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Noninvasive measurement of the 308 nm LED-based UVB protection factor of sunscreens

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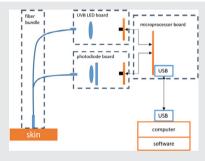
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Abstract

The current method for determining the sun protection factor (SPF) requires erythema formation. Noninvasive alternatives have recently been suggested by several groups. Our group previously developed a functional sensor based on diffuse reflectance measurements with one UVB LED, which was previously evaluated on pig ear skin. Here we present the results of a systematic in vivo study using 12 sunscreens on 10 volunteers (skin types [ST] I-III). The relationship of the UVB-LED reflectance of unprotected skin and melanin index was determined for each ST. The spatial variation of the reflectance signal of different positions was analyzed and seems to be mainly influenced by sample inhomogeneity except for high-protection factors (PFs) where signal levels are close to detection noise. Despite the low-signal levels, a correlation of the measured LED-based UVB PF with SPF reference values from test institutes with $R^2 = 0.57$ is obtained, suggesting a strong relationship of SPF and LED-based UVB-PF. Measured PFs tend to be lower for increasing skin pigmentation. The sensor design seems to be suitable for investigations where a fast measurement of relative changes of PFs, such as due to inhomogeneous application, bathing and sweating, is of interest.

KEYWORDS
diffuse reflectance spectroscopy, in vivo measurement, nonerythema testing, sun protection factor, sunscreen, UVB-LED

1 | INTRODUCTION

The sun is necessary for a healthy vitamin D synthesis and an overall wellbeing; however, if enjoyed uncontrolled it is potentially harmful leading to sunburn, skin aging, and most important to skin cancer.[1–3] The incidence of skin cancer is still growing every year.[4] Thus, a better sun protection strategy is necessary.

An important part of the sun protection strategy is the sunscreen application. There are various sunscreens with different UV-filters, formulations and properties. Until now, for all these sunscreens the sun protection factor (SPF) is determined according to the ISO 24444[5] standard, which refers to an invasive method. The method is based on an erythema induction on protected and unprotected healthy skin, respectively. The minimal erythematous dose (MED) is determined, which is the amount of UV irradiation leading to minimal sunburn. The ratio of the MED on unprotected and protected skin from at least 10 subjects of skin types (ST) I to III is used to determine the SPF. Although this is considered as the reference method to define SPFs, the invasiveness of the method calls for noninvasive alternatives.[6]

In vitro testing based on polymethylmethacrylate plates (PMMA) could not replace in vivo testing so far, due to the lack of reproducibility of absolute absorbance spectra. Major problems are the structure and unique properties of human skin, which can be insufficiently simulated by PMMA plates.[7] Such in vivo properties are biofilm and sebum, which influence the distribution of sunscreen on the skin, thus determining the homogeneity and consequently the effectivity of the UV-filters on the skin surface.

However, the spectral shape of the absorbance can be well measured on PMMA. Therefore, an in vitro spectrum can be used for further calculations of SPF or UVA-PF, if the absolute value of the absorbance is known by an additional in vivo measurement.

This is the basis of ISO 24443[8] for the determination of the UVA-PF, which uses a previously measured in vivo SPF in order to scale the in vitro spectrum.

Similarly, the SPF can be calculated if the spectrum is scaled by the use of an in vivo UVA-PF measurement. The latter is the basis of the so-called hybrid diffuse reflectance (HDRS) method, which was shown to work well by Ruvolo et al[9] and Rohr et al.[10] Their HDRS method uses a solar simulator together with a double monochromator. In 2019, Cole et al. used an approach called polychromatic HDRS, where the scaling factor is determined using a photomultiplier tube and solar simulator as light source for measuring the UVA reflectance.[11]

Other diffuse reflectance spectroscopy (DRS) setups for tissue measurements in the UV wavelength range used lasers or Xenon arc lamps as light sources.[12, 13]

The use of LEDs in DRS setups has been previously shown in the visible wavelength range.[14, 15] Recently, our group developed a LED-based DRS setup (first function sensor design), which is based on photodiodes for detection and one UVB-LED as the light source.[16]

Using LEDs instead of xenon arc lamps or lasers has several advantages. LEDs can be pulsed which allows more flexible illumination. Furthermore, LEDs can be integrated in compact devices, which open up new fields of applications. In contrast to lasers, LEDs provide a narrow spectrum, which can be used to cover the most important wavelength region for erythema induction.

