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RELATIVE ENERGY REQUIREMENTS FOR AN ERYTHEMAL RESPONSE OF SKIN TO MONOCHROMATIC WAVE LENGTHS OF ULTRAVIOLET PRESENT IN THE SOLAR SPECTRUM*

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The production of erythema has been the endpoint most often used to evaluate the biological effects of ultraviolet. Finsen first demonstrated that erythema was caused by ultraviolet (1). The specific wavelengths responsible were studied, and an erythema action curve was derived by Hausser and Vahle (2, 3). This curve is widely accepted as standard (4, 5) and is characterized by having the greatest erythemal effectiveness at 297 mμ, rapid loss of effectiveness at 310 and 280 mμ, and a second maximum at 250 mμ (Fig. 1). Data supporting this curve were reported by Coblentz and Stair (6), Hauser (7), and Luckiesh, Holladay and Taylor (8).

Blum and Terus (9), Magnus (10), and Rottier (11) have presented quantitative data on energy requirements for erythema production by different parts of the spectrum. In each instance less energy was required at shorter wavelengths of 250–260 mμ than at longer wavelengths. Both Rottier and Magnus observed erythema at 280 mμ with doses comparable to those effective at adjacent wavelengths. In 1965 Everett, Olsen and Sayre (12), using a xenon arc grating monochromator, found that, in contrast to the "standard," 250 mμ was the most effective wavelengths and that 280 mμ was just as effective as adjacent wavelengths. They stated that their results agreed with other quantitative data on erythema energy (Fig. 2).

Knowledge of energy requirements for producing erythema at different wavelengths is essential to further understanding of light injury. Since sunlight is the major source of light injury in man, greatest interest is in the erythema-producing ability of the sun's rays at the earth's surface, those longer than 290 mμ in wavelength.

Using a high intensity xenon arc grating monochromator, we have extended previous observations on erythema production and have compared these energy requirements with the available data on solar radiation intensity. In this way the erythemal effectiveness of ultraviolet in sunlight has been determined for human skin and for albino rabbit skin.

METHODS

Skin of the lower abdomen of human subjects and of albino rabbits was exposed to serially increasing amounts of ultraviolet emitted from a high pressure xenon arc grating monochromator. The minimal erythemal dose (M.E.D.), the smallest amount of energy that would produce a barely perceptible erythema within 24 hours, was determined. The human volunteers were adult males who did not have known photosensitivity and who had lightly pigmented skin on the lower abdomen which had not been recently exposed to sunlight nor altered by skin disease. Male and female adult albino rabbits were depilated* 24 hours before being irradiated while under barbital anesthesia. The irradiated sites were examined for erythema at 24 hours. Sites exposed to shorter wavelengths were examined at 8 and 24 hours, according to the data of Everett (13).

The energy values required to produce erythema were determined on human and albino rabbit skin for wavelengths between 220 and 330 mμ at intervals of 10 mμ. At least 100 determinations were made at each point between 250 and 318 mμ. Fewer endpoints were obtained above and below these points because of the inefficiency of these wavelengths and the time required to find an endpoint. These energy values are represented in Figures 3 and 4 by the mean values and 1 standard deviation. In order to fix more precisely the erythema-producing capabilities of the wavelengths in sunlight (above 290 mμ) the M.E.D. was determined at 2 mμ intervals from 290–320 mμ in both humans and albino rabbits.

The M.E.D. was not significantly altered when infra-red energy was applied immediately before

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* Surgex depilatory, Crookes-Barnes Laboratories, Inc., Wayne, N. J.

or after ultraviolet exposure. A G.E. 250-watt infra-red lamp was used 12 inches from the skin surface for a time sufficient to produce a 10°F. rise in skin temperature.

Monochromatic Light Source

The light source used in these experiments is a high pressure xenon arc grating monochromator consisting of three Bausch & Lomb monochromator units with their outputs superimposed on a test site 1.1 cm in diameter (14). In each monochromator a 150-watt xenon arc light source is housed in a standard housing attached to a Bausch & Lomb diffraction grating. The output of one of the monochromators passes directly to the test site while the other two monochromators are perpendicularly arranged, their output being focused by convex lenses and reflected onto the test site by right angle mirrors. Where appropriate in these experiments, a filter is inserted in the beam to reduce scatter radiation and second-order effects.

