# Chapter 10
# Chemistry of Sunscreens

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**Key Points**
- Sun filters can be classified as organic, organic particulates, polymeric, and inorganic particulates.
- The mechanism of action of all types of sun filters is primarily UV absorption.
- A global overview of sun filter approval levels, chemical structures, and absorbance properties is included in this chapter.
- Formulators must select the right combination of filters to deliver photostable, broad-spectrum protection, with high SPF, and optimal aesthetics to drive consumer compliance.
- Regulatory approvals, the breadth and height of a sun filter's UV absorbance, and the sun filter solubility or dispersibility are key parameters that formulators should consider during sunscreen design.

## 10.1 Introduction

Human skin is exposed daily to sunlight, which contains a significant amount of ultraviolet (UV) radiation. It is well known that UV radiation can be harmful and that UV exposure can play a significant role in development of skin damage [23, 27]. Various compounds have been used to protect skin from the harmful rays of the sun over the centuries. It is only over the last 100 years, however, that synthetic UV filters have been developed to protect individuals from sunburn and UV-induced skin cancer [35].

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For practical and historical purposes, the UV spectrum has been divided into UVA1 (340–400 nm), UVA2 (320–340 nm), UVB (290–320 nm), and UVC (100–290 nm). UVC and some of the shorter UVB wavelengths emitted from the sun are filtered out by the ozone before they reach the Earth's surface. Both UVA and UVB rays can damage DNA, lipids, and proteins; produce inflammation; and ultimately result in burns, premature aging, and carcinogenesis [27, 30, 35]. An ideal sunscreen must protect the user from UV radiation across the light wavelength spectrum associated with harmful effects [24, 27].

## 10.2 Mechanism of Action of Sun Filters

Sunscreens protect skin from these harmful rays by forming a protective barrier on skin surface. Most sunscreen active ingredients are organic molecules with conjugated, aromatic chemical structures. The mode of action of these sunscreen active ingredients is primarily UV absorption [24]. By residing on skin surface as a film, these organic molecules effectively transform the harmful UV energy to harmless forms of energy and prevent the UV photons from entering into the skin [25, 30]. The electrons in these chemical structures are "active" because they are capable of energy transfer when hit by UV. Quantum mechanical calculations show that the energy of radiation quanta present in UVB and UVA lies in the same order of magnitude as the resonance energy of electron delocalization in aromatic compounds [35].

The electrons of sunscreen UV filters can accept the energy from UV photons and move to higher electronic energy states. This energy can then be quickly converted to heat by non-radiation energy dissipation or to other forms of light such as fluorescence, phosphorescence, or infrared rays [25]. The electrons will return back to the ground state during the energy transfer, ready to receive the next UV photon. The lifetime of excited states of these molecules is very short; therefore, as long as the chemical structure of the sunscreen is stable at excited states, the process of excitation and returning to ground states can occur continuously and repetitively without any loss of efficacy.

A few sunscreen active ingredients are not photostable. The chemical structures of these non-photostable molecules can change while the chemical is in the excited state (photochemical reactions). When that happens, the original molecules are broken down and not capable of repeating the excitation process and more importantly cannot absorb the next UV photons. With the degradation of the original active ingredients, free radicals (including singlet oxygen) may be generated that may then react with nearby molecules to form photobyproducts. Thus, the efficacy of the sunscreen decreases because less active ingredients remain to absorb more incoming photons.

Sun filters do not need to penetrate into the skin in order to be effective. As soon as the sunscreen film is present on skin surface, there will be at least some level of protection because of its inherent absorption properties. The final protection level may be enhanced as the product dries on the skin and the film structure is optimized [32].

## 10.3 Chemical Classification of Sun Filters

There are a number of different sun filters approved for the use in sunscreen products around the globe. Currently, 16 sun filters are approved for sunscreen products in the United States (Food and Drug Administration and Department of Health and Human Services [14, 15, 39]), 20 in Canada [18], 28 in the European Union [12, 22], 28 in the Association of Southeast Asian Nations [37], and 33 approved by MERCOSUR (Southern Common Market, consisting of Argentina, Brazil, Paraguay, Uruguay, and Venezuela) [37]. The complete listing of approved sun filters in these locations, along with the approved concentrations, is shown in Table 10.1.

Sun filter actives can be classified into the following categories: organic (traditional molecules or polymeric) or particulate (organic particulates or inorganic particulate), as described in subsequent sections 3.1 and 3.2, respectively.

### *10.3.1 Organic Filters*

Organic filters are often referred to as "chemical" filters, but this can be misleading because it suggests that it is possible to have a sun filter that is "nonchemical." Strictly speaking, all active sun filter compounds, both organic and inorganic, are made up of chemical molecules originating from the periodic table, and all function primarily by absorbing light [26].

#### 10.3.1.1 Organic Filters: Traditional Molecules

Traditional organic sun filters are aromatic, small molecules, with molecular weight values <900 g/mol. Today, the most widely used organic filters include avobenzone, oxybenzone, octocrylene, salicylate derivatives (homosalate and ethylhexyl salicylate), cinnamate derivatives (octyl-methoxycinnamate [OMC]), triazone derivatives (Uvinul T150 [ethylhexyl triazone]; UVASorb HEB [diethylhexyl butamido triazone]; Tinosorb S [bis-ethylhexyloxyphenol methoxyphenyl triazine]), benzoate derivatives (Uvinul A Plus [diethylamino hydroxybenzoyl hexyl benzoate]), benzotriazole derivatives (Mexoryl XL [drometrizole trisiloxane]), and camphor derivatives (Mexoryl SX [ecamsule]; terephthalylidene dicamphor sulfonic acid). Anthranilate derivatives (like meradimate) are less commonly used filters because of low efficacy.

