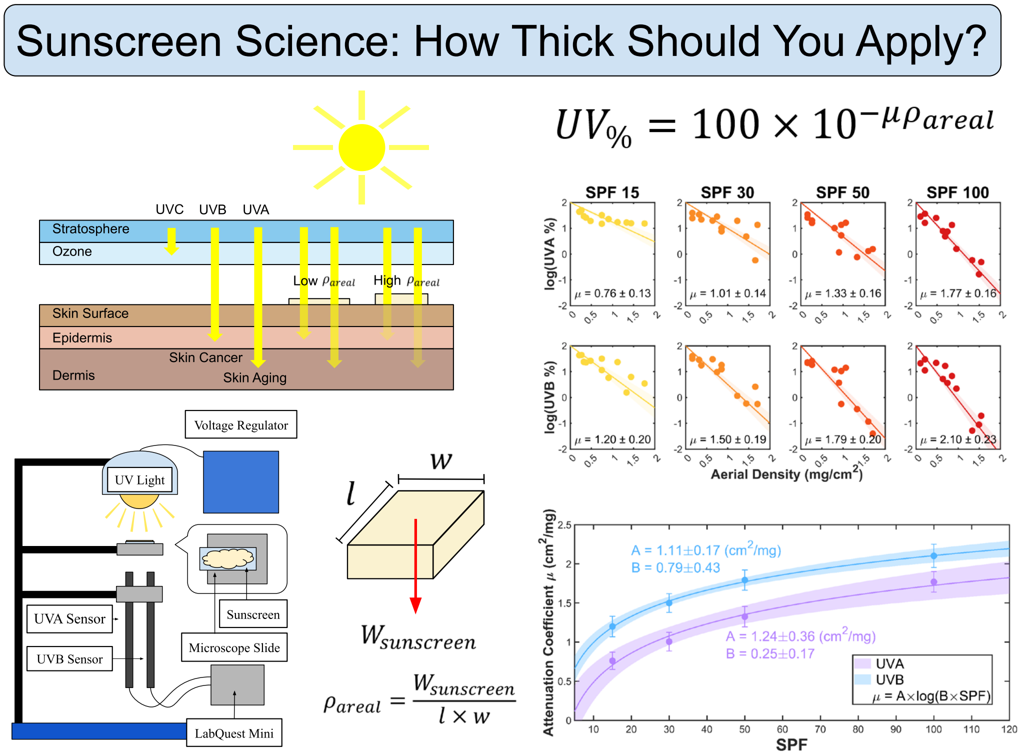
Monday 2-5

The Effect of SPF on the Rate of UV Attenuation

Will Doster

12/7/25
2.671 Measurement and Instrumentation
Monday PM
Dr. Huang

Visual Abstract



Abstract

The interaction between the Sun Protection Factor and areal density of sunscreen, or the weight per unit area, is a critical but not well understood factor in blocking UV. To understand how SPF impacts the relationship between areal density and both UVA and UVB transmission, the influence of SPF on the rate of UV attenuation with increasing areal density was characterized. UV transmission through different SPFs applied at varying areal densities was measured with UV sensors. UV transmission decreased exponentially with areal density, and the attenuation coefficients, determining the rate of attenuation, increased logarithmically from the lowest to highest SPF by 132 ± 38% for UVA and 75 ± 23% for UVB. Consequently, the higher SPF sunscreens approached their standard UV blockage, at an areal density of 2 mg/cm^2, more quickly than the lower SPF sunscreens, suggesting that consumers could employ a higher SPF to mitigate the harm of underapplication.

Keywords: UV Transmission, SPF, Areal Density, Attenuation Coefficient, Beer-Lambert

1. Introduction

UV radiation from the sun accelerates skin-aging and causes skin cancer, with 65,000 skin-cancer deaths occurring yearly [1]. Sunscreen is commonly used to block both UVA and UVB radiation, and its ability to reduce UV transmission is often characterized by its Sun Protection Factor (SPF). However, SPF describes the UV blockage at a specific areal density, or the sunscreen weight per unit area. Previous studies have shown that users employ densities between 25%-50% of this standardized density, largely due to unclear application guidelines, which significantly reduces UV blockage by the applied sunscreen [2]. As a result, understanding how the UV transmission through sunscreen changes with areal density is critical for characterizing and communicating sunscreen efficacy.

