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Review Article

Skin Cancer, Sunscreens and Post-UV Repair: An Expert Consensus on Skin Protection

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Abstract

The sun is essential for life but is responsible for 80-90% of all skin cancers. There are almost 105,000 anticipated melanoma diagnoses in the US in 2025 and non-melanoma skin cancers actually occur 18-20 times more frequently than melanoma. While UV radiation is the primary cause of skin cancer, its risk varies based on ethnicity, genetic background, location, sun exposure patterns and behavior. In the US, sunscreen is the main form of sun protection. As an Over-The-Counter drug, sunscreens are regulated by the FDA, which, to date, has approved 16 ingredients. Of these, only titanium dioxide and zinc oxide are classified as "Generally Recognized As Safe and Effective" (GRASE) while most organic UV filters still await further studies, despite the consensus on their negligible health risks. However, increasing misinformation has reduced public concern about skin cancer risks. Besides, many people fail to apply (enough) sunscreen, reapply it or even use it consistently. Our goal is to remind the fundamental risks associated with unprotected sun exposure, promote reliable sun protection methods and encourage the use of post-exposure skin care to repair sun damage.

Keywords: Melanoma; Skin Cancer; UV Radiation; Sunscreen; UV Filters; Prevention

Introduction

The sun is essential for life. However, sun exposure benefits come with significant individual, social and economic costs - as it accounts for 80-90% of all skin cancers [1]. In 2025, it is estimated that 104,960 new cases of invasive melanoma and 107,240 cases of *in-situ* melanoma will be diagnosed in the United States, with 8,430 expected deaths from melanoma [2]. The prevalence of Non-Melanoma Skin Cancer (NMSC) - Basal Cell Carcinoma (BCC) and Squamous Cell Carcinoma (SCC) - is even 18-20 times higher than melanoma [3]. Between 2016 and 2018, 6.1 million people were treated for skin cancer, with an estimated annual cost of $ 8.9 billion [4]. Even sunburns are a tremendous burden to our healthcare system and budget, with 33,826 visits to emergency departments in 2013 - each visit at that time back in 2013 actually costing an average of $ 1,132 [5].

Sun Radiations and Skin Damages

The World Health Organization (WHO), through its International Agency for Research on Cancer (IARC), recognizes solar and UV radiation as Class 1 carcinogenic [6]. This classification is echoed by numerous regulatory agencies worldwide, including the U.S. National Toxicology Program (NTP) and the Food and Drug Administration (FDA).

Sun radiations consist of Ultraviolet (UV, 100-400 nm), visible light (400-770 nm) and infrared (IR, 770-1,000 nm). While both IR and blue light have deleterious effects [7,8], UV radiation is particularly significant (Fig. 1). The ozone layer effectively filters out high-energy UVC radiation (100-280 nm) and partially blocks UVB (280-320 nm); however, UVA (320-400 nm) are unfiltered. UVA and some UVB rays reach the Earth's surface and penetrate the skin in a wavelength-dependent manner, leading to distinct effects [9,10]. The epidermis absorbs shorter wavelength UVB radiation. Acute exposure to UVB results in redness/erythema, edema, sunburn and immunosuppression. UVB also directly interacts with DNA, primarily causing thymidine-dimer photolesions - which with chronic exposure, may lead to carcinogenic mutations. In contrast, longer wavelength UVA penetrates deeper into the skin, reaching the dermis and generating Reactive Oxygen Species (ROS). Among other harmful effects, these ROS can damage DNA, contributing to carcinogenesis. Besides, UVA plays a major role in photoaging, which manifests by the appearance of wrinkles, pigmentation disorders and loss of skin elasticity [11].