A reflective prism which serves as a shutter mechanism is lowered during exposure by an electronically-controlled solenoid so that the beam impinges directly on the test site. Between exposures the prism covers the test site and diverts the beam into a detector connected to a Bausch & Lomb laboratory recorder. The total energy output of all three units and the duration of exposure is permanently recorded.

When the entrance and exit slits are set to provide a 50 Å bandwidth at ½-power output, the intensity of output in the ultraviolet and visible ranges approximates twice that of the sun outside the earth's atmosphere. Specifically, at 300 mμ and 50 Å bandwidth the calibrated output is 0.66 nw/cm^2-50 Å. Ninety-nine per cent of the energy emitted is within ±5 mμ of the dial setting. An erythema can be produced in human skin with 4–6 seconds of exposure to effective wavelengths.

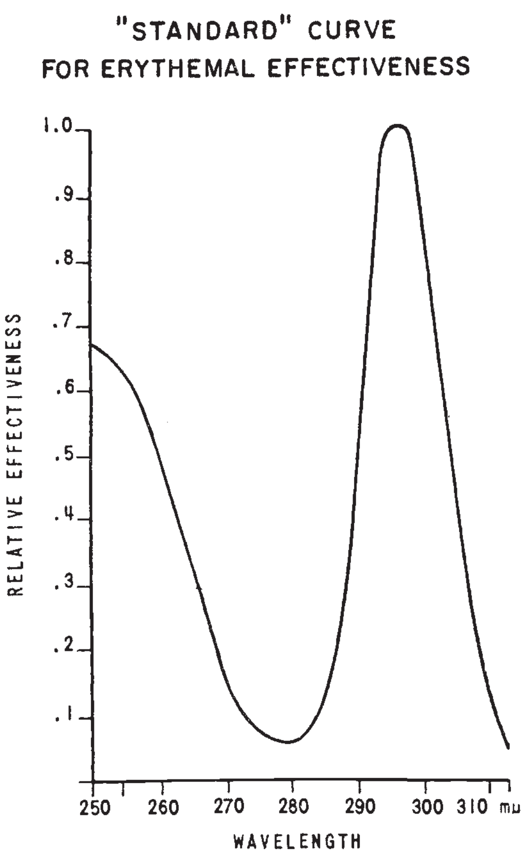

FIG. 1. "Standard" curve for erythemal effectiveness.

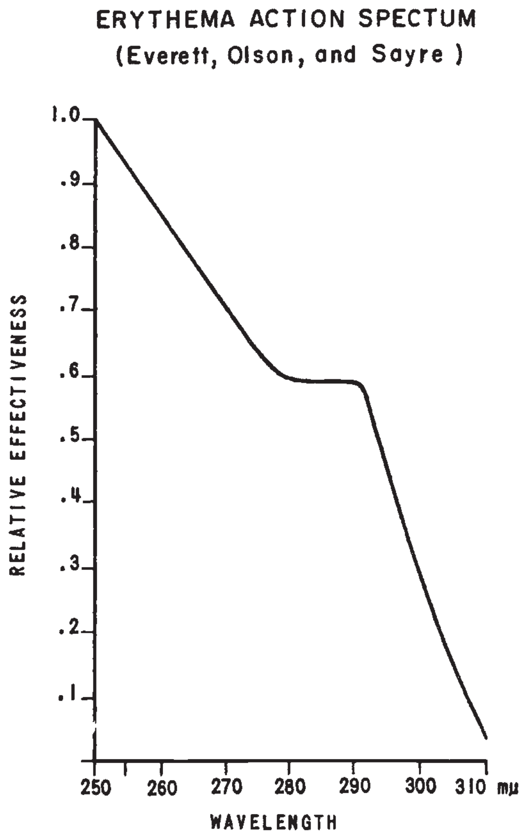

FIG. 2. Erythema action spectrum (Everett, Olsen and Sayre).