The Beer-Lambert law is often used to describe the exponentially decreasing relationship between light transmission through a substance and its areal density. Previous studies have shown that this law effectively applies to the relationship between areal density and UV transmission for sunscreens [3, 4]. However, the effect of SPF on this relationship, specifically in determining the rate of UV attenuation with increasing areal density through controlling the attenuation coefficients in the Beer-Lambert law, has not been characterized. The rate at which UVA and UVB transmission decrease with increasing areal density determines how quickly sunscreens approach their standard UV blockages, occurring at an areal density of 2 mg/cm^2. Characterizing this information enables validation of the theoretical mathematical relationship and improves the information available to consumers to achieve their desired UV protection.

UVA and UVB transmission through sunscreen were measured as a function of areal density and SPF to characterize how SPF affects the rates of UV attenuation. UV sensors measured the transmission from a UV lightbulb through different SPF sunscreens applied at varying areal densities on a microscope slide. Applying the Beer-Lambert law to the transmission data as a function of areal density produced attenuation coefficients for each SPF. The attenuation coefficients were analyzed as a function of SPF to characterize the relationship between SPF and the rate of UV attenuation. These results were compared to the theoretical logarithmically increasing relationship between SPF and the attenuation coefficients. Validation of this relationship would indicate that increasing SPF leads to an increase in the rate of UV attenuation, which could motivate consumers to employ a higher SPF to achieve increased protection at a lower areal density to reduce the harm of underapplication.

2. The Science of Sunscreen

Sunscreens are relied on to provide UV protection, which motivates an exploration of the risks posed by ineffective sunscreen usage and the current understanding of sunscreen effectiveness. Sunscreen's UV blocking ability at the standard areal density is designated by its SPF; however, since underapplication is a common occurrence, it is necessary to explore the Beer-Lambert law to see how UV transmission changes with decreasing areal densities. As this section details how these two factors have been tested in previous studies and the impact they have on sunscreen effectiveness, it demonstrates where this study serves to fill the knowledge gap of how SPF controls the shape of the Beer-Lambert law through influencing the rate of UV attenuation.

2.1 UV Radiation

Ultraviolet radiation is separated into three categories based on wavelength, UVA (315-400 nm), UVB (280-315 nm), and UVC (100-280 nm). The UV radiation on Earth's surface is composed of 95% UVA and 5% UVB, with the atmosphere completely absorbing UVC [1]. UVB is the primary source of sunburn and the development of skin cancer, whereas UVA is responsible for skin aging [5]. Examining the effect of SPF and areal density on transmission of both types of UV radiation is critical in understanding how to effectively avoid the different harms of UV radiation. Depending on a user's purpose of sunscreen application, like blocking UVA to protect against wrinkling or blocking UVB to protect against sunburn, characterizing the effect of SPF on the rate of attenuation of both types of UV can provide users the information to achieve the desired protection.

2.2 Sun Protection Factor

The spectrum of sunscreens is vast, with many combinations of UV blockers [6]. Given the diversity in sunscreen composition, there exists a standardized classification for a sunscreen's ability to reduce UV transmission known as the Sun Protection Factor (SPF).

The procedure for determining a sunscreen's SPF follows the same general format throughout regulation organizations. At various locations on a human body, sunscreen is applied with a standard areal density, defined as the sunscreen weight per unit area, of 2 mg/cm^2. Each location with sunscreen applied has a corresponding location with no sunscreen applied. The partner locations are exposed to increasing amounts of UV radiation.

The SPF is determined to be the ratio of the amount of UV radiation that causes visual redness on locations with sunscreen applied to the amount that causes visual redness on locations with no sunscreen applied. Since the UV transmitted through the sunscreen is the UV radiation that directly causes sunburn on the protected location, the UV transmitted through the sunscreen is equal to the UV that causes sunburn on the unprotected location. It can then be seen that UV transmission through the sunscreen is inversely proportional to SPF, as described in Eq. 1. In this equation, I_p refers to the UV intensity causing sunburn on protected skin, I_u refers the UV intensity causing sunburn on unprotected skin, I_a refers to the intensity absorbed by the sunscreen, I_t refers to the intensity transmitted by the sunscreen, and $UV_{\%}$ refers to UV transmission through the sunscreen.