Due to the integration of the signal by a photodiode, the resulting protection factor (PF) is not equal to a traditional SPF. It may be considered as a LED-based UVB-PF with strong relationship to the traditional SPF since the spectral distribution of the LED and a filter is similar to the product of spectral weighting functions (erythema action spectrum and UV source) as in ISO 24443. Therefore, the aim of such a sensor design is not the traditional SPF determination as in test institutes, but rather to provide a simple and fast estimate of the UVB protection. This could potentially be beneficial for sunscreen development, but also in usability studies, water resistance measurements or other applications, where the measurement of relative changes of protection values is sufficient. In a previous study, we applied this method on pig ear skin.[16] We also found that human skin has a different calibration curve due to the much lower reflectance as compared to the typical reflectance of pig ear skin.[17] The identical setup was already used in application studies, where the water resistance/sweat resistance and inhomogeneity of sunscreens on skin was evaluated.[18]

In this article, we present data of a systematic in vivo study to evaluate the performance of the prototype. The evaluation includes the correlation of the UVB reflectance with a commercial device for the quantification of skin pigmentation. The origin of signal variations was investigated by comparing the spatial variation of the LED-based UVB- reflectance signal to the detection noise level. Last but not least, we investigated how the measured LED-based UVB PF correlates which reference SPF values and how it depends on the skin pigmentation.

2 | MATERIALS AND METHODS

2.1 | Measurement setup

The setup, which is shown in Figure 1, has been described previously.[16] The LED source has a center wavelength of
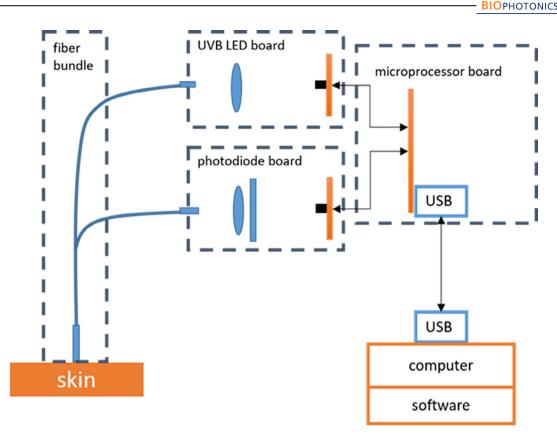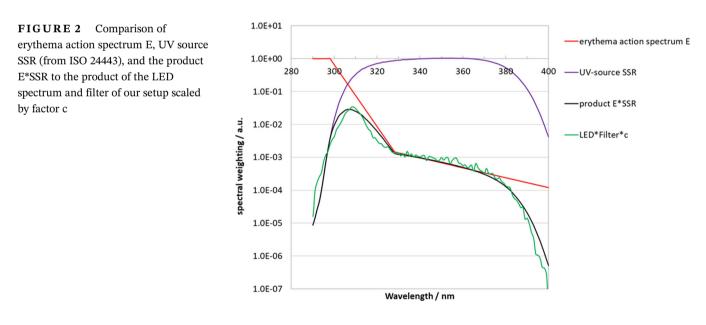
FIGURE 1 Schematic of measurement setup, adapted from ref. [16]

FIGURE 2 Comparison of erythema action spectrum E, UV source SSR (from ISO 24443), and the product E*SSR to the product of the LED spectrum and filter of our setup scaled by factor c

308 nm, see Figure 2.[19] In order to anticipate a strong correlation of SPF and LED-based UVB-PF, the LED spectrum and a filter is chosen to be similar to the product of erythema action spectrum and solar spectrum as in ISO 24443, see Figure 2. Impacts of further optical components such as detector sensitivity were neglected. The UVB LED emission spectrum has a UVB fraction of 84% and a UVA fraction of 16%. A fraction of 90% of the total emission results from emissions below 334 nm.

