Sunburn versus vitamin D induced by UV from solaria and sunlight in New Zealand

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Abstract

Exposures to UV radiation from solaria and sunlight have potentially damaging and beneficial effects that are not yet fully quantified. Here we compare weighted UV irradiances relevant to erythema (sunburn) and vitamin-D production from 2 phototherapy units and 2 commercial solaria with those under clear-skies in summer and winter at Lauder New Zealand (45°S). We find that weighted irradiances from one solarium are an order-of-magnitude greater than for summer sunlight whereas the others are comparable with summer sunlight, and an order-of-magnitude greater than winter sunlight. For most solaria, UV-A irradiances far exceed those in sunlight, constituting a potentially serious health risk. The calculated vitamin D benefit to erythema risk ratios for the solaria are comparable to, or greater than for with summer sunlight, and significantly greater for one of the phototherapy booths (the predominantly UV-B booth). Exposure times to maintain sufficient vitamin-D without inducing erythema are extremely short for the latter solarium, whereas for the others they are comparable to, or less than, those for summer sunlight. For winter sunlight, deduced exposure times for vitamin-D sufficiency are impractically long. In conclusion, the solaria tested should be capable of helping to maintain vitamin-D sufficiency. However there is an attendant risk of erythema; and exposure times are sensitive to the choice of action spectrum. For all solaria the spectrum differs greatly from sunlight with unnaturally high irradiances at some wavelengths, which could have adverse health effects. Their use is not advocated as a way of ensuring vitamin-D sufficiency.

1. Introduction

The health risks from excessive exposure to ultra-violet (UV) radiation are well documented, and include an increased incidences of sunburn and skin cancer (Lucas 2010, Norval et al. 2011). However, despite these risks, there has been increased interest in intentional exposure to UV for cosmetic uses such as inducing a tan, or for possible health benefits such as increased vitamin D status, particularly in view of the multiple roles that vitamin D may play in maintaining human health, including protection against rickets, and possible protection against some forms of cancer (e.g., colon cancer) (Chu et al. 2010, Holick 2007). Dietary intake of vitamin D is generally small in populations such as New Zealand's where there is little food fortification. The main source of vitamin D is initiated by photo conversion of 7

dehydrocholesterol (7-DHC)[a] in the skin to form pre-vitamin D, which is subsequently converted to vitamin D, then serum 25-hydroxyvitamin D [25(OH)D] (Holick 2007).

The relatively high UV irradiances in the New Zealand summer, combined with the relatively light skin colouring of a significant proportion of the population and outdoor lifestyle are all contributing factors to New Zealand, along with Australia, having the highest rate of melanoma skin cancer in the world (Brougham et al. 2010). However, in the New Zealand winter, peak UVI values are only 5 to 10% of those in summer, and this low winter UV is a contributing factor to sub-optimal vitamin D status, especially in the winter and spring months (Chatfield et al. 2007, Rockell et al. 2006).

Here we compare UV irradiances from four solaria, typical of what is found in New Zealand, with solar noon clear-sky irradiances from sunlight measured at Lauder New Zealand (45°S) close to the summer and winter solstices.

2. Methods

2.1 Scope of Study

We compare the outputs of the various sources of UV radiation in terms of their spectral irradiances, and their unweighted UV-B and UV-A outputs. Differences in these may lead to health issues in their own right. There is a wide range in possible benefits and risks of UV exposure, but the physiological effects discussed here are limited to the capacity of the sources to induce erythema (sunburn), or to initiate the production of vitamin D. Erythema from sun exposure is a clear indicator of excessive UV, and the association between sunburn history and skin cancer (Gandini et al. 2005) is the basis of sun-advisory messages such as "don't let your kids get burnt" which are promoted by health agencies such as the Cancer Societies in New Zealand and Australia. We emphasise that other positive and negative health outcomes from UV exposures, with wavelength dependencies, may also be important.