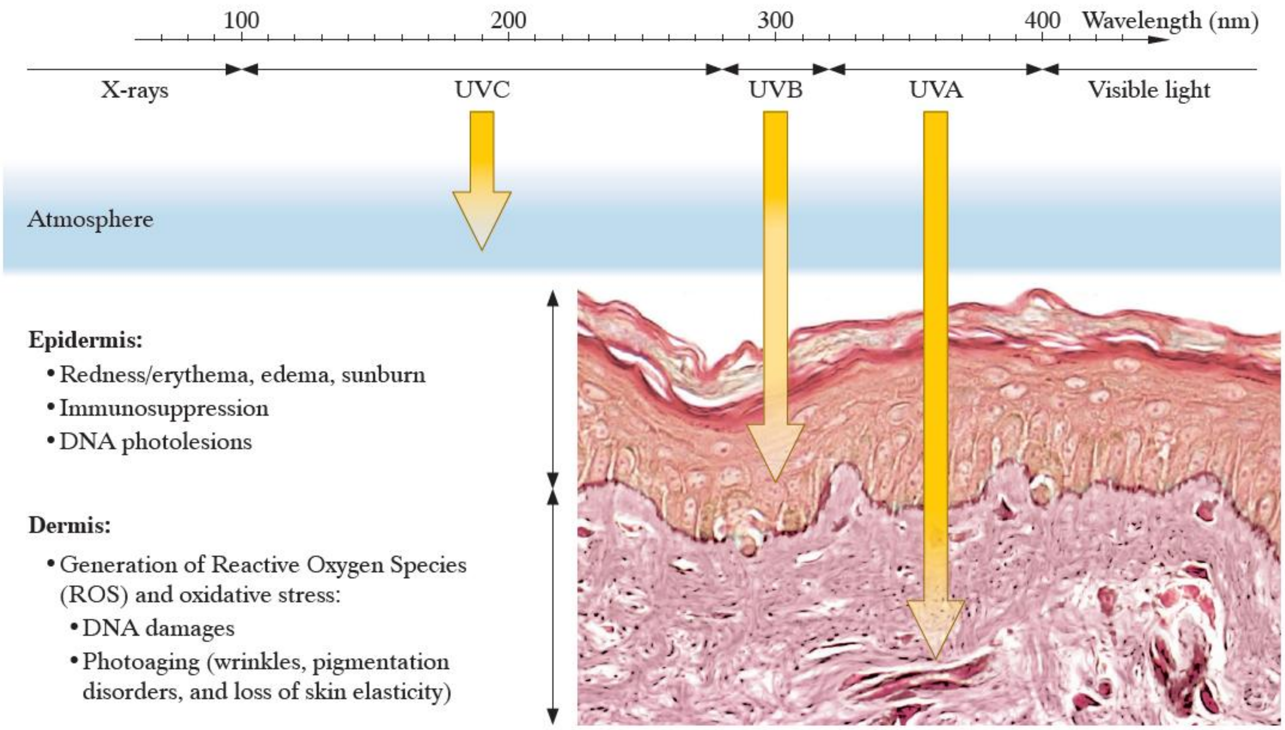

Figure 1: Wavelength dependent entry of UV radiation and their effects on the skin.

Factors Influencing Skin Cancer Risks

While UV radiation is the primary cause of skin cancer, its prevalence varies significantly. For example, the projected melanoma incidence rates (per 100,000 individuals) for 2025 (Fig. 2) range from a high of 51.6 in Iowa to 44.8 in Florida and 28.6 in California - with the lowest rates observed in the District of Columbia (14.6) and Alaska (12.3) [12]. Besides ethnic and individual differences in susceptibility to skin cancer, geographical and behavioral factors also contribute to varying skin cancer risks.

Ethnicity and Genetic Background

Ethnicity and its associated skin color significantly influence skin cancer risk. Skin color is determined by melanin content, a pigment synthesized by melanocytes and distributed in neighboring keratinocytes. Melanin absorbs UV radiation, playing the role of an antioxidant and a reactive oxygen species scavenger [9,13]. Melanin exists in two forms: pheomelanin, a light pigment present in similar amounts across all skin colors and eumelanin, a darker pigment that efficiently blocks UV radiation and is more abundant in darker complexion. Thus, eumelanin concentration largely determines UV sensitivity and skin cancer risk. Consequently, the lifetime risk of developing melanoma is 0.1% in individuals with darker skin (phototype IV-VI), 0.5% in Hispanics (phototype III-V) and 3.0% in fair-skinned Caucasians (phototype I-III) [14]. Similar disparities are observed for SCC and BCC, although these are poorly documented [15].