$$SPF = \frac{I_p}{I_u} = \frac{I_a + I_t}{I_t} \propto \frac{1}{UV_{\%}} \tag{1}$$

Previous studies have verified the inverse relationship between UV transmission and SPF for various sunscreens [7, 8]. However, these studies detailed how UV transmission changes for varying SPF sunscreens applied at the standard areal density of 2 mg/cm^2. Due to the nature of the SPF testing process, when sunscreen is applied below this areal density, standard UV protection is not achieved. Understanding how UV transmission changes with areal density and how SPF impacts this relationship is important to provide users with the information to achieve desired UV protection. In these previous studies, the role SPF plays with changing areal density, specifically in influencing the rate of UV attenuation with increasing areal density, has not been characterized.

2.3 Beer-Lambert Law

The absorption of UV radiation is defined in Eq. 2 in relation to the fractional percentage of UV transmitted through a substance, where A refers to the absorbance.

$$A = -\log_{10} \frac{UV_{\%}}{100} \tag{2}$$

Light absorbance by a substance is described by the Beer-Lambert law, given in Eq. 3, where ϵ refers to the substance's molar absorptivity, c refers to the substance's concentration, and l refers to the path length, or distance the light travels through the substance.

$$A = \epsilon l c \tag{3}$$

The thickness of sunscreen is constitutively related to the areal density as described in Eq. 4, where ρ_{areal} is the areal density of the substance and ρ is the actual density of the substance.

$$l = \frac{\rho_{areal}}{\rho} \tag{4}$$

Combining Eqs. 2, 3, and 4 produces the relationship between UV transmission and areal density described by the Beer-Lambert law, given in Eq. 5. The coefficient μ is the attenuation coefficient, which describes the substance's UV attenuation effectiveness per unit mass per area and characterizes the substance's rate of UV attenuation with increasing areal density.

$$UV_{\%} = 100 \times 10^{-\frac{\epsilon c \rho_{app}}{\rho}} = 100 \times 10^{-\mu \rho_{app}} \tag{5}$$

Previous studies have shown the validity of the Beer-Lambert law for describing UV transmission through sunscreens with changing areal densities [3, 4]. However, these studies employed a single SPF and have not investigated how varying SPF influences the form of the Beer-Lambert law. Given that SPF describes a sunscreen's ability to absorb UV radiation at an areal density of 2 mg/cm^2, a sunscreen's SPF will be related to factors like the molar absorptivity, concentration, and actual density, which determine the sunscreen's attenuation coefficient. As seen in Eq. 5, since the SPF of a sunscreen influences the attenuation coefficient, the SPF value affects the rate of UV attenuation with increasing areal density. Combining Eqs. 1 and 5 produces a theoretical logarithmic form of the relationship between SPF and the sunscreen's attenuation coefficient, as described in Eqs. 6 and 7.

$$\frac{1}{SPF} \propto 10^{-\mu \rho_{app}} \tag{6}$$

$$\mu \propto \log_{10}(SPF) \tag{7}$$

While studies have verified the separate relationships between SPF and UV transmission and between areal density and UV transmission, further work is necessary to characterize the role of SPF in determining the attenuation coefficients in the Beer-Lambert law and in turn, the rate of UV attenuation with increasing areal density. This work additionally serves the purpose of validating the theoretical logarithmic relationship between a sunscreen's SPF and its attenuation coefficient. This will provide consumers with an understanding of how SPF can be utilized to increase the rate of UV attenuation and reduce the harm of underapplication.

3. Experimental Design

A well characterized relationship requires a robust setup to isolate the input SPF and areal density and ensure quality of the measured output UV transmission. The sample preparation to repeatably apply a chosen SPF at a specified areal density is first outlined. The measurement of both the UVA and UVB transmission through the sample and the reduction of the impact of unwanted environmental factors and sunscreen non-uniformity is then discussed. This section explains how UV transmission is controllably produced as a function of SPF and areal density.

