
Summer: Sunshine & Innovative Sunscreens

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Introduction – sunlight and its biological effects on the body

The sun and its light are the main driving force of life on our planet. For the human organism, solar radiation acts as a highly complex biological clock that does more than just supply energy. What looks like simple white light to our eyes shows its true nature when it passes through a three-sided glass prism: the beam breaks into a continuous band of bright spectral colors, like a natural rainbow. From a physical viewpoint, this phenomenon represents a finely tuned spectrum of electromagnetic wavelengths.

At the outer edge lies highly energetic UVC radiation, covering a range of 100 to 280 nanometers, followed by vacuum UV. Because these photons precisely match the absorption maximum of nuclear DNA and RNA, they have a radical, highly cell-destroying effect. Although natural solar UVC does not reach the Earth's surface because it is completely absorbed by the stratospheric ozone layer, the cosmetic industry uses this effect artificially as a highly efficient tool for the chemical-free sterilization of pack-

aging materials and production machines. UVC light is followed by UVB light, which ranges between 280 and 315 nanometers. UVB radiation is also extremely full of energy and biologically highly active. Therefore, it is almost completely absorbed within the top layer of the skin, the epidermis, with only about 10 to 15 percent of UVB rays reaching the basal cell layer. Nevertheless, UVB exposure is vital for human survival, as it starts the body's own creation of vitamin D₃, thereby contributing significantly to bone health and a strong immune system.

Moving further into the longer-wavelength part of the spectrum leads to UVA radiation, which spans between 315 and 400 nanometers. UVA light penetrates deeper into the tissue, allowing about 30 to 50 percent of UVA photons to reach the living dermis. In low doses, UVA radiation has gentle, immune-modulating effects and helps the release of nitric oxide from endothelial cells, which improves local blood flow and helps to temporarily lower blood pressure.

The visible light spectrum ranges from 400 to 700 nanometers, providing not only visual

color perception but also controlling essential neurobiological processes via its short-wave blue band—known as High-Energy Visible Light (HEV) between 400 and 500 nanometers. Wavelengths between 450 and 480 nanometers play a key role in controlling the “happiness hormone” serotonin. When this blue light enters the eye, specialized non-visual photoreceptors on the retina containing the pigment melanopsin absorb these photons and send an electrical signal to the internal clock in the brain. This stops the release of the sleep hormone melatonin, instantly making us awake, focused, and in a good mood.

At the same time, blue light activates the light receptor Opsin-3 inside the skin, which similarly leads to a measurable increase in serotonin levels within the blood plasma. Opsins are evolutionarily ancient, light-sensitive proteins that were long believed to exist only as visual pigments in the retina of the eye. Today, it is well-proven that our skin cells also possess a whole family of these molecular antennas, with different variants reacting to different light colors to control highly specific processes across individual skin regions.

Beyond the blue band, the spectrum changes into green, yellow, orange, and red light. These waves penetrate deeply into the skin and have various local and systemic effects on the body. These include the activation of cytochrome c oxidase inside the mitochondria, which increases energy production in the cell and improves local microcirculation. Furthermore, they work

against inflammation, help to optimize the body's own collagen creation, and accelerate tissue healing.

At the long-wave end of the spectrum, starting at 700 nanometers, Infrared-A (IR-A) radiation delivers comfortable warmth deep into the tissue, stimulates cell metabolism, and, in moderate doses, activates cellular protective mechanisms inside the mitochondria.

In summary, natural sunlight at sea level under a clear sky and at solar zenith consists of about 44 percent visible light, 53 percent infrared radiation (heat energy), and just under 3 percent ultraviolet radiation (of which 95% is UVA and 5% is UVB). However, the exact composition and intensity of this terrestrial spectrum are highly dynamic; they are heavily influenced by geography – such as latitude and topographical height – as well as the season and the connected solar angle of incidence. While radiation in equatorial regions and during the summer solstices shows maximum photobiological activity due to the short atmospheric path at a steep zenith angle, flatter angles at higher latitudes or during winter months lead to a significant weakening, especially within the highly energetic short-wave range.

Although sunlight is vital and essential for human health and well-being, the solar spectrum is still subject to the fundamental rule of Paracelsus: “The dose makes the poison.”. If excessive exposure breaks the evolutionary protective barrier of the skin, the biological benefit turns

into cellular stress and health damage. For instance, too much Infrared-A radiation generates reactive oxygen species (ROS) via thermal effects, activating signaling cascades that upregulate matrix metalloproteinases and break down the skin's own collagen framework in the dermis. Overexposure to visible blue light disrupts the day-night rhythm, increases oxidative stress within the skin, and leads to long-lasting, uneven pigmentation through the activation of Opsin-3 in melanocytes. Chronic overexposure to UVA radiation is known as the primary cause of photoaging, whereas UVB overexposure causes sunburn and direct damage to the genetic code^{4~6)}.