Avobenzone (a dibenzoylmethane derivative) is one of the most efficient UVA-absorbing filters used around the globe, and it is the only UVA-absorbing organic sun filter approved in the USA. However, avobenzone is prone to photo instability because of an enol-to-keto tautomerization as shown in Fig. 10.1 [25]. The enol form of avobenzone absorbs in the UVA (315–400 nm), while the diketo form absorbs in the UVC (200–280 nm) and is prone to degradation [25]. Other photostabilizing ingredients must be used in combination with avobenzone to prevent light-induced degradation [7]. In order to achieve photostability of avobenzone, it must be combined with ingredients

**Table 10.1** List of sun filters approved in the USA, Canada, European Union, ASEAN, and MERCOSUR; alternate names; and approved usage levels per region

| Filter name | Other names | Coverage | US | Canada | EU | MERCOSUR | Australia | ASEAN |
|---|---|---|---|---|---|---|---|---|
| | | | Maximum allowed concentration (%) | | | | | |
| Benzophenone-3 | *Oxybenzone* or 2-hydroxy-4-methoxybenzophenone | UVA/B | 6 | 6 | 10 | 10 | 10 | 10 |
| Benzophenone-4 | *Sulisobenzone* or 2-hydroxy-4-methoxybenzophenone-5-sulfonic acid and its trihydrate | UVA/B | 10 | 10 | 5** | 10 | 10 | 5** |
| Benzophenone-5 | 2-Hydroxy-4-methoxybenzophenone-5--sulfonic acid (benzophenone-5) and its sodium salt<br>Sulisobenzone sodium<br>Sodium hydroxymethoxybenzophenone sulfonate | UVA/B | – | – | * | 5 | 10 | * |
| Benzophenone-8 | Dioxybenzone or 2,2’-dihydroxy-4-methoxybenzophenone<br>Dioxybenzone<br>(2-hydroxy-4-methoxyphenyl)(2-hydroxyphenyl)methanone<br>Methanone (2-hydroxy-4-methoxyphenyl)(2-hydroxyphenyl) | UVA/B | 3 | 3 | – | 3 | 3 | – |
| 3-Benzylidene camphor | 3-Benzylidene camphor | UVB | – | – | 2 | 2 | – | 2 |
| Bis-ethylhexyloxyphenol methoxyphenyl triazine | *Tinosorb S* or (1,3,5)-triazine-2,4-bis{[4-(2-ethyl-hexyloxy)-2-hydroxy]-phenyl}-6-(4-methoxyphenyl) or anisotriazine | UVA/B | – | – | 10 | 10 | 10 | 10 |
| Butyl methoxydibenzoyl methane | *Avobenzone* or 1-(4-tert-butylphenyl)-3-(4-methoxyphenyl) propane-1,3-dione | UVA | 3 | 3 | 5 | 5 | 5 | 5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Camphor benzalkonium methosulfate | *Mexoryl SO* or N,N,N-trimethyl-4-(2-oxoborn-3-ylidene-methyl) anilinium methyl sulfate | UVB | – | – | 6 | 6 | 6 | 6 |
| Diethylamino hydroxybenzoyl hexyl benzoate | *Uvinul A plus* or<br>benzoic acid, 2-[–4-(diethylamino)-2-hydroxybenzoyl]-, hexylester | UVA | – | – | 10 | 10 | 10 | 10 |
| Diethanolamine methoxycinnamate | DEA methoxycinnamate | UVA | – | 10 | – | – | – | – |
| Diethylhexyl butamido triazone | *UVASorb HEB* or<br>benzoic acid, 4,4-((6-((4-(((1,1-dimethylethyl) amino) carbonyl) phenyl) amino) 1,3,5-triazine-2,4-diyl) diimino) bis-(2-) ester) or dioctyl butamido triazone | UVB | – | – | 10 | 10 | – | 10 |
| Disodium phenyl dibenzimidazole tetrasulfonate | *Neo Heliopan AP* or<br>monosodium salt of 2-2’-bis(1,4-phenylene)1H-benzimidazole-4,6-disulphonic acid) or bisimidazylate | UVA | – | – | 10 | 10 | 10 | 10 |
| Drometrizole trisiloxane | *Mexoryl XL* or<br>phenol,2-(2H-benzotriazol-2-yl)-4-methyl-6-(2-methyl-3-(1,3,3,3-tetramethyl-I-(trimethylsilyl)oxy)-disiloxanyl)propyl) | UVA/B | – | 15 | 15 | 15 | 15 | 15 |
| Ethoxyethyl methoxycinnamate | Cinoxate | UVB | 3 | 3 | – | 3 | 6 | – |
| Ethylhexyl dimethylamino benzoate | Padimate O<br>Octyl dimethyl *PABA*<br>Ethylhexyl dimethyl PABA | UVB | 8 | 8 | 8 | 8 | 8 | 8 |
| Ethylhexyl methoxycinnamate | *OMC* or octinoxate<br>Octyl methoxycinnamate | UVB | 7.5 | 7.5 | 10 | 10 | 10 | 10 |