3.1 Experimental Setup

To measure UV transmission through each sample, a 75 mm × 25mm × 1 mm VWR VistaVision microscope slide with applied sunscreen was placed below a ReptiZoo UVB 10.0 light bulb. The light bulb was connected to a Staco Energy Transformer to control the intensity emitted from the light. The microscope slide was placed above Vernier UVA and UVB sensors. The UVA sensor had a resolution of 5 mW/m^2 and the UVB sensor had a resolution of 0.25 mW/m^2. The sensors were connected to a Vernier LabQuest Mini that interfaced with the Vernier LoggerPro software and recorded UV intensity at a sampling rate of 100 Hz for a duration of 30 seconds for each trial. The experimental setup is displayed in Figure 1.

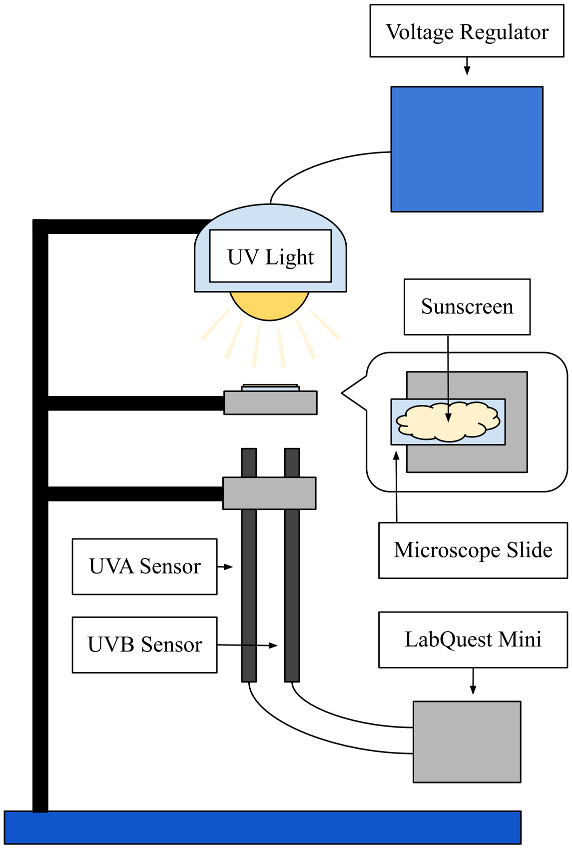


Figure 1: Diagram of the experimental setup for measuring UV transmission through sunscreens. UV sensors measured the transmission from a UV light through the sunscreen applied on a microscope slide. The light intensity was controlled with a voltage regulator and the data was gathered with a LabQuest Mini.

The chosen SPF values for this experiment were 15 SPF, 30 SPF, 50 SPF, and 100 SPF to cover the full range of commonly available SPFs. The sunscreen used in this study was Banana Boat, chosen because of its wide usage, affirmed by Banana Boat's control of 13% of the sunscreen market, which is the second largest share for sunscreen brands [9]. The areal densities ranged from 0 mg/cm^2 to 2 mg/cm^2 to cover the range of areal densities before and up to the standard areal density. Each SPF was tested at 12 areal densities, leading to a total of 48 trials.

3.2 Sample Preparation

To prepare each sample, the microscope slide was washed with warm water and soap to remove any sunscreen from prior tests. The slide was weighed with an 8060-series jewelry scale.

An X-Acto blade was then used to spread the sunscreen uniformly on the slide. After visual uniformity was achieved, the slide was weighed again. The areal density for each sample was calculated with Eq. 8, where $W_{unprotected}$ refers to the slide weight, $W_{protected}$ refers to the slide weight with sunscreen applied, and A_{slide} refers to the area of the slide. The spreading process was repeated until the desired areal density was achieved. After preparation, the slide was moved to the experimental setup to measure UV transmission.

$$\rho_{areal} = \frac{W_{protected} - W_{unprotected}}{A_{slide}} \tag{8}$$

3.3 UV Measurement

Given that the source intensity fluctuates with environmental factors, a baseline test measuring the transmission through the slide without sunscreen applied was completed first for each sample. After the completion of the baseline measurements, the slide was removed, and sunscreen was applied to the slide. After preparation, the slide was then moved back onto the measurement setup. The UVA and UVB intensities were measured three times, with the slide position being adjusted between trials to account for the slightly non-uniform sunscreen thicknesses. Figure 2 displays the intensities measured during the baseline test and one of the sample tests through 15 SPF sunscreen applied at an areal density of 0.5 mg/cm^2.

