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ORIGINAL PAPERS

Blue light protection factor: a method to assess the protective efficacy of cosmetics against blue light-induced skin damage in the Chinese population

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Abstract

Background Previous studies have shown that visible light (VL), especially blue light (BL), could cause significant skin damage. With the emergence of VL protection products, a harmonization of light protection methods has been proposed, but it has not been widely applied in the Chinese population.

Objective Based on this framework, we propose an accurate and simplified method to evaluate the efficacy of BL photoprotection for the Chinese population.

Methods All subjects ($n=30$) were irradiated daily using a blue LED light for four consecutive days. Each irradiation dose was 3/4 MPPD (minimum persistent pigmentation darkening). The skin pigmentation parameters, including L^*, M, and ITA°, were recorded. We proposed the blue light protection factor (BPF) metric based on the skin pigmentation parameters to evaluate the anti-blue light efficacies of different products.

Results We found that the level of pigmentation rose progressively and linearly as blue light exposure increased. We proposed a metric, BPF, to reflect the anti-blue light efficacy of products based on the linear changes in skin pigment characteristics following daily BL exposure. Moreover, we discovered that the BPF metric could clearly distinguish the anti-blue light efficacies between two products and the control group, suggesting that BPF is an efficient and simple-to-use metric for anti-blue light evaluation.

Conclusion Our study proposed an accurate and simplified method with an easy-to-use metric, BPF, to accurately characterize the anti-blue light efficacies of cosmetic products, providing support for further development of anti-blue light cosmetics.

Keywords Skin damage · Pigmentation · Blue light protection factor · In vivo model · Anti-blue light

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1 Introduction

The skin is the largest organ of the human body and protects against environmental stressors, of which light radiation is one of the major causes of skin aging. It has been widely recognized that skin photoaging is mainly induced by ultraviolet radiation (280–400 nm), while visible light (400–700 nm) is considered to have no significant effects [1]. However, various recent studies have identified that visible lights, especially blue lights, could also induce a series of biological changes to the skin, including oxidative stress damage, DNA damage, degraded collagen, and disruption of the skin barrier [2–7].

Blue light is visible light with a wavelength of 400–500 nm, making it a high-energy visible light [8]. Blue light sources can be divided into solar light and artificial visible light, which originates from electronic devices and LED lights. Therefore, we are exposed to blue light radiation for long periods in our daily lives [9]. Meanwhile, blue light has longer wavelengths than UV radiation and could penetrate deeper into the skin [10]. Therefore, blue light can directly reach the dermis of human skin and causes mitochondrial DNA damage and reactive oxygen species (ROS) accumulation, and cellular dysfunction in the dermis [11–14]. Moreover, it is reported that the immediate hyperpigmentation caused by blue light is dimmer and fades more slowly than that caused by UV light [3]. The delayed darkening caused by blue light can persist for more than 3 months without fading [15].

Due to the above-mentioned harmful effects of blue light, many cosmetics claimed to have anti-blue light efficacy have been developed. At the same time, a variety of methods for assessing these cosmetics' protection against blue light or visible light have been developed. Duteil et al. [16] used multiple exposures to evaluate the photoprotection of visible light, and each exposure had a fixed dose of 144 J/cm^2. Then Duteil et al. used a linear regression model to calculate the slope of the Delta ITA° curve between Day 1 and Day 5, then adopted the ratio between the average slope of the control area skin and the average slope of the product to calculate the protection factor. However, considering individual variations, some participants may show weak responses to the fixed exposure dose. Though this ratio is simple, it could become extremely large when the product's effect is good, which would distort the evaluation of products. Therefore, a new method which could better reflect differences of the anti-blue light efficacies between different products is needed.

It is noteworthy that, recently Henry and Krutmann [17] provided a harmonized framework for establishing visible light protection standards, including light source standards, dose ranges, and exposure times. However, its application to the Chinese population is lacking. Therefore, based on this harmonized framework, this study aims to further optimize the anti-blue light efficacy assessment method based on Chinese population, and proposes an accurate and simplified method for comparing anti-blue light efficacies between different products in the Chinese population.

