The Future of Sunscreens – What Lies Beyond SPF 50+?

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Introduction

Following numerous worldwide public campaigns over the last two or more decades, many consumers are aware of the essential role regular application of sunscreens plays in protecting against skin cancer. In particular they are careful to pack sunscreens when going on their summer holidays. And for many years now, consumers have been buying sunscreens with protection factors of 30 or even higher. A recent study in Egypt [1] measured the average daily erythemal dosage received under practical conditions and found that consumers receive about 5 MED whilst lying in the sun at the poolside. Even a sunscreen with SPF 15 would easily be able to significantly reduce the damage level from this erythemal burden to an equivalent of 0.33 MED. This is a long way from being sunburn. Application of an SPF 50+ sunscreen would reduce the amount of erythemal radiation reaching the skin to less than a tenth. Such products have been commercially available for more than a decade, so they should already be having a noticeable effect on skin cancer rates. The puzzling fact is that we are still seeing skin cancer rates already be having a noticeable effect on skin cancer rates. If recognized too late, but even non-melanoma skin cancer, for which there are good treatment options, greatly affects quality of life and can be disfiguring [3]. Its relative prevalence among the population calls for extended action to maintain consumers’ quality of life. Moreover, preventing skin cancer would cut the costs of medical treatment, which are currently in the billions in the US and EU.

Skin cancer is mainly caused by UVB radiation, due to direct interaction with DNA and subsequent molecular alterations. However, the part played by UVA seems to be larger than originally thought [4]. Additionally, UVA light initiates oxidative stress related phenomena which contribute to photo-aging and may be the main reason why Caucasians seem to age much faster than Asians. Since Asians usually wish to avoid looking tanned they generally practice life-long sun radiation avoidance behavior [5, 6]. Hence, despite the fact that theoretically and under laboratory conditions the performance of modern sunscreens is sufficient to fulfill protection expectations, the protection level required to have a positive impact on the detrimental biological effects leading to skin cancer and photo-aging is still not being reached.

The question remains: what causes this discrepancy? A prime reason can be seen in individual consumer behavior with regard to sun exposure patterns, or “sunbathing”, and sunscreen use. Sun exposure has several physiological benefits, e.g. a pleasant feeling of warmth and mood enhancement, [7], often paired with leisure activities and social interaction. These benefits create an unconscious or even conscious desire to seek out sunlight or be outdoors. Sun protection strategies need to take account of these positive effects to avoid being viewed as “spoilsports”. There are already a couple of protection strategies that offer protection without significantly diminishing the pleasure of sun exposure. Sunscreens are a perfect example, being created to protect during outdoor activities. Nevertheless, many studies show that consumers use much less than the amount required to achieve the labeled protection claim [1, 7]. One comprehensive in vivo ring study [8] has shown that the protection claimed on the label declines in a linear fashion with the amount used. Often consumers use only 1/5 of the required amount, bringing the SPF of an SPF 30 labeled sunscreen down to a level of SPF 6. In the context of a beach holiday this could mean slight sunburn, with sunburn a certainty at exposed sites like the tip of the nose and shoulders. Paired with under-usage of sunscreens, this type of consumer sun-seeking behavior creates exposure scenarios which predict neither a reduction in cancer rates nor a prevention of photo-ageing.

There are of course educational options for improving consumer behavior. But in terms of sunscreens, where the technology already has been optimized, there are also two targets we can aim for. First, sunscreens need to be more pleasant to use in order raise the acceptence level; and second, on top of that, it makes sense to think about how to raise performance under conditions of under-usage.

Improving Consumer Acceptance of Sunscreens

Consumers do not go off to the beach or the golf course carrying a balance to weigh out their sunscreen. They judge the amount needed by “feel”, using some sensory endpoints – looking at the amount in the palm, judging shine on the skin after rubout, or testing their skin for a tolerable level of greasiness or stickiness. We conducted a focus group study precise-ly to investigate “what puts consumers off sunscreens?” Two typical statements: “For me the protection given by sunscreen is good … Everything else is mostly just annoying. Rubbing it in is annoying, because it leaves my hands all oily. If you sweat a greasy film forms on the skin – annoying!” or “Less good is
that sun milks with a higher SPF are thicker and difficult to spread and take a long time to dry in”. The biggest problem for people was how the stickiness made sand stick to them or stopped them from doing something. Overall 35% of people found all sunscreens greasy or oily.