RESULTS

The major erythema-producing capability of ultraviolet was found in the range of 250–310 mμ (Figs. 3, 4). Much more energy was required above and below this range to produce erythema. The least energy was required at 260

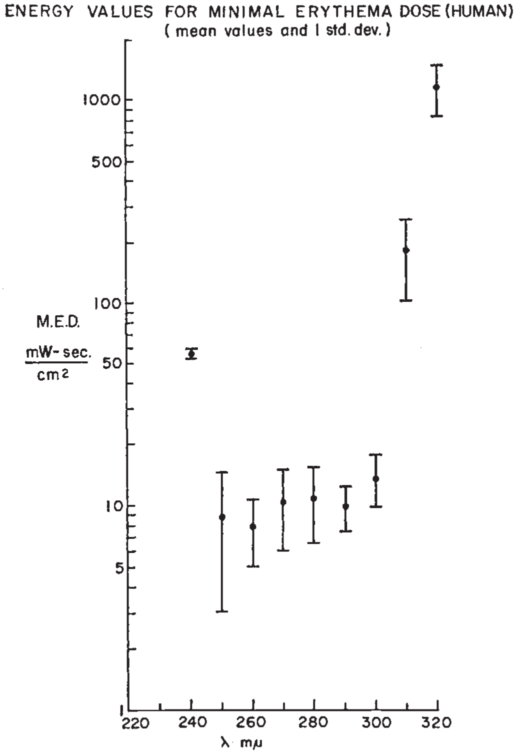

FIG. 3. Energy values for erythema production on human abdominal skin.

mμ for man and at 250 mμ for rabbits. Somewhat more energy was required at 280 mμ than at 260 and 290 mμ, but not to the extent indicated by the "standard" erythema curve.

Energy requirements rapidly increased for wavelengths longer than 300 mμ. It took approximately ten times as much energy to produce erythema at 310 mμ than at 300 and 100 times as much energy to produce erythema at 320 mμ than at 300. Erythema did not occur at 330 mμ even with massive amounts of energy (over 10,000 mW. sec/cm²). When energy values were plotted against wavelength (Figs. 3, 4), the shape of the curve was identical for albino rabbit skin and for human skin, although at each wavelength less energy was required to produce erythema in rabbit skin.

A curve illustrating the effectiveness of erythema production—the erythemal action spectrum or "standard" erythemal curve—is taken as a reciprocal of the energy values required to produce erythema. These reciprocal erythema action spectra for human skin and for albino rabbit skin are shown in Figs. 5, 6, 7 and 8. In this curve the most effective erythema-producing peaks are near 250–260 mμ and at 292 mμ, the former being most efficient. A slight decrease is seen at 280 and a rapid decrease between 300 and 310 mμ and beyond 250 mμ. In Figs. 9 and 10 these data, expressed as relative units, are plotted against wavelength and compared to the "standard" erythemal curve and to the erythema action curve derived by Everett, Olsen and Sayre.

In Fig. 11 the curves shown are those derived by Moon (15) and represent probably the best currently available data on solar irradiation at the earth's surface under specified atmospheric conditions. The conditions for these curves are: sea-level altitude, 2.8 mm of ozone, 20 mm of water vapor, and 300 dust particles per cubic centimeter. Four curves are drawn for different

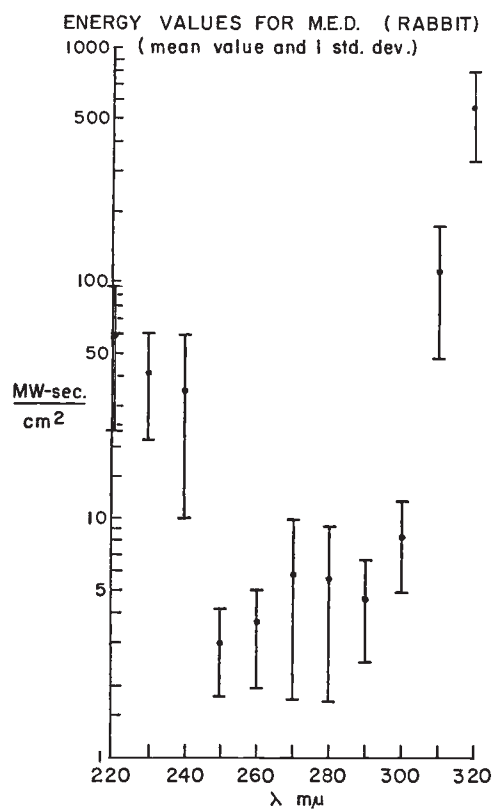

FIG. 4. Energy values for erythema production on albino rabbit skin.