2 Materials and methods

2.1 Subjects

A total of 30 subjects (23 females and 7 males) with Fitzpatrick skin type III [18] from Shanghai were included in this study. All participants met the following inclusion criteria: (1) the participants' age ranged from 18 to 60, (2) without a history of photosensitive skin diseases or anti-allergic drug use within the past 3 months, (3) no clinically visible skin photodamage or hyperpigmentation in the back skin, (4) had not participated in a similar program within 6 months and agreed not to expose their back at all during this study period, (5) not taking any medication or are breastfeeding or pregnant. The mean age of these 30 subjects is 43.20 ± 10.64 years (Table S1). Written informed consent was obtained from each participant. The study was reviewed, approved, and strictly monitored by the ethics committee of Fudan University.

2.2 Measurement of minimum persistent pigmentation darkening (MPPD)

The blue light irradiator (Sellamed VIS 400, Sellas, Germany) utilized in this study exhibits an emission spectrum ranging from 400 to 500 nm, with an input power of 4.2 kW. Notably, its peak emission wavelength is situated at 416 nm. The detailed spectral curve of emission is comprehensively presented in the supplementary material (Fig. S3). The average intensity of the blue light emission, as measured by Spectral Flickering Irradiance Meter (SFIM-300, Everfine, China), was determined to be 120 mW/cm^2. Employing the MPPD as the metric for evaluating the impact of BL irradiation on pigmentation, six circular areas of skin (2 cm^2) were exposed to six levels of light dosage (50 J/cm^2, 60 J/cm^2, 75 J/cm^2, 95 J/cm^2, 120 J/cm^2, 150 J/cm^2) by adjusting the exposure time. Two cosmetic products which claimed to have the efficacy to block or repair the pigmentation caused by blue light were selected and compared in this study.

2.3 Study design

In this study, all participants were irradiated with blue light for four consecutive days to test the anti-blue light efficacy

of two cosmetic products, A and B. Group A and group B represent the results of participants treated with products A and B, respectively. The detailed procedures are also shown in Fig. 1.

On day 0, the minimal persistent pigment darkening (MPPD) [19] test was performed to identify the suitable blue light irradiation dose for each participant (Table S2). For safety concerns, the 3/4 MPPD dose was used for four consecutive days (day 0 to day 3). We selected three sites with equal size (4 cm^2) on the back of the participant for blue light irradiation. Among these three sites, two were treated with an equal amount (2 mg/cm^2) of product A or B for 15 min before and after the daily blue light exposure, while the remaining site was coated with nothing and considered the control group. The absorption curve of product A and B is shown in Fig. S4. The skin color of each site is assessed before applying these products each day using the DSM-III Color Meter (Cortex Technology, Hadsund, Denmark). Brightness L^*, melanin index M, and individual typology angle ITA° were measured [20–22]. The ITA° is calculated based on brightness L^* and yellowness b^* as follows [23].

$$\mathrm{ITA}^\circ = \tan^{-1}\left(\frac{L^* - 50}{b^*}\right) \times \frac{180}{\pi}$$

2.4 The definition of blue light protection factor (BPF)

We proposed the concept of BPF to compare the anti-blue light efficacies of different products. As shown in Fig. 2, we recorded the skin color changes on these 4 days and used a simple linear model, whose intercept is zero, to fit these data for each sample of each group. The θ_{Pi} and the θ_{Ci} are used to represent the angles of the linear model for each sample of the product or the control. Due to the variations of θ_{Ci} for different participants, we calculated the average of θ_{Ci} of all samples in the control group, $\overline{\theta_C}$, as the baseline value. We defined the differences of $\overline{\theta_C}$ minus θ_{Pi} or θ_{Ci} as the BPFs of the product or the control for each sample. The detailed formula of BPF definition is shown as follows:

$$\beta_i = \frac{\sum_{t=1}^{4} y_{it}}{\sum_{t=1}^{4} x_t}$$

$$\theta_{Pi} = \arctan(\beta_{Pi}); \quad \theta_{Ci} = \arctan(\beta_{Ci})$$

$$\overline{\theta_C} = \frac{1}{m}\sum_{i=1}^{m} \theta_{Ci}$$

$$\mathrm{BPF}_{Pi} = \overline{\theta_C} - \theta_{Pi}; \quad \mathrm{BPF}_{Ci} = \overline{\theta_C} - \theta_{Ci}$$

where y_{it} represents the skin color changes of sample i at day t, while x_t represents the day t; β_i represents the slope of the fitted linear model for sample i of each group; θ_{Pi} and θ_{Ci} are the angles of the fitted model for the product and control group, respectively. The $\overline{\theta_C}$ represents the average angles of the control group of all samples; The BPF_{Pi} and the BPF_{Ci} represent the BPF values for sample i of the product and control group. To make the BPF more applicable to different skin color parameters, the delta values of the skin color in this study refer to the absolute skin color changes from the baseline.