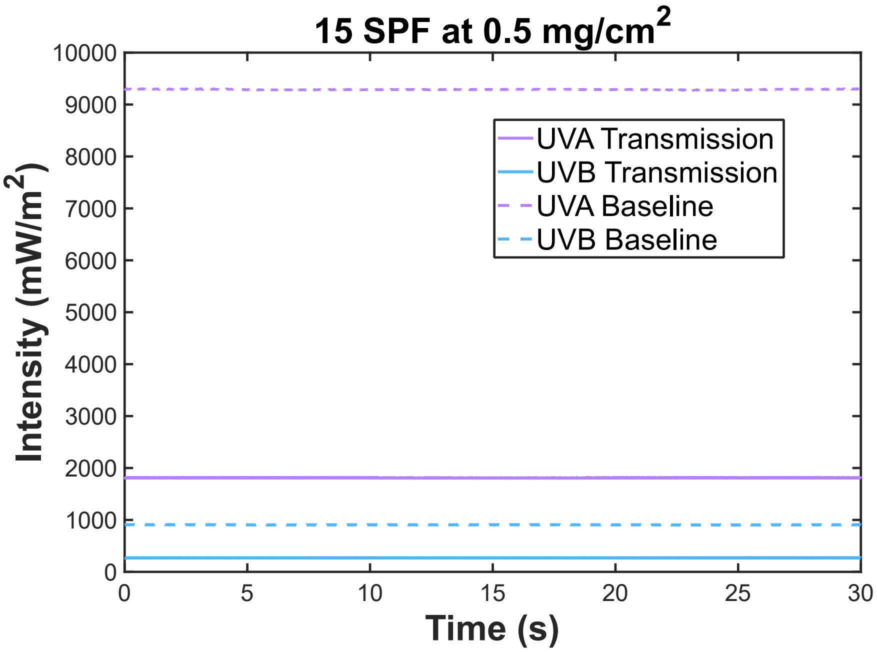


Figure 2: UVA and UVB Intensity measured during baseline test and one sample test through 15 SPF sunscreen applied at an areal density of 0.5 mg/cm^2. A baseline test was completed for each sample to account for changing environmental factors influencing the source intensity. This data was later used to determine the UV transmission through the sunscreen.

The intensities from each trial in the baseline test and each of the three sample tests were averaged over the 30 second duration to produce mean UVA and UVB intensities. The three transmission intensities with different slide positions were averaged to reduce the effect of non-uniformity in sunscreen thickness. The final UV transmissions were determined by normalizing the transmission intensities by the baseline intensities to remove the effects of changing source intensity, producing UVA and UVB transmission as a function of SPF and areal density.

4. Results and Discussion

To fully characterize the effect of SPF on the rate of UV attenuation, this section first analyzes the UVA and UVB transmissions as a function of areal density to produce the corresponding attenuation coefficients for each SPF. This allowed the characterization of the dependence of a sunscreen's attenuation coefficient on its SPF. By producing a direct relationship between SPF and the rate of UV attenuation, this section is able to explore the consequences of the form of that relationship for consumers, providing them the information to understand sunscreen effectiveness and avoid the harm of underapplication.

4.1 UV Attenuation

The UVA and UVB transmissions exhibited exponential decay with increasing areal density. To apply the Beer-Lambert law to the UV transmission data with higher confidence, the logarithm of the UV transmissions was taken, producing an alternate form of Beer-Lambert law as described in Eq. 9.

$$\log(UV_{\%}) = 2 - \mu\rho_{app} \tag{9}$$

The UV transmissions were then fit to the Beer-Lambert law as function of areal density for each SPF as seen in Figure 4. The attenuation coefficients were statistically significant with 95% confidence for each SPF, in agreement with previous studies and verifying the validity of the experimental methods for producing UV transmission as a function of areal density [3, 4].