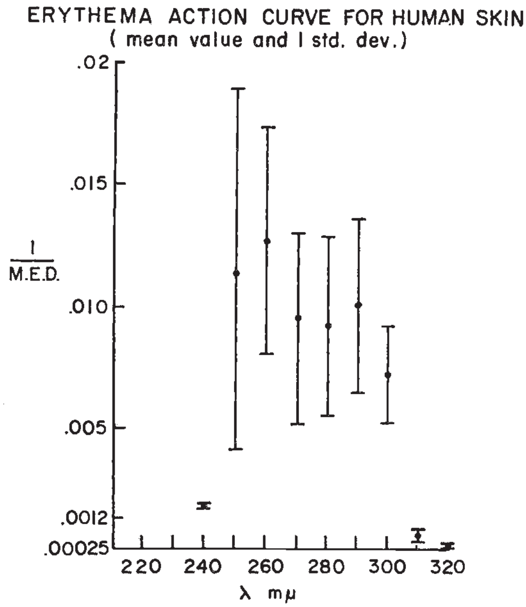

Fig. 5. Erythema action spectrum for human abdominal skin.

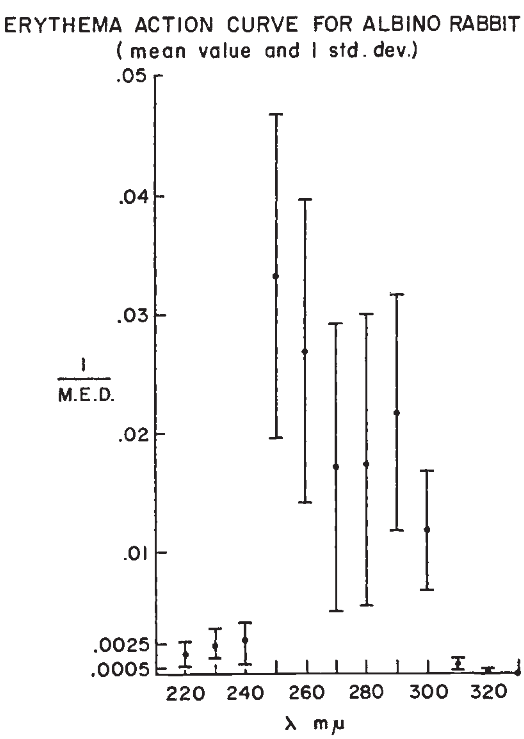

Fig. 6. Erythema action spectrum for albino rabbit skin.

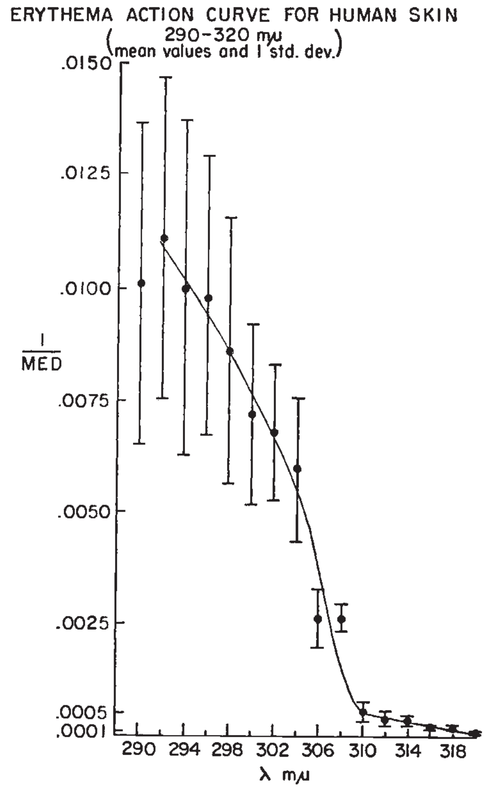

Fig. 7. Erythema action spectrum for human abdominal skin from 290 to 320 mμ.