2.5 Statistics

Differences in delta skin color values and BPF values between the two groups were analyzed using the Wilcoxon signed-rank test, and a P-value < 0.05 was considered statistically significant. All data preprocessing, statistical analysis, and visualization are performed using R-4.0.2 in this study.

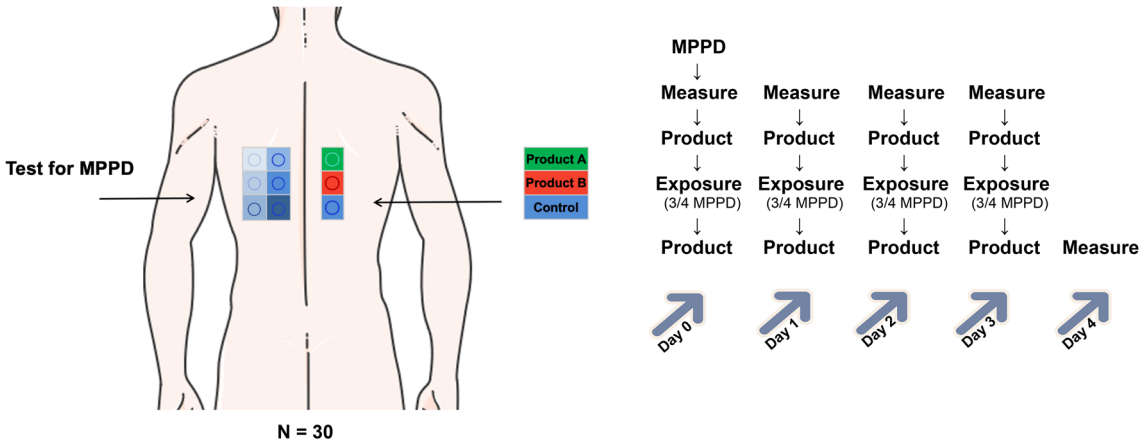

Fig. 1 Study design. *MPPD* the minimal persistent pigment darkening, *N* the number of samples