2.2 Weighting Functions

The relative importance of different wavelengths (λ) in inducing biological effects is described by the "action spectrum". Figure 1 compares the action spectra for erythema(McKinlay & Diffey 1987, Webb et al. 2011) and for the production of pre-vitamin D from 7-DHC in the skin (Bouillon et al. 2006, MacLaughlin et al. 1982). Both are strongly peaked in the UV-B region, but while the production of vitamin D is confined to UV-B wavelengths, the induction of erythema extends to longer UV-A wavelengths. The figure also shows the ratio of these two weighting functions ($R_{DE}(\lambda)$). For wavelengths less than 298 nm, R_{DE} is close to unity. It increases towards longer wavelengths reaching a peak value of 3.5 near 308 nm, and then decreases to zero by 330 nm. Thus the optimal wavelength range for vitamin D synthesis without inducing erythema is between 305 and 312 nm. The overall weighted irradiances are calculated by integrating the spectral irradiance weighted by the action spectra.

2.3 Solaria

The solaria evaluated in this study comprise two walk-in phototherapy booths used in an Auckland dermatological practice, and two commercial sunbeds which were until recently located at the Moana Pool recreational facility in Dunedin.

The two phototherapy booths are designated as Booth A and Booth B, depending in whether they primarily emit primarily UV-A or UV-B radiation. The UV-A chamber (model Daavlin Spectra 305/350) comprises 36 tubes of type "Philips F 72 T12 BL-HO", and the UV-B chamber (model Daavlin Spectra 726-SP-2X) comprises 20 tubes of type "Philips TL 100W/01-FS72". The booths are used for treatment of skin disorders.

