Daily photoprotection to prevent photoaging

DOI:
10.1111/phpp.12688

Document Version
Final published version

Published in:
Photodermatology, Photoimmunology & Photomedicine

Received: 7 December 2020 | Revised: 10 March 2021 | Accepted: 19 April 2021

DOI: 10.1111/phpp.12688

REVIEW ARTICLE

Photodermatology, Photoimmunology & Photomedicine WILEY

Daily photoprotection to prevent photoaging

Jean Krutmann[1,2] | Sérgio Schalka[3] | Rachel Elizabeth Beatrice Watson[4,5,6] | Liu Wei[7] | Akimichi Morita[8]

[1]IUF Leibniz Research Institute for Environmental Medicine, Dusseldorf, Germany

[2]Medical faculty, Heinrich-Heine-University, Dusseldorf, Germany

[3]Medcin Skin research Center and Biochemistry Department, Chemistry Institute of São Paulo University, São Paulo, Brazil

[4]Centre for Dermatology Research, The University of Manchester & Salford Royal NHS Foundation Trust, Salford, UK

[5]Manchester Institute for Collaborative Research on Ageing, University of Manchester, Manchester, UK

[6]NIHR Manchester Biomedical Research Centre, Manchester University NHS Foundation Trust, Manchester Academic Health Science Centre, Manchester, UK

[7]Department of Dermatology, The General Hospital of Air Force PLA, Beijing, China

[8]Department of Geriatric and Environmental Dermatology, Nagoya City University Graduate School of Medical Sciences, Nagoya, Japan

Correspondence
Jean Krutmann, IUF Leibniz Research Institute for Environmental Medicine, Dusseldorf, Germany.
Email: Jean.Krutmann@IUF-Duesseldorf.de

Abstract

Background: Extrinsic skin aging or photoaging was previously thought to be almost exclusively due to solar ultraviolet (UV) radiation. However, recent literature has described other contributing factors and clarification is thus required as to what extent and what type of daily photoprotection is needed to mitigate extrinsic skin aging.

Methods: We reviewed the existing scientific evidence on daily photoprotection, and specific requirements at the product level, to prevent extrinsic skin aging. We critically reviewed the existing evidence on potential ecological and toxicological risks which might be associated with daily photoprotection.

Results: Evidence shows that broad protection against the entire solar range of UVB, UVA, UVA1, visible light, and short infrared (IRA) is required to prevent extrinsic aging. Other exposome factors, such as air pollution and smoking, also contribute to skin aging. Daily broad-spectrum sunscreen photoprotection should thus contain antioxidant ingredients for additional benefits against UV, IRA, and pollution-induced oxidative stress as well as anti-aging active ingredients to provide clinical benefits against skin aging signs, such as wrinkles and dark spots. Broad-spectrum sunscreen containing pigments, such as iron oxide, may be required for melasma prevention. There is no conclusive clinical evidence that daily sunscreen use is unsafe or that it compromises vitamin D synthesis.

Conclusion: Daily use of broad-spectrum sunscreen containing antioxidant and anti-aging active ingredients can effectively reduce extrinsic aging.

KEYWORDS

photoaging, photoprotection, pigmentary disorders, sunscreens, wrinkles

1 | INTRODUCTION

Chronic exposure to sunlight is known to have detrimental effects on human skin by causing skin cancer. In this regard, the use of sunscreens has received considerable attention and corresponding public campaigns have been conducted to educate consumers that regular sunscreen use can effectively reduce skin cancer risk.[1-3]

In addition to causing skin cancer, exposure to sunlight also contributes to extrinsic skin aging. Until recently, exposure to solar ultraviolet (UV) radiation was regarded as the major, if not the only, cause of extrinsic skin aging. As one consequence, cosmetic products for daily photoprotection have been advocated as a potentially effective preventive measure to slow down skin aging. More recently, however, it has become increasingly clear that the situation is much more complex. The solar spectrum is

composed of various wavelengths and there are wavelengths in other spectral regions beyond UV which contribute to extrinsic skin aging. Furthermore, it is now generally accepted that the skin aging exposome includes several other factors, such as air pollution and tobacco smoke.[4] This leaves consumers unsure as to what extent and what type of daily photoprotection is needed to prevent external skin aging. Furthermore, ecological and toxicological concerns have been raised about the daily use of sunscreen products. We therefore felt it was appropriate and timely to review the existing scientific evidence that daily photoprotection is efficient in preventing extrinsic skin aging. Finally, we discuss specific requirements at the product level and critically review the existing evidence as it concerns ecological and toxicological risks which might be associated with daily photoprotection.

2 | CLINICAL SIGNS OF EXTRINSIC SKIN AGING

Wrinkles, laxity, roughness and telangiectasia are clinical hallmarks of both intrinsic and extrinsic skin aging processes, while pigmentary conditions (including lentigines, post-inflammatory hyperpigmentation [PIHP], melasma), yellowing and uneven skin tone are strongly linked to extrinsic skin aging and usually observed on the face, neck, chest, and dorsal hands.[5-7] Clinical signs of photoaging differ depending on age, gender, and especially skin phototype and ethnicity.[8-12] In general, wrinkles appear 10-20 years earlier in fair skin than in Asian skin, while dark-skinned individuals from Asian and African ethnic groups are more prone to actinic lentigines and hyperpigmentation.[8,9]

