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A preliminary study on photoaddition and erythema due to UVB radiation

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Abstract. The spectral irradiance of narrow band and broad spectrum radiation sources have been measured and the erythemally effective irradiance calculated by weighting the spectral irradiance of each source by an erythema action spectrum for human skin and integrating over the range of wavelengths in each spectrum. The ratio of the erythemally effective irradiances determined in this manner have been compared with the ratio of exposure times necessary to produce a delayed minimal perceptible erythema on the trunk skin of fair-skinned subjects irradiated with the two different sources. There was close agreement between the two ratios, supporting the notion of photoaddition applied to erythema elicited by UVB radiation.

1. Introduction

The assumption of linear additivity, or photoaddition, is commonplace in photobiology. Photoaddition is assumed whenever a photobiological action spectrum is multiplied by a spectral irradiance curve of some source of optical radiation to predict or explain an observed response (Parrish *et al* 1978). Ultraviolet erythema is one example where the concept of photoaddition is often applied; for example, by dermatologists engaged in the evaluation of phototherapeutic regimens for skin diseases (Parrish 1982), or by illumination engineers in estimating the erythemal content of different light sources (Brundrett and Johnston 1972).

The notion that photoaddition holds for ultraviolet erythema was first suggested by Adams *et al* (1931). Evidence supporting this was subsequently published by Sayre *et al* (1966) and by Ying *et al* (1974), although Findlay (1967) presents tentative evidence to show that threshold erythemal responses to irradiation with an unfiltered xenon arc lamp cannot be accounted for by applying the principle of photoaddition. Furthermore, other workers have suggested that synergistic or protective interactions may exist between wavelengths. Willis *et al* (1973) found that UVA radiation (315–400 nm) exhibited a photoaugmentative effect on erythema induced by UVB radiation (280–315 nm) and interpreted their findings as a pronounced synergistic effect between UVA and UVB. On the other hand, van der Leun and Stoop (1969) showed that the effect of irradiation of human skin with UVB may be slightly reduced by subsequent exposure to indoor daylight; a phenomenon known as photorecovery or photoreactivation.

In this preliminary study our intention was to limit the spectral power distributions such that for the narrow band and broad spectrum radiations used here, the erythemal efficacy of both radiations was confined almost entirely to the UVB spectrum.

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Consequently any photoaugmentation or photorecovery effects of UVA and visible radiation were assumed to be too small to play any significant role.

If photoaddition is applicable to UVB erythema, and if no significant synergistic or protective interactions exist between wavelengths, it is possible to define an erythemally effective irradiance (W m^{-2}) relative to some reference wavelength λ_0 nm as

$$E_{\text{eff}} = \sum E(\lambda)\varepsilon(\lambda)\,\Delta\lambda \tag{1}$$

where $E(\lambda)$ is the spectral irradiance (W m^{-2} nm^{-1}) at wavelength λ nm at the point of interest, $\varepsilon(\lambda)$ is the relative effectiveness of radiation of wavelength λ nm (normalised to unity at λ_0 nm) in producing the desired end-point, e.g., a delayed minimal erythema observed 24 hours following irradiation, and $\Delta\lambda$ is the wavelength interval used in the summation. In principle, the summation is over all wavelengths for which both $E(\lambda)$ and $\varepsilon(\lambda)$ are non-zero.

The purpose of the present investigation was to measure $E(\lambda)$ using narrow band (monochromatic) and broad spectrum radiations and to compare the ratio of the calculated erythemally effective irradiances with the ratio of exposure times necessary to produce a delayed minimal perceptible erythema (MPE) on the skin of subjects irradiated with radiation of different spectral distributions. Agreement between the E_{eff} ratio and the ratio of exposure times for a MPE would support the idea of photoaddition.

2. Materials and methods

The untanned skin on the backs of five fair-skinned Caucasian males was irradiated with narrow band radiation of wavelength around 300 nm and with broad-spectrum radiation extending from about 285 to 740 nm (approximately 'solar simulated radiation').