The customized fiber bundle consists of a central illumination fiber, with detection fibers arranged at three different distances from the point of illumination. Before detection, the light passes twice through skin and sunscreen layer, which is ensured by the spatial offset of illumination and detection. The signal of each ring of detection fibers is binned on one amplified photodiode. The dark reading is extracted automatically. One reflectance value is the average difference between signal and

TABLE 1 Properties of sunscreens included in the evaluation

Sunscreen Nr	Type of formulation	UV filter (organic and inorganic) INCI	UVA/UVB	Commercial?	Reference SPF of manufacturer measured by test institute (n, number of volunteers)
1	O/W-emulsion	Tris-biphenyl triazine, diethylamino hydroxybenzoyl hexyl benzoate	2.53	no	6 (n = 6)
2	Lotion	Octocrylene, homosalate, ethylhexyl salicylate, butyl methoxydibenzoylmethane	0.50	yes	12 (n = 10)
3	Lotion	Homosalate, octocrylene, ethylhexyl salicylate, butyl methoxydibenzoylmethane	0.54	yes	26 (n = 10)
4	Hydro-dispersionsgel	Ethylhexyl triazone, diethylamino hydroxybenzoyl hexyl benzoate, phenylbenzimidazole sulfonic acid, bis-ethylhexyloxyphenol methoxyphenyl triazine	0.88	no	26 (n = 6)
5	O/W cream	Octocrylene, butylmethoxydibenzoyl-methan, ethylhexylmethoxycin-namat, bis-ethylhexyloxyphenol	1.04	yes	16(n = 10)
6	Spray	Octocrylene, butyl methoxydibenzoylmethane, ethylhexyl salicylate, alcohol denat, bis-ethylhexyloxyphenol	0.73	yes	33 (n = 10)
7	Lotion	Ethylhexyl methoxycinnamate, titaniumdioxide, octocrylene, ethylhexylsalicylate, homosalate, butyl methoxydibenzoylmethane, bis-ethylhexyl hydroxydimethoxybenzylmalonate, bis-ethylhexyloxyphenol methoxyphenyl triazine	0.68	yes	47(n = 10)
8	Lotion	Octocrylene, methylene bis benzotriazolyl, tetramethylbutylphenol, bis-ethylhexyloxyphenol, methoxyphenyl triazine, titanium doxide (nano)	0.5	yes	63.5 (n = 10)
9	Spray	Homosalate, octocrylene, ethylhexyl salicylate, butyl methoxydibenzoyl-methane	0.63	yes	66 (n = 10)
10	Oil	Bis-ethylhexyloxyphenol methoxyphenyl triazine, ethylhexyl triazone, diethylamino hydroxybenzoyl hexyl benzoate	1.5	no	27.6 (n = 6)
11	Fluid	Bis-ethylhexyloxyphenol methoxyphenyl triazine, ethylhexyl triazone, diethylamino hydroxybenzoyl hexyl benzoate	0.71	no	27.1 (n = 6)
12	Fluid	Bis-ethylhexyloxyphenol methoxyphenyl triazine, ethylhexyl triazone, diethylamino hydroxybenzoyl hexyl benzoate, phenylbenzimidazole sulfonic acid	0.90	no	76.7 (n = 5)

Abbreviation: SPF, sun protection factor.

dark, which is acquired eight times per second up to a total measurement time of 4 seconds. Each volunteer was measured on 30 measuring points. The total measuring time amounted to approximately 5 minutes, including cleaning of the probe. The total dose per measurement

position was below the dose limit of 30 J/m^2 effective radiation according to ICNIRP. This corresponds to maximally 1/5 of the MED of ST I.

In case of low signal, negative values are possible due to noise. Negative reflectance values contributed to the

relative standard deviation (RSD) of reflectance values. However, for the calculation of transmission values, negative values were set to zero before application of the square root, see Equation (1). The number of negative reflectance values due to noise increases with the SPF, up to about 20% (on average per sunscreen) of all measurement values at very high SPFs. Further information concerning the buildup of the setup can be found in the patent: EP3365641 (A1).