3 | THE ROLE OF ULTRAVIOLET B AND ULTRAVIOLET A IN PHOTOAGING

Acute UVB irradiation results in decreased dermal and epidermal hyaluronic acid (HA) content and photoexposed skin is characterized by distinct homeostasis of HA.[13,14] Skin aging is associated with loss of skin moisture and one dramatic histochemical change observed in aged skin is the marked disappearance of epidermal HA that has unique capacity in retaining water.[15]

Both UVB (290-320 nm) and UVA (320-400 nm), particularly long-wave UVA1 (340-400 nm), cause photoaging. Because of its physical properties, UVB radiation mainly affects the epidermis, whereas UVA rays can penetrate more deeply into the dermal compartment and directly affect dermal fibroblasts. The dermis is the skin compartment which is primarily affected by photoaging. UVB effects on the dermis are thus thought to be mediated by keratinocyte-derived, UVB-inducible soluble mediators such as selected cytokines, but also matrix metalloproteinases (MMPs), which diffuse down into the dermis where they affect the extracellular matrix (ECM).[16] In contrast, long-wave UVA (UVA1) radiation can directly cause macromolecular damage in dermal fibroblasts and generate mitochondrial DNA deletions for example. Recent evidence suggests that there is interplay between these mechanisms, resulting in controlled dermal ECM turnover.[17] Over time, these result in fibroblast senescence and the production of a fibroblast secretome, which is thought to be a major driver of skin aging.[18]

In vitro, ex vivo and in vivo studies in human skin cells, 3-D skin models and human skin are consistent with the assumption that both UVB and UVA rays contribute to the formation of skin wrinkles and the development of uneven skin pigmentation, including the generation of age spots (solar lentigines).[19,20]

It has been demonstrated that UVA1 exposure induces skin darkening to a similar extent in skin phototypes III to VI with similar cellular changes in all skin phototypes, which highlights the importance of broad-spectrum sunscreen even in dark-skinned individuals.[21]

4 | THE ROLE OF VISIBLE LIGHT AND INFRARED A RADIATION IN SKIN PHOTOAGING

Although chronic UV exposure is widely considered as the major cause of photoaging, all spectral regions (UV, visible light [VL] and near infrared [IR]) cause free radical formation and hence can promote premature skin aging by modulating the expression of ECM molecules, MMPs, and inflammatory cell infiltration in human skin.[22-26] Visible light and short infrared (IRA) penetrate into the hypodermis and thus could potentially impact all the compartments of the skin. Furthermore, VL and IRA may play a role in photoaging in both light and darker skin types so even people with darker skin need solar protection.[27,28]

IRC (3000 nm-1 mm) and IRB (1400-3000 nm) are absorbed at the skin surface or the upper layers of the epidermis and do not contribute to skin aging. In contrast, IRA (700-1400 nm) can penetrate deeper to directly affect cells in the epidermis, dermis, and subcutis to contribute to photoaging.[29] Both murine and human studies showed that IRA causes wrinkles.[25] Furthermore, IRA radiation has been shown to induce MMP-1 upregulation, which was reduced by applying a sunscreen supplemented with an antioxidant cocktail, whereas sunscreen alone did not protect against IRA.[30]

The relevance of VL for skin aging remains unclear and there has been no demonstration of skin wrinkling induced by VL.[31,32] VL, as well as synergistic effects of long-wavelength UVA1 and VL, have been shown to induce long-lasting skin pigmentation in dark skin but not in fair-skinned individuals,[33,34] and it likely interacts with the same melanin precursor as UV.[35] The shorter wavelengths of VL (blue-violet light), via the opsin 3 receptor in melanocytes, cause melanin synthesis.[36,37] There is also circumstantial evidence that VL might also contribute to the pathogenesis of melasma,[38] which might be viewed as a form of skin aging.[39] Adding VL protection (iron oxide) in a well-balanced UVB/UVA containing sunscreen significantly decreased hyperpigmentation.[40]

5 | EXPOSOME FACTORS BEYOND SOLAR RADIATION CONTRIBUTE TO PHOTOAGING

In addition to solar radiation (UV, VL, IR), other exposome factors may contribute to skin aging, including air pollution, smoking, and lifestyle factors (nutrition and sleeping patterns).[4,41] Both epidemiological and mechanistic studies have demonstrated a role of traffic-related air pollution exposure (particulate matter [PM], soot and nitrogen dioxide) and tropospheric ozone skin damage causing premature skin aging with lentigines and/or wrinkle formation in Caucasians and East Asians.[4,41-45] Epidemiological findings suggest that associations of UV radiation with facial skin aging can be negatively affected by PM exposure, which might be explained by the fact that increased PM concentrations in the troposphere reflect and absorb UV rays and thereby reduce the UVB dose reaching the skin. Under certain circumstances, however, UV and PM might be additive for skin aging, as was suggested by in vitro experiments assessing a combined effect of pollution and UVA1 on the skin.[46,47] Additionally, tobacco smoke is an important environmental factor that has been associated with skin aging, causing increased wrinkles and tissue laxity, driven by loss of dermal elastic fibers[48]; smoking also results in pigmentary changes, including hyperpigmentation.[49-51] To protect against high exposure to air pollution, broad-spectrum sunscreens should be combined with additional skin care benefits, for example, antioxidants, to prevent skin pigmentation and extracellular matrix degradation.[52,53] Ideally daily photoprotection strategies should include complete protection against all factors of photoaging.

6 | DOES DAILY PHOTOPROTECTION WITH BROAD-SPECTRUM SUNSCREEN PREVENT PHOTOAGING?

Initial studies in Caucasians showed that daily use of topical, broad-spectrum sunscreen prevents photoaging.