[a] See Appendix for Glossary of Terms

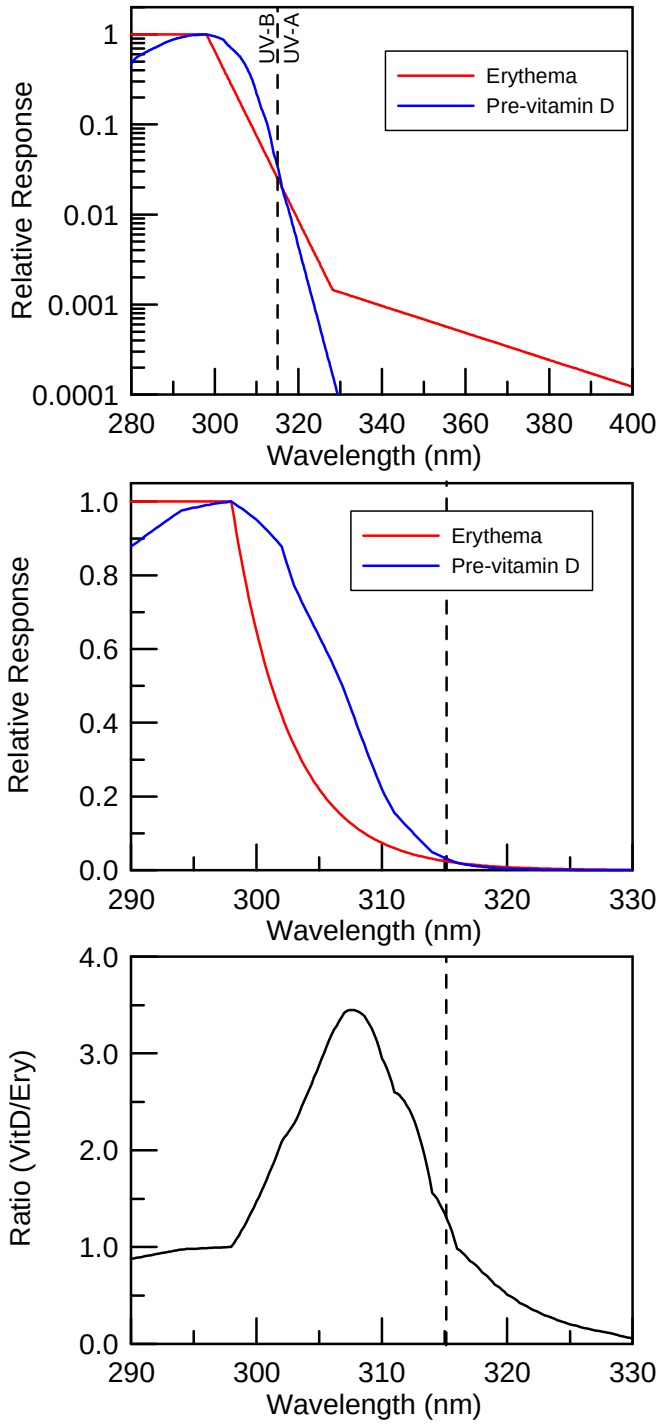

Figure 1. *Upper panel: the action spectra for erythema (McKinlay & Diffey 1987, Webb et al. 2011), and pre-vitamin D production (Bouillon et al. 2006, MacLaughlin et al. 1982). Middle panel: the same data plotted with a linear y-axis scale and a more restricted x-axis. Lower panel: their ratio. In each panel the dashed line demarcates the division between the UV-B (280-315 nm) and UV-A (315-400 nm) spectral regions. Note that since both action spectra include an arbitrary normalisation neither they nor their ratios relate directly to specific physiological changes.*

The two sunbeds, which are used for cosmetic purposes, are designated as Bed 1 and Bed 2. Users lying on these beds are irradiated from above and below. Both beds emit primarily UV-A radiation. Bed 1 is Hapro Luxura model, with 26 "Hapro 100 W R" tubes and a face tube. Bed 2 is an older unlabelled sun bed fitted with 24 newly-purchased "100W Cosmedico brilliant" tubes and a face tube. The fluorescent tubes used in the sunbeds are typical for solaria in common use in New Zealand. The irradiances measured here are comparable with those measured from sunbeds in Australia (Gies et al. 2011) and elsewhere(Nilsen et al. 2011). These latter studies show that there is a wide variability in output between beds. The outputs can also vary substantially over time as the fluorescent tubes age.

2.4 Spectral measurements

Spectral irradiances from the solaria and from sunlight were determined using calibration procedures that are traceable to the USA's National Institute of Standards and Technology (NIST). The uncertainty in solar spectral irradiances is ±5%. Spectra from the solaria were measured with a diode array spectrograph which was cross calibrated against the spectroradiometer. There is considerable spatial variability within the solaria, and we use the means of at least 20 spectra taken from different sites and directions in the chambers. Although the overall spatial variability is large (~20%), the uncertainties in differences between solaria will be smaller because geometric effects are common to all. Further details of the measurement method and the stability of the booths will be described elsewhere.

2.5 Geometric corrections

In the solaria, the irradiance measurements apply to all surface orientations, whereas in sunlight they apply to the upper horizontal surface only. Surfaces oriented towards the sun receive higher irradiances, while those oriented away from the sun receive lower irradiances. In downwelling radiation, these directional effects are large for visible radiation, but less important for UV-B radiation for which at least half of the total is from diffuse skylight, with the fraction from direct sunlight decreasing rapidly as the solar zenith angle (SZA) increases. For example, in the winter spectrum, when the noon SZA is 67°, the direct beam component of UV-B is less than 15% of the total (Zeng et al. 1994). Consequently, the downwelling UV-B radiation is much more isotropic than visible radiation. On the other hand, the upwelling component reflected from the surface is much smaller for UV-B radiation than for visible radiation because of the much lower reflectivity (albedo) of most surfaces in the UV-B region. The overall effect of these factors depends on the SZA, the ozone amounts, and the orientation of surfaces.

For erythema, directional peak irradiances are more important than mean irradiances. In solaria, these peaks are typically 1.15±0.05 greater than the means due to tube-to-tube variability. In sunlight, the peak irradiances occur on surfaces oriented towards the sun, rather than on a horizontal surface. The geometric factors (f_p) to convert to peak irradiances is close to unity for the summer spectrum when the sun is nearly directly overhead, but is 1.35 for the winter spectrum (McKenzie et al. 1997).

