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*Ministry of Health, Welfare and Sport*

# Background report on UV radiation and **sunscreen** products

RIVM letter report 2023-0426
A. van Dijk | M. Woutersen

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# Synopsis

**Background report on UV radiation and sunscreen products**

Exposure to UV radiation has both positive and negative health effects. The positive effects include vitamin D production and lower blood pressure, which protects against heart and vascular disease. The negative health effects are sunburn, skin ageing and skin cancer. These are some of the results presented in an overview document produced by RIVM on the health effects of UV radiation and the functioning of sunscreen products.

Sunscreen products ensure that less UV radiation reaches the skin. The higher a product's Sun Protection Factor (SPF) and the thicker the layer applied to the skin, the more the product protects against sunburn.

It turns out that the layer of sunscreen used in the lab test that determines the SPF is much thicker than the layer applied by consumers (2 mg per square centimetre compared to 0.5 mg). As a result, sunscreen products are often less protective in practice than indicated. SPF50, SPF30 and SPF20, respectively, indicate that people can sit in the sun 50, 30 or 20 times longer without getting sunburnt than without sunscreen. In practice, however, they can only sit in the sun seven, four and two times longer.

Depending on wavelength, UV radiation can be divided into UVA, UVB and UVC radiation. Sunburn is primarily caused by UVB radiation. Sunburn increases the chances of melanoma, the most dangerous form of skin cancer. It was long assumed that only UVB radiation causes skin cancer. However, scientists have increasingly found evidence that UVA radiation also contributes.

Some sunscreen products also protect against UVA radiation to some extent, but the packaging does not clearly indicate how well they do this. There are currently no European labelling requirements to clearly inform consumers about the UVA protection of sunscreen products.

Keywords: UV radiation, SPF, skin cancer, sunscreen, UVA, UVB

# Publiekssamenvatting

## Achtergrond rapport UV straling en zonnebrandproducten

Blootstelling aan UV-straling heeft positieve en negatieve effecten op de gezondheid. Positief zijn de aanmaak van vitamine D en een lagere bloeddruk die beschermt tegen hart- en vaatziekten. Negatieve gezondheidseffecten zijn: verbranding van de huid, huidveroudering en huidkanker. Dit en meer blijkt uit dit overzichtsdocument van het RIVM over gezondheidseffecten van UV-straling en de werking van zonnebrandproducten.

Zonnebrandproducten zorgen ervoor dat minder UV-straling de huid bereikt. Hoe hoger de SPF (Sun Protection Factor) en hoe dikker de op de huid aangebrachte laag, hoe meer een product beschermt tegen huidverbranding.

Het blijkt dat bij de test waarmee in het laboratorium de SPF wordt bepaald een veel dikkere laag zonnebrand wordt gebruikt dan de hoeveelheid die consumenten smeren (namelijk 2 in plaats van 0,5 milligram per vierkante centimeter). Hierdoor beschermen zonnebrandproducten in de praktijk veel minder dan staat aangegeven. SPF50, SPF30 en SPF20 geeft aan dat mensen 50, 30 of 20 maal langer in de zon kunnen zitten zonder te verbranden dan zonder te smeren. In de praktijk is dit maar 7, 4 en 2 maal langer.

UV-straling wordt, afhankelijk van de golflengte, onderverdeeld in UVA, UVB en UVC straling. Huidverbranding wordt vooral veroorzaakt door UVB. Een verbrande huid vergroot de kans op melanoom, de gevaarlijkste vorm van huidkanker. Hierdoor was lange tijd de gedachte dat alleen UVB huidkanker veroorzaakt. De laatste jaren vinden wetenschappers steeds meer bewijs dat ook UVA hieraan kan bijdragen.

Sommige zonnebrandproducten beschermen ook in enige mate tegen UVA. Maar hoe goed ze dit doen staat niet duidelijk op de verpakking. Er zijn nu geen Europese voorschriften om consumenten goed te informeren over de beschermende werking van zonnebrandproducten tegen UVA.

Kernwoorden: UV-straling, SPF, huidkanker, zonnebrand, UVA, UVB

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# Summary

This report was prompted by an investigation by the Netherlands Food and Consumer Product Safety Authority (NVWA) into sunscreen products, which involves taking samples to test Sun Protection Factor (SPF) claims. In particular, the investigation looks at the effects of UV radiation and factors that determine the actual protection provided by sun-screen products.
UV radiation is divided into UVA, UVB and UVC radiation based on wavelength. Many health effects, both positive and negative, are linked to skin exposure to UV radiation. Negative health effects include erythema, skin ageing, skin cancer and immune system suppression. Positive health effects include vitamin D production and blood vessel dilation. The most harmful effect is skin cancer, of which the most common forms are BCC, SCC and melanoma. UV radiation is classified by the IARC as a Group 1 carcinogen, with no limitation as to specific wavelength ranges (UVA, UVB, UVC). There are dose-response relationships with exposure to UV radiation for carcinogenicity and other effects, but there is no threshold dose for skin cancer. Correlations have been shown between various effects, for example between erythema and skin cancer. It has long been assumed that melanoma is caused by UVB, but there is a growing body of evidence suggesting that melanoma can also be partly caused by UVA. Erythema is primarily caused by UVB. The vulnerable, at-risk groups for exposure to UV radiation are children, young people under 25, users of immunosuppressants (such as donor organ recipients), people with skin type I and people suffering from xeroderma pigmentosum. In most cases, cancer from skin burn is the key health risk from high exposure.

Internationally, the quality of sunscreen products is defined by the Sun Protection Factor (SPF). This is based on protection from erythema and is therefore primarily an indication of the degree of protection against UVB radiation. Darker skin types provide better natural protection against UVB radiation; for natural protection against UVA radiation, the skin type makes less of a difference. Due to the better natural suppression of UVB radiation, the relative proportion of UVA radiation is higher for darker skin types than for lighter skin types. This has consequences for the performance of sunscreen products: the weaker the UVA filter, the greater the decrease in protection for darker skin types.
Using a product with an SPF that is lower than claimed can aggravate the prevalence of skin cancer. An increase in the risk of skin cancer does not reveal much at an individual level. The layer thickness used to determine the SPF (2 mg/cm2) is four times the aver-age thickness applied in practice by consumers (0.5 mg/cm2). This means that the actual protection factors of sunscreen products labelled SPF50, SPF30 and SPF20 are not 50, 30 and 20 but only 7, 4 and 2. This raises the question of whether the current category of ‘low-protection’ sunscreen products (SPF 6–15) still have a relevant protective effect.

As is clear from the above, in addition to the extent to which the SPF on the packaging is achieved, other factors also have a sizeable influence

on the protection against UV radiation provided by sunscreen products. Of these factors, the level of protection obtained from the real-life application thickness and the representation of the UVA filter deserve attention.

# 1 Introduction

The harmful effects of UV radiation and the protection provided by sunscreen products are attracting a great deal of attention at present. The subject was discussed in a working group meeting of the European Commission, which expressed an intention to review the 2006 Commission Recommendation on Sunscreens.
In 2023, the NVWA is conducting an investigation into sunscreen products, in which samples are being taken to test Sun Protection Factor (SPF) claims. For the purpose of the publication and enforcement process in this investigation, it is necessary to establish the level of deviation from the claimed SPF, compared with the SPF experimentally determined with a standardized methodology, at which there is a risk of damage to consumers' health. To this end, the NVWA asked RIVM questions about the skin related health effects that may be caused by ultraviolet (UV) radiation, the associated risks and the impact of sunscreen products on these risks. In exploring these themes, particular attention was given to the differences between UVA and UVB radiation. This included differences in definition, in health impact and in the degree of protection provided by sunscreen products. Another area of focus was application thickness, and the impact of the fact that, in accordance with the protocol, SPF tests are performed with a layer thickness four times thicker than is typically applied by consumers. We also turned our attention to vulnerable target groups and sunbeds.
Because similar questions about sunscreen products and UV radiation are also being raised in other contexts at the moment, we chose to take a broader perspective in our answers to certain points.
The purpose of this report is to make an overview of the information compiled to answer the NVWA's questions more widely available, including for an international audience.

A glossary of the terms used can be found at the end of the document.

# 2 The health effects of UV radiation

Some of the information provided below about the health effects of UV radiation is based on the Sunbeds QuickScan (Van Dijk, 2020). Other elements were taken from the Dutch translation of the German Skin Cancer Prevention Guidelines.[1] We will start by explaining what UV radiation is before elaborating on the most relevant health effects of UV radiation. Many health effects, both positive and negative, are linked to skin exposure to UV radiation. Negative health effects include erythema, skin ageing, skin cancer and immune system suppression. Positive health effects include vitamin D production and blood vessel dilation. In addition, exposure to UV radiation usually means that the person is going outside, which suggests physical activity and fresh air. Although not strictly related to UV radiation, these health benefits of exposure to the sun should not be forgotten, because they help prevent obesity, cardiovascular diseases and diabetes. In this report, we only examine the associations of exposure to UV radiation with erythema, skin cancer and vitamin D.

## 2.1 UV radiation

Electromagnetic radiation comes in a wide range of wavelengths called a spectrum. UV radiation is part of this electromagnetic spectrum, with wavelengths of between 100 and 400 nm, slightly shorter than the wavelengths of visible light (see Figure 1).

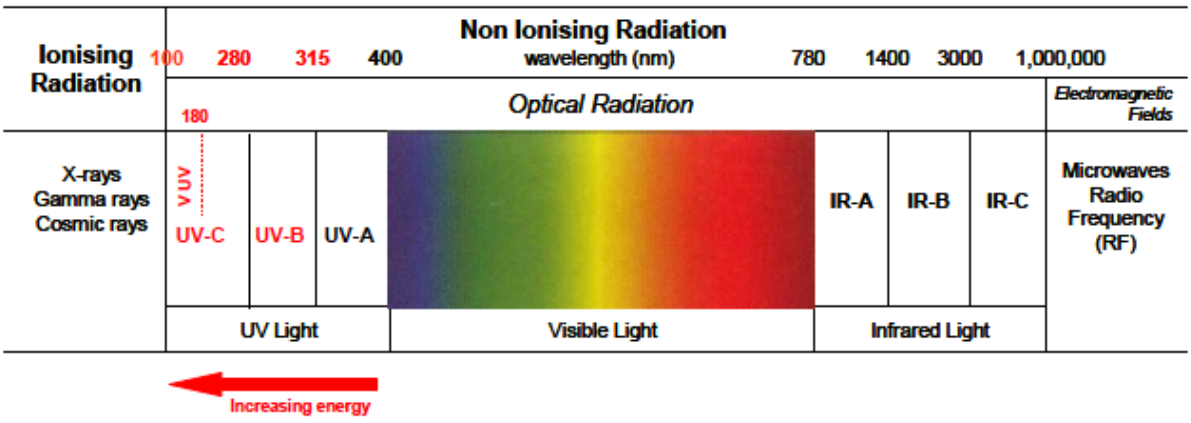


*Figure 1 Electromagnetic spectrum with the sub-range of UV radiation (from https://uv-light.co.uk/what-is-uv-light/)*

Based on wavelength, UV radiation is divided into UVA (wavelengths of 315 to 400 nm), UVB (wavelengths of 280 to 315 nm) and UVC (wavelengths of 100 to 280 nm). UVC from the sun does not reach sea level, since 100% of it is blocked by the ozone layer. UVB radiation from the sun is weakened by the ozone layer, but a small amount still gets through. The fraction of UVB radiation that reaches the Earth's surface depends on the wavelength. UVA simply passes through the air in the atmosphere and is not affected by the ozone layer. In terms of energetic

[1] Available for download from https://www.leitlinienprogramm-onkologie.de/leitlinien/hautkrebs-praevention/

capacity, the UV radiation in sunlight that is present at sea level consists of 95% UVA and 5% UVB. On overcast days, approximately half of the UV radiation is trapped by the clouds, but the other half passes through. In physics terms, the energy or power of a UV source is the sum of the energies or powers of all wavelengths contributing to the UV spectrum of the source.