(continued)

**Table 10.1** (continued)

| Filter name | Other names | Coverage | US | Canada | EU | MERCOSUR | Australia | ASEAN |
|---|---|---|---|---|---|---|---|---|
| Ethylhexyl salicylate | *Octisalate*<br>2-Ethylhexyl salicylate<br>Octyl salicylate | UVB | 5 | 5 | 5 | 5 | 5 | 5 |
| Ethylhexyl triazone | *Uvinul T150*<br>2,4,6-Trianilino-(p-carbo-2'-ethylhexyl-l'oxy)-1,3,5-triazine<br>Octyl triazone | UVB | – | – | 5 | 5 | 5 | 5 |
| Homosalate | 3,3,5-Trimethylcyclohexyl 2-hydroxybenzoate<br>Salicilato de homomentila | UVB | 15 | 15 | 10 | 15 | 15 | 10 |
| Isoamyl p-methoxycinnamate | Amiloxate<br>Isopentyl-4-methoxycinnamate | UVB | – | – | 10 | 10 | 10 | 10 |
| Methyl anthranilate | Meradimate | UVA | 5 | 5 | – | 5 | 5 | 5 |
| 4-methylbenzylidene camphor | Enzacamene<br>3-(4'-methylbenxylidene)d-1 camphor<br>4 MBC | UVB | – | 6 | 4 | 4 | 4 | 4 |
| Methylene bis-benzotriazolyl tetramethylbutylphenol | *Tinosorb M*<br>2,2'-Methylene-bis-6-(2H-benzotriazol-2yl)-4-(tetramethyl-butyl)-1,1,3,3-phenol | UVA/B | – | – | 10 | 10 | 10 | 10 |
| Octocrylene | 2-Cyano-3,3-diphenyl acrylic acid, 2-ethylhexyl ester | UVB | 10 | 10 | 10 | 10 | 10 | 10 |
| Para-aminobenzoic acid | *PABA*<br>4-Aminobenzoic acid | UVB | 15 | 15 | – | 15 | – | – |
| PEG-25 *PABA* | Ethoxylated ethyl-4-aminobenzoate | UVB | – | – | 10 | 10 | 10 | 10 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Phenylbenzimidazole sulfonic acid | *Neo Heliopan Hydro*, Ensulizole<br>2-Phenylbenzimidazole-5-sulfonic acid and its potassium, sodium, and triethanolamine salts<br>Potassium, sodium, and TEA Phenylbenzimidazole sulfonate | UVB | 4 | 4 | 8 | 8 (as acid) | 4 | 8 |
| Polyacrylamido methylbenzylidene camphor | *Mexoryl SW*<br>Polymer of N-[(2 and 4)-[(2-oxoborn-3-ylidene)methyl]benzyl]acrylamide | UVB | – | – | 6 | 6 | – | 6 |
| Polysilicone-15 | *Parsol SLX*<br>Diethylbenzylidene malonate Dimethicone Diethylmalonylbenzylidene Oxypropene dimethicone<br>Dimethicodiethylbenzalmalonate | UVB | – | – | 10 | 10 | 10 | 10 |
| Triethanolamine salicylate | *Neo Heliopan TES*<br>Trolamine salicylate | UVB | 12 | 12 | – | 12 | 12 | – |
| Tris-biphenyl triazine (nano) | 1,3,5 - Triazine, 2,4,6-tris [1,1-biphenyl]-4-1-; ETH-50 | UVA/B | – | – | 10 | – | – | – |
| Terephthalylidene dicamphor sulfonic acid | *Mexoryl SX* | UVA | – | 10 | 10 | 10 | 10 | 10 |
| Benzylidene camphor sulfonic acid | Alpha-(2-oxoborn-3-ylidene)-toluene-4-sulfonic acid and its salts | | – | – | 6 | 6 | 6 | 6 |
| Titanium dioxide | | UVA/B | 25 | 25 | 25 | 25 | 25 | 25 |
| Zinc oxide | | UVA/B | 25 | 25 | * | 25 | No limit | 25 |

*ASEAN* Association of Southeast Asian Nations; *EU* European Union; *MBC* methylbenzylidene camphor; *MERCOSUR* Southern Common Market, consisting of Argentina, Brazil, Paraguay, Uruguay, and Venezuela; *OMC* octyl-methoxycinnamate; *PABA* para-aminobenzoic acid; *US* United States; *UVA* ultraviolet A; *UVB* ultraviolet B

* Inclusion in annex VI expected

** Sum of Benzophenone-4 and Benzophenone-5

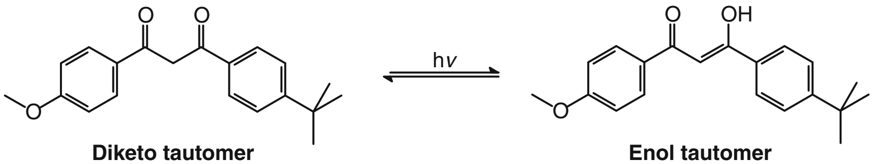



**Fig. 10.1** The keto-to-enol tautomerization of avobenzone (Scheme 2 was reproduced with permission from Kockler et al. [25])

that are efficient in both triplet quenching and singlet quenching. Examples of triplet quenchers are the following UV filters: octocrylene, 4-methylbenzylidene camphor (ex-US), Tinosorb S (ex-US), or emollients such as diethylhexyl-2,6-naphthalate [7]. In addition, higher levels of oxybenzone are known to stabilize avobenzone by the singlet quenching mechanism [7]. A combination of singlet and triplet quenchers is most efficient in stabilizing avobenzone.