In the first study, the effects of chronic sunscreen use on the histologic changes of photoaging were evaluated in 46 patients of mean age 63 years and with a history of skin cancer who were randomized to apply either sun protection factor (SPF) 29 UVB/ UVA (short wavelength UVA2) sunscreen or vehicle daily for 24 months. At 24 months, a decrease in solar elastosis was observed with treatment versus placebo using punch biopsy specimens of preauricular skin analyzed by computer enhancement.[54]

In a larger, randomized, controlled study in younger subjects aged <55 years old (mean age 39 years), which was conducted in Australia in 903 subjects, the effects of regular sunscreen use were assessed at the level of clinical symptoms. Subjects were randomly assigned to apply SPF 15+ broad-spectrum sunscreen daily for 4.5 years (with instructions on how to apply it properly) or to the control group who could apply sunscreen on a discretionary basis (which was usually recreational use). The daily sunscreen group showed no detectable increase in skin aging after 4.5 years and 24% less skin aging than the discretionary sunscreen group (relative odds, 0.76 [95% CI, 0.59-0.98]), as measured by microtopography of dermal elastosis on the back of the hands.[55] As that study was performed between 1992 and 1996 with a broad-spectrum SPF 16 sunscreen with low UVA protection, more recent sunscreens with better UVA protection may be expected to be even more effective at preventing photoaging.[56]

Daily use of a facial UVA/UVB broad-spectrum, photostable sunscreen with SPF 30 (UVA-PF not specified) in 32 subjects for 52 weeks significantly improved clinical evaluation of photoaging (overall photodamage, overall skin tone, crow's feet, fine lines, mottled pigmentation, discrete pigmentation, evenness of skin tone, clarity, and texture). Assessments included dermatologist evaluations and subjects' self-assessment. At week 52, all subjects showed improvements in skin texture and clarity, and the greatest improvements were observed in mottled and discrete pigmentation (52% and 42% mean improvements from baseline, respectively).[57] This study demonstrated that daily use of a facial broad-spectrum photostable sunscreen can prevent uneven pigmentation and may visibly reverse the signs of existing photodamage, in addition to preventing wrinkles and additional sun damage. The authors speculated that daily use of a product with a higher SPF (and a higher UVA-PF) would provide even greater protection and greater improvements in photoaging.[57]

Several studies have been performed in East Asian and South Asian subjects with darker skin types. A single–arm interventional study in 14 elderly Japanese people of mean age 79.6 years old (range: 62-91 years) with photoaged skin, investigated the effects of sunscreen application for 18 months. At the beginning of the study, subjects received instructions from the dermatologist on the proper method of application and were given a leaflet illustrating how much to apply (~2 mg/cm^2) with a sample photograph. Despite this, there were large differences in total amount of sunscreen used. After 18 months of sunscreen application, the only significant difference was observed for skin surface hydration. However, the changes in the number of spots and skin tone uniformity during the study period showed good correlation with the amount of sunscreen used.[58]

A randomized, uncontrolled and investigator-blinded study was conducted in India in 216 subjects, aged 18-45 years old, with skin phototype IV and V with pigmentation irregularities (actinic lentigines and PIHP), who did not previously use sunscreens. Participants were randomized to apply twice daily either sunscreen product A (sun protection factor 50 with high UVA protection factor PA+++) or sunscreen product B (sun protection factor 19 with high UVA protection factor PA+++) before sun exposure for ≥2 hours for 12 weeks. The clinical assessment of the density of pigmented spots and skin radiance showed significant ($P < .001$) improvement in both groups compared to baseline.[59] There were no significant differences detected when the two treatment groups were compared with each other.

In the aggregate, these studies provide compelling evidence that regular use of sunscreens is effective in preventing the development of wrinkles and uneven pigmentation in different ethnic groups.

It has also been speculated that the efficacy of daily photoprotection might be increased by supplementing UV filters with actives that have anti-skin-aging properties and/or that extend the protection beyond the UV spectrum. There is indeed evidence that such combination products are capable of partially preventing and even reverting clinical signs of skin aging.[19,60,61] As an example, a 6-month, randomized, double-blind, vehicle-controlled study of 346 subjects with photoaged skin, as defined by the presence of wrinkles in the periorbital region, evaluated the efficacy of SPF 15 sunscreen and a cream formulation of 0.05% isotretinoin. After once-daily application for 6 months, subjects using sunscreen with 0.05% isotretinoin had statistically significant improvement in the appearance of wrinkles associated with photoaged skin compared with the vehicle group.[62]

The additional benefit of protecting against VL was shown in a randomized controlled trial in 40 melasma patients comparing two UVA/UVB sunscreens, one of which was supplemented with VL protection (tinted and contained iron oxides). The use of the sunscreen with VL protection prevented melasma relapses compared to the UV-only sunscreen, as measured by the evolution of Melasma Area and Severity Index score.[63] Similarly, in a double-blind, randomized trial in 68 melasma patients, UV-VL sunscreen enhanced the depigmenting efficacy of hydroquinone compared with UV-only sunscreen in the treatment of melasma.[64]

Similarly, addition of antioxidants to UV filter-containing sunscreens was found to be effective in protecting against IRA-induced molecular events indicative of skin aging. A vehicle-controlled, double-blind, randomized study in 30 healthy volunteers evaluated the effectiveness of an SPF 30 sunscreen versus the same sunscreen supplemented with an antioxidant cocktail containing grape seed extract, vitamin E, ubiquinone and vitamin C to protect human skin against IRA radiation-induced MMP-1 upregulation. The sunscreen supplemented with antioxidants protected human skin against IRA radiation, which contributes to photoaging, whereas the regular sunscreen did not.[30] Of note, this study used IRA-induced MMP-1 mRNA expression as a surrogate marker for wrinkle formation. A human study comparing regular use of sunscreens with and without IRA protection, however, has not yet been conducted.