The apparatus used to irradiate the subjects consisted of a 900 W xenon arc lamp mounted in a housing with two exit ports at 180° to each other. One exit port was optically coupled to a single diffraction grating monochromator, with the other allowing for modification of the full spectrum radiation by means of an optical filter holder. A liquid-filled light guide, 2 m in length and 5 mm inner diameter, conducted the radiation from either the exit of the monochromator or the exit aperture on the filter side to

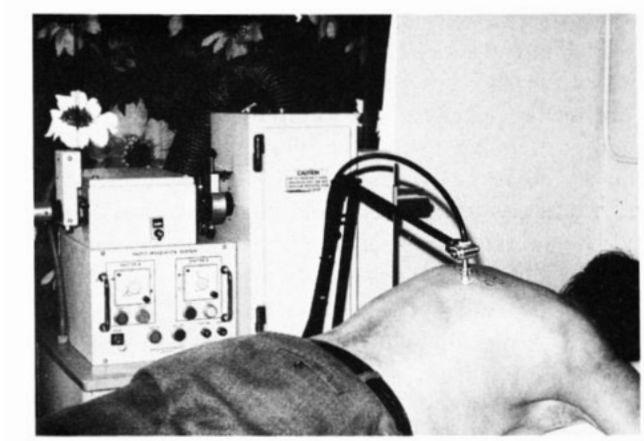

Figure 1. A subject being investigated with the photoirradiation system.

the subject's skin (see figure 1). This light guide transmitted radiation in the spectral interval 240 to 740 nm with 50% or more transmission in the region 300 to 600 nm.

The spectral irradiance at the subject's skin was measured using a semi-automated prototype version of a portable scanning spectroradiometer (Diffey and McKinlay 1983). The bandwidth of the spectroradiometer was kept constant at 3 nm and a wavelength stepping increment $\Delta\lambda$ of 1 nm was used in all measurements. Wavelength calibration was obtained using a HeNe laser (632.8 nm), an argon ion laser (514.5 and 488 nm) and a low pressure mercury discharge lamp (253.7 nm). The spectral sensitivity calibration of the instrument was obtained by reference to a National Physical Laboratory calibrated deuterium spectral irradiance standard. The uncertainty associated with electronic and optical 'noise' was $< \pm 2 \times 10^{-3}$ V. This is equivalent to an uncertainty in spectral irradiance of 2.4×10^{-7} W m^{-2} nm^{-1} at 300 nm.

Each subject was irradiated in an arithmetical series of exposure times in each spectral region as follows:

(i) Narrow band irradiation (central wavelength of 299 nm with full bandwidth at half maximum intensity of 5 nm)—exposure times ranging from 8 to 40 s in steps of 2 s. This spectral region was chosen as it lies approximately midway in the UVB spectrum and the photobiological effects of wavelengths around 299 nm have been studied extensively.

(ii) Broad spectrum irradiation (xenon arc spectrum modified by Schott WG305 glass filter 3 mm thick)—exposure times ranging from 2 to 6 s in steps of 0.2 s. The WG305 filter was inserted to remove the UVC component of the radiation beam since the mechanisms of UVB and UVC erythema are thought to be different (van der Leun 1972).

The irradiated sites were observed visually 24 h following exposure and that exposure which produced a threshold, or just perceptible, reddening of the skin (so-called 'minimal perceptible erythema', MPE) was noted.

3. Results

The spectral irradiances in each of the wavelength regions used in this study are shown in figure 2. No attempt has been made to deconvolute the measured spectral irradiance curves to account for the finite (3 nm) bandwidth of the spectroradiometer.