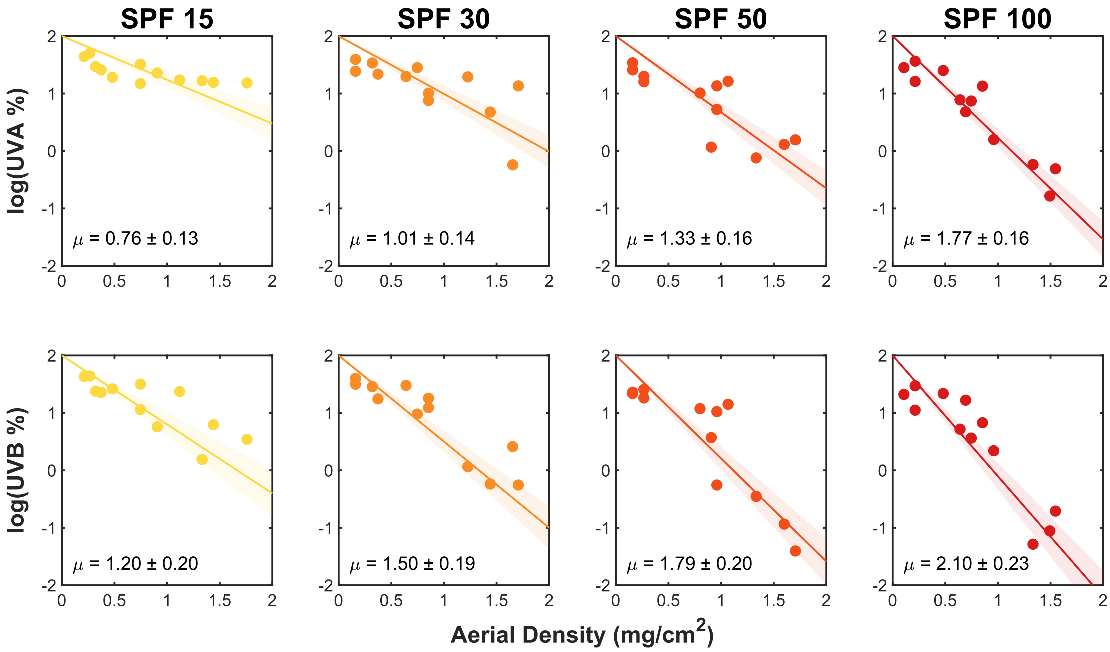


Figure 4: The logarithm of UV transmissions plotted against areal density for all SPF values, displaying an exponentially decaying relationship. All attenuation coefficients were statistically significant with 95% confidence, in agreement with previous studies [3, 4].

The relationship between areal density and UV transmission as described by Beer-Lambert law in Eq. 5 is exponential. As areal density decreases below the standard value of 2 mg/cm^2, the UV transmission rises exponentially. This shows that the protection against UV radiation from sunscreens is lost rapidly if sunscreen is underapplied, emphasizing the importance of achieving the standard areal density. This also motivates an understanding of how SPF impacts the shape of this exponential relationship, as SPF values with higher attenuation coefficients and thus higher rates of UV attenuation could reduce the harms of underapplication, as less areal density would be required to achieve the desired UV protection.

This study relied on visual observations of sunscreen uniformity. To reduce the variance in transmission measurements and increase confidence in the determined curves and attenuation coefficients, future studies could determine a more effective method for spreading sunscreen uniformly at specified areal densities.

4.2 Attenuation Rate Comparison

Fitting the transmissions to the Beer-Lambert law in Figure 4 produces attenuation coefficients, μ, for each SPF for both UVA and UVB transmission. As seen in the Beer-Lambert law in Eq. 5, the attenuation coefficients determine the rate of UV attenuation with increasing areal density. The attenuation coefficients displayed a logarithmic relationship with SPF, verifying the theoretical model described in Eq. 7. The attenuation coefficients increased from the lowest to highest SPF by 132 ± 38% with 90% confidence for UVA radiation and by 75 ± 23% with 80% confidence for UVB radiation. The attenuation coefficients were fit to a logarithmic curve as a function of SPF with 95% confidence for both UVA and UVB radiation as shown in Figure 5.