2.2 | Sunscreen formulations

Ten different sunscreen formulations were investigated in the study including O/W creams, lotions, sprays, oil and hydro dispersion gels (Table 1). The formulations 2, 3, 5, 6, 8 and 9 are commercially available, while the remaining formulations 1, 4, 10, 11 and 12 were made for the study with selected properties by Karrer GmbH. The selected formulations are a roughly representative mix of existing sunscreens and future developments, with different SPF, galenics or UVA/UVB ratios. Most formulations contained organic UV filters and two of them inorganic filters as well. Part of the noncommercial formulations were tested on six volunteers only because the development of these formulation had been ceased..

2.3 | Measurement procedure on human skin

The study was approved by the ethics committee of the Charité-Universitätsmedizin Berlin and was conducted according to the declaration of Helsinki. Volunteers were males and females of ST I to III according to Fitzpatrick, aged between 22 and 59 years. The measurements were performed on healthy skin, avoiding moles, hair, hyper- or hypopigmented areas. After signing informed consent, the untanned skin on the back was chosen for measurements. Four squares of 10 x 10 cm^2 each were measured and marked with a skin marker. The squares were not overlapping and had a sufficient distance (50 mm) between them to avoid mixing of the tested sunscreen formulations. The reflectance of the skin without sunscreen was measured with the probe at 20 positions in each square. With a saturated glove, and a weighting error of less than 1%, 2 mg/cm^2 of sunscreen was applied according to the COLIPA standard method[20] and allowed to penetrate for 30 minutes. This procedure was performed on each of the four squares. Then, each square was measured at 30 positions with the probe placed perpendicularly to the skin. In between each measurement, the probe was cleaned with ethanol. Overlap of measurement areas was strictly avoided.

2.4 | Calculation of LED-based UVB PF

All reflectance signals of skin without sunscreen R_0, were averaged to $\bar{R}_0$, since the variability was low compared to the variability of the reflectance signals with sunscreen $R_{Creme,i}$. Negative values of $R_{Creme,i}$ due to noise were set to zero. For each of the 30 measurement positions on sunscreen, the local transmission was calculated by

$$T_{LEDi} = \sqrt{\frac{R_{Creme,i}}{\bar{R}_0}}, \tag{1}$$

and subsequently averaged to

$$\bar{T}_{LEDi} = T_{LED}. \tag{2}$$

The square root in Equation (1) arises from the assumption that the light transmits twice through the sunscreen layer with a transmission T.[21] Since the estimation of a PF based on a LED UVB-signal centered at 308 nm is different from the calculation based on ISO 24443, we use the term LED-based UVB PF to avoid confusion.

The individual LED-based UVB-PF for each volunteer was obtained by

$$LED-based\ UVB-PF = \frac{1}{T_{LED}}. \tag{3}$$

Subsequently, the average LED-based UVB-PF of all volunteers was calculated for comparison with reference SPF values.

A schematic of the signal processing is shown in Figure 3 and an example of results for one sunscreen and one volunteer is given in Table 2.

2.5 | Correction of photodegradation

Absorbance spectra prior and post irradiation were measured by Institute Dr. Schrader. The in vitro measurements were performed on PMMA plates before and after irradiation using the double monochromator system described by Rohr et al.[10] The irradiation was performed using the system SUNTEST CPS+ (Atlas Material Testing GmbH). The applied irradiance and doses were in accordance with ISO 24443.

The correction was performed on the basis of in vitro transmission values (T) derived from in vitro absorbance values. A correction factor was calculated by
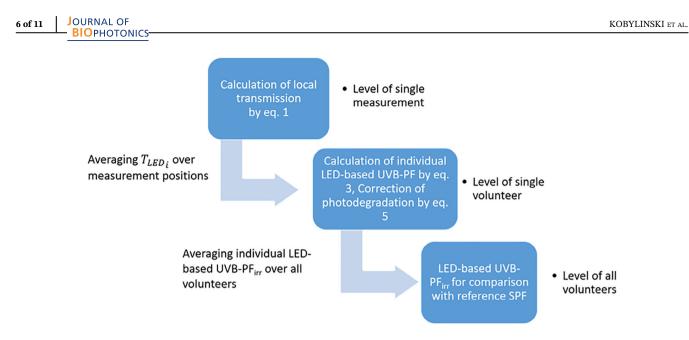
$$c = T_{irr}/T, \tag{4}$$

FIGURE 3 Schematic of signal processing

at the LED center wavelength, where T corresponds to the transmission value prior irradiation and T_{irr} to the transmission value post irradiation.