In order to calculate the erythemally effective irradiance (E_{eff}) in each spectral region it is necessary to adopt some action spectrum for delayed erythema. The numerical values of the action spectrum $\varepsilon(\lambda)$ employed here are based upon the weighted mean values calculated by Diffey (1982) from a statistical analysis of the results of erythema action spectrum studies carried out by six independent groups of investigators in the period (1964–74). These data only cover the spectral range 250–320 nm and so the recent action spectrum data published by Parrish *et al* (1982), which cover the spectral range 250–405 nm, have also been included. The tabulated values of $\varepsilon(\lambda)$ at selected wavelengths used in the present study are given in table 1. Logarithmic interpolation was used to calculate $\varepsilon(\lambda)$ at intermediate wavelengths. From equation 1 the erythemally effective irradiance relative to monochromatic radiation at 300 nm is calculated to be 12.5 W m^{-2} for the narrow band spectrum and 54.3 W m^{-2} for the broad spectrum radiation, which indicates that if photoaddition is applicable and both photoaugmentation and photorecovery are insignificant, irradiation with the narrow band spectrum should take 4.3 times as long to achieve a 24 h MPE than with the broad spectrum radiation.

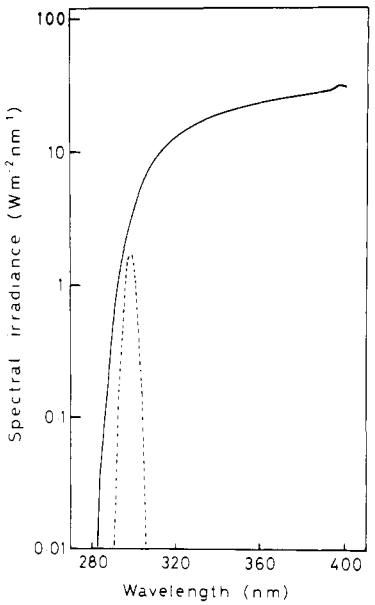

Figure 2. The spectral irradiance in the ultraviolet region (280–400 nm) at the subject's skin. Broken curve, narrow band radiation; full curve, broad spectrum radiation.

Mackenzie (1983) has shown that the distribution of doses required for a MPE amongst normal individuals can be represented more reliably by a lognormal, rather than Gaussian, distribution. Consequently the logarithm of the observed times for a MPE in each of the five subjects for narrow band and broad spectrum irradiation are given in table 2. It may be seen that although there is a wide range in the inter-subject MPE times for a given irradiation spectrum, reflecting differences in the individuals' susceptibility to sunburn, the intra-subject ratio of MPE times for the narrow band and

Table 1. The erythema action spectrum (normalised to unity at 300 nm) used in the present analysis.

Wavelength (nm)	Relative erythemal effectiveness, $\varepsilon(\lambda)$
250	1.74
260	1.90
270	1.43
280	1.31
290	1.43
295	1.51
300	1.00
305	0.51
310	0.075
320	8.7×10^{-3}
334	1.5×10^{-3}
365	5.7×10^{-4}
380	1.9×10^{-4}
405	1.4×10^{-4}

Table 2. Logarithm of exposure times for delayed (24 h) minimal perceptible erythema.

	$\log_{10}$ (time for MPE (s))		
Subject	Narrow band	Broad spectrum	$\log_{10}$ ratio
1	1.08	0.51	0.57
2	1.34	0.70	0.64
3	1.26	0.66	0.60
4	1.20	0.58	0.62
5	1.00	0.41	0.59
Mean	1.18 ± 0.14	0.57 ± 0.16	0.604 ± 0.037

Median ratio = 4.0
95% confidence limits, 3.4 to 4.8

broad spectrum irradiation shows much less variability (coefficient of variation of 6%). Also the median ratio of exposure times for a MPE from the two spectra is 4.0 with a 95% confidence interval of 3.4 to 4.8. The median value of 4.0 agrees closely with the predicted ratio of 4.3 given above.

4. Discussion

The most common approach to photobiological dosimetry is the concept of photoaddition, that is, that the various wavelength components of a source of ultraviolet radiation exposure may be combined in a simple additive manner but incorporating a multiplicative constant (action spectrum) appropriate for each wavelength (Calkins 1982). The results of the present study apparently support this concept with regard to erythema elicited with UVB radiation.