All in all this indicates that the sensory properties of sunscreen could generally benefit from some improvements. We therefore investigated almost a hundred commercially available sunscreens for their sensory profile and features, using descriptive sensory analysis by a highly trained in-house sensory panel. Descriptive sensory analysis provides a powerful tool to measure intensities of sensory attributes of lotions [9]. Statistical investigations deepened our understanding of ranges, sensorial relationships and differences, as well as the variation of sensory attributes found in this market. We then compared the identified ranges with our market insights to identify directions for improvement that would best target consumer preferences and appreciation.

1. Methodologies for Sensory Measurement

We analyzed in-house prototype formulas, as well as the commercially available sunscreen lotions, by descriptive sensory analysis. The panel assessed 28 sensory parameters, including parameters at different time points of application. The procedure followed a methodology developed and trained by Sensory Spectrum Inc./US. Application of the lotions to the volar forearm followed a strict protocol and is basically divided into three distinct phases: “Rubout”, followed by “Immediate Afterfeel” and 20 minutes later “Afterfeel, 20 min”. Each phase can be characterized by several, mostly independent, sensorial dimensions (Tab. 1), which are assessed either by touch or look and always scaled in relation and comparison to a set of trained standards for each parameter. Primarily, this delivered a landscape of sensory intensity ranges commonly found for the sunscreen lotion product category. We also sorted them into SPF 30 and 50 products. Correlation analysis and hierarchical clustering enabled us to identify products with a higher degree of similarities or differences.

2. Results of Sensory Testing

2.1. Sensorial Ranges of Commercial Sunscreens

A range plot on the sensory attributes offers an overview of commonly represented sensory features of sunscreens in the market. With percentiles it is possible to further narrow down the mainstream sensory properties of a given attribute. Fig. 1

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**Tab. 1** Sensorial Dimensions investigated for sunscreens. The Afterfeel attributes had been assessed directly after the rub out concluded and then again after 20 min.
shows this by example for the rubout phase. Once ranges are known, known single products can be drawn into the range map to investigate how much they differ from or are similar to the median sensory property of sunscreen lotions. This can help to sharpen focus for certain features that may play a role in consumer acceptance. It is also interesting to look at outliers with this feature and speculate about the acceptance of certain features which are clearly far off the median.

2.2. Sensorial Relationships
Following correlation analysis and hierarchical clustering on the correlations we were able to arrange the products according to their level of similarity. Fig. 2 shows the result graphically represented in the form of a family tree. The height of each node indicates the similarity between its leaves – the shorter the connection line, the more similar the products are. With the help of a chart like this it is possible to identify where a product will place itself in the market in respect of its sensory profile, e.g. the DSM Formula is very similar to Product 54, and quite similar to Product 31. The chart can also help to navigate development prototypes to a certain desirable corner of the sensory landscape. The outliers revealed by this method (top of the dendrogram, e.g. Products 1, 2, and 4) are also worth looking at. These have sensory features which are quite uncommon for this product category.

2.3. Sensory Deviation Mapping of a Sunscreen Lotion
Our trained sensory panel together with market insights enabled us to define the direction for a sensorially optimized sunscreen. The sensory panel was able to digitally create a dream sunscreen profile. Interestingly, this revealed two consumer types: Most abundant were those who preferred a sunscreen that could be described as “easy to distribute”, “not greasy, particularly in the dried out stage”, “not sticky”, “not shiny” with a “dry tough” finish. Ideally it would be more or less imperceptible on the skin. But there was another, probably minor, preference type which went for “high in gloss” and “greasy, with the perception of a large amount but without a sticky skin feel”. Such consumers would probably choose an oil formula sunscreen. Since the more abundant preference type went for a dry touch finish we created a “Sensorial Deviation Analysis Tool” based on 100+ sunscreens (Fig. 3). The zero line represents Analysis Tool the global sensory average of all tested formulas. This analysis reveals areas where the formula would benefit from improvement to become above-average (red zone) and also where the formula is already comparably good (green zone). The tool makes it easy for the formulator to recognize directions for development.

2.4. Ways to Improve Sensory Profiles of Sunscreens
If a sensorial direction is specifically being analyzed for improvement, formulators can use a couple of strategies to modify a given sensory profile. However, sensory dimensions are often interlinked. Moreover, they may be linked to performance, meaning a beneficial change in one dimension may have adverse effects on another feature. This is particularly true if several ingredients in a formula need to be changed. A very easy method is therefore to keep the basic structure...
of the formula constant and just add a sensory modifier to achieve the desired result. Currently, many sunscreens lack a “dry tough/low shine” feature. We therefore created a series of sensory modifiers to fix both of these features at the same time, without having a major impact on other sensory properties and the basic performance. Fig. 4 shows an example. The first version of one formula we created proved to lack a dry and matt finish. It was too greasy and its playtime feature was too long. Without changing the remaining composition of the formula we utilized a new sensory modifier and turned our initial version into a formula with a beautifully dry and even matt finish, with some silicone aspects.