The corrected LED-based UVB-PF (PF_{irr}) was obtained by

$$LED-based\ UVB-PF_{irr} = \frac{1}{T_{LED,irr}} = \frac{1}{T_{LED}*c}$$
$$= \frac{LED-based\ UVB-PF}{c}. \quad (5)$$

Calculation of the correction using a ratio of the corresponding absorbance values instead of Equation (4) and a transformed Equation (5) was compared and led to comparable results for the data set here.

2.6 | Melanin index measurements

Before sunscreen application the selected areas were first measured at 20 positions with a Mexameter (Courage + Khazaka electronic GmbH, Cologne), avoiding an overlap, to obtain the index of melanin. Eight additional data sets without MX measurements and skin typing were only included in Figures 7 and 8.

2.7 | Statistics

Averages and SD were calculated based on Excel (Microsoft Office). Significance of the linear correlation coefficient in Figure 8 was tested based on ref. [22].

TABLE 2 Example of results on level of single volunteer for sunscreen Nr 6 and P05

Type of (intermediate) result	Value of result	Remarks
$\bar{R}_0$	4.01E+01	
RSD of $R_{0,\ i}$	35%	Not used for PF estimation
Average $R_{Creme,i}$	6.00E−02	Not used for PF estimation
RSD of $R_{Creme,i}$	217%	Not used for PF estimation
T_{LED}	2.9%	Average of $R_{Creme,i}/\bar{R}_0$) over i measurement positions
$LED-based\ UVB-PF$	34.5	$1/T_{LED}$
c	1.14	
$T_{LED,irr}$	3.3%	
$LED-based\ UVB-PF_{irr}$	30.2	$1/T_{LED,irr}$

Abbreviations: PF, protection factor; RSD, relative standard deviation.

3 | RESULTS

3.1 | Relationship of UVB reflectance and melanin index

First, we evaluate how the UVB reflectance relates to skin pigmentation as quantified by the Mexameter. The melanin index (MI) increases with ST as expected, see Figure 4. The MI values correspond to the range of expected values given by the manufacturer dependent on
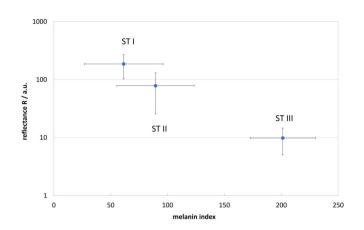
FIGURE 4 Relationship of UVB reflectance and melanin index, averaged for each skin type (ST) I to III. Error bars represent the SD of n volunteers
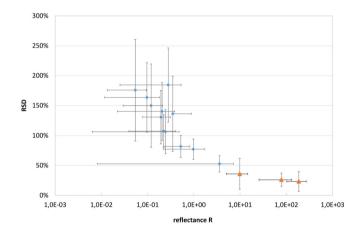

FIGURE 5 Average RSD (intrapersonal variation of reflectance on 30 measurement positions) for each sunscreen in relation to the reflectance signal R (blue dots). Error bars for each sunscreen correspond to the SD of 10 volunteers (interpersonal variation). RSD values of skin without sunscreens were averaged for skin types I (n = 17), II (n = 90) and III (n = 9) (orange triangles). Error bars of untreated skin correspond to SD of 17, 90 and 9 volunteers for skin types I, II and III, respectively. RSD, relative standard deviation

ST (ST I: 0–150, ST II: 50–250, ST III 150–500). The volunteers with ST III can be well separated with both methods. However, the values of volunteers with ST I and ST II overlap, while the separation is better in UVB reflectance values.