Conversely, for pre vitamin D production, mean values are more important than peak values because the production of vitamin D is proportional to the area of skin irradiated. In solaria the radiation field is approximately isotropic, but in sunlight it is not. For example, when the SZA is small (e.g., at noon in summer) the UV dose received by a person standing vertically is less than for a person lying horizontally. But when the SZA is large (e.g., in winter) the vertical orientation receives more than the horizontal orientation. Further, the total UV dose received depends on posture, with a probable minimum for the fetal position, and a maximum when limbs are widely splayed. To characterise these effects

it would be preferable to measure omni-directional fluxes (e.g., the actinic flux) rather than irradiances. However, even then it would be impractical to fully characterise these effects for all conditions. Here we use factors calculated for a cylindrical approximation to the human form (Pope and Godar, 2010). Using this approximation, the geometric correction factors (f_m) to convert to mean irradiances over the skin area are 0.35 and 0.55 for summer and winter sunlight respectively, 0.9 for the horizontal sunbeds where lateral radiation is less intense, and 1.0 for the phototherapy booths.

3. Results

3.1 Irradiances

Figure 2 shows spectral irradiances from the two phototherapy booths and sunlight for clear skies at solar noon (about 12:45 NZST) near the summer and winter solstices at Lauder, Central Otago, New Zealand (45°S, 170°E, alt 370 m). There are marked differences between all sources. The spectrum of Booth B is dominated by a strong emission at 311 nm. Spectra from the two commercial sunbeds are broadly similar to that for Booth A.

For the solaria, irradiances at some wavelengths within the UV region far exceed those from summer sunlight. Compared with erythema, the weighted irradiances for vitamin D production tend to be larger in the UV-B region, but are smaller in the UV-A region, reducing to zero for wavelengths greater than 330 nm.

Weighted irradiances are shown in Table 1. For three solaria, the UV-B irradiances are similar to that from summer sunlight; but the UV-A irradiances far exceed those from sunlight, and may constitute an unknown health risk that is not quantified further here. There is a huge variability in these UVI[b] values, covering more than two orders-of-magnitude. The UVI from Booth B is more than 10 times that for summer sunlight, and for winter sunlight it is less than 10% of that for summer sunlight. The ratio of erythemally-weighted and pre-vitamin D irradiances ($R_{DE} = UV_{VitD}/UV_{Ery}$) also varies greatly between sources. The geometric factors (f_p, and f_m respectively) are applied to convert to peak values that are most relevant to erythema, and to mean skin-area weighted values that are most relevant to the production of pre-vitamin D.

3.2 Benefits for Vitamin D Production versus Risks of Erythema Induction

R_{DE} in Table 1 provides an estimate of the benefit-to-risk ratio for each source, where the benefit is for the production of vitamin D, and the risk is against the induction of erythema. The values in Table 1 assume equal skin areas are exposed to the mean irradiances from each source. By this criterion the UV-A sources (i.e., Booth A, and the two sun-beds) are comparable with winter sunlight, while the ratio is twice as large for the UV-B source (Booth B) and summer sunlight.

In Table 2 we show the geometrically-adjusted risks and benefits from each source relative to summer sunlight. For winter sunlight, both the risks and benefits are reduced by a factor of 10 compared with summer sunlight. For one of the UV-A beds (Bed 1) both the risks and benefits are less than for summer sunlight. For the other two UV-A solaria (Booth A and Bed 2) the risk is slightly greater than for summer sunlight, while the benefits are more than twice as great. For the UV-B booth (Booth B), the risk is increased by more than a factor of ~15 compared with sunlight, while the benefit is increased a factor of ~45. The benefit/risk ratios for each source are comparable with

[b] UVI = 40 x UV_{Ery} when the latter is in units of Watts per square metre (Wm^{-2})

summer sunlight, except for Booth B, which is three times larger. The ratio is slightly lower for winter sunlight and slightly larger for the other three solaria.