**Interaction of UVC radiation with human tissue**
Because UVC radiation from the sun does not reach the Earth's surface, it is not relevant to this project. For the same reason, there is little epidemiological knowledge about the health impact of UVC radiation on humans. Of the three types of UV radiation, UVC is potentially the most dangerous, because it contains the highest energy per photon and could thus cause the greatest damage to human tissue (see the ICNIRP Report, McKinlay, 2004). However, due to its short wavelength, it does not penetrate very far into tissue, so the risk from UVC radiation probably mainly relates to eye damage. The UVA/UVB/UVC classification is artificial and not prompted by biological arguments. In rats, it has been observed that UVC radiation contributes to the risk of SCC (a type of skin cancer; see below) (IARC, 1992). Whether UVC radiation could also penetrate the stratum corneum of human skin and contribute to skin cancer is unknown. Nevertheless, ICNIRP (2004) has specified exposure limits for UVC radiation. For the eye, these limits should be considered 'absolute'. The uncertainty in the body of evidence against a risk from UVC radiation for skin cancer in humans means that, for skin, these exposure limits should be considered a 'recommendation'.

**Interaction of UVB radiation with human tissue**
When skin is irradiated with UVB, the majority will not penetrate past the epidermis (see Figure 2). A small fraction of UVB will reach the stem cells in the basal layer. After mutation, these cells could form the basis for skin cancer. UVB radiation contains so much energy that it can lead to 'direct hits': the DNA becomes so damaged that an unsuccessful attempt to repair the cell can lead to a mutation relevant to the formation of skin cancer. For this type of damage, there is no threshold dose: a hit is a hit. UVB will not (or will barely) penetrate to the dermis that lies below the basal layer.

**Interaction of UVA radiation with human tissue**
UVA radiation penetrates deeper into the skin than UVB radiation, reaching the dermis or even the tissue below. UVA radiation is too weak to directly damage the DNA in such a way as to cause mutations that could lead to skin cancer. However, UVA radiation can create free radicals: molecules with unpaired electrons that are highly reactive. They can damage DNA, which can lead to carcinogenic mutations. However, as explained later in this report, it is likely that a threshold dose applies to this route from UVA exposure to skin-cancer-relevant DNA damage.

The health effects associated with exposure to UV radiation are covered in Sections 1.2, 1.3 and 1.4.

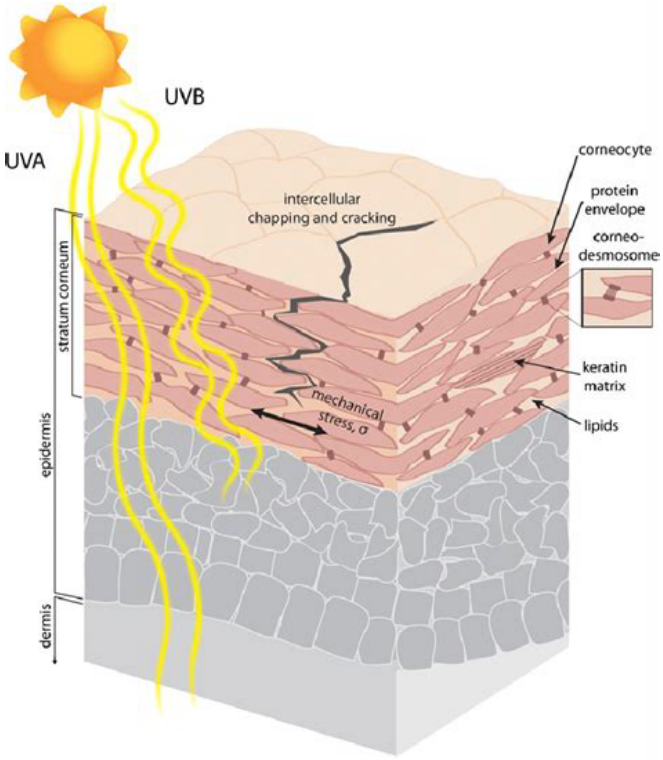


*Figure 2 Schematic illustration of the layers of the skin. UVA radiation penetrates deep into the dermis. UVB radiation is mainly absorbed in the epidermis, but a small fraction reaches the stem cells in the basal layer (Biniek et al. 2012).*

## 2.2 Erythema (skin burn, sunburn) and the UV Index

Exposure of the skin can lead to erythema (burning of the skin by UV radiation, sunburn, redness), an acute subcutaneous inflammatory response that typically lasts for four to seven days. Cells irreparably damaged by UV radiation release signalling molecules (cytokines), which activate blood vessel dilation so the damage can be cleared away. This dilation of blood vessels gives a red colour to the skin. With severe erythema, part of the epidermis may be shed (peel off). Erythema is the first effect of UV radiation that most people notice. For this reason, this health effect is internationally used as a reference effect to inform people of the extent to which it is relevant for them to protect themselves from the sun as well as to inform them of the effectiveness of sunscreen products (see WHO, 2002).

How effectively UV radiation can induce erythema depends on the wavelength. Accordingly, when discussing erythema, by international agreement, the power (or energy) of a UV source (the sun or a sunbed) is expressed in units of erythema-weighted power (or energy). For this calculation, the contribution of each wavelength on the spectrum is weighted by the effectiveness of radiation with that wavelength in causing skin redness. This effectiveness is described by the 'erythema action spectrum', the red line in Figure 3. This action spectrum was calculated for fair skin (Fitzpatrick skin type II, see explanation below) and has not been adapted for other skin types. As an example, we show how this works for sunlight. The green line in Figure 3 shows the physical spectrum of the sun at sea level. It can be seen that sunlight

contains little UVB (5%) and a lot of UVA (95%). The blue area shows the erythema-weighted spectrum (the green line multiplied by the red line). Now the UVB:UVA ratio is almost inverted: the erythema-weighted solar spectrum is dominated by UVB.

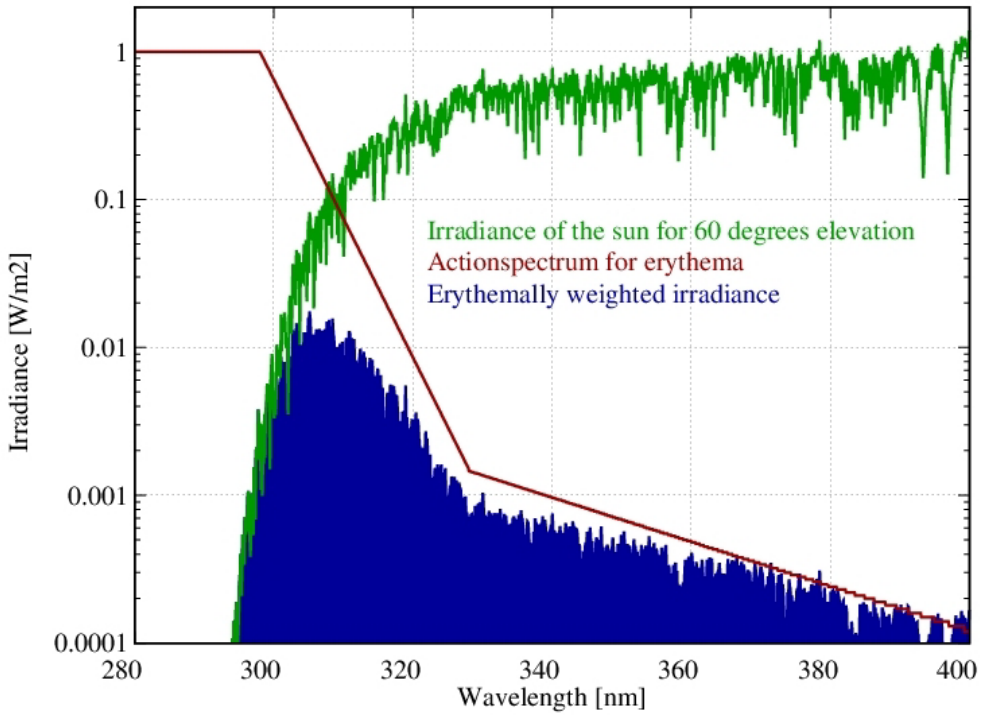


*Figure 3 Relationship between the physical UV spectrum and the erythema-weighted spectrum*

Internationally, the UV Index is used to indicate the strength of the sun's rays. The UV Index is equal to 40 times the erythema-weighted irradiance in W/m$^2$. This produces a figure that typically stays below 10 in the Netherlands but can climb as high as 15 elsewhere in the world. When the UV Index is at 3 or above, the international recommendation is to avoid the sun, wear clothing that covers the skin and apply a sunscreen product. When the UV Index is at 5 or above, the international recommendation is to go outside only when absolutely necessary. These recommendations are based on the 'standard' skin type, II. This is because this skin type is common in the Netherlands and is relatively sensitive. Higher skin types are automatically well protected by the recommendations for skin type II. The recommendations are not based on type I, the more sensitive skin type, because that would result in an unnecessarily strict set of restrictions for the vast majority of the population.

An objective measure for the erythema-weighted dose is the Standard Erythemal Dose (SED), where 1 SED is equal to 100 J/m$^2$ of erythema-weighted irradiance received. Erythema is also subject to a threshold dose, known as the MED (Minimal Erythemal Dose). The MED varies from person to person. Fitzpatrick [Fitzpatrick, 1988] created a skin type classification with six categories based on the MED value and the ability to adapt following exposure to UV radiation. Characteristic values for the various Fitzpatrick skin types are shown in Table 1. In this table, burning

relates to the state 24 hours after exposure and tanning to the state 7 days after exposure.

*Table 1 Minimal erythemal dose for various skin types*

| Fitzpatrick skin type | Reaction to UV exposure | Features | MED [SED] |
|---|---|---|---|
| I | Always burns, never tans | Pale skin, red or blond hair | 2–3 |
| II | Usually burns, tans less than average | Pale skin, dark-blond to chestnut-brown hair | 2.5–3.5 |
| III | Sometimes burns, average tanning ability | Light brown skin, dark hair | 3–5 |
| IV | Rarely burns, tans more easily than average | Dark-skinned Mediterranean, light-skinned Asian | 4.5–6 |
| V | Never burns, always tans to dark brown | Dark-skinned Asian | 6–10 |
| VI | Never burns, no visible change of colour | Afro-Caribbean | 10–20 |

## 2.3 Skin cancer

In 2009, the International Agency for Research on Cancer (IARC) classified UV radiation originating from the sun and the artificial sources used in sunbeds as a Group 1 carcinogen (proven to be 'carcinogenic to humans') (IARC, 2012 [the actual publication was not issued until three years after the decision]). This is the category with the strongest body of evidence. This classification was assigned with no limitation as to specific wavelength ranges (UVA, UVB), based on proven epidemiological and fundamental scientific findings. The most common forms of skin cancer are:

- **Basal cell carcinoma and squamous cell carcinoma:** in the previous IARC report from 1992, the causal link between exposure to sunlight and basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) was still based on descriptive data from populations with skin types I, II and III, with positive associations being found between being born or living at a low latitude and the rare occurrence of these tumours in areas of the skin that are seldom exposed to the sun. That report also relied on case-control studies and cohort studies, in which exposure to the sun was retrospectively deduced based on participants' memories.