Can We Further Improve Current High-Performance Sunscreens?

Modern sunscreen technology is already able to deliver SPF 50+ sunscreens (in the EU this equals a measured SPF > 60). But as we have seen, the way consumers use them under beach conditions could bring the performance down significantly due to marked under-application. It would therefore be desirable to have even higher factors [10], but creating a SPF 50+ formula is already a challenge to formulators – in particular when this formula, which already requires a high loading of oily UV filters, also needs to have sensory attributes that are pleasing to the consumer. Otherwise consumers might be tempted to use it even more sparingly. Hence there is a contradiction between the performance of sunscreens and maintaining or enhancing their proper use. This represents a serious challenge.

We decided to investigate whether the contradiction could be minimized and under what conditions. For this purpose it was necessary to understand sunscreen application better, in particular at a microscopic level on human skin. Earlier data and theoretical calculation showed that sunscreens could perform much better than they do [11]. However, the skin’s rough surface and the application procedure forces the sunscreen to form a very irregular film, which in turn considerably diminishes performance [12]. While this phenomenon has been recognized for more than three decades, we still do not understand in microscopic detail how a sunscreen film forms on skin – knowledge which is necessary if we want to unlock a sunscreen’s true performance by creating a more improved film on human skin from it. We therefore investigated how these films form, in order to understand whether we would ever be able to create a stable and perfect film on human skin which achieves maximum performance.

We began by analyzing the sunscreen application process in detail and separating it into 3 phases: application, post-application, and the resting phase.

The application phase is controlled by a lot of externally applied periodic shear, whilst during the post-application phase internal forces make the semi-solid material flow and finally, in the resting phase, no flow happens. Sunscreen flow is driven by surface tension gradients, arising from forced irregular film geometries and concentration differences, which are caused by the evaporation of water or other solvents. During this phase, the rheological or flow behavior of the semi-dried sunscreen is thought to be crucial. To achieve a high-performing skin “coating”, it is desirable to have a spatially evenly distributed film exactly following the profile of the skin with a constant thickness; a situation very similar to paint coatings on rough substrates [13]. Creating a film of this type would inevitably require considerable investment of time and effort. Therefore it would obviously be wise to know beforehand whether such an ideal geometry would have any chance of surviving the flow driven by the internal forces, and which properties such a film would need to stop it simply converting back to the much less favorable situation – a smooth upper surface with fully filled up wrinkles and little material left to cover up the rest of the skin between the wrinkles. This is how current sunscreens regularly tend to behave. Calculations backed by literature data [14] suggest that at least 50% of the applied sunscreen has space to reside in these fine lines at use levels of 2 mg/cm². However, what is not understood is whether the sunscreen flows into the fine lines during or after the active application phase. The objective of our experiments was to answer this question and to investigate whether more optimal film arrangements are possible and would remain stable.
For this purpose we revisited skin roughness profiles, analyzed the principle geometrical patterns of human skin and built this into a model. We measured the rheological behavior of dried sunscreen films and modeled the flow behavior of the post-application phase in silico on a model substrate with an in silico “wrinkle”. The model enabled application of different film thicknesses and sunscreen material properties (e.g. rheology and surface tension). A surprising and encouraging endpoint for the flow was discovered. We further evaluated whether Marangoni forces [15] caused by surface tension gradients would help us to reverse an irregular, low performance film by “drawing” material out of the wrinkle towards the skin surface. This is the effect which draws wine upwards along the walls of a wine glass, and is triggered by evaporation.

1. Methodology and Model Used to Calculate Sunscreen Flow in silico

Human skin exhibits two major wrinkle features. First: the skin consists of fine lines with a depth of about 50–200 µm and a width of about 40–100 µm. These wrinkles surround triangular-like plateaus of about 600 µm edge length. The plateaus account for about 80% of the surface and make up the main target area for sun protection by a sunscreen. On top of the plateaus is the second roughness feature: small length scale furrows with a depth of about 1 µm and a similar width, surrounding corneocytes with a diameter of about 30 µm. When compared to the initial sunscreen film thickness (about 20 µm before water evaporation), the small wrinkles are of negligible size. This general picture is represented in Fig. 5. In this study we therefore focused on the larger scale furrows.