Genetic background is also important. Individuals have a 74% increased risk of melanoma if a first-degree relative has a history of skin cancer [16], which is estimated to be the case in 5-10% of all melanomas [17]. This genetic predisposition has led to the identification of highly penetrant germline mutations, notably those affecting specifically CDKN2A (Cyclin-Dependent Kinase Inhibitor 2A), CDK4 (cyclin-dependent kinase 4), MITF (melanocyte inducing transcription factor) or BAP1 (BRCA1-Associated

Protein 1) [18]. Recent studies have identified additional genes related to pigmentation and DNA repair, further complicating the genetic landscape [19]. Given the availability of relevant markers, genetic testing for melanoma susceptibility should be considered for individuals with a family history of the disease.

Another significant risk factor is the presence of nevi (moles), which are benign accumulations of melanocytes that may be congenital or acquired. One third of melanoma cases are associated with nevi, which number and size directly correlate with melanoma risk [20,21]. Although most nevi remain stable, their transformation rate into melanoma is extremely low (below 0.0005% per year) [22]. The exact interconnection between nevi and melanoma is not fully understood, but congenital nevi often harbor mutations also found upon melanoma transformation. This is the case with the mutation of the BRAF (B-Raf) proto-oncogene that is found in 80% of benign nevi and associated with more than half of all melanomas. However, the limited growth of nevi shows this sole mutation is insufficient to cause malignant transformation [23]. Different pathways may drive the development of melanoma arising from nevi and de novo melanoma [24].

To be complete, two additional factors influence skin cancer risk. First, immunodeficiency - whether consecutive to organ transplantation or diseases such as HIV/AIDS - is a well-documented risk factor for all cancers, including skin cancer. Prolonged immunosuppressive therapies increase SCC risk by up to 250-fold, BCC risk by 10-fold and melanoma risk by up to 8-fold [24,25]. The second factor is obesity. Although obesity is a recognized risk factor for many cancers, studies have found that a high Body Mass Index (BMI) is associated with a reduced risk of both SCC (by 32-37%) and BCC (by 19-29%). However, this apparent protective effect may not be direct. It could be related to the fact that obese individuals are less likely to engage in outdoor activities, thereby reducing their sun exposure [26]. Besides, some studies have shown a negative impact of excess weight on melanoma risk, but this finding is not consistent across all research. Interestingly, while obesity typically worsens cancer prognosis, recent data suggest that it may improve survival rates in melanoma patients treated with targeted and immune therapies [27].