  Since 1992, studies have been published that used more objective measures for the UV dose, as well as studies looking at non-oncological skin conditions caused by cumulative sun exposure, such as solar lentigines (also called pigment spots or age spots) and actinic keratosis.

  For BCC, all studies except one (Corona et al., 2001) showed a positive association with erythema (at any point in life or

regularly). All of the studies that looked at actinic keratosis (Green, 1996; Corona, 2001; Walther, 2004; Pelucchi, 2007) also showed that this was a strong risk predictor. It has been suggested that the association of BCC with sun exposure may depend on the histological subtype of the BCC (Bastiaens, 1998).

For SCC, although case-control studies show very little association with erythema, cohort studies uniformly show a significant, positive association. The presence of actinic keratosis, some of which is a precancerous stage of SCC, produced the strongest association found (Green, 1996). SCC is caused by the integrated UV dose, i.e. by chronic exposure, and is mainly attributed to the UVB component.

- **Melanoma:** occurs in the pigment cells of the skin. Until the end of last century, in studies into the association of skin cancer with sunlight, melanoma was regarded as a single entity, regardless of whether it appeared in the skin, mucosa, the genitals or the eye. Only lentigo maligna melanoma (on the face, slow growing) and acral lentiginous melanoma (on the palms of the hands, on the soles of the feet and under the nails) were excluded from studies. The first type, paradoxically, because there was a causal link with cumulative sun exposure, and the second type for the opposite reason: it occurred primarily on the soles of the feet. In the IARC report from 1992, the evaluation of the causal relationship between exposure to sunlight and melanoma was mainly based on descriptive data and data from case-control studies. The key exposure data came from participants' memories. 'Intermittent exposure to sunlight', which was loosely compared with certain sun-intensive activities such as sunbeds, 'outdoor recreation' and holidays in sunny climates, showed a moderate to strong correlation with melanoma. However, chronic and more continuous exposure, the equivalent of 'occupational exposure' and 'total sun exposure', showed weak, non-existent or even negative associations with melanoma.

  These results for melanoma risk have since been collectively interpreted as the 'intermittent sun exposure hypothesis' (Fears et al., 1977), which argues that melanoma occurs as the result of a pattern of intermittent, intense episodes of sun exposure, rather than as the result of a chronic dose. Other studies that have looked at skin conditions caused by sun damage, such as the presence or a history of actinic keratosis, or signs of other sun-related skin damage, have almost uniformly found a strong positive association with melanoma. The inconsistency of the evidence with regard to the apparently negative association of reported chronic sun exposure with melanoma was noted but not adequately explained.
  Since then, various systematic reviews and meta-analyses have been published on the association of melanoma with sun exposure. In one of the largest meta-analyses, based on 57 studies published up to September 2002 (Gandini et al., 2005a,b), the relative melanoma risks were summarised as follows:

- erythema (ever/never): 2.0 (95% confidence interval of 1.7–2.4);
- intermittent sun exposure (high/low): 1.0 (95% confidence interval of 0.9–1.0);
- total sun exposure (high/low): 1.3 (95% confidence interval of 1.0–1.8);
- actinic keratosis (present, past/none): 4.3 (95% confidence interval of 2.8–6.6).

In considering the incidence of melanomas, IARC 2012 discusses the following three factors in greater detail:

*Skin areas:* various studies have revealed differences in age-specific melanoma incidence for different areas of the skin (Holman, 1980; Houghton, 1980; Elwood & Gallager, 1998; Bulliard & Cox, 2000). The numerous studies into melanoma incidence by area of skin (Weinstock, 1989; Urso, 1991; Green, 1992; Krueger, 1992; Rieger, 1995; Whiteman, 1998; Carli, 1999; Hakansson, 2001; Winnepenninckx & van den Oord, 2004; Cho, 2005; Purdue, 2005; Nikolaou, 2008) collectively show that melanomas on the head and neck are strongly associated with actinic keratosis and that melanomas on the torso are strongly associated with naevi (moles). Similar findings have been reported in case-case studies (Whiteman, 2003, 2006; Siskind, 2005; Lee, 2006).

*Skin pigmentation:* two observations made in epidemiological studies could help substantiate the assertion that melanoma is not caused by chronic sun exposure. First, outdoor workers (who experience chronic exposure to UV radiation) appear to have no increased risk of melanoma (IARC, 1992; Armstrong & Kricker, 2001). Second, outdoor workers in general have an above-average ability to tan (Green, 1996; Chang, 2009). Outdoor workers tend to be constitutionally protected against skin damage from the sun and have a lower risk of skin cancer than workers in other professions, due to self-selection based on skin pigmentation. Such self-selection was observed in a non-Hispanic white study population from Philadelphia and San Francisco (USA), in which the average number of hours worked outdoors generally increased with the ability to tan (Fears, 2002). The role of base sensitivity in influencing sun exposure in the aetiology of melanoma has long been acknowledged (Holman, 1986; Nelemans, 1995).

*Latitude:* patterns of exposure change with latitude, due to latitude-based differences in exposure opportunity and behaviour (Elwood & Diffey, 1993; Gandini, 2005a,b). This means the way in which sun exposure is reported can vary between studies conducted at different latitudes, making it difficult to compare studies and their outcomes. One way of getting around this problem is by using the 'environmentally available UV radiation' (Fears, 2002; Kricker, 2007) for individuals during their lives, calculated using their residential history, to quantify the possible exposure to UV radiation for each individual.

Two case-control studies, both conducted at temperate latitudes (Connecticut (USA), 42 degrees north, see Chen, 1996, and Italy, 37–45 degrees north, see Naldi, 2005) presented skin-area-specific melanoma risks in relation to latitude. Remembered episodes of erythema throughout life generally had a predictive value for melanomas in all skin areas in both case-control studies and in the pooled analysis (RR 1.0-2.0). People with skin conditions caused by cumulative sun damage had an increased risk of melanoma in certain skin areas: the presence of solar lentigines was correlated with an increased chance of melanoma on the lower limbs, while actinic keratosis was associated with melanoma on the head and neck (Chang, 2009; RR 3.1, CI: 1.4–6.7; based on three studies from high to low latitudes, in which solar keratoses were measured). The omission of numerous studies into the lentigo maligna melanoma subgroup, which is known to be associated with cumulative sun exposure, may have resulted in an underestimate of the association with melanomas on the head and limbs.

### 2.3.1 *Is there a threshold dose for skin cancer?*

If there were a threshold dose for the development of skin cancer from UV radiation, that would leave open the possibility of safe exposure. As described above, by far the majority of studies into the link between exposure to UV radiation and skin cancer are epidemiological studies. These studies looked at whether there is a correlation between exposure, determined as the integrated UV dose (for SCC), erythema incidence as a proxy for exposure (for melanoma) and everything in between (for BCC), and the development of skin cancer. These studies produced no information, or only very limited information, about the mechanism of action, which is related to the answer to the question of whether there is a threshold dose. However, *in vitro* research into sunlight shows that UVA radiation is mutagenic in yeast and human cells and UVB radiation in bacteria and human cells (IARC, 2012). Mutagenicity from direct DNA damage is generally considered to be a mechanism of action without a threshold value. Slaper showed that mice exposed to UVB radiation will always develop SCC eventually, no matter how low the selected dose rate (Slaper, 1987). The total dose is decisive only for the SCC risk.

Reichrath et al. (2018) referred to research by Zastrow et al. (2015) and Zastrow & Lademann (2016), in which a plausible threshold dose in humans was determined. This would apply to indirect DNA damage from oxygen radicals dislodged by UVA but not to direct DNA damage from UVB. This hypothesis is not or not yet widely supported, but it has also not been invalidated. There has been no speculation on a threshold dose for UVB, but it is accepted that there is none, due to the direct interaction with the DNA of skin cells: UVB has so much more energy than UVA that it can damage DNA directly, which can lead to mutations (IARC, 2012). Because there is no dose at which there is no possibility of this happening, there is no threshold dose. This is in line with the observation that SCC is caused by the integrated UV dose and the fact that the SCC-weighted irradiance spectrum of the sun is strongly dominated by UVB.

Based on current knowledge as described above, we can assume that, in general, there is no threshold dose for UV-radiation-induced skin cancer.

2.3.2 *Increased evidence of elevated melanoma risk from UVA radiation*

It has long been assumed that melanoma is caused by UVB, but there is a growing body of evidence suggesting that melanoma can also be partly caused by UVA (Van Weelden et al. 1988, De Gruijl 2002, Sample & He, 2018).

The recent provisional and final proposals from the FDA regarding sunscreen products (FDA, 2021) provide a good summary of the current body of evidence. The passage below has been copied verbatim from the FDA's proposal and italicised to indicate that it is a quote.

*Since publication of the 2011 L&E Final Rule and Max SPF PR, the strength of scientific evidence linking UVA exposure to skin cancers and other harms has increased. This evidence suggests that UVA wavelengths continue generating DNA lesions hours after UV exposure (Premi et al. 2015) and that if left unrepaired, these DNA lesions can form UV-induced mutations in many genes that have been detected in both melanoma and nonmelanoma skin cancers (Brash 2016; Hodis et al. 2012; Krauthammer et al. 2012; Ziegler et al. 1994). Further, unlike UVB-induced DNA lesions, which attenuate with skin depth, recent evidence indicates that DNA lesions induced by UVA I exposure show the opposite pattern, with both increased DNA lesions in the basal layer of the epidermis (where melanocytes and proliferating keratinocytes reside) and less efficient DNA lesion repair in the basal layer (Tewari et al. 2013; Tewari et al. 2012).*

*Damage to cells in the basal layer (if left unrepaired or if inefficiently repaired) can lead to mutations in critical genes that increase the possibility that normal cells will transform into cancer cells. While inefficient DNA repair is a concern for all individuals exposed to UV radiation, this concern is particularly acute in those with xeroderma pigmentosum (a disease caused by a disorder of the DNA repair system), who have extreme sensitivity to UV radiation, and who develop both nonmelanoma skin cancer and melanoma with a high frequency and very early in life (DiGiovanna and Kraemer 2012). In addition to the skin cancer-related risks associated with UVA exposure, increasing evidence shows that UVA I radiation also produces immunosuppression (Damian et al. 2011; Marionnet et al. 2014). This, too, is a general concern for all individuals, but is especially dangerous for certain at-risk populations (such as organ transplant recipients and others on immunosuppressive drugs).*

*Given the above-described evidence, we are concerned about the existing potential for inadequate UVA protection in marketed sunscreen products. This is a particular concern with respect to high SPF sunscreen products that do not pass FDA's current critical wavelength-based broad spectrum test or that (though they pass our current broad spectrum test) have inadequate uniformity in their UVA protection. Consumers using these products may, while successfully preventing sunburn, accumulate excessively large doses of UVA radiation, thereby exposing themselves to additional risks related to skin cancer and early skin*

*aging. The International Agency for Research on Cancer has found that high SPF sunscreen products are associated with longer intentional UV exposures (Autier et al. 2007), raising the concern that use of these products may result in significant doses of UVA radiation. We note that concerns relating to inadequate UVA protection came up in several comments we received in response to the 2011 Max SPF PR, and that these comments raised particular concerns about inadequate UVA protection in high SPF products. This concern has also grown over time in the published literature (Diffey 2012; Diffey 2009; Wang et al. 2008; Diffey 2001).*

The SPF stated on the packaging of sunscreen products provides an indication of the UVB protection (see the definition of SPF further on in this report). The above account from the FDA shows that UVA protection needs to be linked to UVB protection, so that a product offers protection against both UVA and UVB radiation.