What is sunburn and how can we protect ourselves against it?

When a toxic dose of UVB radiation hits the epidermis, the DNA of keratinocytes acts as a direct chromophore that absorbs the incoming photons. This energy breaks chemical bonds inside the double helix, forming faulty covalent connections between neighboring pyrimidine bases. These are known as cyclobutane pyrimidine dimers (CPDs). The DNA becomes molecularly deformed at these sites, making an error-free reading of the genetic code impossible. If cell-internal repair mechanisms fail to fix this damage in time, a cascade is started. The damaged cells release pro-inflammatory cytokines, leading to a massive widening of the blood vessels inside the dermis. The skin becomes painfully red, swollen, and burning – resulting in a classic sunburn. Cells with irreparably destroyed DNA activate the tumor suppressor protein p53,

which starts programmed cell death (apoptosis). These dying cells are histologically visible as “sunburn cells,” and the skin then peels to remove the destroyed tissue. At the same time, UV exposure leads to a temporary local immune suppression by activating epidermal Langerhans cells, making the body briefly more open to infections (e.g., herpes outbreaks after sunbathing).

If these lesions remain unfixed due to repeated overexposure, permanent damage develops, as any cell survival despite mutated DNA dramatically increases the risk of skin cancer. This process moves through clinical stages, starting with chronic UVB damage where cells of the epidermis mutate and form local keratinization disorders. These rough areas are known as actinic keratosis and represent an early stage of light skin cancer. If this stage progresses further, it develops into a locally destructive squamous cell carcinoma or a basal cell carcinoma. Lifelong protection against too much UVB radiation is therefore essential and can reduce the development of skin cancer by up to 90%.

However, because humans feel a psychological and physiological urge to enjoy the sun – frequently exceeding evolutionarily useful limits – the organism needs external help. Effective sun protection is therefore not a cosmetic lifestyle choice, but a medical necessity. Comprehensive photoprotection includes avoiding direct sun (especially midday sun, which makes up 50% of the daily sun dose) by using tools like parasols, sun hats/caps, and UV-protective clothing,

alongside the application of appropriate sunscreens⁷⁾.

Sunscreen today

Humanity's attempt to shield itself from the destructive peaks of solar radiation is not a new phenomenon, but goes back to ancient Egypt. Ancient formulators used plant extracts or applied thick pastes of mineral mud or clay, which functioned as physical blockers in their primitive form. In the early 20th century, the glycoside esculin was extracted from horse chestnut because of its moderate UV-absorbing capability, before the first synthetic filters followed in the 1930s. The Australian chemist Milton Blake developed one of the first commercial sunscreens in 1932, and in 1938, chemistry student Franz Greiter created a protective ointment – the legendary “Gletscher Crème” (Glacier Cream) – after a painful sunburn while climbing the Piz Buin. In 1956, Franz Greiter developed a standardized metric for photoprotection and introduced the Sun Protection Factor (SPF). By today's standards, his original Glacier Cream had an SPF of 2. From these early, simple sunscreens, modern formulation technology has evolved into highly sophisticated galenics. Contemporary sunscreens combine soluble organic filters, which absorb UV energy and convert it into harmless heat, with particulate inorganic (nano-)filters like zinc oxide, which reflect and scatter light. Today's products offer a wide selection of formulations for various applications, providing broadband protection and frequently reaching SPF values above 50.

The required level of photoprotection depends on the user, their location, and their activities. According to WHO guidelines, adequate protection is achieved when the daily UV index is multiplied by 3, and a formulation matching or exceeding this calculated factor is applied to exposed skin at a dose of 2 mg/cm². Because sunscreen can be removed by sweating, swimming, or friction from textiles and sand, reapplication every 2 hours is highly recommended.

Modern photoprotection

Photoprotection is essential, and global sunscreen consumption is experiencing strong growth. For 2026, the global market value is estimated to exceed 16 billion USD, with an annual growth rate projected at 5% to 9%, leading to an expected annual revenue of 20 to 30 billion USD by 2031. While this development is highly positive – given that effective photoprotection successfully works against skin cancer development – it also introduces risks that make the development of advanced sunscreens and new testing methods necessary.