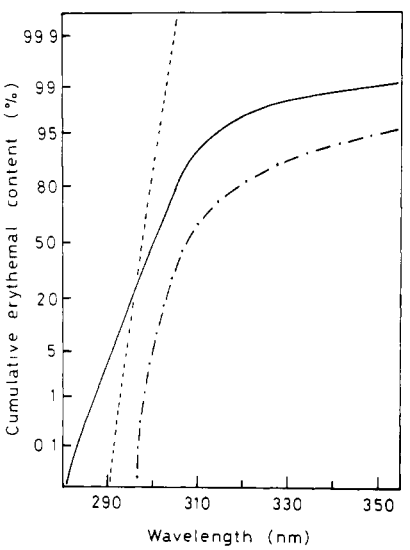

Figure 3. The cumulative erythemal content of three different sources of radiation. Broken curve, narrow band radiation; full curve, broad spectrum radiation; chain curve, midday summer sunlight in the UK.

If, however, the cumulative erythemal content of a source of optical radiation up to any given wavelength Λ is expressed as

$$\sum_{0}^{\Lambda} E(\lambda)\varepsilon(\lambda)\,\Delta\lambda / E_{\text{eff}}$$

it may be seen from figure 3 that for the broad spectrum radiation used in the present study, the UVA component of the radiation beam only contributes 4% of the erythemally effective dose required for a minimal perceptible erythema, and is probably too low to play any significant photoaugmentative role, assuming such a phenomenon exists. Figure 3 also shows the cumulative erythemal content of terrestrial midday summer sunshine in the UK (latitude 53 °N, solar zenith angle 30°, ozone thickness 0.32 cm) and indicates that under these conditions solar UVA contributes about 25% of the erythemally effective exposure.

Finally, the results of this study may not necessarily apply to sources of radiation which contain significant erythemal quantities of UVA radiation in addition to the UVB. In these cases photoaugmentation and/or photorecovery may be important.

Résumé

Etude préliminiare de la photoadditivité pour l'érythème dû au rayonnement UVB.

Les auteurs ont mesuré la répartition spectrale de l'émission de sources à bande étroite et de sources à large bande. Ils ont calculé l-éclairement énergétique efficace pour la production de l'érythème (débit de dose érythémale) en pondérant l'éclairement énergétique spectrique dû à chaque source avec les données du spectre d'action de l'érythème de la peau humaine et en intégrant sur la bande spectrale relative à chaque spectre d'émission. Les rapports des débits de dose érythémale obtenus par la méthode précédente ont été comparés aux rapports des durées d'exposition respectivement nécessaires avec les deux types de sources pour produire l'érythème retardé minimal perceptible sur le torse de sujets à peau claire. Un bon accord a été observé entre les deux types de rapports, confortant l'hypothèse de la photoadditivité pour l'érythème produit par le rapport ultraviolet.

Zusammenfassung

Eine vorläufige Untersuchung über Photoaddition und Erythema aufgrund von UVB-Strahlung.

Die Spektrale Strahlungsdichte schmalbandiger und breitbandiger Strahlungsquellen wurde gemessen und die erythemwirksame Strahlungsdichte berechnet durch Wichtung der spektralen Strahlungsdichte einer jeden Quelle mit Hilfe eines Erythemaktionsspektrums für menschliche Haut und durch Integration über den Wellenlängenbereich eines jeden Spektrums. Das so bestimmte Verhältnis erythemwirksamer Strahlungsdichten wurde verglichen mit dem Verhältnis der Bestrahlunszeiten, die nötig sind ein verzögertes, minimal wahrnehmbares Erythem bei hellhäugtigen Personen zu erzeugen, die mit zwei verschiedenen Quellen bestrahlt worden waren. Die gute Übereinstimmung zwischen den beiden Verhältnissen unterstützt die bisherigen Vorstellungen über die Photoaddition bei ultravioletten Erythemen.

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