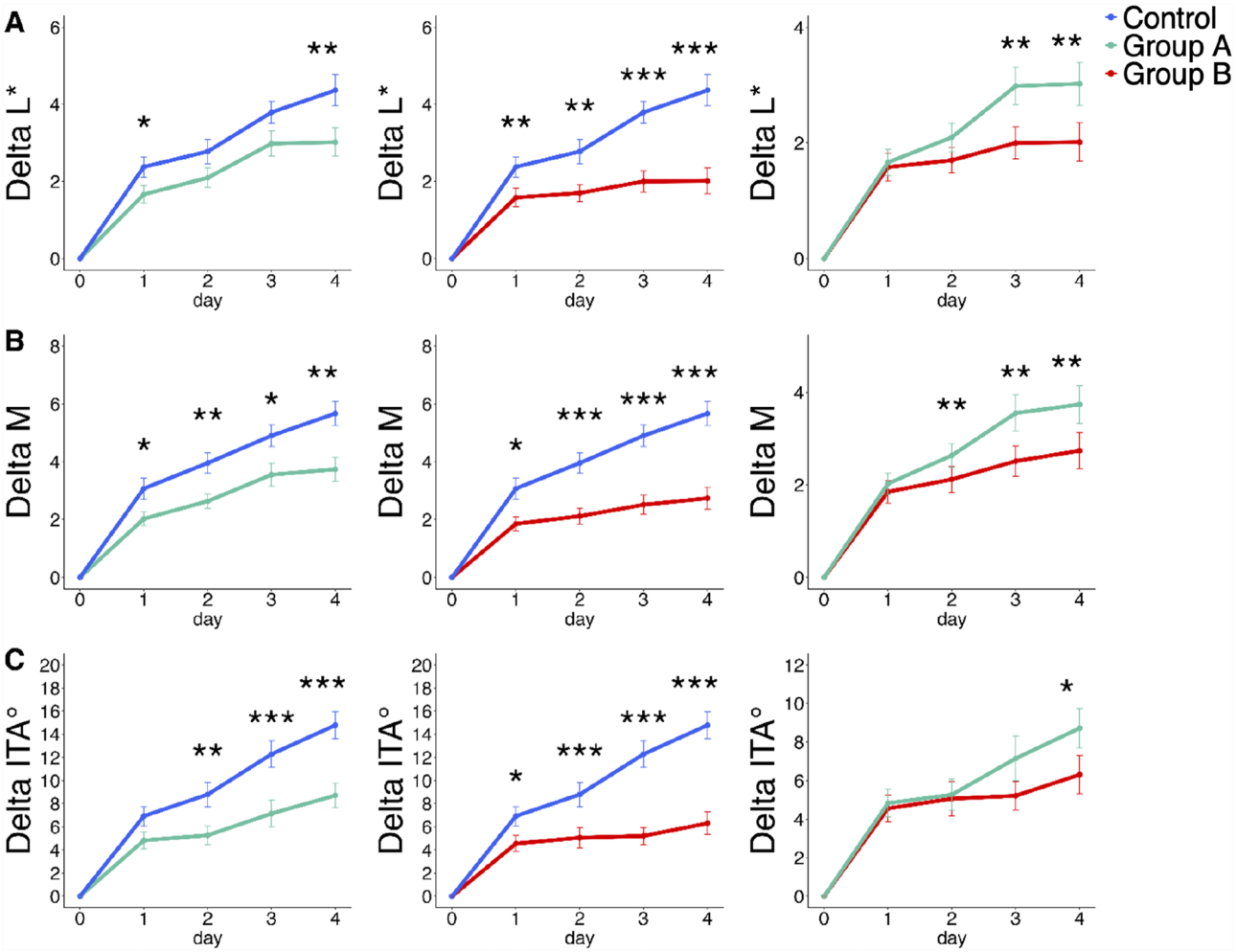

Fig. 2 The changes of delta L^* (mean ± SE) values from day 0 to day 4 for four consecutive days of blue light exposure. **A**–**C** The changes of pigmentation measurements (delta L^*, delta M, and delta ITA°) over time. Data are expressed as mean ± standard error of each group. P values were calculated using the Wilcoxon signed-rank tests. ** $P < 0.01$, * $P < 0.05$. ** $P < 0.01$, * $P < 0.05$

3 Results

3.1 Constructing an in vivo model to reflect the skin color changes after blue light radiation

As shown in Fig. 1, we proposed an in vivo model to assess the anti-blue light efficacy of products. On day 0, we assessed and obtained each participant's MPPD dose. After that, all participants (Table S1) were exposed to blue light exposures (3/4 MPPD doses) for four consecutive days. The skin color changes from day 0 to day 4 were measured (Fig. 2). We found that the changes of all skin colors indicators, including L^*, M, and ITA° were increased significantly and continuously after blue light irradiation in all three groups. For example, the delta values of L^*, M, and ITA° increased by 4.36, 5.67, and 14.79 on day 4 compared to day 0 in the control group, respectively (Table 1). Moreover, the delta values in groups A and B on days 1–4 were significantly lower than those of the control group, suggesting that both products A and B could protect skin against blue light irradiation (Fig. 2, Table 1).

In addition, we compared the anti-blue light efficacy between group A and group B (Fig. 2). It was found that group A and group B showed no significant differences in delta values on day 1 (Fig. 2). However, the delta values of group B were significantly lower than those of group A on day 4, suggesting that product B may have more potent anti-blue light efficacy (Table S3). These results indicate that our model, based on multiple blue light exposures, could better reflect the anti-blue light capacity of the product than the model with only one-time blue light irradiation.

3.2 BPF could be an effective indicator to assess the anti-blue light efficacy of products

Our multi-times blue light exposure design provides us with a series of skin color changes, enabling us to better evaluate