2.3.3 *Dose-response relationships and dose quantities*

We have taken the relationships (and parameter values) from Slaper et al. (1996). For SCC, the total number of tumours $Y(a)$ in a birth cohort with age $a$ can be found using the following proportionality relationship:

$$Y_{\mathrm{SCC}}(a) \sim \Phi(a)^c a^{d-c}$$

In this formula, $\Phi(a)$ represents the cumulative UV dose up to age $a$, while the parameters $c = 2{,}5 \pm 0{,}7$ and $d = 6{,}6 \pm 0{,}4$ are derived from epidemiological studies. For BCC and melanoma (CM), the dose-response relationships are a little more complex:

$$Y_{\mathrm{BCC,CM}}(a) \sim \sum_x D(x)\Phi(x)^{c-1}(a-x)^{d-c}$$

Here, $D(x)$ is the dose received at age $x$. This formula places greater emphasis on childhood exposure than in the relationship for SCC. The parameters are estimated to be $c = 1{,}4 \pm 0{,}4$ and $d = 4{,}9 \pm 0{,}6$ for BCC, and $c = 0{,}6 \pm 0{,}4$ and $d = 4{,}7 \pm 1{,}0$ for melanoma.

The incidence can be estimated by differentiating these relationships by age for the total number of tumours. The scale factors that make these relationships absolute can be estimated using the latest registration figures.

The coefficient $c$, which is given above for the three types of skin cancer under consideration, is known as the 'biological amplification factor'. This factor indicates (for small dose changes) the percentage by which the incidence will change if the dose increases by 1%.

The dose-response relationships given above are applicable at the population level and cannot be used to estimate individual risk. The development of skin cancer is largely a random process. Individuals with equal sensitivity have a chance of developing skin cancer through exposure, but it is not possible to predict who will do so.

As previously discussed, the dose quantity that should be used in the above relationships varies with the type of skin cancer. Three different dose quantities are clear: (1) the integrated dose (annual or lifetime dose), (2) the integrated dose (annual or lifetime dose) whereby only everything that exceeds a yet-to-be-determined threshold dose rate (one dose per unit of time in which the skin is able to process the dose) is included and (3) the number of times (per year) that an individual experiences erythema. For the first two quantities, there are still many decisions to make in terms of the wavelengths to be included and their relative weightings. For SCC, the SCUP-h-weighted integrated UVB dose is the obvious choice (see De Gruijl, 1994 for the derivation, and also ISO, 2016 for the current version of the SCUP-h action spectrum; see also the glossary at the end of this report). For BCC, no action spectrum has been measured, so the SCUP-h action spectrum, which relates the health effect to UVB radiation, is usually used for BCC too. In terms of dose quantity, in light of the body of evidence cited, it would be sensible to combine (1) and (3). For melanoma, a combination of (3) applied to the UVB dose and (2) applied to the UVA dose should be used. The two different action spectra, with the wavelength-dependent efficiencies of these dose quantities in contributing to melanoma formation, are yet to be established.

Everyone behaves differently, so it is impossible to know, or even to estimate, the actual UV dose received by every individual. Differences between countries in terms of climate-related exposure behaviour also show that it is impossible to determine the exposures of different populations and thus to compare them using a universal questionnaire. A practical assumption that is often used to avoid the difficulties involved in estimating exposure using questionnaires is that all the various dose quantities are proportionate to the 'environmentally available UV dose'. This is the UV dose available on a horizontal surface with an unobstructed horizon, such as the roof of a tall building or the beach. Unlike the actual UV dose received by individuals, the environmentally available UV dose can be reasonably estimated with a radiation transfer model based on satellite observations of ozone layer thickness and cloud cover. It is then assumed that everyone receives a fixed fraction of this environmentally available UV dose. This is taken into account in scale or standardisation factors of the dose-response relationships. This approach does not take account of latitude-dependent sunlight availability over the course of the day, nor does it take account of the horizontal portion of the UV flux reflected by human skin or the latitude dependency thereof.

### 2.3.4 *Vitamin D*

Skin makes vitamin D under the influence of UV radiation. This occurs when the sun is high, at a rate that is usually estimated based on a rule of thumb known as Holick's rule (see Dowdy et al., 2010): ¼ MED over ¼ of the skin gives 1,000 IU (= 25µg) vitamin D (oral intake equivalent). When the sun is in a lower position, the vitamin D production per erythemal dose is less efficient. The production of vitamin D can be described with first-order kinetics, whereby the production is linear to the dose. In the Netherlands, exposure to UV radiation from the sun is the primary source of vitamin D. We obtain the rest from food (an average of 4 µg/d, see Van Rossem et al., 2020).

Vitamin D produced from sunlight in spring and summer is largely stored in body fat. In winter, when the sun is low, vitamin D produced with UV radiation in the summer and retrieved from the fat is the primary source of vitamin D for many people, more than food. There is a significant overlap between the part of the UV spectrum that leads to the production of vitamin D, the part that causes erythema and the part that causes SCC. This means that the benefit of vitamin D production is difficult to view in isolation from the risk of erythema or SCC. Vitamin D is made in the epidermis under the influence of UVB. Young et al. (2019) have demonstrated that, even with careful use of sunscreen products, reasonable vitamin D production without burning is, in theory, still possible. As well as via UV radiation, it is also possible to increase vitamin D levels in the body with food or food supplements.

In countries at temperate latitudes, population groups with dark skin have systematically lower vitamin D levels on average than people with pale skin (Lips, 2007). Datta et al. (2021) have shown that dark skin is only slightly less efficient at vitamin D production. They also found that, when dark-skinned individuals go outdoors, they expose approximately three-quarters of the amount of skin exposed by pale-skinned individuals, so this cannot explain the difference either. The dominant explanation for the difference found in 25(OH)D levels (normal vitamin D levels) is that individuals with a migration background expose themselves to the sun a lot less in their leisure time. The findings of Datta et al. are shown below in a graphical abstract taken from the article in question. These results makes sense when we remember that the pigment (eumelanin) that gives dark skin its colour is found mainly in the epidermis, in a thin layer directly above the basal layer with its stem cells, or is highly localised in keratinocytes directly above the nuclei (to protect the DNA), while 7-DHC (provitamin D), the raw material for the photosynthesis of vitamin D, is mainly found in the cell walls of the keratinocytes in the epidermis. Accordingly, even in dark-skinned individuals, UV radiation is able to reach the relevant raw material for vitamin D production more or less unimpeded by the epidermis, while the DNA (particularly in the stem cells) is much better protected than in pale-skinned individuals. For a long time, it was believed that the lower vitamin D levels were due to the fact that dark skin is better protected from UV radiation, meaning all UV-driven health effects were slower, including vitamin D production, but Datta’s research contradicts this belief.

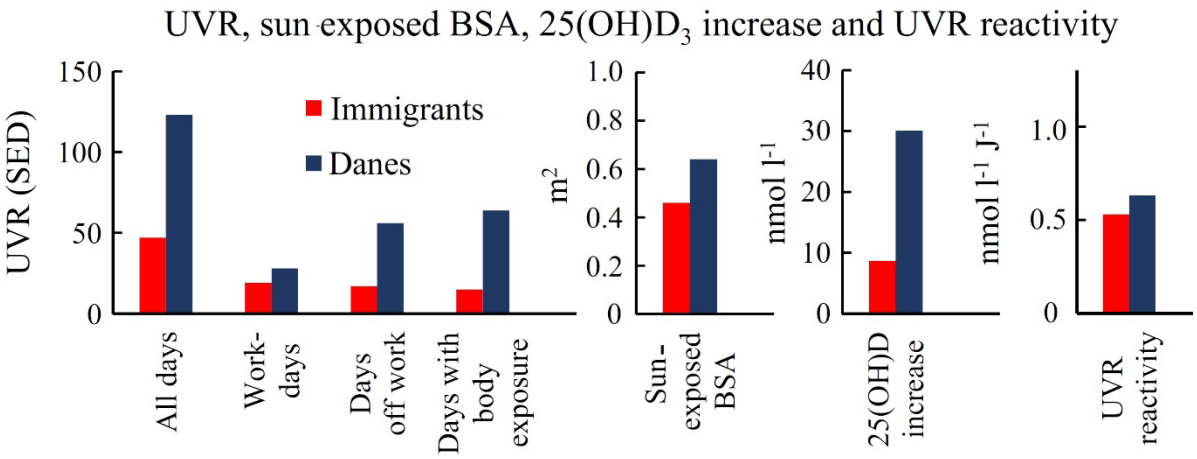


*Figure 4 Findings from Datta et al. (2021) showing that the lower vitamin D levels of dark-skinned migrants in countries at temperate latitudes are not caused by dark-skinned migrants having a lower ability to produce vitamin D but by the fact they spend less of their leisure time outdoors. UVR is the UV dose received, and BSA is the exposed body surface area.*

# 3 Vulnerable target groups for exposure to UV radiation

In no particular order, they are (figures are for the Netherlands):

**Children (3.3 million aged 0–18 years):** because they are still growing, their cells divide more quickly, and dividing cells are more sensitive to incurring DNA damage. In addition, young people's skin still has a long future ahead of it, so there is more to gain from protecting their skin, particularly from burning. There is also a latency period between skin exposure/damage and the development of skin cancer. This period varies between cancer types, but it is typically 15 (melanoma) to as many as 50 years (SCC). This means exposure later in life may present much less risk than childhood exposure.

**Young people up to the age of 25 (1.6 million aged 18–25 years):** young people (particularly men) bare their skin relatively frequently, without protection (see Görig, 2018). If they do apply sunscreen, a protection factor that is too low creates a higher risk, because increased exposure to UV radiation at a younger age increases the chance of getting skin cancer later in life.

**Donor organ recipients (1,402 transplants in 2022):** these individuals use immunosuppressants to ensure the received organ is not rejected. This impairs the ability of their immune system to recognise and repair skin damage and makes it easier for mutations to accumulate. As a result, donor organ recipients face a relatively higher risk of skin cancer.

**People with skin type I** (pale, freckles, red hair): this type of skin burns the fastest and never acclimatises to the sun. Even in September, they are just as sensitive to the sun as in March, whereas in people with skin type II or higher, the skin may have built up protection to a factor equal to SPF 3 at temperate latitudes or up to 10 at Mediterranean latitudes; see Diffey (2021). Erythema is most closely associated with melanoma (as opposed to BCC or SCC), so people with skin type I have an increased risk of melanoma.

**People suffering from xeroderma pigmentosum (1 in a million):** this is a hereditary disorder whose sufferers cannot go into the sun at all without protection. They are dependent on the proper functioning of protective measures, including sunscreen products. People with this condition are at a significantly increased risk of all types of skin cancer.