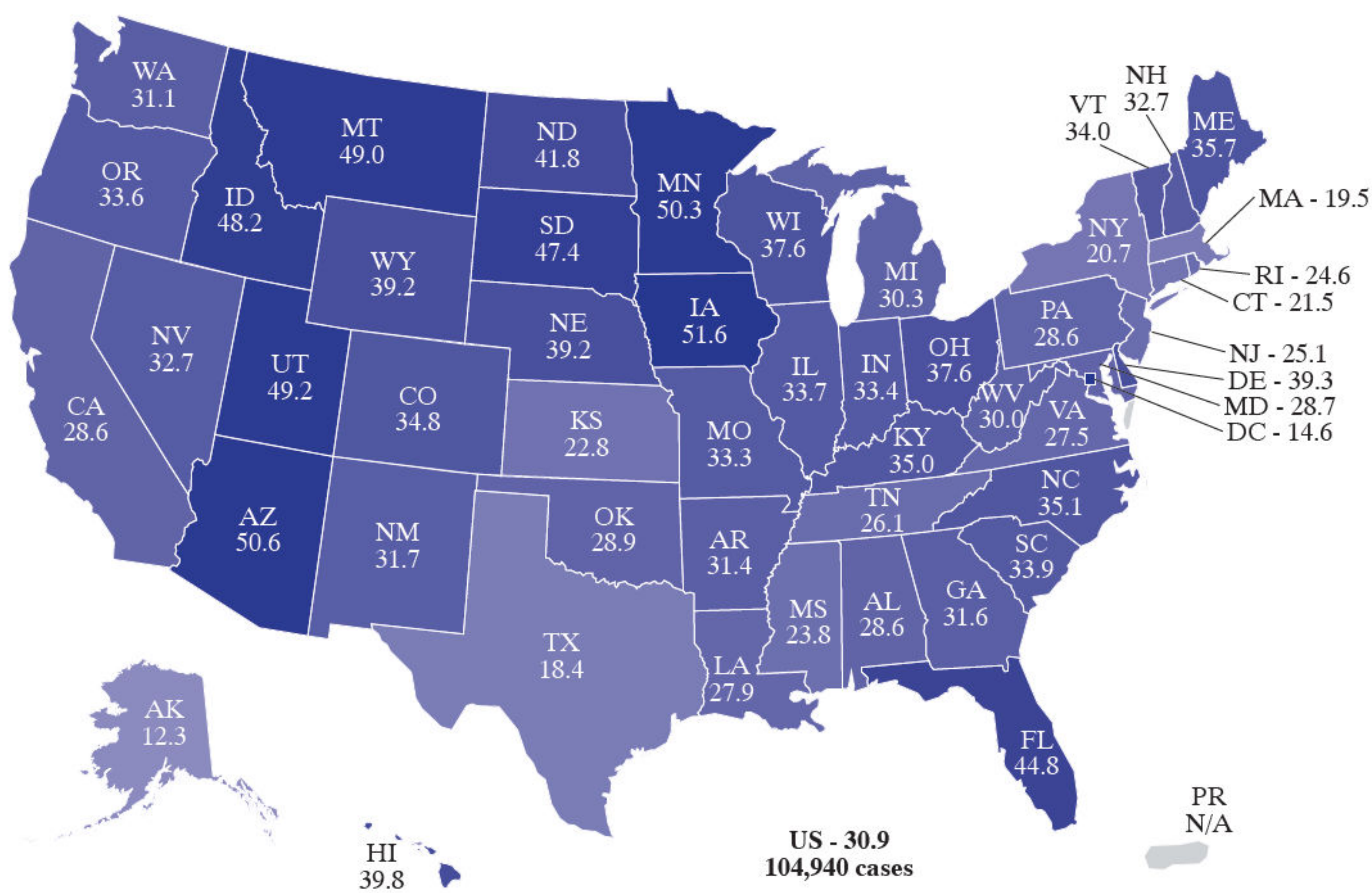

Figure 2: Projected incidence rates of melanoma (per 100,000 individuals) for 2025 [12].

Sun Intensity

Many factors influencing sunlight intensity do in fact affects cancer risk [9,28]. Factors that reduce atmospheric absorption of solar radiation - such as proximity to the equator, high altitude, reduced cloud coverage, low particulate pollution and stratospheric ozone depletion - entail higher risks. While it is possible to estimate how each of these factors contribute to an individual's UV exposure, accurately quantifying their impact on skin cancer is challenging [28]. Local, seasonal and behavioral variations are critical. Temperature, the number of sunny days and the environment - especially the presence of green spaces - affect behavior and community norms, ultimately influencing sun exposure and consequently, skin cancer risk [29-32].

Chronic Versus Occasional Exposure

The pattern of UV exposure, whether chronic or intermittent and acute, is a key factor in skin cancer risk. Chronic, long-term exposure is primarily associated with SCC with outdoor workers experiencing double the risk compared to indoor workers due to exposure to UV doses often exceeding recommendations [33-37]. On the other hand, BCC and melanoma are most closely related to intermittent and acute UV exposure, particularly a history of sunburn [38-40]. Several studies have linked sunburns at a young age with an increased risk of melanoma [41-43]. However, in a re-analysis using a five sunburns-per-decade scale across all age groups, Dennis, et al., found that the odds ratio for melanoma risk was higher in adulthood (3.08) than in childhood (1.43) or adolescence (1.28), suggesting that sunburns have a cumulative effect on melanoma risk, regardless of the age at which they occur [39]. Therefore, recreational sun exposure deserves particular attention. With an increase in outdoor leisure and sports activities in recent decades, recreational exposure has become more likely to result in sunburn due to inadequate sun protection, leading to a 60% increase in melanoma risk [44].

Differences in sun exposure behavior between men and women also impact melanoma risks. Younger women, particularly those who engage in tanning, have a 1.5 times higher risk of developing melanoma than men until age 40 or 50. However, melanoma rates are three times higher in men older than 75, likely due to cumulative occupational exposure [14,45].

Sunscreens

While UV exposure is the most significant risk factor for skin cancer, it is also the most readily preventable. In addition to seeking shade and wearing protective clothing, applying sunscreen is an essential part of the protective strategy [46-48].