3.2 | Inhomogeneity of reflectance of skin with sunscreen

In order to investigate the origin of signal variations, the spatial variation of the LED-based UVB-reflectance signal
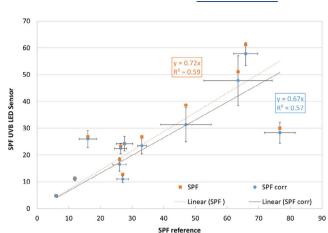

FIGURE 6 SPF as determined with LED-sensor vs. reference of test institute. Orange squares: SPF values without correction of photodegradation. Blue dots: SPF values with correction of photodegradation. Error bars of measured SPF correspond to the SEM of 10 volunteers. For reference values, the error bar corresponds to the SEM given in Table 1 (if available) or is set to ±17% according to Ref. [5]. SPF, sun protection factor

was analyzed for the complete data set of this study. Figure 5 shows the RSD of the reflectance measured at 30 positions of the sunscreen-treated skin area for each sunscreen as an average over 10 volunteers. The corresponding values are also presented for the native skin reflectance as an average over all volunteers of the same ST.

As the detector noise is approximately 0.1 units (root mean square), the RSD is due to the sample inhomogeneity for reflectance values >0.1 units.

For the sunscreens with R of approximately 0.1 or less (high and very high LED-based UVB-PFs), the RSD is dominated by detection noise and can therefore not be interpreted as inhomogeneity.

For skin with sunscreen applied, the RSD is larger than for native skin and rises with decreasing reflectance (increasing SPF). This suggests that at R > 0.1 the sample inhomogeneity is mainly due to the inhomogeneity of the sunscreen layer.

3.3 | Correlation of LED-based UVB-PF and SPF reference

The LED-based UVB-PF is not identical to the traditional SPF, since it relies on the integration of a UVB-LED reflectance. Figure 6 shows that the correlation of the LED-based UVB-PF determined by UV LED sensor and SPF reference can be described by a linear regression with $R^2 = 0.59$. Correction of photo degradation leads to lower SPF values and slightly reduced correlation.
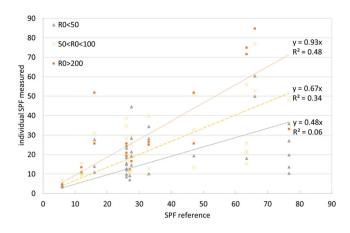
FIGURE 7 Correlation of LED-based UVB-PF measurements on individual volunteers with SPF reference, restricted to different ranges of reflectance values of native skin R_0. SPF, sun protection factor
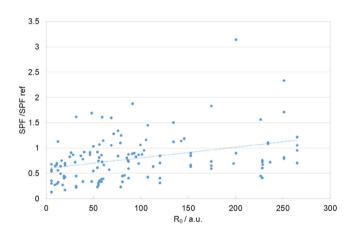

FIGURE 8 LED-based UVB-PF normalized to SPF reference for individual combinations of volunteers and sunscreens, dependent on R_0. The linear correlation ($R^2 = 0.13$) between R_0 and the normalized PF is significant with $P < 0.001$. SPF, sun protection factor

3.4 | Influence of skin color on LED-based UVB-PF

Since R_0 decreases with skin pigmentation, the dependency of individual LED-based UVB-PF results on R_0 are interpreted as effect of the skin pigmentation. Table 3 and Figure 7 show that the slope m of the linear regression of measured individual LED-based UVB-PF and reference SPFs decreases with decreasing UVB reflectance R_0. This is in accordance with previous results on pig ear skin,[17] where R_0 was about one order of magnitude larger and the slope more than twice as high as on human back skin (see Table 4).

Consequently, if results of skin with the whole range of measured R_0 vales are included, this leads to reduced squared correlation coefficient ($R^2 = 0.33$) for individual LED-based UVB-PFs and SPFs. If the correlation is restricted to reflectance values $R_0 > 90$ (ST I and lower pigmented ST II), R^2 improves from 0.33 to 0.54.

Figure 8 shows the dependency of the ratio LED-based UVB/SPF reference on the reflectance R_0. The corresponding correlation is low ($R^2 = 0.13$), but significant.