Primary criticisms of current sunscreens include eye stinging during sweating or swimming in the sea, potential skin penetration of UV filters into the systemic circulation, and low environmental biodegradability. The first two problems are well-known and can be effectively solved through suitable galenic measures. However, it is vital that these parameters are monitored, tested, and optimized – a task that is currently difficult due to the scarcity of adequate testing models. The introduction of UV filters into the

environment is another critical issue, which is best solved by creating environmentally compatible, readily biodegradable UV filters. Because such chemical development takes a long time, it is important to focus on smart galenic design to ensure sufficient water resistance for the specific activity. Test methods capable of simulating real-world environmental conditions – such as sweating, swimming in lakes, oceans, or pools, as well as surfing and sailing (where much higher shear rates act upon the skin) – are needed to guide the development and optimization of formulations that stay stable during use but are easily washable afterward. Furthermore, the establishment of simple tests to evaluate the aquatic toxicity of finished formulations is highly desirable, as galenic matrices and the combination of different substances do not always behave additively based on individual component data.

In addition to these performance points, many contemporary sunscreen products have a sticky consistency that consumers find unpleasant and disruptive on the skin. Applying the required dose of 2 mg/cm² represents a major practical challenge for users, yet it must be done to achieve the labeled SPF *in vivo*. Consequently, there is a strong demand to develop formulations that require a lower application density, spread easily, and remain non-sticky, preventing users from looking like “freshly breaded Wiener Schnitzels” when coming into contact with sand or dirt. However, realizing this wish is exceptionally difficult in reality, as SPF measurements must occur under standardized conditions requiring a fixed dose of 2 mg/cm². Even if a for-

mulation achieves sufficient protection at a lower application rate, this benefit cannot be legally claimed because it cannot be measured via standardized norms. Thus, innovative and expressive testing methodologies are required to facilitate the development and verification of user-friendly formulations.

Another critical point is addressing the entire solar spectrum. Effective UVB protection extends the time a user spends in the sun. Consequently, while the cumulative UVB dose is minimized, the exposure to UVA, visible light, and infrared radiation increases proportionally with the sunscreen's SPF. The potential damage caused by UVA has already been acknowledged. However, the damage induced by excessive visible and infrared light is not yet consistently countered in commercial sun protection products. To bridge this gap, it is highly recommended to integrate antioxidants in adequate concentrations and optimized galenic vehicles to deliver them into deeper skin layers, while simultaneously preventing the penetration of UV filters into the skin.

Current research and outcome

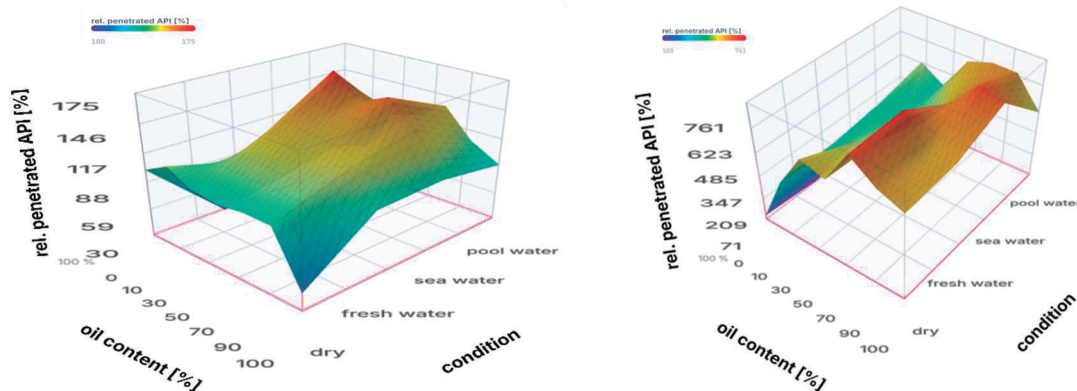
The Sunscreen Research Center has been actively addressing these challenges since 2024, aiming to develop and establish modern formulations and innovative testing methodologies. Various *ex vivo* techniques are available to investigate the penetration dynamics of active ingredients and UV filters into and through the skin barrier. Separately or in combination, these models facilitate spatially and temporally resolved profiling of UV filter penetration. A

unique feature of these setups is their capacity to simulate real-world environmental impacts.