At present, there is no clear evidence that topical application of DNA repair enzymes or nicotinamide, which is highly effective in preventing actinic keratosis, have benefits in reducing the incidence of chronic sun exposure-related photoaging.[65-67]

7 | CURRENT CONCERNS AND CONTROVERSIES IN THE USE OF TOPICAL PHOTOPROTECTION

The studies described above support the beneficial effects of sunscreen to prevent photoaging. However, certain challenges remain, as discussed in a recently published review by Krutmann et al.[68]

7.1 | Should photoprotection include UVA protection?

Sunscreens were originally developed to minimize erythema (sunburn) and sun protection factor (SPF) is thus mainly an index of UVB protection, measuring eythema. However, it is now widely accepted that other acute and chronic pathogenic effects may occur after cumulative exposure to sub-erythemal doses of solar UVR, including UVA and an ideal sunscreen should protect against the entire solar UVB/UVA range.[20,69]

7.2 | Does photoprotection impair vitamin D synthesis?

There are concerns that sunscreen may block the beneficial effects of UVR, for example, vitamin D synthesis, antimicrobial effects, tanning and photoadaptation. Several recently published reviews have concluded that broad-spectrum sunscreens for daily use in real-life settings are unlikely to compromise vitamin D synthesis, even after application of proper amounts.[70,71] Vitamin D screening for vitamin D supplementation should be restricted to those at risk of hypovitaminosis, such as patients with photosensitivity disorders requiring strict sun avoidance and photoprotection.[71]

7.3 | Is sunscreen photoprotection safe for daily use?

As photoaging prevention requires daily use of sunscreen, the safety of these products is critical. UV absorbers are regulated as cosmetics in most countries in Europe and Latin America, as well as Japan, as over-the-counter drugs in the United States and Canada, and as therapeutic drugs in Australia. Similarly, various different UV filters are available in the different regions. The United States Food and Drug Administration (FDA) published a prior pilot study on four commercially available organic sunscreen products (lotion, aerosol spray, non-aerosol spray and pump spray)[72] and a randomized clinical trial on the effect of sunscreen application on plasma concentration of six sunscreen organic filters under single-dose and maximal use conditions.[73] All six tested active ingredients and all of the formulations, resulted in measurable blood levels of the active ingredient. However, this study was conducted in situations that do not accurately reflect the reality of sunscreen applications (dose per cm^2, surface, and frequency of application). The authors suggest performing larger-scale studies to assess the clinical implications of these findings, as the fact that an ingredient is absorbed through the skin and into the blood does not necessarily mean that the ingredient is unsafe. Furthermore, daily photoprotection concerns limited surface areas which are exposed to the sun all year long, such as the face and hands. The FDA calls for further industry testing to determine the safety and effect of systemic exposure of sunscreen ingredients, especially with chronic use, and these results do not indicate that individuals should refrain from the use of sunscreen. Inorganic

TABLE 1 Summary of the main criteria for topical sunscreens for daily photoprotection to prevent photoaging

	Topical sunscreen criteria
Sunscreen application	Apply daily
	Apply proper amount
	Apply on whole face including eyelid and periorbital regions
Protection against UVB, UVA, UVA1, and VL	SPF of at least 30 with high UVA-PF (the PF should be adapted to the latitude and skin type)
Additional protection against IRA and pollution	Antioxidant ingredients
Prevention of skin aging signs	Anti-aging active ingredients
Prevention of melasma and actinic lentigo	Tinted sunscreen with UVB, UVA1 and HEV protection
Obtain optimal compliance	Good cosmeticity, sensoriality and tolerability
	Avoid white residues

Abbreviations: HEV, high energy visible blue-violet light; IRA, infrared; SPF, sun protection factor; UV, ultraviolet; VL, visible light.

sunscreens have been linked to frontal fibrosing alopecia but at present there remains insufficient evidence to establish a direct causal relationship.[74]

7.4 | Is sunscreen photoprotection deleterious for the environment?

Another controversial topic is the environmental impact of sunscreen, especially organic UVR filters and their toxic effects on marine ecosystems and aquatic organisms.[75-78] The chronic effects of common sunscreen UV filters and preservatives were tested on the photosynthetic efficiency of scleractinian coral and several organic UV filters showed no significant decrease in coral photosynthetic efficiency and hence were not likely to cause coral bleaching, but zinc oxide was more toxic.[79] To put these concerns into perspective we would like to emphasize that the major cause for coral bleaching is global warming and the concomitant increase in water temperature, although oxybenzone may further weaken coral experiencing global warming.[80] Further studies are warranted on the in-situ concentrations of UV filters and preservatives as well as their individual and combined effects on corals.[79]