UVA and UVA Labeling

Since the first commercial sunscreen was introduced in 1928, numerous UV-absorbing compounds have been developed over the years, however, no new filters have been approved by the FDA (Food and Drug Administration) since 1999 [49]. Accurate evaluation of their efficacy and clear labeling are essential to understand product effectiveness and safety. Two different labeling systems exist. The Sun Protection Factor (SPF), introduced in 1974, measures UVB protection [49]. SPF corresponds to the ratio between the minimum energy triggering an erythema in a protected skin zone compared to that required in an adjacent unprotected skin area. According to the FDA, effective protection is achieved with SPF values of 15 or higher. Conversely, several systems are used to indicate protection against UVA radiation - but none have gained the traction of the SPF system. In the US, the FDA has established a standardized "broad spectrum" test to assess UVA protection relative to UVB protection [50]. This test is based on the capacity of a sunscreen applied onto a UV-transparent plate to transmit/absorb radiation across the UVB and UVA spectrum, as measured by UV spectrometry.

US Sunscreen Regulation

In most countries, sunscreens are classified as cosmetics; however in the US, they are classified as non-prescription Over-The-Counter (OTC) drugs. As such, they fall under the jurisdiction of FDA monographs, which govern active ingredients, maximum concentrations, testing protocols, claims and labeling requirements. Compared to Europe and Asia, where a broad range of UV-filter ingredients is permitted, the FDA had approved only 16 active ingredients, most of which provide effective UVB protection but offer limited UVA protection. Efforts to improve and modernize US sunscreen regulations have been ongoing [51,52]. The Sunscreen Innovation Act of 2014 sought to expedite the review process for new ingredients, especially those effective against UVA, but with no success. In 2019, the FDA issued a proposed rule on sunscreens addressing ingredient requirements, maximum SPF levels, broad-spectrum requirements, dosage forms and labeling standards [53]. A key aspect of this order was to classify sunscreen ingredients into three categories. Zinc oxide and titanium dioxide were the only ingredients listed "Generally Recognized As Safe and Effective" (GRASE). Para-aminobenzoic acid and trolamine salicylate were classified as not GRASE and subsequently removed from the market. The status of all other ingredients was deemed to require further investigation to determine their GRASE status. In 2020, the Coronavirus Aid, Relief and Economic Security (CARES) Act reformed OTC drug regulations for certain drugs, including those for sunscreens - allowing for updates to be made through administrative orders as new scientific data or safety concerns arise. By the end of 2021, the FDA issued a deemed final order for sunscreens, which is currently in effect. A proposed order was also issued to amend the final order. However, this proposed order will only become effective once it is finalized and the FDA has not communicated any date. The two orders differ significantly regarding the list of ingredients recognized as GRASE, the upper limit for SPF and broad-spectrum requirements. Thus, the current situation remains largely similar to that of 2011.

UV Filters

The active ingredients in sunscreens are UV filters. They are categorized into two main types: inorganic (or mineral) and organic (or chemical) UV filters. These categories differ not only in their nature but also in their protective abilities, environmental impact and potential toxicity (Fig 3). The FDA approves two inorganic UV filters, titanium dioxide and zinc oxide, which are the only two ingredients recognized as GRASE. While large particles of these minerals act by reflecting and scattering UV radiation, modern microparticles (<100 nm) actually primarily absorb UV rays by mobilizing electrons within their atomic structure [54,55]. Titanium dioxide microparticles also predominantly absorb UVB, while zinc oxide microparticles offer protection across the UVA-UVB spectrum. For this reason, the two compounds can be combined to provide broad-spectrum UV protection [56]. Stable and inert, these two compounds remain on the skin's surface without penetrating beyond the stratum corneum, minimizing health and environmental risks [57].

The primary concern with these compounds initially stemmed from the use of large microparticles in early formulations, which reflected visible light and created a white cast, particularly noticeable on individuals with darker skin. This issue has since been mitigated by significant efforts in developing smaller microparticles, creating tinted formulations and optimizing the formulation chassis to make sunscreens cosmetically acceptable and encourage their use.