Parameter (unit)	Booth A	Booth B	Bed 1	Bed 2	Winter Sun	Summer Sun
UV-A (315-400 nm, Wm^{-2})	188.0	15.2	105.8	131.4	18.0	61.6
UV-B (280-315 nm, Wm^{-2})	1.83	55.4	0.708	2.03	0.180	2.07
UV Index (UVI)	15.6	158	6.8	13.9	1.0	11.3
UV_{Ery} (Wm^{-2})	0.391	3.94	0.17	0.347	0.026	0.282
UV_{VitD} (Wm^{-2})	0.455	8.97	0.181	0.485	0.032	0.567
R_{DE} =UV_{VitD}/UV_{Ery}	1.16	2.27	1.06	1.40	1.22	2.01
$f_p = UVI_{peak}/UVI_{mean}$	1.07	1.05	1.28	1.16	1.35	1.00
f_m= Mean Geom Factor	1.0	1.0	0.9	0.9	0.55	0.35

Table 1. *Measured parameters from the solaria compared with noon sunlight at 45°S at the summer and winter solstices. Measurement uncertainties are ±15% for the solaria and ±5% for sunlight.*

	Ratio Relative to summer sunlight					
	Booth A	Booth B	Bed 1	Bed 2	Winter Sun	Summer Sun
Risk (from UV_{Ery})	1.5	14.7	0.77	1.4	0.12	1
Benefit (from UV_{VitD})	2.3	45.2	0.82	2.2	0.09	1
(VitD Benefit)/(Ery Risk)	1.6	3.1	1.1	1.5	0.7	1