# 4 Protection against UVA and UVB radiation

UVA and UVB are ranges of wavelengths of ultraviolet radiation: UVB radiation has wavelengths of 280 to 315 nm, and UVA radiation has wavelengths of 315 to 400 nm. Sunbed and other lamps and the sun emit both UVA and UVB. The difference between lamps and the sun comes from the mix (spectrum) of UVA and UVB contributions to the radiation.

## 4.1 Difference in exposure to UVA and UVB from high sun, low sun and sunbeds

UVA and UVB from a sunbed give exactly the same health effects as from the sun. Traditional sunbeds emit a much larger relative proportion of UVA (out of the total UV radiation they emit) than the sun. See Figure 5, for example. This figure also shows that the relative proportion of UVA when the sun is low is greater than when the sun is high. This is relevant, because there is also a small proportion of UVA radiation that causes erythema, and historically, many sunscreen products have provided much poorer protection against UVA than UVB radiation. Due to the differences in emphasis on UVB or UVA between the different sources of UV radiation, the actual protection from a protective product depends on the choice of source. Note that this figure has a logarithmic vertical axis, which means the areas under the lines in the graph are not a good indication of energy contributions.

## 4.2 Impact of sunscreen product use on UV-related health effects

### 4.2.1 *Irradiance spectrum*

UV radiation comes in a wide range of wavelengths called a spectrum. The spectrum and intensity of UV radiation vary according to the source. Figure 5 shows irradiance spectra $I(\lambda)$ for four sources: the sun at its highest position of the year in the Netherlands (21 June, late spring/early summer, at midday, at an elevation angle of 60 degrees), the sun at its highest position in the ‘early spring/late summer’ season (21 March/21 September, at midday, at an elevation angle of 30 degrees) and two conventional sunbeds.

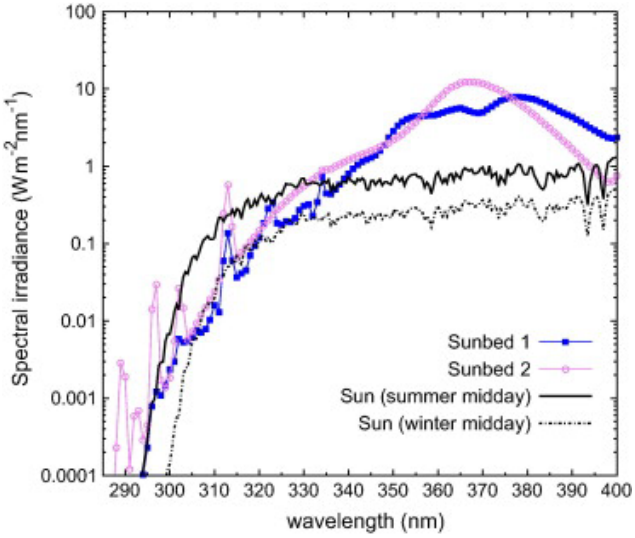


*Figure 5 Irradiance spectra for the sun at two elevations and for two sunbeds. (Figure taken from Sola, 2015)*

### 4.2.2 *Action spectrum*

UV radiation has numerous health effects. All of these health effects have their own 'action spectrum'. This is an empirical function that indicates, for each wavelength, the efficiency of UV radiation at that wavelength in producing the intended health effect, compared with the efficiency of UV radiation with a self-selected reference wavelength. The action spectrum of each UV-related health effect has a different emphasis within the UV spectrum to which an individual is exposed. The assumption when using action spectra is 'additivity': that the effects resulting from the various wavelengths can be added together. The traditional view was that the health effects of UV radiation could mainly be attributed to the short-wave UVB radiation, with wavelengths of 280 to 315 nm: erythema (NEN, 2019), non-melanoma skin cancer (characterised by the SCUP-h action spectrum, see De Gruijl, 1994 and NEN, 2006) and vitamin D production (see CIE, 2006). Nowadays, it is increasingly evident from the scientific literature that UV radiation with other wavelengths, such as UVA (315–400 nm), is also involved in negative health effects. These include immune system suppression (De Gruijl, 1997; Damian, 2011), deactivation of DNA repair mechanisms (Kciuk, 2020), formation of free radicals deep in the dermis (which is related to melanoma formation) (Zastrow, 2009) and melanoma formation (Sun, 2020). See also Section 1.3.2. Figure 6 shows the action spectra $A(\lambda)$ for most of the effects just mentioned, based on data from the publications cited, as well as the action spectrum for the conversion of trans-urocanic acid to cis-urocanic acid, a biomarker for exposure to UV radiation (McLoone, 2005).

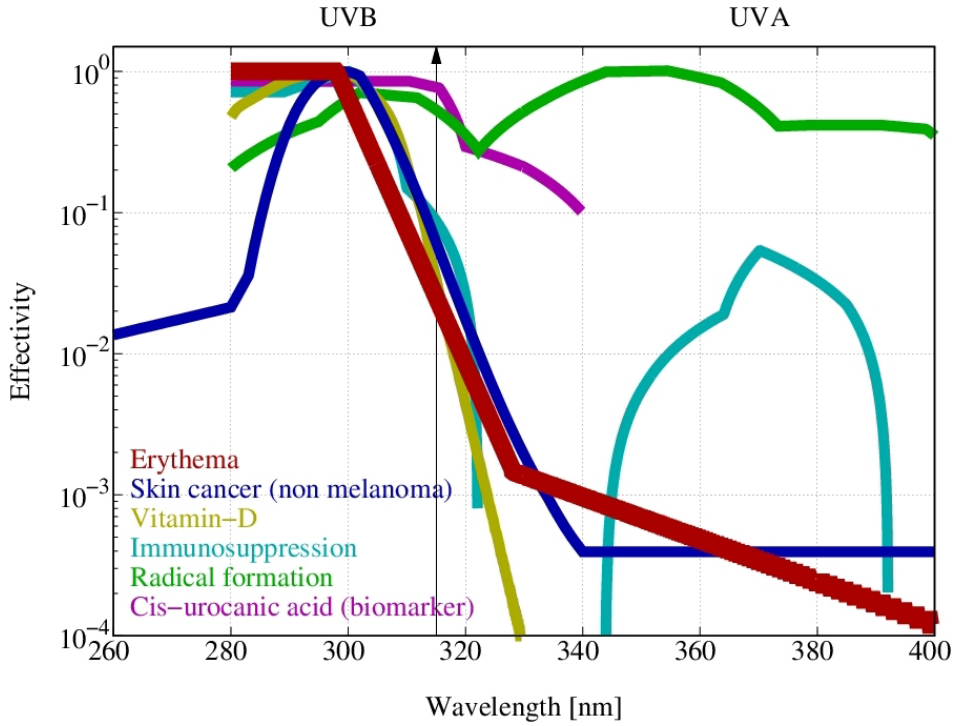


*Figure 6 Action spectra for various health effects of UV radiation*

4.2.3 *Transmission spectra of sunscreen products*

Sunscreen products mitigate the incoming UV radiation heading for the skin with a wavelength-dependent factor $T(\lambda)$ which we call transmission. According to the Beer-Lambert law, when light is propagated through a medium, a fixed, medium-dependent fraction, per unit of length travelled, passes through:

$$T(r) = e^{-\mu r}$$

where $\mu$ is the extinction coefficient of the product, and the product $\mu r$ of the extinction coefficient and the layer thickness is called the 'optical thickness'. The transmission spectra for five different products are shown in Figure 7. Only Product 5 has a high-quality UVA filter with 5 Boots stars (see below). The high quality of the UVA filter is clear from the fact that the green line in the graph is relatively low for the longer wavelengths; it is only at a relatively long wavelength that it no longer provides protection equal to the SPF of the product. A transmission spectrum is considered to have an ideal neutral density filter when it has the same value for all wavelengths.

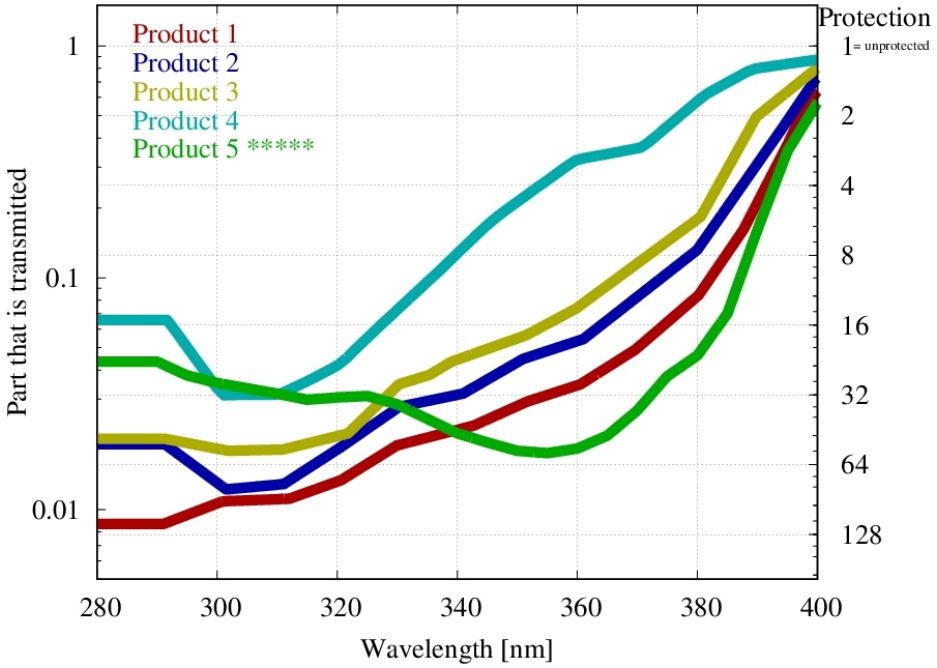


*Figure 7 Transmission spectra for various sunscreen products. Product 5 is the only one containing a high-quality UVA filter with five Boots stars (see Section 3.5). The optical thickness is equal to -ln(transmission).*

Internationally, the quality of a sunscreen product is indicated by the SPF (Sun Protection Factor, see ISO, 2022). The SPF indicates how many times higher the UV dose can be, when a product is used, before a group of test subjects experience erythema, compared with unprotected exposure. The SPF is thus essentially determined *in vivo*, on a phenomenological basis, using a selected health effect. A standardised irradiance spectrum has been agreed for this test. It is similar to that of the sun at the zenith, but with an even higher proportion of UVB radiation. For technical reasons, the test must be performed with a standardised layer thickness of 2 mg of the active substance per $cm^2$. *In vitro* methods have also been developed to determine the SPF, and it is also possible to estimate the SPF on a theoretical basis *in silico* based on the formula of the product.

In 2006, the EU proposed (EU, 2006) replacing the SPF with categories as follows:

*Table 2 2006 EU proposal for grouping SPFs into categories*

| SPF on label | Measured SPF | Category |
|---|---|---|
| 6 | 6–9.9 | Low protection |
| 10 | 10–14.9 | Low protection |
| 15 | 15–19.9 | Medium protection |
| 20 | 20–24.9 | Medium protection |
| 25 | 25–29.9 | Medium protection |
| 30 | 30–49.9 | High protection |
| 50 | 50–59.9 | High protection |
| 50+ | 60 or above | Extremely high protection |

4.2.4 *Development of a UV-driven health effect*

The development of a health effect over time $G$ is determined by the sum $XG$ of the irradiance, action spectrum and transmission (all of which can vary over time) across all wavelengths of the product.