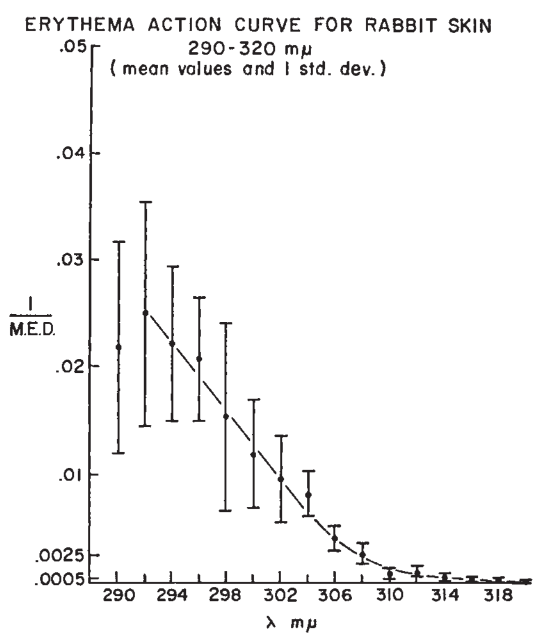

Fig. 8. Erythema action spectrum for albino rabbit skin from 290 to 320 mμ.

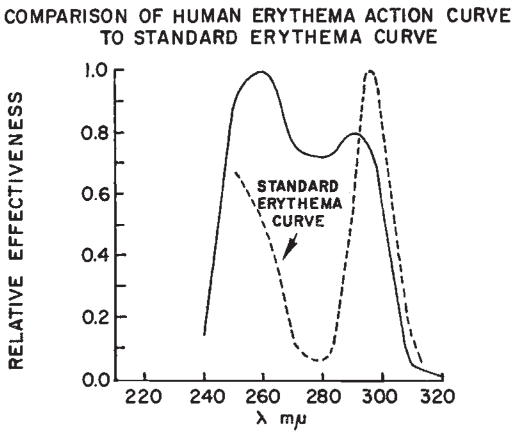

FIG. 9. Erythema action spectrum compared to standard erythema curve.

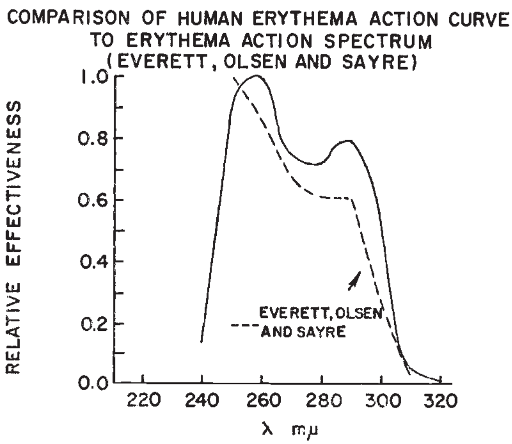

FIG. 10. Erythema action spectrum compared to erythema action spectrum of Everett, Olsen and Sayre.

air masses (m); specifically m = 0 (outside the atmosphere), m = 1 (1 atmospheric air mass, *i.e.* sun at zenith), m = 2, and m = 3. Moon recommends the use of values for m = 2 as the best single standard solar radiation curve for conditions in the United States. Air mass for other conditions of latitude and time can be estimated readily since the air mass varies with the secant of the zenith angle.