Cinnamates are very efficient UVB absorbers but also have issues with photostability. OMC is a member of the cinnamate class that is known to react with avobenzone to produce non-UV light-absorbing photoproducts. Hence, combinations of avobenzone and OMC are unfavorable and should be avoided because of enhanced photo instability [7, 33].

Salicylate derivatives are photostable, UVB-absorbing filters that have a long history of usage. They are excellent solubilizers for crystalline UV filters, including oxybenzone and avobenzone, however the absorption efficiency of these filters is quite low.

Oxybenzone (a benzophenone derivative) is used in many US sunscreen formulations with absorbance in the UVB (290–320 nm) and the UVA2 region (320–340 nm). Padimate O is a derivative of para-aminobenzoic acid that is a liquid and is oil soluble. It is a very effective UVB filter with one of the highest molar extinction coefficients of the approved filters. It is not widely used in products over concern that the parent molecule, para-aminobenzoic acid, has been associated with allergic reactions. Octocrylene is another oil-soluble UVB filter that has been widely used to provide increased sun protection factor (SPF) values and to also boost the photostability of avobenzone when used in combination. Ensulizole (phenylbenzimidazole sulfonic acid) is a water-soluble filter and is used in products formulated to feel lighter and less oily, such as daily use cosmetic moisturizers. Currently, it is not permitted to be combined with avobenzone in the USA and must be used in combination with on other UVA absorbers (such as zinc oxide) to provide broad-spectrum protection.

#### 10.3.1.2 Organic Filters: Polymeric

*Parsol SLX.* Parsol SLX, or polysilicone-15, is made of organic chromophores attached to a polysiloxane chain and is approved for use outside North America. The average molecular weight is >6000 daltons [10], so it is envisioned that the molecule is large enough to reduce permeation through the skin [20], making it ideal for

**Table 10.2** Relative lipophilicity of sunscreen chemicals based upon their calculated partition coefficients between octanol and water

| CTFA name | Other names | Log *P* at 25 °C |
|---|---|---|
| Glyceryl PABA | 1,2,3-Propanetriol,1-(4-aminobenzoate) | −0.02 |
| Benzophenone-4 | Sulisobenzone | −1.51 |
| PABA | p-Aminobenzoic acid | 0.74 |
| Benzophenone-8 | Dioxybenzone | 2.15 |
| Cinoxate | Ethoxyethyl methoxy cinnamate | 2.55 |
| Benzophenone-3 | Oxybenzone | 2.63 |
| Ethyl dihydroxypropyl PABA | Ethyl-4-bis(2-hydroxypropyl-aminobenzoate) | 2.84 |
| Amyl dimethyl PABA | Amyl dimethyl PABA | 4.53 |
| Butylmethoxy dibenzoylmethane | Butylmethoxy dibenzoylmethane | 4.86 |
| Menthyl anthranilate | Methyl-O-aminobenzoate | 5.05 |
| Octyl salicylate | 2-Ethylhexyl salicylate | 5.30 |
| Homosalate | Homomenthyl salicylate | 5.61 |
| Octyl methoxy cinnamate | Ethylhexyl-p-methoxycinnamate | 5.65 |
| Octocrylene | Octyl cyanodiphenylacrylate | 5.69 |
| Octyl dimethyl PABA | 2-Ethylhexyl-p-dimethyl aminobenzoate | 6.08 |

Modified with permission from Agrapidis-Paloympis et al. [1]
*CTFA* Cosmetic, Toiletry, and Fragrance Association; *PABA* para-aminobenzoic acid

mild applications. The polysiloxane backbone not only links the chromophores together, but it also provides a pleasant aesthetic to skin or hair [29]. Unfortunately, this polymeric filter only absorbs in the UVB ($\lambda_{max}$ = 312 nm) part of the spectrum and needs to be combined with UVA filters to achieve broad-spectrum protection.

#### 10.3.1.3 Organic Filters: Solubility in Cosmetic Vehicles

In order for a UV-absorbing organic filter to be an effective sunscreen, it must be soluble in at least a portion of the sunscreen formulation. Today's organic sun filters are typically oil soluble or water soluble and occasionally alcohol soluble. The sun filter's partition coefficient (log *P*) between octanol and water gives an indication of the relative lipophilicity, where lower log *P* values indicate a higher degree of water solubility, as shown in Table 10.2 [1].

Oil-soluble filters are used in a wide variety of sunscreen products, including both recreational and daily use products. Recreational-use sunscreen products are typically formulated for enhanced water resistance through the addition of film-forming polymers. A high content of oily sun filter compounds can lead to a heavy and greasy aesthetic on the skin. For products that do not require a high level of water resistance, water-soluble sun filters may be used either alone or in combination with oil-soluble sun filters to create formulations with enhanced aesthetic properties and potentially improved user compliance. Ensulizole (2-phenylbenzimidazole-5-sulfonic acid), Neo Heliopan AP (disodium phenyl dibenzimidazole tetrasulfonate) and Mexoryl SX are examples of water-soluble sun filters.