Table 2. *Geometrically-adjusted values relative to those for summer sunlight.*

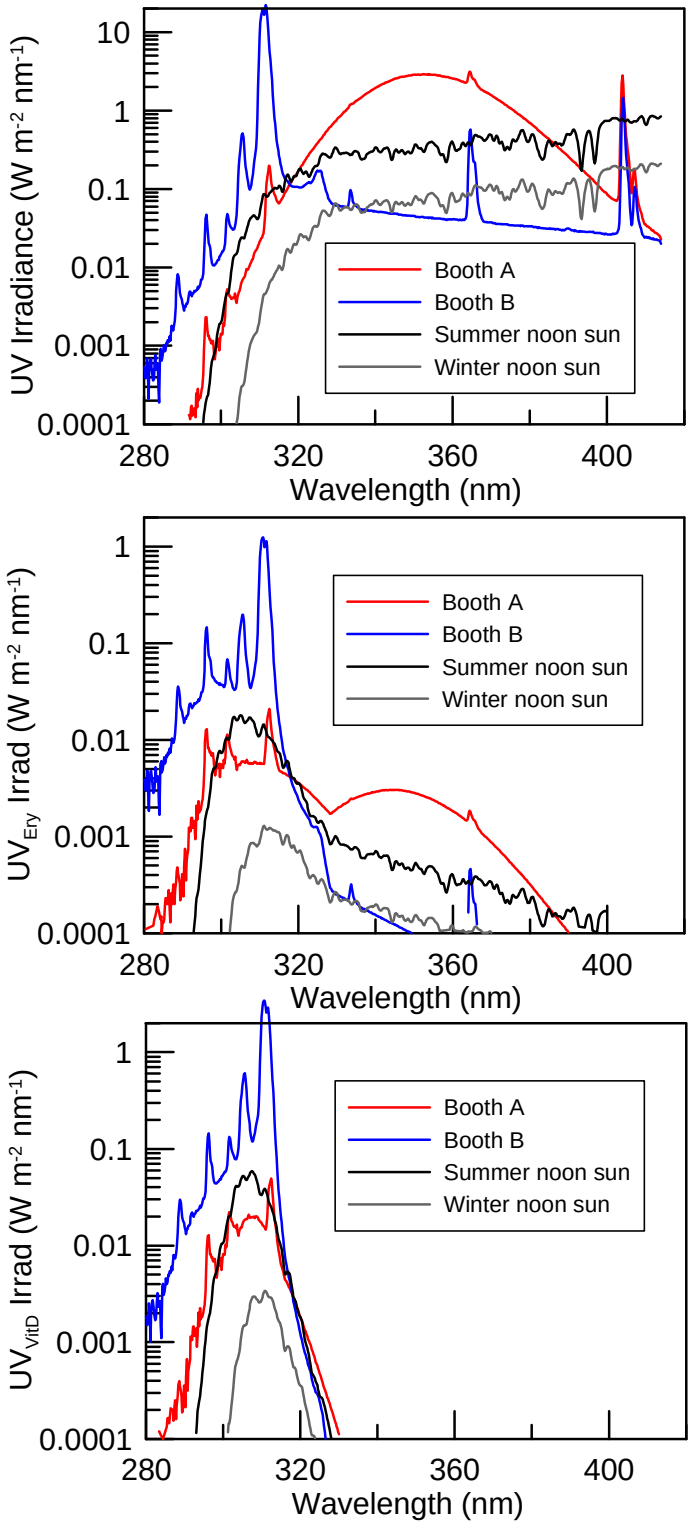

Figure 2*. Upper panel: Spectral irradiances of two UV booths in Auckland compared with irradiances on a horizontal surface measured under clear skies at noon at 45°S in near the summer solstice (21 December) and the winter solstice (21 June). Middle panel: corresponding erythemally-weighted spectral irradiances. Lower Panel: corresponding vitamin D weighted spectral irradiances.*

3.3 Estimated Range of Optimal Exposure Times

The ratios in Table 2 can be converted to approximate exposure times necessary for erythema and vitamin D sufficiency, using published values of the respective times from summer sunlight (McKenzie et al. 2009). These exposure times depend on skin type, and additionally the skin-area exposed for vitamin D sufficiency. The results are approximate, because in practice, the critical exposure times for both the end-points vary greatly between individuals, depending on their skin sensitivity and other factors in the case of vitamin D.

The maximum exposure time (T_{max}) is that needed to induce erythema (sunburn). The recommended threshold exposure between Fitzpatrick's skin type I and II is 2.5 SED[c] (ANZS 2008, Fitzpatrick 1988) was used because individuals with skin type I are advised against using sunbeds. For the summer sunlight spectrum, the time taken to receive 2.5 SED is approximately 15 minutes.

The minimum exposure time (T_{min}) is that needed to maintain blood serum vitamin D sufficiency. We adopt the criterion that vitamin D sufficiency is equivalent to a daily dietary intake of 1000 IU[d] (Vieth et al. 2007). It has been shown that 1 MED of full-body exposure to simulated sunlight is equivalent to 20,000 IU (Holick 2004b), so vitamin D sufficiency is achieved with a daily exposure of 6% of the body to 1 MED, or equivalently, an exposure of 25% of the body to 0.25 MED (Holick 2002), or a full-body exposure to 0.06 MED, which corresponds to about 1 minute per day of full body exposure to summer noon sunlight.

The resulting ranges of approximate exposure times are shown in Figure 3. The red shaded area represents exposure periods longer than those that would induce erythema in fair skins. The blue shaded area represents exposure periods shorter than those needed to maintain vitamin D sufficiency for daily full-body exposures. The unshaded area between these extremes represents the window of opportunity in exposure times for each source for optimal outcomes according to these two criteria.

To illustrate the sensitivity of the results to the choice of action spectrum, the dashed blue lines show exposure times for vitamin D sufficiency as calculated from an alternative action spectrum measured at Queensland University of Technology (QUT), for the conversion from 7-DHC to pre-vitamin D (Olds 2010). If that spectrum were valid, then the time required to maintain vitamin D sufficiency would be shorter for the three UV-A solaria, but longer for the UV-B booth (Booth B) and for winter sunlight.

For different skin types, the exposure times in Figure 3 should be scaled according to the number of SEDs per MED (Fitzpatrick 1988). This is valid for pre-vitamin D production as well as erythema because the wavelengths involved are similar in each case. For the most sensitive skin type (skin type I), the exposure times should be decreased, and for darkest skin types they should be increased by a factor of 10 or more (Holick 2004b). Similarly, the times should be scaled according the effective sun protection factor (SPF) of any sunscreens while recognising that, because of the application thickness is usually somewhat less that the application design criterion 2 mg/cm^2 (Gies 2011), the effective SPF is usually less than the advertised value. The exposure times must also be increased markedly for exposures through glass windows, which in New Zealand sunlight typically transmit less than 10% of UV_{Ery} and less than 1% of $UV_{VitD.}$

[c] 1 SED = 1 Standard Erythemal Dose = 100 Jm^{-2} of erythemally-weighted irradiance.

[d] IU = International Unit, where 1000 IU corresponds to 25 μg of vitamin D. One teaspoon of cod-liver oil contains approximately 400 IU of vitamin D (Hollis 2005).