Consequently, the SPF measured with our sensor tends to be lower for higher pigmented skin, which has lower UVB reflectance R_0. This is in accordance with studies on the invasive in vivo test, where a similar trend of decreasing SPFs with increasing MED of untreated skin was reported, also in part for higher ST, only. [23–25]

4 | DISCUSSION

4.1 | Correlation of UVB-Reflectance and melanin index

We found a plausible relationship of UVB reflectance values and skin pigmentation values as quantified by the melanin index. The MI, which is based on visible wavelengths, increased while the UVB reflectance decreased. Separation of STI and STII was even better with UVB reflectance. This suggests that the pigmentation level may be accessed by UVB reflectance measurements. However, a systematic comparison of MED and UVB reflectance would be required, before an application of the UVB measurement for UV sensitivity estimations can be justified.

4.2 | Spatial variation of reflectance signals

It is widely accepted that the homogeneity of the sunscreen application is important for the protection effect. The point-by-point measurement of skin reflectance using the described sensor potentially allows to measure the homogeneity of UV reflectance and thus sunscreen distribution at a spatial resolution of about 5 mm.[26] Our results show that the point-by-point variation of the reflectance increases with increasing LED-based UVB-PF. The reflectance values of high and very high LED-based UVB-PFs are however close to or below the noise limit (0.1 units). One can conclude that comparison of sunscreen distributions by this method requires the comparison of sunscreens with a similar SPFs as shown by Schleusener et al.[26]

TABLE 3 Dependence of slope m and R^2 of linear regression obtained as in Figure 7 on reflectance signal of native skin

Reflectance signal R_0	m	R^2	N (number of individual measurements)
<50	0.48	0.06	38
50–100	0.67	0.34	43
100–200	0.88	0.55	19
>200	0.93	0.48	16
>90	0.91	0.54	46
0–265	0.69	0.33	116

TABLE 4 Comparison of slope m for data averaged per sunscreen over n = 10 human volunteers or n = 10 pig ears (as in ref [17])

	m	R^2	N
Data human skin in Figure 6	0.72	0.59	120 (12 sunscreens x 10 volunteers)
Data pig ear skin from ref. [17]	1.86	0.85	54 (9 sunscreens, 6 pig ears)

4.3 | Correlation with traditional SPF values

To the best of our knowledge, this is the first in vivo study, which shows that that there is a measureable reflectance signal using UVB-LEDs despite the low reflectance of skin in the UVB. Furthermore, the correlation in terms of R^2 is not high, but significant, which shows that there is a clear relationship of the LED-based UVB-PF and the traditional SPF. The reasons for the detectable UVB-LED reflectance might be.

1. In this functional sensor design, all detection fibers are binned on one detector, which improves the signal-to-noise ratio as compared to spectrally resolved setups.

2. The residual UVA contribution between 320 and 400 nm is 16%. During the light propagation in the skin and sunscreen, the fraction of UVB light will experience higher extinction than the UVA fraction of the LED spectrum. Consequently, the fraction of residual UVA in the detected light will be higher than 16%. Thus, the detected signal is not pure UVB but also partially UVA.

The reason for the good correlation of LED-based UVB-PF and reference SPF might be due to the LED emission spectrum. Our reflectance value is an integral measure, influenced by the optical response function (e. g., the LED spectrum and detector response) of the system. Therefore, the LED-based UVB-PF determined does not correspond to the traditional definition according to ISO 24443. We obtain a polychromatic estimate of the SPF, however, with a maximum of spectral weighting very close to the maximum of the product of traditional weighting functions, see Figure 2. This is why UV-lasers, assuming a comparable size would be available, are not advantageous for this measurement setup.

Photostability correction has only a small effect for the sunscreens investigated here, which seem to be rather stable. However, this might be different for other sunscreens. Therefore, depending on the application, additional photostability measurements are recommended.

The data do not fit perfectly for all investigated samples. UVA and fluorescence contribution could not be confirmed as origin for the outliers. The results could differ depending on the chosen filters or viscosity of the sunscreen. Due to limited statistics, an origin could not be found yet.