Furthermore, filter solubility is important for maintaining formulation efficacy as some filters, including octyl triazone, benzophenone-3, butyl methylbenzylidene camphor, and methoxydibenzoylmethane, may crystallize out of solution if not properly solubilized [40], making the protective film less uniform on the skin. In addition, solvent polarity has been found to affect $\lambda_{max}$ and critical wavelength in formulations [1].

## *10.3.2 Particulate Filters*

While most organic filters must be dissolved into either the oil or water phases of a formulation to be effective, particulate sunscreens are not dissolved in either phase, and they exist in particle suspensions. Particulate filters are commonly used in mild and baby sunscreen products, and they have been demonstrated in several studies to stay on the surface of the skin [8, 16]. There are two types of particulate sunscreen filters: organic and inorganic.

### 10.3.2.1 Particulate Organic Filters

Methylene bis-benzotriazolyl tetramethylbutylphenol (i.e., MBBT or Tinosorb M) is considered to be an organic particulate filter. Pure MBBT is a solid powder with a particle size in the micron range, and the commercially available Tinosorb M is a MBBT suspension. The mechanism of action for Tinosorb M is mostly absorption with slight contributions from particulate scattering [19].

### 10.3.2.2 Inorganic Particulates

The inorganic particulate sunscreen class includes titanium dioxide ($TiO_2$) and zinc oxide (ZnO). It is important to point out that these particulate sunscreen active ingredients also absorb UV, with very little reflection and scattering in the UV portion of the spectrum [4], so it is not appropriate to call them "physical sunscreens." While the UV absorption action of Tinosorb M is not very different from other organic molecules, for $TiO_2$ and ZnO, the electrons in the crystals can freely move from the valence band to the conductance band when exposed to UV. This is because the energy band gap in $TiO_2$ or ZnO is lower than the energy conveyed by UV photons, allowing UV to excite the free electrons in these semiconductor-like materials.

Particulate inorganic sunscreen active ingredients also protect skin from harmful UV by absorbing, reflecting, and scattering; however, recent findings indicate that the primary means of protection is by absorption (roughly 95 %) and the remaining 5 % by scattering and reflecting. Incident light that is absorbed or backscattered by the particle sunscreens does not enter into the skin. Scattering of reflected photons increases the actual optical length of the UV photons as they pass through the absorbing sunscreen layer. The scattering by sunscreen particles depends on factors that include the volume concentration of the particles, the relative refractive index of the particle to the medium and/or coating, the particle size, and the scattering wavelength [11].

For the UV wavelength range, the absorption and scattering power of single $TiO_2$ or ZnO particles generally increases with the size of the particle, up to about 100 μm. We generally recognize, however, that absorption power increases monotonically when the particle size is smaller. This is because the number of particles has to increase with smaller and smaller particle size when evaluated for a fixed volume fraction (weight percentage). Therefore, the overall absorption power for the system becomes greater with smaller particle sizes. Based on both theoretical calculation and experimental measurement, the light scattering of particulate sunscreen ingredients ($TiO_2$, ZnO, and Tinosorb M) does not contribute significantly to the attenuation of UV (290–370 nm) when compared absorption. For long UVA and visible light wavelength range (370–760 nm), however, reflection contributes much more to the protective effects of $TiO_2$ and ZnO particles when applied on skin surface because of very limited absorption of these ingredients within the visible wavelength range. Since absorption and scattering of UV light depend on both the volume fraction of particles in the medium and also the uniformity of the particles, dispersion of particles in sunscreen formulation plays a critical role in the efficacy of UV attenuation. It is also critical to make sure the inorganic particles are photostable and do not lead to generation of free radicals. Effective surface treatment of inorganic particles ensures photostability of these inorganic sunscreens. Examples of surface treatments include alkoxy silane, dimethicone, methicone, polyhydroxystearic acid and aluminum stearate, silica, alumina, etc. Photostability also depends on the type of the inorganic crystal. For example, antase is known to be less stable than rutile grade $TiO_2$.

ZnO has gained popularity as a mild, safe, and effective sun filter in the past 10 years. It is the only other effective UVA1 filter besides avobenzone that is approved in the USA. $TiO_2$ has high UVB efficacy, but does not provide significant UVA protection. On the other hand, ZnO provides very uniform UVB and UVA protection across the whole spectrum, providing a flat spectral absorption curve [36]. Figure 10.2a shows a comparison between absorbance of $TiO_2$ and ZnO. It is desirable to maximize light attenuation while limiting the scattering in the visible region, as consumers do not like to see a white/blue haze on their skin. Formulators need to balance the particle size, dispersion, solvent, and volume fraction to achieve an aesthetically acceptable and effective inorganic sunscreen product.