This can be described by the dose-response relationship:

$$\frac{d}{dt}G = f(X_G(t))$$

For this formula, $X_G$ is calculated using the formula below, in which $A(\lambda)$ is the action spectrum, $I(\lambda)$ the irradiance and $T_{\text{product}}(\lambda)$ the transmission spectrum of the sunscreen product:

$$X_G = \int_{\lambda} I(\lambda)A(\lambda)T_{\text{product}}\,\mathrm{d}\lambda$$

Since each health effect has its own action spectrum, preventing each individual negative health effect requires a unique UV filter with an effect-specific focus on attenuating the UV spectrum. Sunscreen products are traditionally designed to prevent the 'redness' effect (sunburn, erythema). This is almost exclusively a UVB effect. For this reason, traditional sunscreen products provide good protection against UVB radiation and poor or moderate protection against UVA radiation. The EU's UVA logo (see EU, 2006) guarantees that the UVA protection is at least one-third of the UVB protection (the SPF) stated on the packaging. According to this directive, the UVA protection must be determined using the action spectrum for Persistent Pigment Darkening (PPD), which means that, in practice, only wavelengths of 340 to 400 nm are considered. If someone used an SPF X product so they could be exposed for X times longer, using a product without a UVA filter would lead to an X-fold UVA dose, while using one with an EU UVA logo would lead to a three-fold UVA dose (weighted for PPD).

4.2.5 *Impact of the use of sunscreen products on health*

Using the data in Figures 6 and 7 in the previous section, it is possible to estimate the impact of the choice of UV source and the sunscreen product on the health effects under consideration. This involves a shift in the ratios of the various health effects per UV dose received for erythema (i.e. on the skin itself, under the applied layer of sunscreen product). We would expect to see the following shifts in health effects when a sunscreen product is used, compared with unprotected exposure:

- The dose related to the risk of non-melanoma skin cancer will be slightly (10% to 20%) lower (see Section 1.3).
- When a product with a non-ideal neutral density filter (i.e. UVA protection < UVB protection) is used, vitamin D production will be reduced by half (see Section 1.4).
- The UVA dose related to immune system suppression or the formation of free radicals deeper in the skin (believed to be involved in the development of melanoma) will be many times (three to eight times) higher with a non-ideal neutral density filter because the individual will spend longer in the sun. The

same applies to the use of a sunbed combined with a sunscreen product with a non-ideal neutral density filter (see Sections 3.2.1 and 3.2.2).
- When a product containing a good approximation of an ideal neutral density filter is used, the relative dose for most endpoints will be comparable with what it would be for a lower total dose.
- When a sunbed is used in combination with a sunscreen product with a non-ideal neutral density filter, vitamin D production will virtually shut down.

## 4.3 Sunscreen product use can shift the ratio of health effects

Exposure to UV radiation increases the risk of all UV-related health effects. It is therefore desirable for a sunscreen product to not only protect against erythema, but, at a minimum, to provide equal protection against all other UV-related health conditions. This requires a product with a neutral density filter, i.e. a filter that attenuates the UV radiation for all wavelengths, including that of UVA, by the same factor. Only a sunscreen product with a perfect neutral density filter can reduce the weighted doses for all of the various health effects equally. Using such a product would mean that, in the event of redness (unintentional or otherwise) (because an individual was exposed for too long), there would not suddenly be an increase in the frequency of occurrences in the skin that could lead to melanoma. With a neutral density filter, this reasoning also applies to any UV-related health endpoints that are as yet unrecognised. This idea was articulated by Ostwalder and Herzog (2010): *'The "ideal sunscreen" should provide uniform UVB/UVA protection, because this assures that the natural spectrum of sunlight is attenuated without altering its quality and thus being in harmony with evolution.'*

In the Netherlands, a sunscreen product does not have to have a UVA filter to be sold as a sunscreen product. The EU logo for products that claim to have a UVA filter guarantees UVA suppression equal to one-third of the UVB suppression (the SPF). No differentiating labelling has been agreed on that would allow consumers in the EU, when purchasing a sunscreen product, to choose one with a higher quality of UVA filter than is covered by the EU's standard UVA logo.

## 4.4 When the sun is low, the protection is less than what is promised by the SPF

When the sun is low, as it often is in the Netherlands, the protection factor promised by the SPF on the packaging is often not achieved, because the lamp used for SPF tests has a different spectrum than low-angle sunlight. This lamp contains a relatively high proportion of UVB, greater even than the sun in its highest possible elevation: in the zenith. As a result, the actual protection an individual receives (even if they apply the specified layer thickness of 2 mg/cm$^2$) may drop as the proportion of UVA increases. With a product that mainly suppresses UVB, as the sun goes down, protection will decrease by a factor greater than 2 (Young et al., 2010). This is the case in the Netherlands, for example, where the angle of the sun is often low. At the beginning and end of the day – at the times when children are attending out-of-school care, for example – protection from a standard product with a mainly

UVB filter will be reduced even further (see Figure 8). The solution to this problem is a product with a neutral density filter.

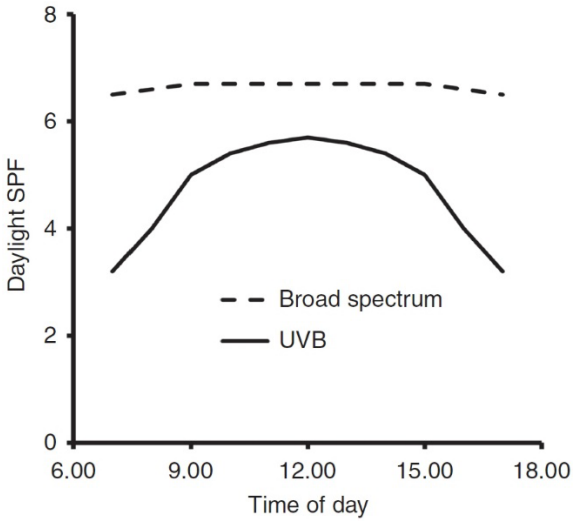


*Figure 8 Dependence on protection from erythema as a function of time of day. The continuous line corresponds to a product that only blocks UVB radiation. This UVB product has an SPF on the bottle of 8.6. The striped line corresponds to a 'broad-spectrum product' (see next section) with a stated SPF of 7 (Young et al., 2010).*

## 4.5 Quality measures for UVA filters in sunscreen products

The following labels have been developed to indicate the quality of the UVA filter in a sunscreen product:

- EU UVA logo: to be able to affix an EU UVA logo to a product (see EU, 2006), the product must suppress UVA radiation by a factor of at least one-third of the SPF; i.e. a product with SPF 50 must provide UVA suppression by a factor of at least 17. This UVA suppression is determined using a 'solar simulator' (a standardised lamp with a spectrum similar to that of the sun at its zenith, using a spectrum weighted for persistent pigment darkening – see further down this list).
- 'Broad spectrum'. In 2019, the FDA issued a proposal for the introduction of a voluntary 'broad spectrum' claim, under which the UVA filter would be subject to more stringent requirements. It was submitted as a final proposal in 2021. See the FDA reports in the list of references. This American label is awarded when the critical wavelength is above 370 nm. The critical wavelength indicates the wavelength at which 90% of the product's absorption of UV radiation is caused by the attenuation of wavelengths that are equal to or shorter than this critical wavelength (see https://www.fda.gov/regulatory-information/search-fda-guidance-documents/labeling-and-effectiveness-testing-sunscreen-drug-products-over-counter-human-use-small-entity#_Toc341188738 and An update on sunscreen requirements: The deemed final order and the proposed order | FDA).
- PPD (persistent pigment darkening): this involves looking at how much longer a person would have to be exposed to UV radiation to become permanently tanned, which is an effect dominated by

UVA radiation. This exposure prolongation factor was given the acronym PPD to characterise the UVA protection. With a product with a PPD of 10, you would therefore have to spend 10 times longer in the sun to become tanned. The PPD is stated on products in many Asian countries.

- PA: this system is equivalent to the PPD system, but it uses a different scale. The PPD factor is indicated by a series of plus signs. The more plus signs, the better the UVA protection: PA++ = PPD 4 to 8, PA+++ = PA 8 to 16 and PA++++ = PPD 16+. This system is widely used in Japan and Korea.
- Boots stars: the star rating system was developed in the UK a quarter of a century ago for the pharmacy chain Boots by Prof. Brian Diffey. It compares the quality of UVA suppression P(UVA) with the SPF. This ratio depends on the SPF. The following characteristics apply:

| | | P(UVA):SPF ratio | | |
|---|---|---|---|---|
| **Stars** | **Optical thickness(A:B)[%]** | **SPF50** | **SPF30** | **SPF20** |
| * | 20–40 | 0.04–0.10 | 0.07–0.13 | 0.09–0.17 |
| ** | 40–60 | 0.10–0.21 | 0.13–0.26 | 0.17–0.30 |
| *** | 60–80 | 0.21–0.46 | 0.26–0.51 | 0.30–0.55 |
| **** | 80–90 | 0.46–0.68 | 0.51–0.71 | 0.55–0.74 |
| ***** | 90–100 | 0.68–1 | 0.71–1 | 0.74–1 |

After a certain period of exposure, the quality of the product may decline, and the percentages according to the Boots protocol may be lower than in this table. For a product with 5 stars, the optical thickness after exposure must still be at least 86%; for 4 stars, it must be in the range 76–85%, and for 3 stars it must be 57–75%. The number of stars indicates how flat the absorption spectrum of a sunscreen product is. These days, labels with 1 or 2 stars are no longer used. This is now the standard system used to certify products in the UK, Ireland and Australia. Boots star labels are also increasingly being used in Belgium. In the Dutch retail sector, products with a Boots label are scarce and often expensive.

## 4.6 Difference in protection offered by sunscreen products for different skin types

Higher skin types (darker skin colours) contain more eumelanin than lower skin types. This pigment confers better protection against UV radiation. Lower skin types are able to tan over time, under the influence of UV radiation, but the pigment created in this tanning process is pheomelanin, a different type of melanin. The spectral absorption coefficients for both types of melanin are shown in Figure 9.

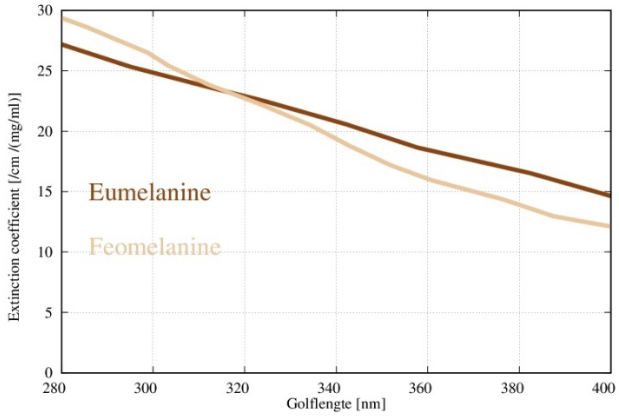


*Figure 9 Spectral extinction coefficient of eumelanin and pheomelanin*

We could ascribe the differences in MED value for the various Fitzpatrick skin types purely to the difference in melanin. However, this would not be entirely accurate, because part of the difference is due to a difference in the thickness of the epidermis. The effect of melanin and the thickness of the skin add an additional transmission spectrum $T_{\mathrm{skintype}}$, just as sunscreen products do. This spectral protection is calculated relative to skin type II, which has been chosen as a reference. The mathematical equation given earlier for the effect-weighted UV dose is therefore:

$$X_G = \int_{\lambda} I(\lambda)A(\lambda)T_{\mathrm{skintype}}(\lambda)T_{\mathrm{product}}(\lambda)\,\mathrm{d}\lambda$$

Figure 10 illustrates these additional transmission spectra $T_{\mathrm{skintype}}$, which are naturally present in the skin. The values for the various skin types are scaled so that they result in the MED value ratios shown in Table 1.