When the reciprocal of the erythema values (Figs. 7 and 8) are multiplied by the values for solar radiation for each wavelength, a product curve similar to the relative index curve of Blum (4) can be derived which allows an estimation of the time required to produce erythema under the specified conditions of solar radiation. In this calculation, the reciprocal of energy values M^2/(watt. sec.) will be multiplied by the values for solar radiation watts/(M^2 − μ). The product of M^2/watt. sec. × watts/(M^2 − μ) is equal to 1/(sec. − μ) and may be plotted against the wavelength (Figs. 12 and 13). The area beneath such a product curve is then proportional to a reciprocal of time 1/(sec.).

Thus, by measuring the area under the product curve, the time necessary to produce erythema can be calculated. Such product curves and calculations are shown for air mass of 1, 2, and 3 in Figs. 10 and 11. Under these conditions a minimal erythemal time for human skin would be approximately 4 minutes for an air mass of m = 1, 20 minutes for m = 2, and 80 minutes for m = 3. For albino rabbit skin the values are, respectively, 2.5 minutes, 15 minutes, and 55 minutes.

These values compare favorably with actual observations for erythema production in sunlight in our area (altitude 50 feet above sea level and 30° N. latitude). A group of human volunteers placed in noonday sunlight during the second week of June developed erythema on abdominal skin in an average time of 15 minutes, with some values being between 5 and

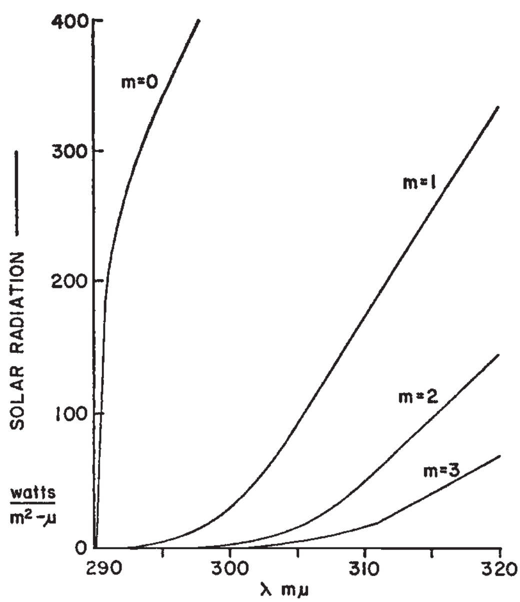

FIG. 11. Solar radiation under specified atmospheric conditions (after Moon).

10 minutes. In late August, approximately 25 minutes were required.

DISCUSSION

Our quantitative observations of the erythema-producing capabilities of ultraviolet support and extend the observations of Everett, Olsen and Sayre (12), that the most efficient erythema-producing wavelengths are in the range of 250 to 260 mμ. The efficiency is nearly as great at 280 mμ as adjacent wavelengths, in contrast to the great decrease in efficiency at 280 mμ indicated by the standard erythemal action curve. We also observed a rapid decrease in effectiveness at 240 mμ and at 310 mμ. Energy requirements were very high at 320 mμ and erythema was not produced at 330 mμ even with very long exposures.

Similarities to the standard erythema curve were also observed in that one peak of effectiveness occurred between 290 and 300 mμ and a definite though slight drop in effectiveness occurred at 280 mμ.

While it is of interest to determine the erythema-producing capabilities of the entire spectrum, we are mainly interested in that portion of the spectrum in sunlight. This is the main source of electromagnetic wave energy in our natural environment and the major cause of medical problems.

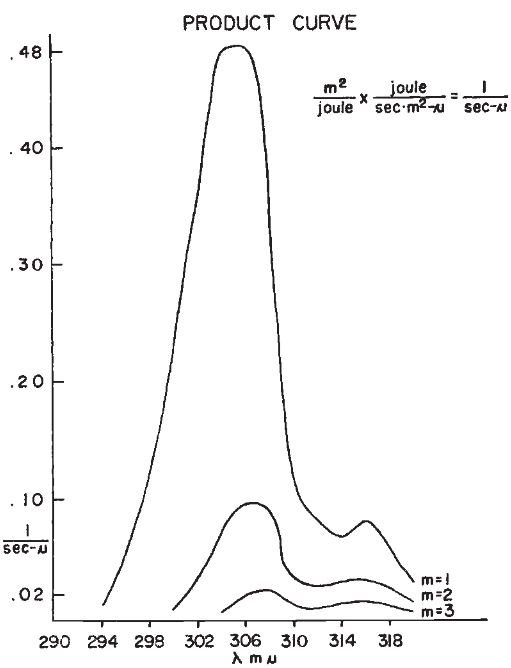

FIG. 12. Product curve for human abdominal skin.