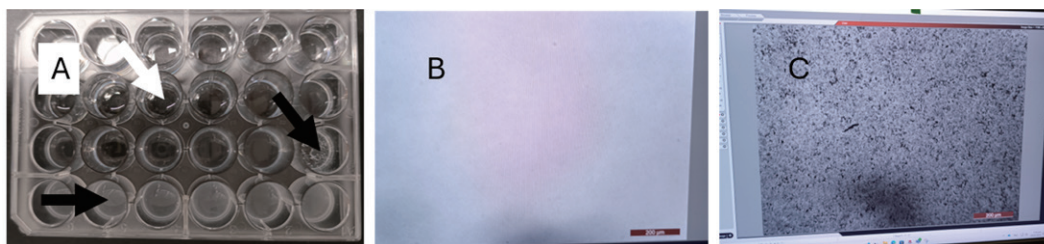
These simulations include swimming and bathing in freshwater lakes, seawater, or chlorinated pools, as well as sweating, textile-induced wear, and friction from beach sand. Distinct climate zones can also be modeled by modifying temperature and relative humidity. Preliminary results show that the dermal penetration of UV filters and other topically applied substances depends heavily on these environmental variables, highlighting a highly complex interplay of parameters. Currently, a reliable, generalized prediction regarding the penetration efficiency or speed of an active agent or UV filter across different vehicles and environments remains unfeasible, making industrialized, case-by-case testing highly advisable. Key insights reveal that hydrophilic substances incorporated into hydrophilic bases are rapidly washed out of the skin. However, when emulsifiers and lipids are introduced into the formulation, this washout effect

is significantly reduced. While lipophilic substances are inherently less prone to water-induced washout, the chemical nature of their vehicle exerts a far greater influence on their penetration efficiency than is observed with hydrophilic counterparts. Crucially, electrolytes – such as those present in marine or pool water – profoundly change penetration behavior compared to freshwater, capable of more than doubling both the cumulative amount of penetrated active ingredient and its penetration depth ⁽⁸⁾, Figure 1).

Further investigations target the impact of solar radiation and sunscreen products on the skin's natural antioxidant capacity. Our data showed that not only sunlight but also sunscreens themselves can induce oxidative stress on the skin, underlining the critical importance of combining specific antioxidants directly with UV filter systems. Additional research addresses the phenomenon of sunscreen-induced eye stinging. We successfully showed that when sunscreens

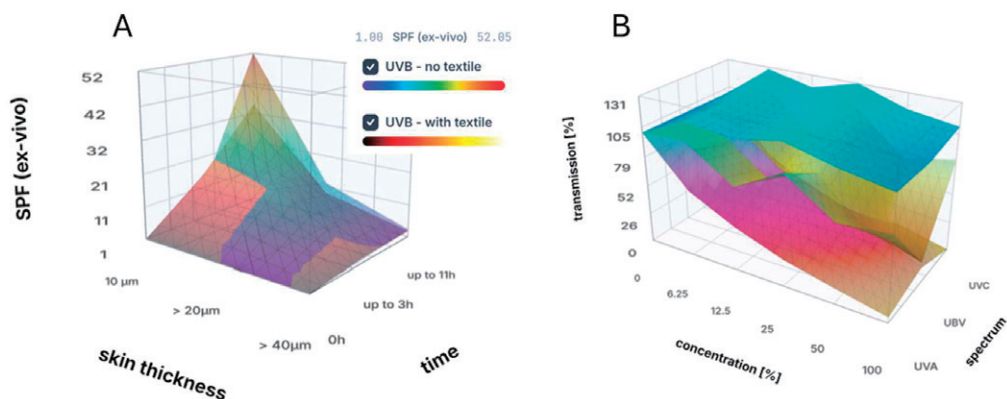


■ Fig. 1 Influence of formulation design and environmental conditions on active ingredient penetration.



■ **Fig.2 Visualization of the mechanism underlying sunscreen-induced eye irritation.**

A: 24-well plate from a bird's-eye view—the white arrow indicates a clear sunscreen extract. The black arrows show the extracts after artificial seawater was added, clearly revealing the formed precipitates. B: Microscopic image of a sunscreen extract prior to the addition of artificial seawater. C: Microscopic image of a sunscreen extract after the addition of artificial seawater, clearly showing the formed microparticles. Error bar = 200 μm .