8 | REQUIREMENTS FOR DAILY PHOTOPROTECTION FOR SKIN AGING PREVENTION

Dermatologists advocate a multi-pronged approach to minimizing UVR exposure including lifestyle modifications, UVR protective clothing and sunglasses, and topically applied sunscreen products.[74] The main criteria for topical sunscreens for daily photoprotection to prevent photoaging are summarized in Table 1. A high UVA-PF should take priority over high-SPF values, which may have insufficient long UVA1 protection. In general, an SPF of at least 30 should ensure UV protection over the whole day even if small amounts are applied. However, the skin type, latitude and altitude should be taken into consideration and a higher SPF for example may be required at lower latitudes. Furthermore, while high-SPF products require higher concentrations of actives and thus have potentially higher health risks if they penetrate the skin and higher environmental risks, sunscreen is generally under-applied at only 25% of the recommended dose, which may compromise photoprotection. Analysis by UV imaging in 57 participants revealed that eyelid and periorbital regions were disproportionately missed during routine sunscreen application (median 14% missed in the eyelid region vs 7% of rest of face missed, $P < .01$).[81] This highlights the importance of sunscreens with good cosmeticity and tolerability, as well as wearing sunglasses. Sunscreens should contain antioxidant ingredients to provide additional benefits against UV, IRA and pollution-induced oxidative stress and contain anti-aging active ingredients to optimize clinical benefits against skin aging signs such as wrinkles and dark spots. Formulations that leave white residues are not desirable, especially for dark-skinned individuals, whereas formulations that are easy and pleasant to apply are likely to result in better adherence to daily photoprotection. Tinted broad-spectrum sunscreens containing pigments such as iron oxide to protect against VL may be required for melasma prevention and for the prevention of cutaneous hyperchromias (actinic lentigo).[40]

ACKNOWLEDGEMENTS

Editorial assistance was provided by Helen Simpson, PhD, ISMPP CMPP™, of My Word Medical Writing and funded by Vichy Laboratoires.

CONFLICT OF INTEREST

Dr Krutmann reports personal fees from Laboratoires Vichy (L'Oreal) related to this work; grants and personal fees from Amway, grants and personal fees from Beiersdorf, grants and personal fees from bitop, grants and personal fees from Blue Lagoon, grants and personal fees from Estee Lauder, grants and personal fees from Evonik, grants and personal fees from Galderma, grants and personal fees from Henkel, grants and personal fees from Horphag, grants and personal fees from ISDIN, grants and personal fees from Kiessling, grants and personal fees from Lancaster-Coty, grants and personal fees from La Roche Posay, grants and personal fees from L'Oreal, grants and personal fees from Lycored, grants and personal fees from Mary Kay, grants and personal fees from Procter & Gamble, grants and personal fees from Repairogen, grants and personal fees from RepliCel, grants and personal fees from Skinceuticals, grants and personal fees from SkinMedica, an Allergan Company, grants and personal fees from Stada, grants and personal fees from Symrise, grants and personal fees from Unilever, grants and personal fees from Vichy,

grants and personal fees from Walgreen-Boots-Alliance, outside the submitted work. Dr Schalka has received speaker and consultancy fees from Johnson & Johnson, La Roche Posay, ISDIN, Mantecorp Brasil, Galderma Brasil, NAOS France, consultancy fees from Pierre Fabre, Vichy, Farmoquímica Brasil, AMIFAR Spain, speaker fees from Beiersdorf and investigator fees from Libbs Brasil, outside the submitted work. Dr Watson has received consulting fees from Nestle Skin Health, NAOS, Allergan, and research funding from Walgreens Boots Alliance, outside the submitted work. Dr Wei has nothing to disclose. Dr Morita has nothing to disclose.

DATA AVAILABILITY STATEMENT

This is a review article and no data is available.

ORCID

Jean Krutmann https://orcid.org/0000-0001-8433-1517
Rachel Elizabeth Beatrice Watson https://orcid.org/0000-0002-5162-7503
Akimichi Morita https://orcid.org/0000-0001-8372-3754