In addition, reference measurements were obtained from different volunteers and different test institutes, which is known to cause deviations of SPF results.

Another reason for deviations of LED based UVB- PF with SPF reference values might be the dependency on skin pigmentation. The effect of R_0 on the slope of the linear regression function (which can be considered as calibration curve) was also observed when measurements on human skin were compared to measurements on pig ear skin.[17]

A similar effect is known for the invasive in vivo SPF-test.[23–25] This suggests that the correlation studies of DRS based SPF measurements and the invasive in vivo SPF-test should ideally be performed on the same skin sites or at least with the same distribution of skin types. This was not the case in our study.

Nevertheless, this simple technique could be applied for applications where the SPF values themselves are not crucial, but the changes are of interest. Examples are sunscreen resistance to water, clothes and sweat, the determination of inhomogeneous application of sunscreen, or stability over time and behavior after reapplication. Due to the limited spectral range, UVB filters can be captured while UVA filters might be washed off differently. Our LED-based setup was previously used for the investigation of sunscreen distribution and sweat resistance[22],[18] A study on the persistence of sun protection and reapplication was recently reported by Ruvolo et al.[27] using the HDRS method, which depends on UVA in vivo measurements.

4.4 | Potential improvement of LED-based UVB-PF measurement

Figures 7 and 8 illustrate a dependency of LED-based UVB-PF on the pigmentation of the skin even though reflectance values are normalized by R_0 during the LED-based UVB-PF calculation (see Equation (1)). To reduce the variation, a small range of native reflectance (pigmentation levels) should be used to determine the LED-based UVB-PF (e.g., $R_0 > 200$). Furthermore, the more light is reflected the better is the determination of high LED-based UVB-PF values (e.g., $R_0 > 200$). Thus, ST I would be preferred for these measurements. However, for routine testing it is not feasible to reduce the selection of volunteers to the volunteers with ST I, only.

To reduce the deviation of the measured LED-based UVB-PF from the reference value, the calculation of the LED-based UVB-PF by Equations (1)-(3) might be improved, taking into account the nonlinear influence of untreated skin reflection. For such calculations, all sunscreens should be measured once on the same volunteers. This was not the case in the presented study.

5 | SUMMARY AND CONCLUSION

Using only one UVB LED with a peak maximum at 308 nm, a good correlation of the measured LED based UVB-PFs with SPF reference values of test institutes was obtained, while using less than one fifth of the minimal UV dose required for invasive tests. No additional in vitro spectrum was used.

In contrast to a spectrally resolved measurement, this measurement has limited accuracy because the spectral weighting functions for erythema effectiveness and solar spectrum cannot be applied. Therefore, the aim of this method is not to replace the spectrally resolved and more precise HDRS method for SPF determination, which is also a noninvasive method. However, the described less expensive sensor may be applied for difference measurements where absolute SPF values are not the main interest, such as distribution of sunscreen on a volunteer's body, or time course measurements after bathing and sweating.

CONFLICTS OF INTEREST
Carina Reble, Georg Wiora, and Georg Khazaka are employees of Courage + Khazaka electronics GmbH, which has an interest in commercialization and is owner of a patent. The other authors declare no financial or commercial conflict of interest.

AUTHOR CONTRIBUTIONS
Carina Reble, Ingo Gersonde, Martina C. Meinke and Jürgen Lademann were involved in conceptualization.

Ingo Gersonde, Carina Reble and Naysha Lobo-Ploch were involved in construction and building up the system.

Carina Reble, Ingo Gersonde, and Susanna Kobylinski were involved analyzing the data.

Susanna Kobylinski, Sabine Schanzer, Naysha Lobo-Ploch, Ludger Kolbe and Hans Karrer were involved in investigation.

Carina Reble and Susanna Kobylinski wrote the original draft. Ingo Gersonde, Georg Wiora, Georg Khazaka, Martina C. Meinke and Jürgen Lademann performed writing-review and editing.

Jürgen Lademann, Martina C. Meinke, Georg Khazaka and Georg Wiora were responsible for project management.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author.

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