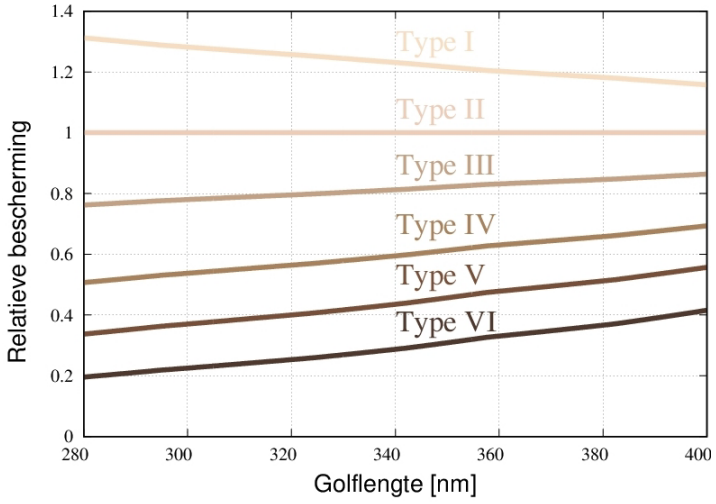


*Figure 10 Spectra for the various Fitzpatrick skin types of the additional protective transmission factor $T_{skintype}$ provided by eumelanin, in comparison with skin type II, which has been chosen as the reference.*

It is, in fact, not correct to work with a single, universal action spectrum (in this case for erythema) that is the same for all skin types but was

determined for skin type II. Multiplying the action spectrum for skin type II by the wavelength-dependent transmission factor for each skin type, as a correction factor, is likely to give a better estimate:

$$A_{\text{skintype}}(\lambda) \approx A_{\text{skintype II}}(\lambda) T_{\text{skintype}}(\lambda).$$

One way of understanding this issue would be to re-measure the erythemal action spectrum for dark-skinned individuals. Because the transmission of eumelanin (as shown in Figure 9) is particularly low at shorter UVB and other wavelengths, it is likely that an action spectrum for dark skin types, compared with that for skin type II, would be more focused on the longer wavelengths that penetrate more easily. In other words, there would be a stronger focus on UVA than for skin type II. The lines in Figure 10 show that higher skin types primarily have better natural protection against UVB radiation (the shorter wavelengths), and that there is less variation in skin type-related natural protection against UVA radiation (due to the smaller transmission): in Figure 10, the values are closer together on the right-hand side than on the left.

For 'standard' skin type II, erythema is mainly caused by UVB. For this reason, the filters in many commercially available sunscreen products focus on the UVB part of the spectrum, while their UVA protection is often much weaker. We have just seen that darker skin types already provide some additional, natural protection compared with lighter skin types, particularly in the UVB range. The level of additional natural protection provided by darker skin types in the UVA range is lower. We will now compare the proportions of UVA and UVB that contribute to the erythema-weighted irradiance for the various skin types. For the higher skin types, due to the relatively strong extra, natural suppression of UVB radiation, the relative proportion of UVA radiation is higher than for the lower skin types. This has consequences for the performance of sunscreen products, because it means that the added value of a sunscreen product decreases with the MED value of the user. This phenomenon was described by Damian et al. (1999). This reduction in protection with skin type is due to the fact that sunscreen products block the same wavelengths of UV radiation as the pigment in dark skin. For these wavelengths, using the product will be of little benefit to dark-skinned individuals. UV radiation of other wavelengths that also causes erythema is not blocked by these products, even though individuals with a dark skin type would actually benefit from such protection.

# 5 Risk factors leading to lower protection from sunscreen products

## 5.1 Risk of SPF being too low in a non-compliant product

The risks from using a sunscreen product that does not comply with the SPF stated on the packaging are not essentially different from the risks of using a product that does comply, but there is a subtle difference in degree. With a non-compliant product, the acute 'sunburn' discomfort will occur more often.

When using 2 mg/cm$^2$ of a sunscreen product, a user is entitled to expect that a product with SPF X will allow them to be exposed X times longer before the user receives 1 MED and thus reaches the point where sunburn is measurable (though very mild). If a product with SPF X stated on the label actually has an SPF of Y, then, after the prolonged period of exposure calculated on the basis of SPF X, on the skin beneath the product, this person will have received a dose of:

dose received by the skin beneath the protective product = 1 MED * X / Y

For the three most common types of skin cancer, a dose-response relationship in the following form applies:

prevalence $\sim$ dose$^{\lambda}$

where $\lambda$ is the biological amplification factor and has values of 1.4 for BCC, 2.5 for SCC and 0.6 for melanoma. Long-term accidental use of an SPF Y product with SPF X displayed on the packaging will amplify the prevalence of skin cancer by a factor of $(X/Y)^{\lambda}$.

This formula provides the amplification of the prevalence of skin cancer, but not the risk of skin cancer itself. In terms of the actual risk, a broad range of factors play a role, meaning that the range across the population is extremely wide. These factors include genetics, behaviour, location and climate. The use of sunscreen products is only one of these factors.
It is not reasonable to assume that individuals with a non-compliant product, who are becoming burnt sooner than expected, would continue to use this product in the same way for the rest of their lives. It is more likely that they would either purchase a different product or expose themselves for a shorter period of time, because they will have noticed that they would otherwise become burnt.

Because SPF categories are based on protection time in relation to burning, rather than a quantitative increase in health risk, it is not possible to specify a hard limit at which an SPF deviation would result in a health risk. In theory, every deviation (to the extent that it is not within the margin of error for the measurement method) means the product provides a lower level of protection/shorter protection time than expected. And even without a deviation, that protection is already lower

than claimed, taking into consideration the actual application behaviour of consumers – see 4.2.

## 5.2 Risk from not scaling down SPFs based on actual consumer layer thickness

When measuring SPF as a quality of a sunscreen product *in vitro* or *in vivo* in an accredited laboratory, the protocol requires a layer thickness of 2 mg/cm$^2$. If measurements were to be performed with a thinner layer thickness, technical issues would arise due to the required roughness of the surface to be treated. Research shows that normal consumer behaviour when applying a sunscreen product produces a median layer thickness of 0.5 mg/cm$^2$ (Heerfordt, 2018), only a quarter of the layer thickness in the lab test protocol. Although this difference is well known to cosmetics manufacturers, the irradiance reduction factor measured in the lab with a layer four times thicker is not scaled down to match the real-life situation of consumers, nor is this issue communicated to consumers.

In the Heerfordt study mentioned above, the median SPF of the sunscreen products used on beaches in Denmark was 20, but due to the thinner layer thickness, the actual protection against UV radiation from the sun was a reduction factor of 2. For products with a different SPF, the impact of actual application is shown in Figure 11 below (data from Liu, 2012). It is recommended that the level of protection stated on labels be aligned with consumers' actual application behaviour, rather than advising consumers to apply the product with a thickness sufficient to achieve the SPF.

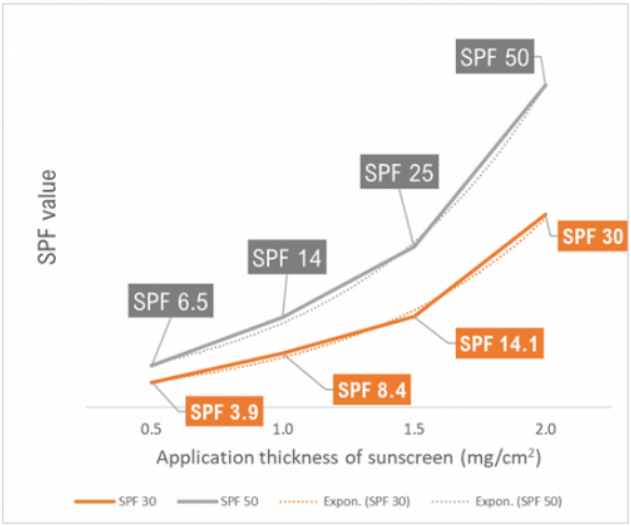


*Figure 11 Protection from erythema as a function of the layer thickness applied (Liu, 2012). A thickness of 2.0 mg/cm$^2$ is the lab condition under which SPF is measured according to the protocol; 0.5 mg/cm$^2$ is the median thickness found by Heerfordt (2018) for the real-life application behaviour of Danish consumers.*

Determining criteria for enforcement is a policy decision, not a knowledge-based decision, particularly in the present case of sunscreen products that do not comply with their SPF. In the 2006 Commission Recommendation, a factor of 6 for UVB protection, and one-third of that

for UVA protection, was specified as the minimum for a product to be referred to as a sunscreen product.

## 5.3 Risk from the inevitable variation in layer thickness

There will always be significant variation in the layer thickness applied, even when the individual concerned has been trained in the correct application of sunscreen products. The protection from erythema that individuals obtain when a lab technician applies a sunscreen product to their skin at the recommended layer thickness of 2 mg/cm$^2$ varies by a factor of 2 between the highest and lowest values (Garmyn et al., 1986). When consumers apply the sunscreen product themselves, the variation in layer thickness and in the protection obtained is even greater. The protection varies non-linearly with the layer thickness; see Figure 11. If we make this relationship linear for an initial estimate, then the impact of a difference in dose from variation in layer thickness is also a factor of 2. According to Garmyn's study, this in turn has the consequence that a substantial proportion of users are receiving a UV dose up to 40% higher than average (assuming that the distribution function of the applied thicknesses has a factor of $\sqrt{2}$ in width, both upwards and downwards). When people use a sunscreen product to get as much exposure as possible while just barely avoiding redness, and they calculate the length of time for which they can safely remain in the sun based on the SPF, then half of this group of calculating consumers will nevertheless get burnt, or, in any event, have a significantly higher chance of developing erythema, and thus also skin cancer. We are assuming here that the distribution function of the layer thickness is reasonably symmetrical around a modal value. In practice, people's behaviour is not so precisely tuned that they can narrowly avoid erythema by using a sunscreen product in combination with a calculated possible duration of exposure.

## 5.4 Risk from a mediocre UVA filter (a non-ideal neutral density filter)

The previous chapter showed that a product with a UVA filter that is not as good as the UVB filter presents greater risks than a product with an ideal neutral density filter. This includes amplification of the following risks: (1): insufficient protection of higher skin types (Section 3.6), (2): insufficient protection at temperate latitudes (Section 3.4), (3): insufficient protection when the sun is low (Sections 3.2.1 and 3.4), (4): a higher risk of the health effects caused primarily by UVA rather than UVB (Section 3.2.5): for example, the creation of free radicals and suppression of the immune system are significantly amplified.