REFERENCES

1. van der Pols JC, Xu C, Boyle GM, Parsons PG, Whiteman DC, Green AC. Expression of p53 tumor suppressor protein in sun-exposed skin and associations with sunscreen use and time spent outdoors: A community-based study. *Am J Epidemiol*. 2006;163(11):982-988.
2. Green AC, Williams GM. Point: Sunscreen use is a safe and effective approach to skin cancer prevention. *Cancer Epidemiol Biomarkers Prev*. 2007;16(10):1921-1922.
3. Green AC, Williams GM, Logan V, Strutton GM. Reduced melanoma after regular sunscreen use: Randomized trial follow-up. *J Clin Oncol*. 2011;29(3):257-263.
4. Krutmann J, Bouloc A, Sore G, Bernard BA, Passeron T. The skin aging exposome. *J Dermatol Sci*. 2017;85(3):152-161.
5. Flament F, Bazin R, Laquieze S, Rubert V, Simonpietri E, Piot B. Effect of the sun on visible clinical signs of aging in Caucasian skin. *Clin Cosmet Investig Dermatol*. 2013;6:221-232.
6. Flament F, Bazin R, Qiu H, et al. Solar exposure(s) and facial clinical signs of aging in Chinese women: Impacts upon age perception. *Clin Cosmet Investig Dermatol*. 2015;8:75-84.
7. Trojahn C, Dobos G, Lichterfeld A, Blume-Peytavi U, Kottner J. Characterizing facial skin ageing in humans: Disentangling extrinsic from intrinsic biological phenomena. *Biomed Res Int*. 2015;2015:318586.
8. Nouveau-Richard S, Yang Z, Mac-Mary S, et al. Skin ageing: A comparison between Chinese and European populations. A pilot study. *J Dermatol Sci*. 2005;40(3):187-193.
9. Vierkötter A, Hüls A, Yamamoto A, et al. Extrinsic skin ageing in German, Chinese and Japanese women manifests differently in all three groups depending on ethnic background, age and anatomical site. *J Dermatol Sci*. 2016;83(3):219-225.
10. Flament F, Amar D, Forichon M, Caron J, Negre C. Distinct habits of sun exposures lead to different impacts on some facial signs of chinese men of different ages. *Clin Cosmet Investig Dermatol*. 2019;12:833-841.
11. Flament F, Velleman D, Yamamoto S, et al. Clinical impacts of sun exposures on the faces and hands of Japanese women of different ages. *Int J Cosmet Sci*. 2019;41(5):425-436.
12. Ayer J, Ahmed A, Duncan-Parry E, et al. A photonumeric scale for the assessment of atrophic facial photodamage. *Br J Dermatol*. 2018;178(5):1190-1195.
13. Averbeck M, Gebhardt CA, Voigt S, et al. Differential regulation of hyaluronan metabolism in the epidermal and dermal compartments of human skin by UVB irradiation. *J Invest Dermatol*. 2007;127(3):687-697.
14. Tzellos TG, Klagas I, Vahtsevanos K, et al. Extrinsic ageing in the human skin is associated with alterations in the expression of hyaluronic acid and its metabolizing enzymes. *Exp Dermatol*. 2009;18(12):1028-1035.
15. Papakonstantinou E, Roth M, Karakiulakis G. Hyaluronic acid: A key molecule in skin aging. *Dermatoendocrinol*. 2012;4(3):253-258.
16. Quan T, Qin Z, Xia W, Shao Y, Voorhees JJ, Fisher GJ. Matrix-degrading metalloproteinases in photoaging. *J Investig Dermatol Symp Proc*. 2009;14(1):20-24.
17. Hibbert SA, Watson REB, Griffiths CEM, Gibbs NK, Sherratt MJ. Selective proteolysis by matrix metalloproteinases of photo-oxidised dermal extracellular matrix proteins. *Cell Signal*. 2019;54:191-199.
18. Waldera Lupa DM, Kalfalah F, Safferling K, et al. Characterization of Skin Aging-Associated Secreted Proteins (SAASP) produced by dermal fibroblasts isolated from intrinsically aged human skin. *J Invest Dermatol*. 2015;135(8):1954-1968.
19. Shanbhag S, Nayak A, Narayan R, Nayak UY. Anti-aging and sunscreens: Paradigm shift in cosmetics. *Adv Pharm Bull*. 2019;9(3):348-359.
20. Marionnet C, Tricaud C, Bernerd F. Exposure to non-extreme solar UV daylight: Spectral characterization, effects on skin and photoprotection. *Int J Mol Sci*. 2014;16(1):68-90.
21. Marionnet C, Nouveau S, Hourblin V, et al. UVA1-induced skin darkening is associated with molecular changes even in highly pigmented skin individuals. *J Invest Dermatol*. 2017;137(5):1184-1187.
22. Cho S, Lee MJ, Kim MS, et al. Infrared plus visible light and heat from natural sunlight participate in the expression of MMPs and type I procollagen as well as infiltration of inflammatory cell in human skin in vivo. *J Dermatol Sci*. 2008;50(2):123-133.
23. Schroeder P, Haendeler J, Krutmann J. The role of near infrared radiation in photoaging of the skin. *Exp Gerontol*. 2008;43(7):629-632.
24. Liebel F, Kaur S, Ruvolo E, Kollias N, Southall MD. Irradiation of skin with visible light induces reactive oxygen species and matrix-degrading enzymes. *J Invest Dermatol*. 2012;132(7):1901-1907.
25. Barolet D, Christiaens F, Hamblin MR. Infrared and skin: Friend or foe. *J Photochem Photobiol B*. 2016;155:78-85.
26. Hudson L, Rashdan E, Bonn CA, Chavan B, Rawlings D, Birch-Machin MA. Individual and combined effects of the infrared, visible, and ultraviolet light components of solar radiation on damage biomarkers in human skin cells. *FASEB J*. 2020;34(3):3874-3883.
27. Albrecht S, Jung S, Müller R, et al. Skin type differences in solar-simulated radiation-induced oxidative stress. *Br J Dermatol*. 2019;180(3):597-603.
28. Langton AK, Alessi S, Hann M, et al. Aging in skin of color: disruption to elastic fiber organization is detrimental to skin's biomechanical function. *J Invest Dermatol*. 2019;139(4):779-788.
29. Schieke SM, Schroeder P, Krutmann J. Cutaneous effects of infrared radiation: From clinical observations to molecular response mechanisms. *Photodermatol Photoimmunol Photomed*. 2003;19(5):228-234.
30. Grether-Beck S, Marini A, Jaenicke T, Krutmann J. Effective photoprotection of human skin against infrared A radiation by topically applied antioxidants: Results from a vehicle controlled, double-blind, randomized study. *Photochem Photobiol*. 2015;91(1):248-250.
31. Cohen L, Brodsky MA, Zubair R, Kohli I, Hamzavi IH, Sadeghpour M. Cutaneous interaction with visible light: What do we know. *J Am Acad Dermatol*. 2020. https://doi.org/10.1016/j.jaad.2020.03.115. [Epub ahead of print]
32. Narla S, Kohli I, Hamzavi IH, Lim HW. Visible light in photodermatology. *Photochem Photobiol Sci*. 2020;19(1):99-104.