The other 12 ingredients that the FDA authorize are "organic compounds", characterized by one or more aromatic rings conjugated to various groups, frequently a carbonyl group. These filters protect the skin by absorbing UV radiation, causing a transient polarization and/or conformational change in their molecular structure. By releasing harmless heat or light radiations, they return to their ground state, allowing the process to repeat, at least as long as the photostability of the compound enables it [54,58]. Given the high energy levels of these excited states, the compounds must return to their ground state quickly and their structure must be optimized to prevent phototoxic or photoallergic reactions with skin proteins or oxygen [54].

Organic UV filters absorb photons of wavelength around their absorption maximum, which limits the wavelengths they shield. Therefore, sunscreens combine various filters to achieve the desired UV protection spectrum. Additionally, they need to be sufficiently water-resistant to ensure long-lasting protection. While some filters raised concerns about their impact on marine ecosystems [58,59], recent studies have also demonstrated systemic absorption in humans, exceeding the FDA's threshold of 0.5 ng/mL plasma concentration [60,61]. Although further studies are required to determine the safety of these compounds and their GRASE status, the current consensus is that the health risks remain negligible [58,62,63].

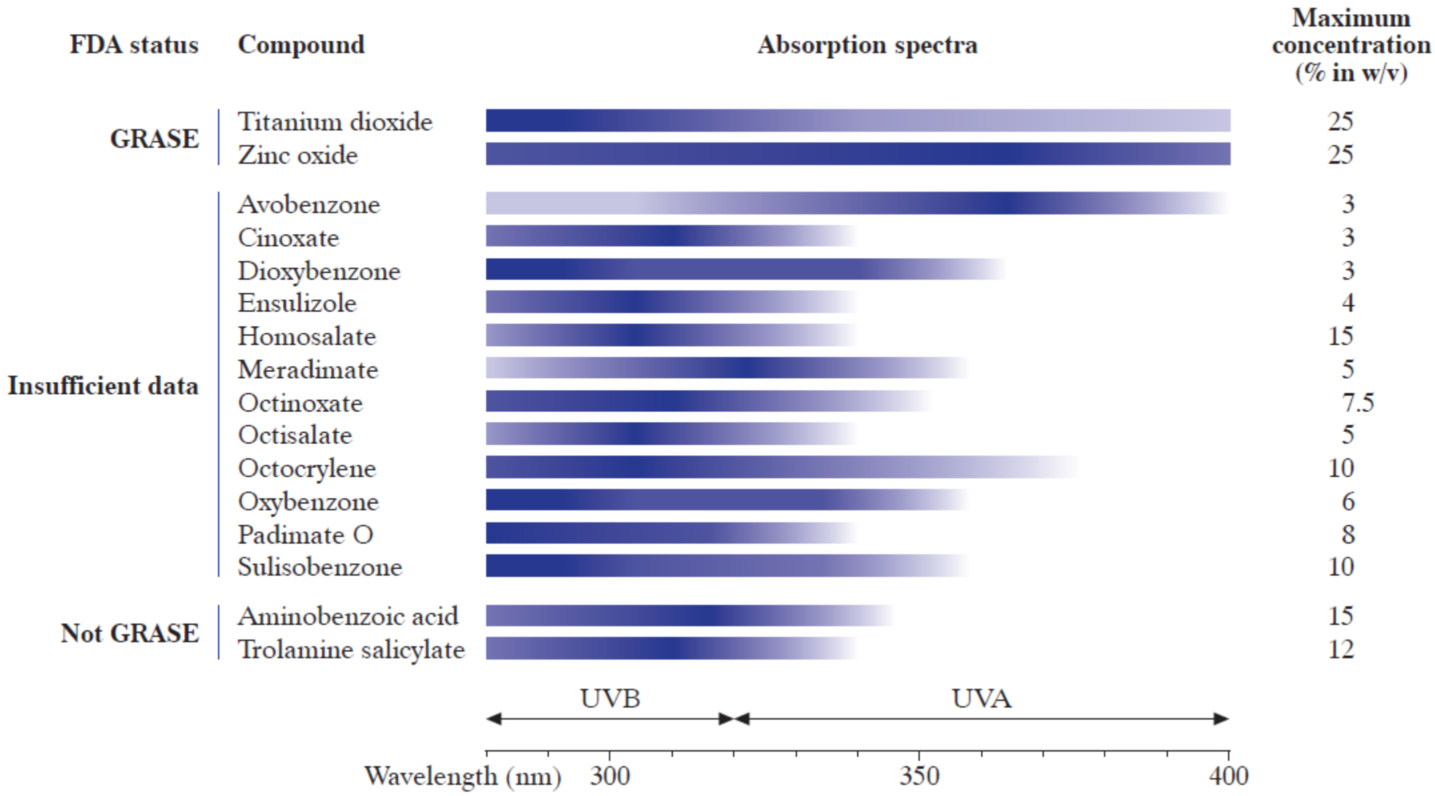

Figure 3: Standardized absorption profile of the FDA-approved UV filters with their maximum concentration allowed in finished sunscreens.

The Sunscreen "Fear"

Despite overwhelming scientific evidence supporting the use of sunscreen, social media has seen a rise in posts downplaying the risks of sun exposure. Even more concerning is the proliferation of posts questioning the safety of commercial sunscreens, with claims that they pose serious health risks. As a result, numerous Do-It-Yourself (DIY) sunscreen recipes have appeared online, often containing oils and, sometimes, non-nano zinc oxide particles. While some natural compounds do possess UV-filtering properties, the majority of DIY sunscreen recipes are void of UV-filtering compounds [58]. They are unlikely to achieve a UV protection efficacy close to that of commercial sunscreens, exposing users to a false sense of security and increasing their risk of overexposure. In addition, there is no standardization or consistency in these formulations that may even have contaminants and deactivating ingredients - all in all, putting people at risk. By contrast, commercially available sunscreens contain carefully selected UV filters and undergo extensive safety evaluations. Although some organic UV filters have been found in the human body, there have been no reports of harmful clinical consequences [58,62,63]. The FDA being committed to ensuring the safe use of sunscreen throughout lifetime, it will undoubtedly take action should any credible concerns arise.