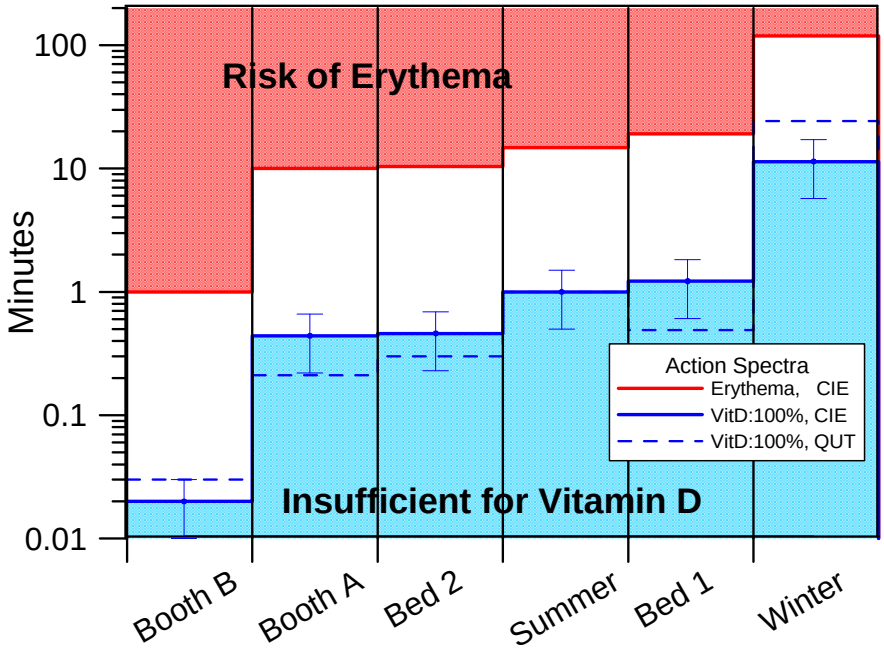

Figure 3. *Approximate exposure time in minutes for erythema and to maintain vitamin D sufficiency (equivalent to 1000 IU per day) for full-body exposure.*

If smaller skin areas are exposed as is likely in sunlight (especially in winter), then the exposure times for vitamin-D sufficiency will be longer. It may not be reasonable to simply assume that the times scale with body area. Firstly, different areas of the body have different levels of pigmentation. Further, the thickness of the skin and variations in the skin transmission as a function of wavelength may also be important. Nevertheless it is clear that if just the hands and face are exposed; representing ~10% of the total skin surface area, then the blue curves would shift up by approximately one order of magnitude. In that case, there would be only a very small window in time between receiving too little UV to maintain vitamin D sufficiency without erythema.

4. Discussion

There has been discussion in the literature (Norval et al. 2009) about the validity of the action spectrum for pre vitamin D (Bouillon et al. 2006). For example, there is an inconsistency regarding summer/winter differences in vitamin D production (McKenzie et al. 2009). As shown by Figure 3, future revisions in the action spectrum for production of pre-vitamin could affect the inferred benefits. These ratios are also influenced significantly by the factor 0.35 used for summer sun. For cloudy skies, or for horizontal orientation, the benefits from summer sunlight could be significantly larger, making the ratios for other sources smaller. For single-sided sunbeds the benefits would be halved.

Recently it was argued that differences in spectral output between the artificial source used in Holick's study(2002) and sunlight were not properly taken into account, and that the exposure periods necessary in summer sunlight may be significantly less than noted above (Dowdy et al. 2010). Further, when estimating absolute exposure times, possible non-linearity in UV dose versus response in pre-vitamin D must be considered. Because the products of 7-DHC photolysis absorb UV-B, there is a threshold above which continued irradiation is less effective in producing pre-

vitamin D (Holick et al. 1981). Early work showed that non-linearities become important for exposures longer than 15 to 30 minutes to summer sunlight (MacLaughlin et al. 1982), which corresponds to a threshold typically greater than 1 MED. More recently it was found that the production of *in-vitro* cholecalciferol from 4 MED was only 50% more than that from 2 MED (Olds et al. 2008). Subsequent work found that the change in vitamin D remained linear up to 1 MED in sunlight (Olds 2010). The studies used to derive the dose-responses used here were from simulated sunlight for an exposure of 1 MED (Holick 2004b). Any departures from linearity would lead to over-estimates of the exposure times for smaller doses.