## 10.4 Sun Filter Efficacy: Breadth and Height of UV Absorbance

A key performance metric for sun filters is absorbance intensity and breadth of coverage. Dilute solution UV spectroscopy is used to determine filter efficacy and is commonly reported as a specific extinction, E(1 %, 1 cm), value. E(1,1) corresponds to the absorbance at the peak wavelength ($\lambda_{max}$) for a 1 % solution in a cuvette with a 1 cm

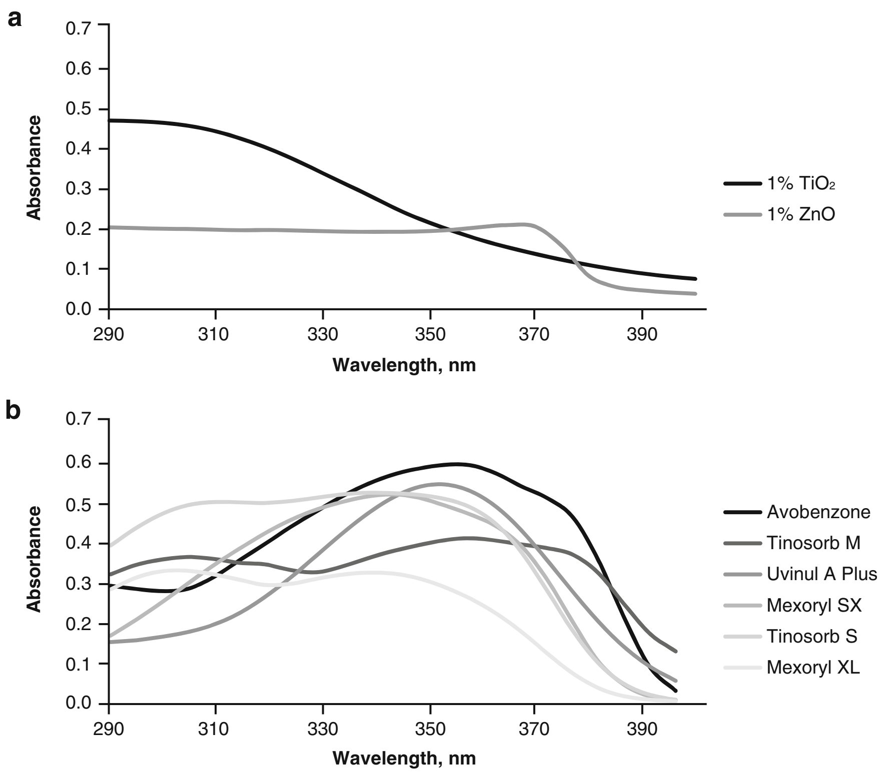


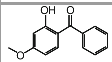
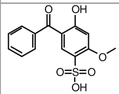
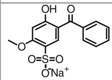
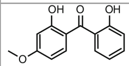
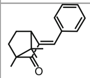
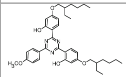
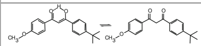
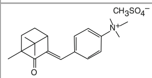
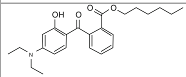
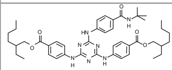
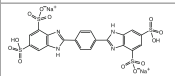

**Fig. 10.2** The absorbance spectra for various sunscreen agents at 1 %; (**a**) TiO2 and ZnO, and (**b**) key global UVA-absorbing filters

path length [35]. Table 10.3 shows the wavelength of absorbance maximum and specific extinction value for common organic filters, along with the molecular structures and molecular weight values [35].

Avobenzone is the most efficient UVA-absorbing filter with an E(1,1) value of 1,110 (357 nm), followed by Uvinul A plus (E[1,1] is 925 [354 nm]), Mexoryl SX (E[1,1] is 750 [345 nm]), and Tinosorb S (E[1,1] is 750 and 820 [310 and 343 nm, respectively]). Figure 10.2b shows the absorbance spectral overlay for key UVA filters (each at 1 %).

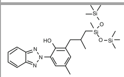
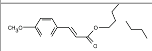
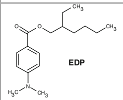
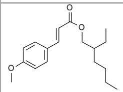
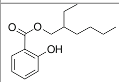
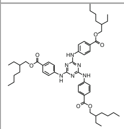
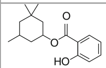
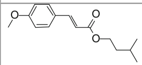
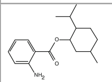
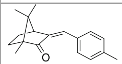
Although UVA protection is getting quite a bit of attention in recent years, UVB protection is critical to appropriate protection from the sun, as the action spectra for erythema, basal cell carcinoma, and squamous cell carcinoma are all known to be driven by UVB [6, 9]. Uvinul T150 (ethylhexyl triazone) and Uvinul HEB (diethylhexyl butamido triazone) are the two most efficient UVB filters with E(1,1) values of 1550 (at 314 nm) and 1460 (at 311 nm), respectively. Ethylhexyl diaminobenzoate, phenylbenzimidazole sulfonic acid, and several cinnamate derivatives are also very strong UVB absorbers. Benzophenone derivatives are modest UVB absorbers, and salicylate derivatives are typically relatively weak UVB absorbers.