Another common argument against sunscreens is that they may lead vitamin D3 deficiency. Vitamin D3, essential for skeletal integrity, is synthesized in the skin through the action of UVB radiation. Sunscreen-induced vitamin D3 deficiency is against scientific evidence. A meta-analysis has shown that real-life use of moderate SPF sunscreens (~SPF 16) does not significantly impact vitamin D3 levels [64]. While similar results remain to be confirmed for high SPF sunscreens recommended now, it is unlikely that their use would lead to deficiency, as all sunscreens allow some degree of UV permeability [65]. Although individual factors such as sun intensity (latitude, cloud cover, etc.), phototype and age affect vitamin D production, a study has shown that at a latitude of 46°, just 10 to 15 minutes of unprotected sun exposure during summer is sufficient to produce 1,000 IU of vitamin D3, more than twice the recommended daily dose of 400 IU [66,67]. Furthermore, even though dietary vitamin D intake is limited, oral supplementation remains an option.

The final issue that fueled the sunscreen controversy is the environmental impact of UV filters. Both organic and inorganic UV filters can be washed off the skin and enter aquatic ecosystems, with organic UV filters being the most extensively studied [63]. These filters are suspected of contributing to coral bleaching and there is evidence of organic filters accumulating in the food chain [59,63]. However, UV filter concentrations vary depending on the location. While higher in bathing areas and in superficial water, they are lower offshore and in deeper water [68]. Further research is necessary to clarify the role of UV filters in coral bleaching, as climate change, rising ocean temperatures, increased salinity from industrial runoff, acidification and microbiome changes are all recognized as major contributing factors [69]. Nonetheless, the environmental effects of UV filters are under close scrutiny and many manufacturers have voluntarily ceased using compounds suspected of toxicity. Besides, certain ingredients have already been banned in states such as Hawaii (oxybenzone and octinoxate) and Florida (benzophenone-3, octinoxate, octocrylene and 4-methylbenzylidene camphor).

In Canada, the 2024 Sun Awareness Survey conducted by the Canadian Dermatology Association highlights the impact this debate has on public perception and behavior [70,71]. Since 2018, the proportion of people concerned about skin cancer risk due to sun exposure has dropped from 59% to 53%. Alarmingly, 32% of the population now believes that the dangers of sun exposure are exaggerated, an increase of 7% since 2018 and 9% since 2019. Consequently, the proportion of people applying sunscreen when going outdoors went down to 65%, compared to 71% in 2018 and 70% in 2019.