■ **Fig.3 Spatially and temporally resolved *ex vivo* SPF measurements.**

A: Influence of textile wear on SPF – cutaneous penetration kinetics over time post-application; B: Influence of distinct UV filters and their concentrations on the transmission of various wavelengths (UVB filter vs. UVA filter vs. antioxidant without intrinsic UV-filtering properties)..

come into contact with electrolytes – such as via sweating or salt water – poorly soluble precipitates can form (Figure 2A). These precipitates consist of microparticles (Figure 2A) that provide a clear mechanical explanation for the widely known sensation of stinging eyes.

A novel development is the measurement of *ex vivo* SPF, which determines light transmission

through skin or skin-mimicking materials under real-world conditions⁹⁾. For the first time, this method allows researchers not only to determine a static SPF value but also to monitor spatial and temporal variations in photoprotection dynamically (Figure 3A). The application can be extended to other wavelength regions, such as UVA light (Figure 3B). This enables the comprehensive evaluation of broadband protection

and its fluctuations under shifting environmental stressors (e.g., filter washout during swimming), facilitating a deeper understanding that drives the engineering of optimized sunscreen formulations with tailored product properties.

Additional assays to evaluate aquatic toxicity are currently under development, utilizing bioluminescent test organisms. Alterations in bioluminescence serve as an analytical readout to determine the impact of specific formulations on aquatic ecotoxicity. The combination of these diverse methodologies enables highly efficient testing of photoprotective agents and allows for systematic optimization aligned with target product profiles.

Summary

Summer and sunshine promote health and well-being—provided they are enjoyed in the correct dosage. Sunscreens are essential tools to achieve this balance. Modern photoprotective products should feature lightweight, non-sticky textures that offer excellent spreadability. Because the galenic vehicle fundamentally dictates a sunscreen's core properties—including eye stinging, penetration kinetics, water resistance, aquatic toxicity, and SPF performance—targeted galenic optimization is paramount to achieving maximum efficacy and consumer compliance. To facilitate these advancements, novel testing methodologies are urgently required. These are currently being developed and optimized at the University of Marburg in close collaboration with the University of Auckland. Industrial partnerships are already active and highly welcome.

References:

- 1) Sklar, L.R.; Almutawa, F.; Lim, H.W.; Hamzavi, I. Effects of ultraviolet radiation, visible light, and infrared radiation on erythema and pigmentation: a review. *Photochemical & photobiological sciences : Official journal of the European Photochemistry Association and the European Society for Photobiology* 2013, 12, 54–64, doi:10.1039/c2pp25152c.
- 2) International Agency for Research on Cancer (IARC). Radiation; [publisher not identified]: [Place of publication not identified], 2012, ISBN 9789283213215.
- 3) World Health Organization; International Agency for Research on Cancer. Solar and ultraviolet radiation; IARC; Distributed for the International Agency for Research on Cancer by the Secretariat of the World Health Organization: Lyon, Geneva Switzerland, 1992, ISBN 9789283212553.
- 4) Schroeder, P.; Lademann, J.; Darvin, M.E.; Stege, H.; Marks, C.; Bruhnke, S.; Krutmann, J. Infrared radiation-induced matrix metalloproteinase in human skin: implications for protection. *The Journal of investigative dermatology* 2008, 128, 2491–2497, doi:10.1038/jid.2008.116.
- 5) Setty, S.R. Opsin3-A Link to Visible Light-Induced Skin Pigmentation. *The Journal of investigative dermatology* 2018, 138, 13–15, doi:10.1016/j.jid.2017.09.025.
- 6) Brar, G.; Dhaliwal, A.; Brar, A.S.; Sreedevi, M.; Ahmadi, Y.; Irfan, M.; Golbari, R.; Zumárraga, D.; Yateem, D.; Lysak, Y.; et al. A Comprehensive Review of the Role of UV Radiation in Photoaging Processes Between Different Types of Skin. *Cureus* 2025, 17, e81109, doi:10.7759/cureus.81109.
- 7) Marson, J.; Farberg, A.; Glazer, A.; Litchman, G.; Svoboda, R.; Winkelmann, R.; Rigel, D. Expert Consensus on Sunscreen for the Primary Prevention of Skin Cancer: Results of the Skin Cancer Prevention Working Group Conference. *J of Skin* 2021, 5, 190–202, doi:10.25251/skin.5.3.1.
- 8) Assessing the dermal penetration of UV-Filters in different environmental conditions. *EuroSun 2026*, Basel, 2026.
- 9) Keck, C.M., C. Ferdinand, E. Saleski. Method and System for Space- and Time-Resolved Profiling of Light-Protective Properties of Topical Formulations on Skin and Skin Mimics Under Real- World Conditions, May 2026.

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