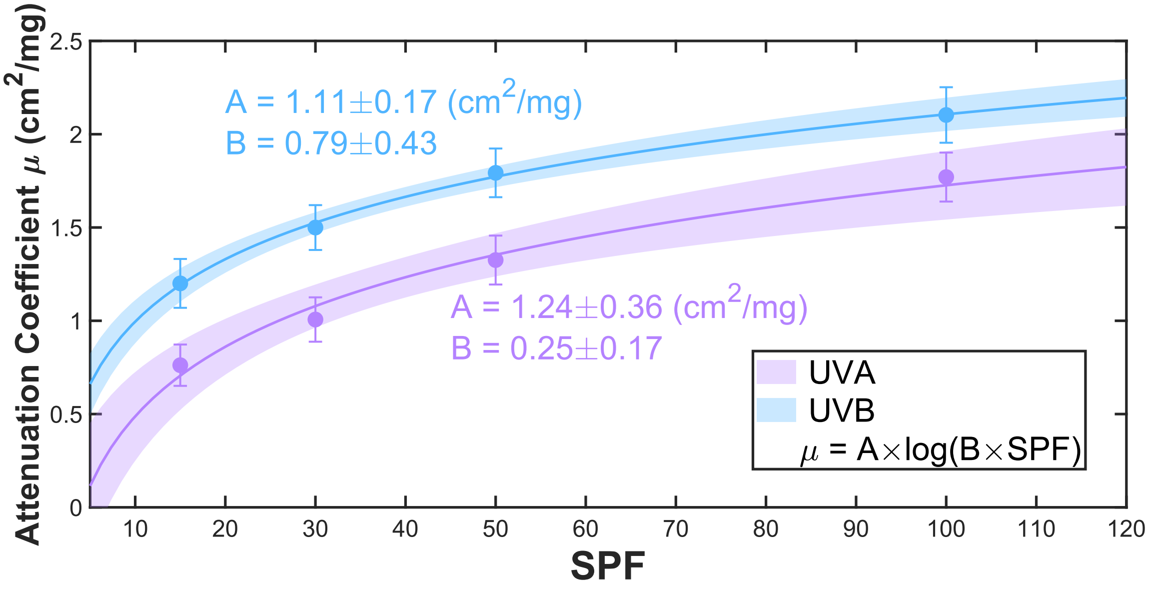


Figure 5: The attenuation coefficients from the Beer-Lambert law plotted against SPF for both UVA and UVB radiation. The attenuation coefficients increased logarithmically with SPF with 95% confidence for both UVA and UVB radiation. The rate of UV attenuation with increasing areal density thus increased with SPF, so the higher SPF sunscreens approached their standard UV protection at an areal density of 2 mg/cm^2 more quickly than lower SPF sunscreens, presenting a potential solution for underapplication.

As previously mentioned, the attenuation coefficients determine the rate of UV attenuation. Given that the attenuation coefficients increased with SPF, the higher SPF sunscreens offered a higher rate of UV attenuation with increasing areal density as compared to lower SPF sunscreens. Graphically, the higher SPF sunscreens exhibited a steeper exponential relationship between areal density and UV transmission. Therefore, the higher SPF sunscreens approached their standard UV blockage, at an areal density of 2 mg/cm^2, at a faster rate than lower SPF sunscreens.

With this information, sunscreen users who are likely to employ a low areal density of sunscreen could utilize higher SPF sunscreens to reduce the rate of exponential growth of UV transmission with decreasing areal density. Since UV transmission through higher SPF sunscreens does not increase as rapidly with underapplication, the sunscreen users could receive UV protection closer to the standard UV protection for the lower SPF sunscreen when they underapply if they employ a higher SPF sunscreen.

It should be noted that due to the logarithmic nature of this relationship, the rate of increase in the attenuation coefficient decreased as SPF increased. This suggests that at higher SPFs, the reduction of the harm of underapplication is lower with increasing SPF than at lower SPFs. Practically, if a consumer is seeking to avoid the harm of underapplication of a higher SPF sunscreen, this trend suggests they should increase their SPF more than if they were seeking to avoid the harm of underapplication of a lower SPF sunscreen.

Figure 5 also shows that the attenuation coefficients were statistically greater for UVB radiation than UVA radiation for all SPFs with 90% confidence, with the largest difference being 58 ± 29%. Therefore, the tested sunscreens had a higher rate of UVB attenuation than UVA attenuation with increasing areal density for all SPFs. Since SPF values are determined based on visual redness and UVB radiation is largely responsible for sunburn, it's likely that as a result, sunscreens are more effective at attenuating UVB than UVA radiation. Consumers who apply sunscreen primarily to avoid skin-aging, caused largely by UVA radiation, may experience a faster increase in unwanted UVA radiation with decreasing areal density as compared to UVB radiation and could particularly benefit from employing a higher SPF sunscreen.