There are several other significant contributions to the error budget in the derived exposure times. These include uncertainties in spectral measurements, non-uniformities of the radiation fields, and geometric considerations. We estimate the overall uncertainty in the derived exposure times to be ±50%. That uncertainty applies only to skin for which 1 MED = 2.5 SED. In practice, even for the same skin sensitivities there will be further variations in response as a function of other factors such as age and obesity (Holick 2004a). The exposure times also scale with MED and the UV sun blocking factor (SPF) of any sunscreens used; and skin sensitivity is likely to change with acclimation to UV exposure due to skin-thickening and the build-up of melanin.

5. Conclusions

Solaria in common use in New Zealand have potential benefits as well as their well-known risks. One possible benefit is to maintain healthy levels of vitamin D in the winter months when natural levels of UV relevant for its production are less than 10% of those in summer. However, caution is advised. The use of these solaria poses unknown health risks for the unnaturally high irradiances at some wavelengths in both the UV-B and UV-A regions. For both of the sunbeds tested and one phototherapy booth, the integrated UV-A irradiances far exceed those ever experienced in sunlight.

Biologically weighted irradiances from three UV-A solaria tested are comparable with summer sunlight, while that from the UV-B solarium was about a factor of 10 greater. After corrections are applied to account for the geometric differences inherent in each source, the benefit/risk ratios for vitamin D production compared with erythema are comparable to, or slightly larger than, summer sunlight for the two sunbeds and for the UV-A phototherapy booth; but are significantly greater for the UV-B phototherapy booth.

Given evidence of association with increased melanoma risk (Cust et al. 2011), poor adherence to protective standards in an unregulated commercial environment (Paul et al. 2005) and the possibility of other unquantified risk factors that may arise from the unnaturally high irradiances that occur at some wavelengths from these sunbeds, their use cannot be advocated as a means of ensuring vitamin D sufficiency. More effective methods, which come at much lower financial costs and health risk, include prudent exposure to natural sunlight in summer, with possible dietary supplementation in the winter. Fortification of foods can also contribute.

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Appendix: Glossary of terms

7-DHC	7-dehydrocholestrol, pro-vitamin D in the skin.
25(OH)D	25-hydroxyvitamin-D, the form of vitamin D measured in blood serum.
MED	Minimum Eythemal Dose is a measure of the accumulated erythemally weighted UV energy that would cause the first perceptible sign of reddening (i.e., erythema). The energy-equivalent depends on the skin type. For the most sensitive skin types, 1 MED is approximately 2 SED. For skin type II, 1 MED is approximately 2.5 SED (Fitzpatrick 1988).
R_{DE}	Ratio of pre vitamin-D-weighted UV irradiance to erythemally-weighted irradiance.
SED	Standard Erythemal Dose is a measure of the accumulated erythemally-weighted UV energy, where 1 SED = 100 J m^{-2}
SPF	Sun Protection Factor (for sunscreen products).
UV	Ultraviolet (radiation).
UV-B	Radiation in the range 280 to 315 nm (or, extending to 320 nm for UV-B′).
UV-A	Radiation in the range 315 to 400 nm (or, starting at 320 nm for UV-A′).
UV_{Ery}	Erythemally-weighted (or "sun-burning") UV radiation. Mainly UV-B, but including a small component of UV-A radiation (McKinlay & Diffey 1987).
UV_{VitD}	Vitamin-D-weighted UV radiation to that leads to the photo-production of pre-vitamin D in the skin.
UVI	UV Index: a unitless measure of the strength of erythemally-weighted UV radiation (UVI = 40 x UV_{Ery} where the latter is in units of Wm^{-2} (i.e., J m^{-2} s^{-1})) for dissemination to the public. At mid northern latitudes the peak UVI is approximately 10, and values greater than that are often considered as "extreme".

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