Table 1 Statistical analysis of the delta values between products and control

Item	Group	Day	Mean of Group A/B	Mean of control	*P*	95% CI
Delta L^*	Group A VS Control	1	1.66	2.38	**4.97E − 02**	**[− 1.44, 0.01]**
	Group A VS Control	2	2.1	2.78	7.32E − 02	[− 1.34, − 0.02]
	Group A VS Control	3	2.98	3.79	8.79E − 02	[− 1.69, 0.07]
	Group A VS Control	4	3.02	4.36	**5.38E − 03**	**[− 2.27, − 0.42]**
	Group B VS Control	1	1.58	2.38	**8.71E − 03**	**[− 1.50, − 0.09]**
	Group B VS Control	2	1.7	2.78	**3.22E − 03**	**[− 1.74, − 0.42]**
	Group B VS Control	3	2	3.79	**2.76E − 06**	**[− 2.43, − 1.16]**
	Group B VS Control	4	2.01	4.36	**9.98E − 07**	**[− 3.17, − 1.52]**
Delta *M*	Group A VS Control	1	2.03	3.07	**2.21E − 02**	**[− 1.89, − 0.20]**
	Group A VS Control	2	2.63	3.95	**3.74E − 03**	**[− 2.10, − 0.54]**
	Group A VS Control	3	3.55	4.9	**2.62E − 02**	**[− 2.37, − 0.34]**
	Group A VS Control	4	3.74	5.67	**1.04E − 03**	**[− 3.03, − 0.84]**
	Group B VS Control	1	1.85	3.07	**1.20E − 02**	**[− 2.10, − 0.34]**
	Group B VS Control	2	2.12	3.95	**6.92E − 06**	**[− 2.61, − 1.06]**
	Group B VS Control	3	2.51	4.9	**3.86E − 07**	**[− 3.13, − 1.65]**
	Group B VS Control	4	2.74	5.67	**1.99E − 06**	**[− 3.97, − 1.89]**
Delta ITA°	Group A VS Control	1	4.83	6.92	6.06E − 02	[− 4.03, − 0.16]
	Group A VS Control	2	5.27	8.8	**7.61E − 03**	**[− 5.93, − 1.13]**
	Group A VS Control	3	7.15	12.28	**3.45E − 04**	**[− 7.78, − 2.49]**
	Group A VS Control	4	8.71	14.79	**6.08E − 04**	**[− 9.27, − 2.88]**
	Group B VS Control	1	4.55	6.92	**2.93E − 02**	**[− 4.26, − 0.48]**
	Group B VS Control	2	5.06	8.8	**8.72E − 04**	**[− 6.24, − 1.23]**
	Group B VS Control	3	5.21	12.28	**6.91E − 07**	**[− 9.62, − 4.52]**
	Group B VS Control	4	6.3	14.79	**1.99E − 06**	**[− 11.47, − 5.5]**

the anti-blue light capacities of each product. However, it would be much more concise and practical to use a single metric to evaluate the anti-blue light efficacy of the product. Therefore, we proposed the blue protection factor (BPF) concept by incorporating skin color measurements of both the product and control group for all 4 days (Fig. 3). Briefly, for each participant, we generated a linear model to best fit the skin color changes in these 4 days for both the product group and control group separately. Therefore, we obtained the angles of these two linear models as θ_P and θ_C, and the averaged angles of the control group, $\overline{\theta_C}$. The BPF for each sample was calculated as the difference between θ_C (control group) or θ_P (product group) and $\overline{\theta_C}$. A higher BPF represents better anti-blue light efficacy for the product (Fig. 3).

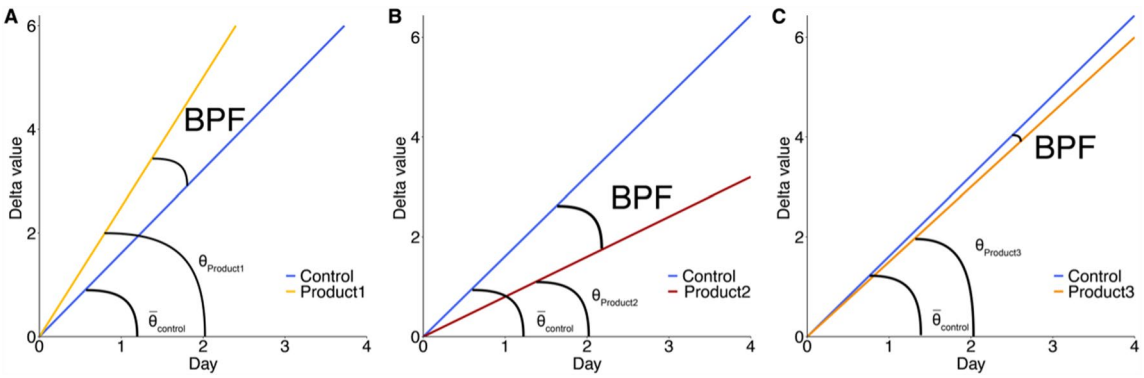

Fig. 3 The diagram of BPF. Panel **A**–**C** represents the different scenarios of the products to be tested and the definition of BPF. Delta value represents the difference between the skin pigmentation measurements after each exposure to blue light and the values of the baseline (day 0). The fitted linear model is calculated based on the delta values over 4 days for each group. θ represents the angle between delta values and the *x*-axis in these figures. The BPF of a product for each sample is defined as the differences of θ_{Pi} minus $\overline{\theta_C}$