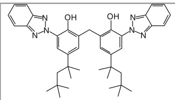
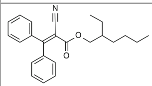
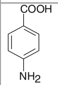
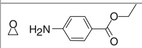
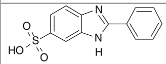
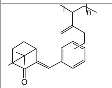
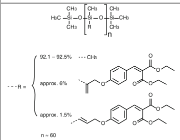
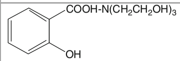
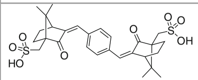
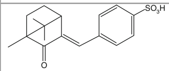
**Table 10.3** List of sun filters, chemical structures, molecular weight, lambda max values, and specific extinction values E(1 %, 1 cm)

| Filter name | Chemical structure | Molecular weight (g/mol) | Coverage | $\lambda$ MAX 1 | $\lambda$ MAX 2 | E1 (1 %, 1 cm) | E2 (1 %, 1 cm) |
|---|---|---|---|---|---|---|---|
| Benzophenone-3 |  | 228 | UVA/B | 286 | 324 | 630 | 400 |
| Benzophenone-4 |  | 308 | UVA/B | 286 | 324 | 440 | 360 |
| Benzophenone-5 |  | 330 | UVA/B | 285 | 323 | 430 | 345 |
| Benzophenone-8 |  | 244 | UVA/B | 284 | 327 | 380 | 300 |
| 3-Benzylidene camphor |  | 240 | UVB | 294 | | 860 | |
| Bis-ethylhexyloxyphenol methoxyphenyl triazine |  | 628 | UVA/B | 310 | 343 | 745 | 820 |
| Butyl methoxydibenzoylmethane |  | 310 | UVA | 357 | | 1,110 | |
| Camphor benzalkonium methosulfate |  | 410 | UVB | 284 | | 590 | |
| Diethylamino hydroxybenzoyl hexyl benzoate |  | 398 | UVA | 354 | | 925 | |
| Diethylhexyl butamido triazone |  | 766 | UVB | 311 | | 1,460 | |
| Disodium phenyl dibenzimidazole tetrasulfonate |  | 675 | UVA | 335 | | 770 | |

(continued)

**Table 10.3** (continued)

| Filter name | Chemical structure | Molecular weight (g/mol) | Coverage | λ MAX 1 | λ MAX 2 | E1 (1 %, 1 cm) | E2 (1 %, 1 cm) |
|---|---|---|---|---|---|---|---|
| Drometrizole trisiloxane |  | 502 | UVA/B | 303 | 341 | 310 | 300 |
| Ethoxyethyl methoxycinnamate |  | 250 | UVB | | | | |
| Ethylhexyl dimethylamino benzoate |   | 277 | UVB | 311 | | 990 | |
| Ethylhexyl methoxycinnamate |  | 290 | UVB | 311 | | 850 | |
| Ethylhexyl salicylate |  | 250 | UVB | 305 | | 165 | |
| Ethylhexyl triazone |  | 823 | UVB | 314 | | 1,550 | |
| Homosalate |  | 262 | UVB | 306 | | 180 | |
| Isoamyl p-methoxycinnamate |  | 248 | UVB | 308 | | 980 | |
| Methyl anthranilate |  | 275 | UVA | 336 | | 190 | |
| 4-Methylbenzylidene camphor |  | 254 | UVB | 300 | | 930 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Methylene bis-benzotriazolyl tetramethylbutylphenol |  | 659 | UVA/B | 305 | 360 | 400 | 495 |
| Octocrylene |  | 362 | UVB | 303 | | 340 | |
| Para-aminobenzoic acid |  | 137 | UVB | 283 | | 640 | |
| PEG-25 para-aminobenzoic acid |  | 1,265 | UVB | 309 | | 180 | |
| Phenylbenzimidazole sulfonic acid |  | 274 | UVB | 302 | | 920 | |
| Polyacrylamido methylbenzylidene camphor |  | [323.44]n | UVB | 297 | | 610 | |
| Polysilicone-15 |  | 6,000 | UVB | 312 | | 160–190 | |
| Triethanolamine salicylate |  | 287 | UVB | 298 | | 120 | |
| Terephthalylidene dicamphor sulfonic acid |  | 607 | UVA | 345 | | 750 | |
| Benzylidene camphor sulfonic acid |  | 320 | | 294 | | 860 | |
| Titanium dioxide | — | 80 | UVA/B | 280–350 | | | |
| Zinc oxide | — | 81 | UVA/B | 280–390 | | | |

*E* specific extinction, *UVA* ultraviolet A, *UVB* ultraviolet B

In addition to absorbance intensity, it is also important to consider the breadth of protection. Avobenzone and Tinosorb M provide the widest long-range UVA1 protection, followed by Uvinul A plus, then Mexoryl SX, Tinosorb S, and Mexoryl XL. There are no approved sunscreens, however, that absorb significant amounts of light in the very longest part of the UVA spectrum and into the blue portion of the visible light spectrum. There is emerging research showing that light coming from these parts of the spectrum can contribute to skin pigmentation changes [3, 28].

Although extinction coefficients are widely used to provide quantitative comparison of sun filters, the relevancy of dilute solution spectroscopy measures to real-world sunscreen product application must be considered. As a sunscreen product dries to form a highly concentrated thin film, Beer's law does not apply, and so real-world sunscreen performance is most likely not dictated solely by the dilute solution absorbance values. The film structure and properties may be directly relevant to a sunscreen's final performance on skin as a thin film [32]. Thin-film transmission measurements on defined substrates are now used throughout the sunscreen industry to simulate real-world efficacy.