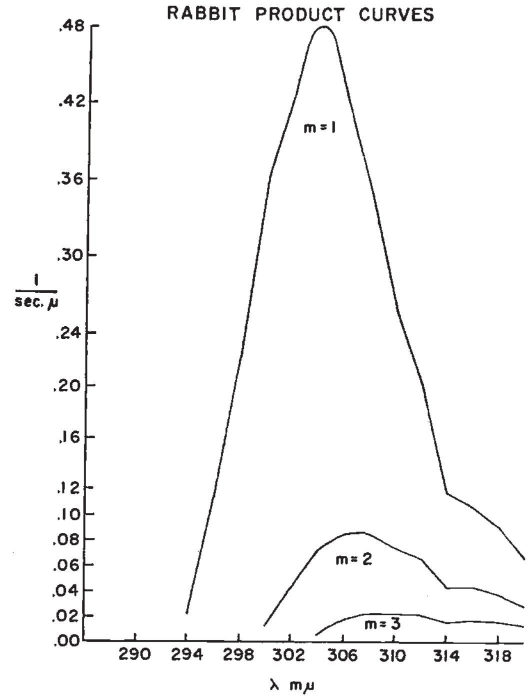

FIG. 13. Product curve for albino rabbit skin.

By application of an equation in which the reciprocal of energy values is multiplied by the values for solar ultraviolet radiation, a product curve has been derived which allows additional observations on solar erythema production. Although the most effective erythema-producing wavelengths are at 250 mμ, virtually no solar ultraviolet radiation shorter than 295 mμ reaches the earth's surface even with the sun at zenith and with an air mass of 1. Thus these shorter wavelengths do not contribute to solar erythema.

Using the conditions Moon (13) described as standard conditions representative for the United States, the product curves illustrate that peak erythema production actually occurs with much longer wavelengths—those in the range of 302 to 310 mμ. Furthermore, as the air mass increases, the total intensity decreases, shorter wavelengths are eliminated, and the peak effectiveness shifts slightly toward longer wavelengths. This can be seen by comparing curves for m = 1, 2, and 3. At m = 1 the peak efficiency is at 305 mμ; m = 2 at 306 mμ; and m = 3 at 308 mμ.

With an air mass of 2, as in Figs. 12 and 13, the very inefficient erythema-producing wavelengths at 320 mμ actually account for as much solar erythema as the very efficient wavelengths at 310 mμ. In the same manner, wavelengths at 316 mμ are equal to 302 mu in effectiveness.

Another observation is that as the air mass increases, as it does in northern latitudes and in the early morning and late afternoon, longer wavelengths assume a proportionately greater role in solar erythema production. When m = 1, the wavelengths longer than 314 mμ account for only 10 per cent of the erythema effect. Conversely, when m = 3, wavelengths longer than 314 mμ account for 34 per cent of the erythema production while those between 304 and 310 mμ account for 66 per cent, and none below 304 mμ. Results of calculations using this formula for minimal erythemal time are very close to the minimal erythema time determined from experiments using natural sunlight.

SUMMARY

A high intensity grating monochromator was used to determine erythema-producing effectiveness of ultraviolet on untanned human abdominal skin and albino rabbit skin. Greatest efficiency was observed at 250–260 mμ with a second peak at 292 mμ, a slight drop at 280 mμ, and a rapid decrease at 240 and at 310 mμ.

A product curve was derived by multiplying the reciprocal of erythema energy values by the values for solar radiation under specific atmospheric conditions. This curve demonstrates that maximum solar erythema production occurs at 305–308 mμ and that longer wavelengths, though inefficient, account for a significant proportion of solar erythema because of the great amount of energy in sunlight at these wavelengths. Wavelengths shorter than 294 do not contribute to solar erythema.

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