Meanwhile, we can perform the non-parametric statistical to compare the efficacies between different products or between product and control group. The detailed definitions and calculations of BPF are described in Sect. 2.

Based on the previous definition, we calculated the BPF values for each sample in both product and control groups. As shown in Table 2, we found that the BPF values of groups A and B were significantly higher than that of the control group, suggesting that these two products both could provide anti-blue light efficacy in our study. Moreover, the BPF values of group B were significantly higher than group A, which is in accordance with our previous results (Table S3), suggesting that BPF could distinguish the anti-blue light efficacies between different products (Table 3, Fig. S1). Taken together, these results indicate that the BPF could be a reliable and valuable indicator in assessing the anti-blue light efficacy of the candidate product.

4 Discussion

Previous studies have provided solid methods for testing the UVA/UVB sunscreen products in vivo on human subjects [24–26]. However, recent studies suggested that visible lights, particularly blue light, could also induce significant skin pigmentation [2, 6], while the methods for evaluating the anti-blue light efficacy of cosmetic products are various and have limitations.

Duteil et al. [16] used multiple exposures to evaluate the photoprotection of visible light, and each exposure had a fixed dose of 144 J/cm^2. However, considering individual variations, some individuals might have weak or no response to this dose. In this study, to better control the varied effects of a fixed BL dose among different samples, we choose to irradiate the skin continuously at a lower BL dose. To determine the appropriate BL dose, we first performed gradient dose irradiation to find the minimal persistent pigment darkening dose (MPPD) by observing the skin tanning reaction, and then selected 3/4 MPPD as the test dose.

Duteil et al. [16] used a linear regression model to calculate the slope of the Delta ITA° curve between Day 1 and Day 5, then adopted the ratio between the average slope of the control area skin and the average slope of the product to calculate the protection factor. Although this calculation method is simple, it could result in an infinite protection factor when the product's effect is extremely good, which is not well practical. To address this problem, based on the linear change of the skin color measurements of the product group and the control group, we use the angle between the fitting curve and the horizontal line to characterize the protection ability. The angle value changes between 0° and 90°, which is convenient for comparisons between products. Additionally, we analyzed the L^*, M, and ITA° parameters, and their efficacy was comparable.

Noteworthily, Henry and Krutmann provided a very good framework for establishing visible light protection standards, including light source standards, dose ranges, and exposure times. On the contrary, our method is a practical implementation of the framework and is more operational and suitable for skin testing in the Chinese population.

In the present study, we conducted an in vivo method based on four consecutive blue light exposures (each with 3/4 MPPD doses) to assess the anti-blue light efficacy of products. We found that the intensity of pigmentation increased gradually and linearly with the accumulation of blue light exposures. In addition, we proposed the concept of BPF, which might provide a sensitive and effective method to assess the anti-blue light efficacy of sunscreens. It should be noted that the participants enrolled in our study are exclusively categorized as Fitzpatrick type III, a prevalent skin

Table 2 Statistical analysis of the BPF values between products and control

Item	Group	Mean of Group A/B	Mean of Control	*P*	95% CI
L^*	Group B VS Control	23.24	2.74	**8.01E − 08**	**[13.77, 27.22]**
	Group A VS Control	15.77	2.74	**1.20E − 02**	**[4.49, 21.58]**
M	Group B VS Control	24.95	2.37	**3.54E − 08**	**[15.45, 29.72]**
	Group A VS Control	16.99	2.37	**7.30E − 04**	**[7.40, 21.85]**
ITA°	Group B VS Control	39.15	3.54	**3.54E − 08**	**[21.27, 49.94]**
	Group A VS Control	25.43	3.54	**2.09E − 04**	**[9.32, 34.45]**

Table 3 Statistical analysis of the BPF values between group A and group B

Item	Group	Mean of Group A	Mean of Group B	P	95% CI
L^*	Group A VS Group B	15.77	23.24	**1.75E − 02**	**[− 0.07, 15.00]**
M	Group A VS Group B	16.99	24.95	**8.14E − 03**	**[0.88, 15.05]**
ITA°	Group A VS Group B	25.43	39.15	**3.84E − 02**	**[0.04, 27.40]**

type within the Chinese population, and further studies are required to corroborate the efficacy of the proposed method across a more heterogeneous population.