The post-application leveling of sunscreen on a non-deformable substrate was modeled. The non-flat topology of the skin was approximated by a single furrow and plateau. A two-dimensional cross-section was modeled, resulting in the domain given in Fig. 6. Since fluid inertia and gravity do not play a role during leveling, the two-dimensional Stokes equations, which are solved numerically, apply. Sunscreens level due to surface tension and surface tension gradients. The latter arise due to differences in the surface tension coefficients of individual constituents of a sunscreen. Both effects are incorporated in the numerical model.

The flow behavior of sunscreens shows two particular effects: yield-stress and shear-thinning. If stresses in the sunscreen fluid are lower than the yield-stress they will not flow, while if stresses are greater they flow like simple Newtonian fluids with a typical viscosity of 10 Pa s (e.g. water, oil). A fluid undergoes shear-thinning when the viscosity monotonically decreases above a certain shear-rate. Although a sunscreen is typically an emulsion of water and oil, containing particles and other constituents, it can be treated as a single homogeneous fluid having the rheology described above.

2. Result of in silico Sunscreen Flow Experiments

In order to prevent flow into the furrows the following two hypotheses have been evaluated:

- A high yield-stress will arrest flow and prevent flow into the furrows.
- Strong Marangoni effects, due to lateral solvent concentration differences which result from drying of the applied product, lead to a flow out of the furrow, thus leading to thicker layers on the plateaus.

For the large-scale furrows the velocity of the flow field after one second (!) of leveling is shown for a yield-stress of 1, 10 and 100 Pa in Fig. 7 on the left. Only the left half of the furrow is simulated. This clearly shows that yield-stress will block flow into the furrows when it is at about 100 Pa. Since a typical yield-
stress of sunscreen is 1–10 Pa, 100 Pa is unrealistically high. Surprisingly, at longer leveling times however, even the flow for the yield-stress of 1 Pa will arrest, since it pinches off as shown in Fig. 7 on the right. This leads to two separate domains; one on the plateau and one in the furrow. This means that fluid cannot flow in either direction anymore, hence preserving a large amount of sunscreen on the plateau.

For the Marangoni flow the initial situation was chosen to be a fully filled furrow, which represents the worst scenario. The furrow depth is 100 μm and the layer thickness at the plateau is 10 μm. A strongly on surface tension depending result is shown in Fig. 8 after 260 seconds of drying. This clearly shows that material can be drawn from the furrow to the plateau, yet the film will disrupt at a certain time point, after which no further flow from furrow to plateau is possible. Hence the Marangoni effect helps to some degree, but is not strong enough to empty a wrinkle to any great extent.

**Conclusion**

Modern sunscreens already reach a high level of performance, but we still have some way to go to in terms of skin cancer prevention and slowing facial aging. There are two dimensions to this problem. One area of focus lies in improving sensory features, while a second would involve improving performance even further, particularly with a use level lower than 2 mg/cm². To optimize sensory features we analyzed about 100 commercial sunscreens for their preferred ranges and compared the results with some market insights from consumers. This clearly revealed a sensorial improvement direction for many of the 20 sensory dimensions we measured. Particularly relevant targets for most consumers are achieving a not-too-greasy, more matt appearance which after drying results in a dry, non-sticky touch resembling untreated skin. More pleasing sensory features would increase the likelihood that consumers will unconsciously use larger amounts and consequently achieve better protection, hence improving overall skin health.

With the aim of improving performance we investigated the flow of sunscreens on skin, for which we also used in silico tools. The investigation revealed that the performance of a sunscreen depends heavily on the rubout process and that while flow does change the geometry of the resulting film, it is not to any great extent. Unfortunately irregularities created during rubout cannot be fixed by creating formulas with intelligent flow behavior post-application. Therefore further improvement of the performance of sunscreens, especially those which are already high-performing, needs to focus on...
modulating the rubout phase. Fig. 9 shows a model which makes it easier to understand the strong variations not uncommonly observed when measuring sunscreen performance, not only in vivo but also in vitro. Depending on the rubout procedure there will be more or less material in the wrinkle and consequently more or less material left to cover the plateaus, where the sunscreen’s performance is “made”. Greater film thickness on the plateau would result in higher performance. But pressure on application and long rubout times encourage filling of wrinkles and tend to drive performance down. Consumers should be recommended not to rub out a sunscreen too hard, too intensively or for too long. The advice should be: distribute lightly and allow the film to dry. The application phase thus becomes the most important area of research for novel performance enhancing strategies.

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**Literature**