33. Mahmoud BH, Ruvolo E, Hexsel CL, et al. Impact of long-wavelength UVA and visible light on melanocompetent skin. *J Invest Dermatol*. 2010;130(8):2092-2097.
34. Kohli I, Chaowattanapanit S, Mohammad TF, et al. Synergistic effects of long-wavelength ultraviolet al and visible light on pigmentation and erythema. *Br J Dermatol*. 2018;178(5):1173-1180.
35. Ramasubramaniam R, Roy A, Sharma B, Nagalakshmi S. Are there mechanistic differences between ultraviolet and visible radiation induced skin pigmentation? *Photochem Photobiol Sci*. 2011;10(12):1887-1893.
36. Duteil L, Cardot-Leccia N, Queille-Roussel C, et al. Differences in visible light-induced pigmentation according to wavelengths: A clinical and histological study in comparison with UVB exposure. *Pigment Cell Melanoma Res*. 2014;27(5):822-826.
37. Regazzetti C, Sormani L, Debayle D, et al. Melanocytes sense blue light and regulate pigmentation through Opsin-3. *J Invest Dermatol*. 2018;138(1):171-178.
38. Passeron T, Picardo M. Melasma, a photoaging disorder. *Pigment Cell Melanoma Res*. 2018;31(4):461-465.
39. Passeron T, Nouveau S, Duval C, et al. Development and validation of a reproducible model for studying post-inflammatory hyperpigmentation. *Pigment Cell Melanoma Res*. 2018;31(5):649-652.
40. Martini APM, Maia Campos PMBG. Influence of visible light on cutaneous hyperchromias: Clinical efficacy of broad-spectrum sunscreens. *Photodermatol Photoimmunol Photomed*. 2018;34(4):241-248.
41. Passeron T, Krutmann J, Andersen ML, Katta R, Zouboulis CC. Clinical and biological impact of the exposome on the skin. *J Eur Acad Dermatol Venereol*. 2020;34(Suppl 4):4-25.
42. Vierkötter A, Schikowski T, Ranft U, et al. Airborne particle exposure and extrinsic skin aging. *J Invest Dermatol*. 2010;130(12):2719-2726.
43. Flament F, Bourokba N, Nouveau S, Li J, Charbonneau A. A severe chronic outdoor urban pollution alters some facial aging signs in Chinese women. A tale of two cities. *Int J Cosmet Sci*. 2018;40(5):467-481.
44. Araviiskaia E, Berardesca E, Bieber T, et al. The impact of airborne pollution on skin. *J Eur Acad Dermatol Venereol*. 2019;33(8):1496-1505.
45. Schikowski T, Hüls A. Air pollution and skin aging. *Curr Environ Health Rep*. 2020;7(1):58-64.
46. Soeur J, Belaidi JP, Chollet C, et al. Photo-pollution stress in skin: Traces of pollutants (PAH and particulate matter) impair redox homeostasis in keratinocytes exposed to UVA1. *J Dermatol Sci*. 2017;86(2):162-169.
47. von Koschembahr A, Youssef A, Beal D, Gudimard L, Giot JP, Douki T. Toxicity and DNA repair in normal human keratinocytes co-exposed to benzo[a]pyrene and sunlight. *Toxicol In Vitro*. 2020;63:104744.
48. Langton AK, Tsoureli-Nikita E, Merrick H, et al. The systemic influence of chronic smoking on skin structure and mechanical function. *J Pathol*. 2020;251(4):420-428.
49. Yin L, Morita A, Tsuji T. Tobacco smoke extract induces age-related changes due to modulation of TGF-beta. *Exp Dermatol*. 2003;12(Suppl 2):51-56.
50. Doshi DN, Hanneman KK, Cooper KD. Smoking and skin aging in identical twins. *Arch Dermatol*. 2007;143(12):1543-1546.
51. Tamai Y, Tsuji M, Wada K, et al. Association of cigarette smoking with skin colour in Japanese women. *Tob Control*. 2014;23(3):253-256.
52. Marrot L. Pollution and sun exposure: A deleterious synergy. mechanisms and opportunities for skin protection. *Curr Med Chem*. 2018;25(40):5469-5486.
53. Huang N, Mi T, Xu S, et al. Traffic-derived air pollution compromises skin barrier function and stratum corneum redox status: A population study. *J Cosmet Dermatol*. 2020;19(7):1751-1759.
54. Boyd AS, Naylor M, Cameron GS, Pearse AD, Gaskell SA, Neldner KH. The effects of chronic sunscreen use on the histologic changes of dermatoheliosis. *J Am Acad Dermatol*. 1995;33(6):941-946.
55. Hughes MC, Williams GM, Baker P, Green AC. Sunscreen and prevention of skin aging: A randomized trial. *Ann Intern Med*. 2013;158(11):781-790.
56. Iannacone MR, Hughes MC, Green AC. Effects of sunscreen on skin cancer and photoaging. *Photodermatol Photoimmunol Photomed*. 2014;30(2–3):55-61.
57. Randhawa M, Wang S, Leyden JJ, Cula GO, Pagnoni A, Southall MD. Daily use of a facial broad spectrum sunscreen over one-year significantly improves clinical evaluation of photoaging. *Dermatol Surg*. 2016;42(12):1354-1361.
58. Mizuno M, Kunimoto K, Naru E, Kameyama K, Furukawa F, Yamamoto Y. The effects of continuous application of sunscreen on photoaged skin in Japanese elderly people - the relationship with the usage. *Clin Cosmet Investig Dermatol*. 2016;9:95-105.
59. Sarkar R, Garg VK, Jain A, et al. A randomized study to evaluate the efficacy and effectiveness of two sunscreen formulations on Indian skin types IV and V with pigmentation irregularities. *Indian J Dermatol Venereol Leprol*. 2019;85(2):160-168.
60. McDaniel DH, Waugh JM, Jiang LI, et al. Evaluation of the antioxidant capacity and protective effects of a comprehensive topical antioxidant containing water-soluble, enzymatic, and lipid-soluble antioxidants. *J Clin Aesthet Dermatol*. 2019;12(4):46-53.
61. Wang SQ, Balagula Y, Osterwalder U. Photoprotection: A review of the current and future technologies. *Dermatol Ther*. 2010;23(1):31-47.
62. Griffiths CE, Maddin S, Wiedow O, Marks R, Donald AE, Kahlon G. Treatment of photoaged skin with a cream containing 0.05% isotretinoin and sunscreens. *J Dermatolog Treat*. 2005;16(2):79-86.
63. Boukari F, Jourdan E, Fontas E, et al. Prevention of melasma relapses with sunscreen combining protection against UV and short wavelengths of visible light: A prospective randomized comparative trial. *J Am Acad Dermatol*. 2015;72(1):189-190.e1.
64. Castanedo-Cazares JP, Hernandez-Blanco D, Carlos-Ortega B, Fuentes-Ahumada C, Torres-Álvarez B. Near-visible light and UV photoprotection in the treatment of melasma: A double-blind randomized trial. *Photodermatol Photoimmunol Photomed*. 2014;30(1):35-42.
65. Yarosh DB, Rosenthal A, Moy R. Six critical questions for DNA repair enzymes in skincare products: a review in dialog. *Clin Cosmet Investig Dermatol*. 2019;12:617-624.
66. Kimball AB, Kaczvinsky JR, Li J, et al. Reduction in the appearance of facial hyperpigmentation after use of moisturizers with a combination of topical niacinamide and N-acetyl glucosamine: Results of a randomized, double-blind, vehicle-controlled trial. *Br J Dermatol*. 2010;162(2):435-441.
67. Bissett DL, Oblong JE, Berge CA. Niacinamide: A B vitamin that improves aging facial skin appearance. *Dermatol Surg*. 2005;31(7 Pt 2):860-865; discussion 5.
68. Krutmann J, Passeron T, Gilaberte Y, et al. Photoprotection of the future: Challenges and opportunities. *J Eur Acad Dermatol Venereol*. 2020;34(3):447-454.
69. Marionnet C, Pierrard C, Golebiewski C, Bernerd F. Diversity of biological effects induced by longwave UVA rays (UVA1) in reconstructed skin. *PLoS One*. 2014;9(8):e105263.
70. Neale RE, Khan SR, Lucas RM, Waterhouse M, Whiteman DC, Olsen CM. The effect of sunscreen on vitamin D: A review. *Br J Dermatol*. 2019;181(5):907-915.
71. Passeron T, Bouillon R, Callender V, et al. Sunscreen photoprotection and vitamin D status. *Br J Dermatol*. 2019;181(5):916-931.
72. Matta MK, Zusterzeel R, Pilli NR, et al. Effect of sunscreen application under maximal use conditions on plasma concentration of sunscreen active ingredients: A randomized clinical trial. *JAMA*. 2019;321(21):2082-2091.
73. Matta MK, Florian J, Zusterzeel R, et al. Effect of sunscreen application on plasma concentration of sunscreen active ingredients: A randomized clinical trial. *JAMA*. 2020;323(3):256-267.