Beyond Sunscreen

Sunscreen application is the most common form of sun protection in the US [72]. However, 44-42% of men report never using sunscreen, while 43% of women regularly apply it to their face and 34% apply it to other exposed areas [73]. Although many users choose sunscreens with relatively high SPF values (15 or higher), the actual amount applied is often far below the recommended 2 mg/cm^2, with a study showing it is as low as 0.5 mg/cm^2 [59,73]. Moreover, a high SPF sunscreen does not imply that UV radiation is entirely blocked. As previously mentioned, SPF represents the ratio between the minimal erythemal dose of UVB for protected skin and that of an unprotected skin. Therefore, an SPF 30 sunscreen still allows 3.33% of UVB radiation that can cause erythema to pass through, while an SPF 50 allows 1.67% to penetrate [59]. Regardless of SPF, some UVB will always reach the skin. Even in the case of broad-spectrum sunscreens -which, according to the 2019 proposed rule, are those with a UVA 1/UV protection ratio of at least 0.7 - also enable some UVA radiation to enter the skin. Essential in minimizing sun damages, sunscreen alone is insufficient.

Avoiding sun exposure and seeking shade is an effective protection measure. When not possible, hats, UPF clothing and sun protective umbrellas could help, but are poorly adopted in the US. While protection is essential, a comprehensive sun safety strategy must also address repair of any UV damage that may have occurred.

There is limited information on the potential benefits of topical cosmetic product application after UV exposure. A recent study, though, has reported promising *in-vitro* and *ex-vivo* results when evaluating a proprietary amino acid complex [74]. In isolated fibroblasts, the complex protected collagen I from reduced synthesis induced by UVA exposure. When applied topically, lotions containing the complex prevented UV-induced inflammation and collagen degradation. Most interesting were the results obtained on reconstructed human epidermis, which compared various regimens involving an SPF 46 sunscreen containing a zinc oxide and titanium dioxide, UVA-UVB irradiation and post-exposure application of a cosmetic serum containing the amino acid complex. The combination of sunscreen application before UV irradiation and the serum afterward was the only regimen that prevented inflammation, oxidative stress, cell division arrest, skin barrier alteration and thymidine dimer formation. For all these parameters, this combination yielded results comparable to those of non-irradiated samples, results that neither sunscreen alone nor cosmetic serum application could achieve.

This preliminary study highlights the potential for a comprehensive and efficient skin cancer prevention strategy, combining photoprotection and post-exposure repair. These findings relying on *in-vivo* and *ex-vivo* models, further confirmation by a bona fide clinical trial is necessary. These results must also be validated under real-life conditions, where factors such as insufficient sunscreen use, rub-off from clothing and wash-off by bathing often reduce sunscreen effectiveness. Yet, these realities further emphasize the need for cosmetic products that can prevent and/or repair UV-induced skin damage after exposure [46,75,76].

Conclusion

After a few decades of growing awareness regarding the dangers of unprotected sun exposure, rising concerns about the safety and environmental impact of sunscreens are fueling a growing online controversy that could turn the tide to the progress made. It is essential to recall the fundamentals of sun protection: unprotected sun exposure, whether recreational or occupational, is the leading cause of skin cancers, which affect one in five Americans during their lifetime. Practicing sun safety and sun protection is essential. While sunscreen is the most commonly used form of protection in the US and has been proven to reduce the skin cancer incidence, complementary solutions exist. Seeking shade and wearing protective clothing are also effective behaviors. There is no need to turn to the risk of unproven DIY sunscreen recipes found online, which are very likely to be inconsistent and result in inadequate protection. For those concerned about health risks, opting for sunscreens with physical UV filters, such as zinc oxide or titanium dioxide, is a viable option. Additionally, individuals worried about environmental impacts can choose sunscreens that avoid ingredients suspected to damage coral reefs. However, it is important to remember that no sunscreen can provide complete protection - and sunscreen need to be re-applied. Whenever possible, using actual scientifically validated after-sun cosmetics should be encouraged to further reduce the risk of skin cancer.

Conflicts of Interest

The authors are consultants for EltaMD, serving on the Scientific Advisory Board.

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Authors' Contributions

All authors contributed to conceptualization, treatment execution, manuscript writing and final approval.

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