5. Conclusions

UVA and UVB transmissions were measured through sunscreens of different SPFs applied at varying areal densities to characterize the effect of SPF on the rate of UV attenuation with increasing areal density, or sunscreen weight per unit area. The UV transmission through every SPF exhibited an exponentially decreasing relationship, as described by the Beer-Lambert law, which emphasizes the criticality of applying sunscreens with the standard areal density to achieve the desired UV protection, as underapplication will lead to an exponential increase in UV transmission. The Beer-Lambert law produced an attenuation coefficient, which described the rate of UV attenuation with increasing areal density, for each SPF for both UVA and UVB radiation.

The attenuation coefficients increased logarithmically from the lowest to highest SPF by 132 ± 38% for UVA radiation and 75 ± 23% for UVB radiation. Therefore, the increase in UV transmission with decreasing areal density is less rapid for higher SPF sunscreens. This suggests that if underapplication is a risk, a higher SPF can be used to reduce the rate of increase in UV transmission and achieve greater UV protection. The attenuation coefficients were larger for UVB radiation than UVA radiation, with a largest difference of 58 ± 29%, likely due to the SPF testing process biasing UVB attenuation. Consumers with the primary goal of blocking UVA radiation could thus experience a faster increase in UVA radiation with underapplication and could particularly benefit from employing a higher SPF sunscreen.

This study answers the question of how SPF influences the rate of UV attenuation with increasing areal density as described by the Beer-Lambert law. This provides users with information to more effectively select an SPF to protect against the harm of underapplication. The study also verifies the theoretical mathematical model for the relationship between a sunscreen's SPF and its attenuation coefficient. This study could be extended to verify these results for additional brands and formulations of sunscreens to increase confidence in the presented relationship between SPF and the rate of UV attenuation.

Acknowledgments

The author would like to acknowledge Dr. Hughey and Dr. Huang for their help in shaping this study and Dr. Bruner for her help in developing the resulting communications.

References

[1] Narayanan, D., Saladi, R., and Fox, J., 2010, "Ultraviolet Radiation and Skin Cancer," International Journal of Dermatology, **49**, pp. 978–86. https://doi.org/10.1111/j.1365-4632.2010.04474.x.

[2] Ou-Yang, H., 2012, "High-SPF Sunscreens (SPF ≥ 70) May Provide Ultraviolet Protection Above Minimal Recommended Levels by Adequately Compensating for Lower Sunscreen User Application Amounts.," Journal of the American Academy of Dermatology, **67**(6), pp. 1220–7. https://doi.org/10.1016/j.jaad.2012.02.029.

[3] Lepoivre, E., 2025, "Generalized Beer-Lambert Law for Evaluating the Absorption of Heterogenous Sunscreen Films," Applied Materials & Interfaces, **17**, pp. 27895–27905. https://doi.org/10.1021/acsami.5c02458.

[4] Schultheiss, A., 2018, "On the Validity of Beer-Lambert Law and Its Significance for Sunscreens," Photochemistry and Photobiology. https://doi.org/10.1111/php.12861.

[5] Chien, A., and Jacobe, H., 2025, "UV Radiation & Your Skin," Skin Cancer Foundation. [Online]. Available: https://www.skincancer.org/risk-factors/uv-radiation/.

[6] Gabros, S., Patel, P., and Zito, P., 2025, *Sunscreens and Photoprotection*, StatPearls Publishing. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK537164/.

[7] Khunkitti, W., 2014, "Method for Screening Sunscreen Cream Formulations by Determination of In Vitro SPF and PA Values Using UV Transmission Spectroscopy and Texture Profile Analysis," Journal of Cosmetic Science, **65**(3), pp. 147–59.

[8] Throm, C., and Schluesener, J., 2021, "In Vivo Sun Protection Factor and UVA Protection Factor Determination Using (Hybrid) Diffuse Reflectance Spectroscopy and Multi-Lambda-LED Light Source," Journal of Biophotonics, **14**(2). https://doi.org/10.1002/jbio.202000348.

[9] 2025, "How Sunscreen Brands Are Winning in 2025," evidnt. Available: https://evidnt.co/blog/sunscreen-category-trends-2025-market-leaders-innovation-clean-suncare/.