74. Suozzi K, Turban J, Girardi M. Cutaneous photoprotection: A review of the current status and evolving strategies. *Yale J Biol Med*. 2020;93(1):55-67.
75. Mitchelmore CL, He K, Gonsior M, et al. Occurrence and distribution of UV-filters and other anthropogenic contaminants in coastal surface water, sediment, and coral tissue from Hawaii. *Sci Total Environ*. 2019;670:398-410.
76. Meng Q, Yeung K, Kwok ML, Chung CT, Hu XL, Chan KM. Toxic effects and transcriptome analyses of zebrafish (Danio rerio) larvae exposed to benzophenones. *Environ Pollut*. 2020;265(Pt A):114857.
77. Cocci P, Mosconi G, Palermo FA. Sunscreen active ingredients in loggerhead turtles (Caretta caretta) and their relation to molecular markers of inflammation, oxidative stress and hormonal activity in wild populations. *Mar Pollut Bull*. 2020;153:111012.
78. Yan S, Liang M, Chen R, Hong X, Zha J. Reproductive toxicity and estrogen activity in Japanese medaka (Oryzias latipes) exposed to environmentally relevant concentrations of octocrylene. *Environ Pollut*. 2020;261:114104.
79. Fel J-P, Lacherez C, Bensetra A, et al. Photochemical response of the scleractinian coral Stylophora pistillata to some sunscreen ingredients. *Coral Reefs*. 2019;38(1):109-122.
80. Wijgerde T, van Ballegooijen M, Nijland R, et al. Adding insult to injury: Effects of chronic oxybenzone exposure and elevated temperature on two reef-building corals. *Sci Total Environ*. 2020;733:139030.
81. Pratt H, Hassanin K, Troughton LD, et al. UV imaging reveals facial areas that are prone to skin cancer are disproportionately missed during sunscreen application. *PLoS One*. 2017;12(10):e0185297.

How to cite this article: Krutmann J, Schalka S, Watson REB, Wei L, Morita A. Daily photoprotection to prevent photoaging. *Photodermatol Photoimmunol Photomed*. 2021;00:1–8. https://doi.org/10.1111/phpp.12688