded area, when coupled with vitamin D intake from the common diet (20) without any comment about location, season, or time of day. Other organizations concerned also announced similar words of guidance to the public. These generate a misunderstanding regarding how to obtain vitamin D₃ from solar radiation. This study enables the provision of much more useful information about the necessary solar exposure time for vitamin D₃ synthesis for the people who live in Japan, especially for elderly persons, infants, expectant mothers, and then for the people who live in the northern part of Japan. Here, it must be noted that the exposure time would vary depending on the area of skin exposed as defined in Eq. (3). When clothes without sleeves or short trousers are worn the exposure time required for vitamin D₃ synthesis can be considerably reduced or more vitamin D₃ can be produced for a given exposure period. In this study exposure time required for cloudy conditions could not be analyzed because cloud amount and thickness were not able to be specified with UV observation.

Finally, it should be noted that this study was based on the results determined by Davie and Lawson (8), and Davie et al. (9). In our study, the skin type parameter used in calculations was defined as 0.83, compared to the European population sampled for the Davie and Lawson (8) study. Because the skin type of Japanese people might be different from that of the European population, the rate of production of vitamin D₃ following UV exposure for Japanese people should be determined by measuring plasma 25-hydroxyvitamin D₃ after UV exposure. Moreover the area of the back of hands and the face are not always horizontal in everyday life but I_{CIE} is defined as flux density for a horizontal plane area and is not always isotropic. Thus it is assumed that there are some discrepancies between the calculation results and the real exposure time. These problems should be analyzed experimentally in future studies. Engelsen and Kylling (21) developed a calculation allowing the UV exposure time required for vitamin D₃ synthesis to be determined by inputting location, season, time, atmospheric conditions, skin area exposed, skin type, and the necessary quantity of vitamin D₃ to be produced in the body. We compared our results for the same conditions of location, atmospheric parameters, etc., at Tsukuba. We found that the exposure time obtained in this study is longer than that of Engelsen and Kylling (21). It might be caused by the differences mainly of calculation system, production rate for UV for vitamin D₃ synthesis, and estimation of exposed skin area. These discrepancies will be the next subject in the future, including the Japanese production rate for UV for vitamin D₃ synthesis.

Acknowledgments

We would like to thank the many students of Tokyo Kasei University who assisted us in the processing of the calculation system and helped with further discussions of the SMARTS2 model. We express our gratitude to N. Ohkawara (Japan Meteorological Agency), who provided us with the data necessary for this research.

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