## 10.5 Combinations of Filters

There is no single sun filter available today that on its own can provide high-SPF and broad-spectrum protection without aesthetic drawbacks. With the current state of UV filter technology, sunscreen products today require the right combination of filters in the formulation to obtain both high efficacy in UV protection and optimal aesthetics to enhance compliance. Formulations containing oil-soluble filters may feel occlusive and or greasy [30]. Combinations of different filters may be used to improve the sensory profile, as well as provide broad-spectrum protection. In the USA, "broad spectrum" can be claimed if the in vitro determined critical wavelength value is ≥370 nm [15]. In Europe, products must achieve a 1:3 ratio of PFA (protection factor UVA):SPF [21]. Although many sunscreen products in the market claim broad spectrum, it is hard to differentiate between their UVA efficacies. Not all broad-spectrum sunscreens are created equal because they may have different degrees of UVA protection (amplitude of absorbance curve in UVA) with different filter combinations [5].

### *10.5.1 US-Approved Filter Combinations*

A common combination of organic filters used in the US market to achieve high-SPF, broad-spectrum, and photostable protection is oxybenzone, octocrylene, homosalate, avobenzone, and 2-ethylhexyl salicylate (octisalate). This five-ingredient combination is found in many different product lines, and the proportions and concentrations are adjusted to provide the desired protection. Octocrylene, homosalate, and octisalate provide strong UVB protection, oxybenzone provides broad-spectrum UVB and UVA2 protection, and avobenzone provides the longer-wavelength UVA1 protection. In addition, both octocrylene and oxybenzone enhance the photostability of avobenzone by singlet and triplet quenching.

The inorganic filters $TiO_2$ and ZnO are often used together. ZnO is typically used to achieve breadth of protection, while $TiO_2$ brings higher SPF. The combination of avobenzone and ZnO is currently not permitted in the USA [14]. The agency did not approve the combination of ZnO with avobenzone in the latest monograph publications.

### *10.5.2 Ex-US Filter Combinations*

In Europe and Latin America, many more filters are approved for combination use, such as Tinosorb S, Tinosorb M, Uvinul T150, Uvinul A Plus, Mexoryl SX, or Mexoryl XL. In Europe, it is common to omit oxybenzone. In Latin America, many formulations include a combination of traditional organic filters and a small amount of $TiO_2$. In Japan, very light and fluid textures are preferred, and mildness is very important; $TiO_2$, ZnO, OMC, and Tinosorb S are widely used ingredients.

### *10.5.3 SPF Boosting Through Formulation and Film Structure*

Beyond the filter combinations selected for a sunscreen product formulation, formulation excipients, emulsion structure, and the sunscreen film structure are also important for determining the final sunscreen performance. The presence of film formers or emollients in the formulation [31, 34], the sunscreen rheological properties [2, 17], and the structures of the dried down sunscreen film [13, 38] have all been linked to sunscreen performance. Figure 10.3 illustrates how surface roughness plays a role in creating holes in a sunscreen film, and that the thickness of the sunscreen film above the skin peaks may be quite small [32]. It can be envisioned that the physical properties of the sunscreen film may act to increase the film thickness above the peaks and reduce settling into the valleys to create a more ideal film structure as in Fig. 10.3a [32].

## 10.6 Conclusion

A variety of organic sun filters are available for use with different properties, and it is important for formulators to understand their chemistry to maximize efficacy and create sunscreen products with an acceptable level of SPF and broad-spectrum protection. With the current state of sunscreen technology, it is necessary for formulators to select

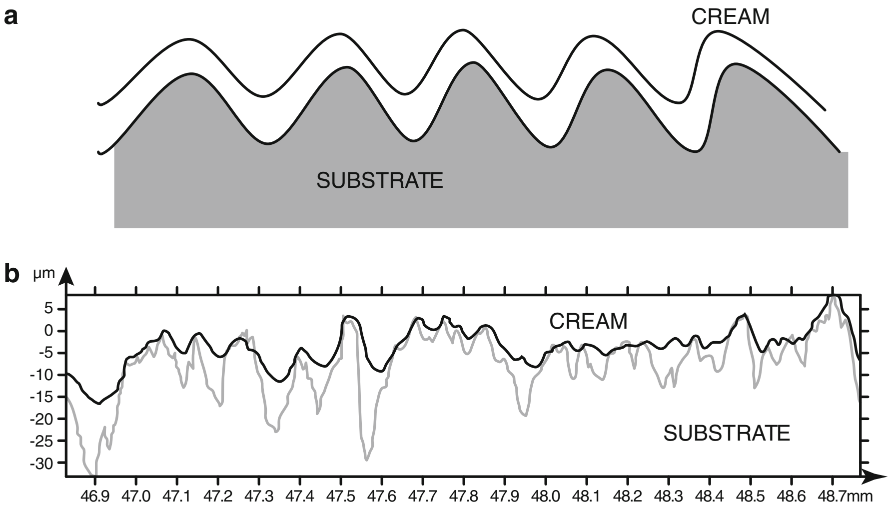



**Fig. 10.3** Sunscreen distribution on a surface (**a**) ideal distribution (**b**) real distribution (Reproduced with permission from Osterwalder et al. [32])

a combination of sun filters to bring photostable, high-SPF, and broad-spectrum protection to consumers. There is a widespread misconception that inorganic sunscreens operate by a different mechanism than organic sun filters; the mechanism of action for both, however, involves UV absorbance. It is also critical for formulators to consider the aesthetic of filters and to design formulation vehicles to maximize the sunscreen product aesthetic, as sunscreen user compliance will continue to be the biggest challenge to protecting consumers from solar radiation.

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