It is of concern that, as mentioned previously, different individuals showed considerably various responses to both UV radiation and visible light exposures. Consistent with previous studies [27], in the present study, we found the MPPD doses of participants enrolled in this study ranged from 50 to 95 J/cm^2 (Table S2). Therefore, the heterogeneity of the population for MPPD presents new challenges for assessing the anti-blue light efficacy of the product, i.e., we should not irradiate everyone using one single dose. Otherwise, some subjects will overreact and have an adverse reaction, while others may not have a tanning reaction at all at that dose, thus seriously interfering with our study. To address this concern, we treated each participant with different doses (3/4 MPPD doses) to improve our method's efficacy and safety.

In addition, due to the longer wavelength and lower energy of blue light compared with UV light, we adopted the multiple exposures design, which is consistent with previous studies [16, 17], to better reflect the blue light-induced skin damage and the anti-blue light efficacy of the product against blue light. As shown in Fig. 2, we found that there is no significant difference between product A and B when we only examined the delta pigmentation value on day 1, while product A exhibited significantly better protection than product B in later days, further supporting our adoption of the multiple exposures design.

The multiple exposures design could lead to better characterization of the anti-blue light efficacy of the products, while the increased amount of data makes it harder to compare the anti-blue light efficacies between different products. However, the BPF could take full advantage of the multiple exposures design and provide a single metric for product comparison. Moreover, we could yield a BPF value of the product for each participant, enabling us to perform statistical tests between different groups and to better reflect the differences in anti-blue light capacities between different products.

The individual ITA° of the volunteers and its variation over time in each experimental area can be found in the supplementary file (Table S4, Fig. S2). These findings suggest that additional factors beyond mere phototype classification, including genetic predisposition, environmental or lifestyle-related variables, may exert discernible influences on the cutaneous reactions to blue light radiation. Consequently, further studies are warranted to clarify the multifaceted elements contributing to the observed responses following exposure to blue light.

As mentioned in the Sect. 1, the exposure to blue light that people experience daily mainly comes from sunlight and modern lighting devices. The International Commission on Illumination (CIE) has released a position statement asserting that the blue light hazard efficiency is intimately related to the maximum blue light safe radiance or irradiance of blue light [28]. A study comparing blue-light levels emitted from portable electronic devices with sunlight found that the solar radiances in the same spectral range are larger both under clear and cloudy conditions than electronic device [29]. Recent studies have suggested that prolonged exposure to blue light may have biological effects on the skin [2, 6]. However, the evidence that exposure to blue light increases the risk of photochemical injury during normal use conditions is inconclusive [30–32]. Consequently, the term "blue light" in this study predominantly denotes the constituent emanations inherent in natural sunlight.

In conclusion, we proposed a simple method, along with an easy-to-use metric, BPF, to accurately characterize the anti-blue light efficacies of cosmetic products. Our method and metric could statistically and explicitly distinguish the anti-blue light efficacies of different products, providing a basis for the development of effective anti-blue light products in future.

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Author contributions RZ contributed to conceptualization, data curation, investigation, methodology, writing—original draft; WP contributed to conceptualization, data curation, investigation, methodology, writing—original draft; XZ contributed to conceptualization, investigation, methodology; YD contributed to investigation, methodology; JX contributed to investigation, methodology; MZ contributed to investigation, methodology; YT contributed to conceptualization, methodology; WL contributed to conceptualization, investigation, methodology; JK contributed to conceptualization, investigation, methodology; JW contributed to conceptualization, data curation, investigation, methodology; YM contributed to conceptualization, data curation, investigation, supervision, writing—original draft, writing—review & editing.

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Data availability The data that support the findings of this study are available from the corresponding author, Yanyun Ma, upon reasonable request.

Declarations

Conflict of interest ZYZ is an employee of Skin shield. YD, JX, and MYZ are employees of Shiseido. RZ, WLP, YMT, WL, JK JCW, and YYM have no personal conflict of interest.

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