## 5.5 Risk from calculating the UV index based on irradiance instead of actinic flux

When the UV index is used as a measure of exposure, the exposure will be underestimated in situations with high levels of UVA: as the sun goes down, the UV index declines rapidly. This is, in part, artificial and unfounded. This is because the UV index is based on an assumption of exposure geometry: irradiance, the amount of sunlight that falls on a horizontal plate. If the plate is unevenly irradiated, the irradiance decreases with the cosine of the angle. Irradiance is a fairly poor

measure for human exposure, because humans move around in the sun and also capture light on their sides and face. A better measure would be the actinic flux or horizontal flux; see Figure 12 (see also Van Weele, 1995; Webb, 2002). If the UV index were based on actinic flux, this new measure for the UV index would be up to 50% higher when the sun is low than is currently the case when irradiance is used.

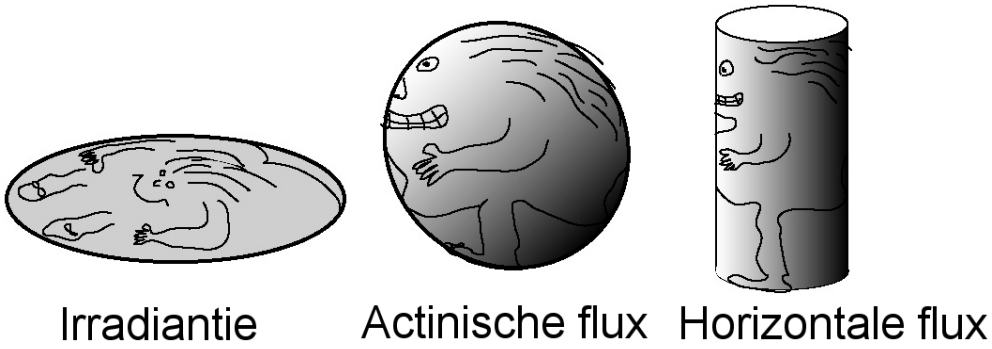


*Figure 12 Three models for an individual's exposure to sunlight: irradiance, actinic flux and horizontal flux.*

Higher actual irradiation of consumers when the sun is low than is represented by the measure used for the UV index means that sun protection in low-angle sunlight is more necessary than is generally believed. The erythema-weighted UVA-to-UVB ratio is significantly greater when the sun is low than when the sun is high, and many sunscreen products provide a relatively low level of UVA protection from erythema compared with their UVB protection, typically 1:3 in EU-approved products. The solution to this problem is, once again, a product with a neutral density filter, which attenuates UVA and UVB equally well.

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# 7 Definitions

**25(OH)D3** The form in which the body stores vitamin D; this is what is measured when determining vitamin D levels.
**7-DHC** (provitamin D) The raw material in the skin from which vitamin D is made, under the influence of UV radiation.
**Actinic flux** A measure of exposure to UV radiation whereby radiation from all directions is given the same weight.
**Actinic keratosis** A skin condition that is considered to be a precancerous stage of skin cancer.
**Action spectrum** A mathematical function that gives the efficiency per wavelength of a selected UV-driven effect.
**Basal cell carcinoma (BCC)** Skin cancer of the keratinocytes in the basal layer. This is the most common form of skin cancer. It almost never metastasises, so it makes little contribution to skin cancer mortality.
**Basal layer** A layer of stem cells at the interface between the epidermis and the dermis. It is located at a depth of approximately 70 microns.
**BCC** Basal cell carcinoma.
**Biological amplification factor** The change in effect, measured in percentage points, if the dose increases by 1%.
**Blueshift** A shift towards shorter wavelengths.
**Boots star rating** A quality system for the UVA filter in a sunscreen product, introduced by the British pharmacy chain Boots, which is also used to differentiate high-quality UVA filters.
**Broad spectrum** American quality measure for the UVA filter in a sunscreen product.
**Cataract** Clouding of the lens of the eye.
**Cis-urocanic acid** A foreign substance produced from trans-urocanic acid following exposure to UV radiation. Used as a biomarker for UV radiation exposure.
**Critical wavelength** The shortest wavelength at which a product achieves 90% total absorption of radiation. It is a quality measure for the UVA filter of a sun protection product: the higher the better.
**Cytokines** Signalling molecules.
**Dermis** Sits below the epidermis and the basal layer.
**DNA damage** Can result from normal biological processes, such as metabolism, but can also be caused by radiation (including UV radiation). Occurs thousands of times per day, per cell. If not repaired, or if poorly repaired, DNA damage can lead to mutations. Some mutations increase the likelihood of cancer.
**DNA lesion** Localised DNA damage.
**Elevation** The angle of the sun above the horizon (in degrees).
**Environmentally available UV dose** Irradiance in a location with an unobstructed horizon.
**Epidermis** The outermost layer of the skin, approximately 70 micrometres thick. Its deepest layer is the basal layer, containing stem cells; above that lie the germinal layer, with living keratinocytes, and the stratum corneum, with dead cells.
**Erythema** Skin burn, sunburn, skin redness.
**Erythemal dose** UV dose weighted by the action spectrum for erythema.

**Eumelanin** Naturally occurring brown pigment colour, mainly found in darker skin types.
**FDA** Food and Drug Administration, an agency of the United States federal government that controls the quality of food and drugs in the broad sense.
**First-order kinetics** A model for the development over time of concentrations of substances in the body, whereby the rate of conversions is fixed and proportional to the concentrations.
**Fitzpatrick skin type** Classification of skin types into six categories based on colour, tanning ability and sensitivity to erythema.
**Free radical** A molecule or atom available to bond with another molecule or atom. Free radicals will take any available opportunity to form a bond. This can damage the partner molecule or its DNA.
**Horizontal flux** A measure of exposure to UV radiation whereby only the horizontal component of the radiation is counted.
**IARC** International Agency for Research on Cancer. Part of the World Health Organization (WHO).
**Intermittent exposure** Short episodes of heavy exposure alternating with periods of no exposure.
**Irradiance** A measure of exposure to UV radiation whereby only the vertical component of the radiation is counted.
**Keratinocyte** The main cell type in the epidermis.
**Lumisterol** A photoproduct created when previtamin D is exposed to UV radiation. A component of the photosynthesis of vitamin D.
**MED** Minimal Erythemal Dose. The quantity of erythema-weighted UV radiation that causes barely perceptible redness of the skin. It is a personal measure of UV sensitivity. The personal MED is usually expressed as the objective SED.
**Melanocyte** Pigment cell.
**Melanoma** Skin cancer of the pigment cells. The most dangerous form of skin cancer.
**Mutagenicity** The degree to which an agent or type of damage leads to mutations.
**Mutation** A change in DNA caused by the defective repair of DNA damage.
**Naevus/naevi** Mole(s).
**NER** Nucleotide Excision Repair. A mechanism to repair DNA damage, in which a block of around 30 base pairs are replaced simultaneously with a correct piece of DNA. When this mechanism is active, cytokines are released.
**Neutral density filter** A UV filter that suppresses all wavelengths equally.
**PA** A quality system for the UVA filters of sun protection products, primarily used in Japan and Korea.
**Pheomelanin** A reddish pigment; the dominant pigment in red-haired individuals. It is produced when the skin is exposed to UV radiation.
**Pigment cell** (melanocyte) A dendritic cell that produces melanosomes and transfers them via its long branches to neighbouring keratinocytes, which use them to protect their nuclei (not their cell walls). Pigment production occurs in response to a demand from the signalling molecules (cytokines) released during NER repairs of DNA damage caused by UV radiation. All skin types have the same number of pigment cells; only their rate of pigment production is different.

**PPD** Persistent Pigment Darkening. A quality system for the UVA filters of sun protection products. It looks at how much longer a person would have to be exposed to UV radiation to become permanently tanned, which is a UVA effect.
**Previtamin D** Substance created when 7-DHC (provitamin D) is exposed to UV radiation. A component of the photosynthesis of vitamin D.
**Proliferating cells** Cells that are still dividing.
**Provitamin D** (7-DHC) Raw material in the skin for vitamin D photosynthesis.
**Redshift** The shift of a spectrum towards longer wavelengths.
**SCC** Squamous cell carcinoma.
**SCUP-h** 'Skin Cancer Utrecht Philadelphia, human', the name of the action spectrum for SCC. This action spectrum is based on measurements from a study that began in Utrecht and continued in Philadelphia. An action spectrum was established for mice and then translated for humans by offsetting the transmissions (of mice and humans).
**SED** Standard Erythemal Dose. 1 SED is equal to 100 $J/m^2$ of erythema-weighted irradiance.
**Skin types** See Fitzpatrick skin type.
**Solar lentigo** (liver spot, pigment spot, age spot) Benign pigmented skin abnormality occurring in elderly people with pale skin types whose skin has been repeatedly damaged by the sun.
**Spectrum** Specification for each wavelength.
**SPF** Sun Protection Factor. A quality measure used mainly for the UVB filter of a sun protection product. The SPF is determined with an industrial lamp that has a slightly higher UVB fraction than the sun north of the equator, at a layer thickness of 2 $mg/cm^2$, which is four times thicker than what consumers use.
**Squamous cell carcinoma (SCC)** Skin cancer of the squamous cells. In terms of incidence, it is the middle of the three most common types of skin cancer. It can metastasise but does not always do so. This type of skin cancer results from chronic exposure to UV radiation.
**Stratum corneum** The outermost layer of the epidermis, which contains dead cells.
**Tachysterol** A photoproduct created when previtamin D is exposed to UV radiation. A component of the photosynthesis of vitamin D.
**Threshold dose** The dose below which the body can process the received dose without consequences.
**Trans-urocanic acid** A naturally occurring substance in the epidermis that, when exposed to UV radiation, is partially converted to cis-urocanic acid, which is not found naturally in the skin. The concentration of cis-urocanic acid is a measure of a person's recent exposure to UV radiation.
**Transmission** (or transmission spectrum) Fraction of UV radiation that passes through the epidermis.
**UV flux** The quantity of UV radiation that passes through a surface.
**UV Index** International measure of the intensity of UV radiation, defined as 40 times the erythema-weighted irradiance in $W/m^2$ at a location with an unobstructed horizon. When the UV Index is at 3 or above, it is recommended that you protect yourself from the sun; when it is at 5 or above, more stringent measures are advised. Multiplying the

UV Index number by 0.9 indicates the SED that will reach you every hour if the horizon is not obstructed.
**UVA** UV radiation with wavelengths of 315 to 400 nm. The older value of 320 nm is sometimes used as a boundary instead of 315 nm. UVA radiation is not affected by the ozone layer.
**UVA-I** UV radiation with wavelengths of 340–400 nm. A subrange of UVA radiation.
**UVA-II** UV radiation with wavelengths of 315–340 nm. A subrange of UVA radiation.
**UVB** UV radiation with wavelengths of 280–315 nm. The older value of 320 nm is sometimes used as a boundary instead of 315 nm. UVB radiation is affected by the ozone layer, but it can pass through it when the sun is high in the sky.
**UVC** UV radiation with wavelengths of 100 to 280 nm. UVC radiation from the sun is completely blocked by the atmosphere/ozone layer.
**WHO** World Health Organization.
**Xeroderma pigmentosum** A congenital disease that means the individual has no resistance to UV damage and must therefore keep their skin covered at all times. It occurs when one of the variants of the NER mechanism is deactivated.
**Zenith** The point directly above the observer.
**Zenith angle** The position of the sun relative to the horizon, measured in degrees from the zenith.

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