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ULTRAVIOLET RADIATION DOSIMETRY

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Chapter 31.4

Ultraviolet Radiation Dosimetry

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I. Introduction

Dosimetry is the science of radiation measurement. No persuasion should be needed as to the importance of dosimetry and in dermatology there are two principal reasons why ultraviolet radiation (UVR) should be measured:[1]

1. To allow consistent radiation exposure of patients over many months and years within a local department.
2. To allow the results of irradiations made in different departments to be published and compared.

It is important to distinguish between these two objectives. The first requires *precision*, or reproducibility. The radiometer is used as a monitor to give a reference measurement and so it needs to be stable. *Accuracy*, i.e., absolute calibration against some accepted standard, is not essential. The second objective requires both precision and accuracy. Here the radiometer must not only be stable from one day to the next, but also the display (in, say, milliwatts per square centimeter) must be traceable to absolute standards. While electrooptical technology has improved over the years, resulting in the availability of versatile and precise ultraviolet radiometric equipment, these improvements have not been accompanied by improved accuracy. Indeed the accuracy of administered radiation doses in psoralen photochemotherapy leaves much to be desired *(vide infra)*.

II. Radiometric Terms and Units

In clinical and photobiological UVR dosimetry it is customary to use the terminology of radiometry rather than that of photometry, since photometry is based on visible light measurements that simulate the human eye's photopic response curve and, strictly speaking, a source that emits only UVR has a zero intensity in photometric terms.

The common radiometric terminology is listed in Table 1. Terms relating to a beam of radiation passing through space are the "radiant energy" and "radiant flux". Terms relating to a source of radiation are the "radiation intensity" and the "radiance". The term "irradiance", which is the most commonly used term in photobiology, relates to the object (e.g., patient) struck by the radiation. The radiometric quantities in Table 1 may also be expressed in terms of wavelength by adding the prefix "spectral".

The time integral of the irradiance is strictly termed the "radiant exposure", but is sometimes expressed as "exposure dose", or even more loosely as "dose". The term "dose" in photobiology is analogous to the term "exposure" in radiobiology and not to "absorbed dose". As yet the problems of estimating the energy absorbed by critical targets in the skin remain unsolved.

A. Radiometric Calculations

The most frequent radiometric calculation is to determine the time for which a patient, who is prescribed a certain dose (in J/cm^2), should be exposed when the radiometer indicates an irradiance in mW/cm^2. The relationship between these three quantities (time, dose, and irradiance) is simply

$$\text{Exposure time (minutes)} = \frac{1000 \times \text{prescribed dose } (J/cm^2)}{60 \times \text{measured irradiance } (mW/cm^2)} \quad (1)$$

B. Units of Biologically Effective Ultraviolet Radiation

In addition to the radiometric quantities given above, derived quantities of effective irradiance and dose related to a specific photobiological action spectrum are often used in photomedicine. The effective irradiance is obtained by weighting the spectral irradiance of the radiation at wavelength λnm by the effectiveness of

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TABLE 1 Radiometric Terms and Units

Term	Unit	Symbol
Wavelength	nm	λ
Radiant energy	J	Q
Radiant flux	W	ϕ
Radiant intensity	Wsr^{-1}	I
Radiance	$Wcm^{-2}\ sr^{-1}$	L
Irradiance	Wcm^{-2}	E
Radiant exposure	Jcm^{-2}	H

radiation of this wavelength to cause a particular photobiological effect (e.g., minimal erythema) and summing over all wavelengths present in the source spectrum. This can be expressed mathematically as

$$\Sigma E(\lambda) \cdot S(\lambda) \cdot \Delta\lambda \qquad W/m^2 \qquad (2)$$

$E(\lambda)$ is the spectral irradiance in $W/m^2/nm$ at wavelength λnm and $\Delta\lambda$ is the wavelength interval used in the summation. $S(\lambda)$ is a measure of the effectiveness of radiation of wavelength λnm relative to some reference wavelength in producing a particular biological endpoint. As it is a ratio, $S(\lambda)$ has no units. The effective irradiance is equivalent to a hypothetical irradiance of monochromatic radiation having a wavelength at which $S(\lambda)$ is equal to unity. The time integral of effective irradiance is the effective radiant exposure (also called the *effective dose*).

A unit of effective dose commonly used in photodermatology is the *minimal erythema dose* (MED). One MED has been defined as the lowest radiant exposure of UVR that is sufficient to produce erythema with sharp margins 8 to 24 hours after exposure.[2] Another end point often used is a just-perceptible reddening of exposed skin. The dose of UVR necessary to produce this *minimal perceptible erythema* is sometimes also referred to as an MED.[3] Furthermore, in unacclimatized white skin there is a four- to fivefold range in MED for exposure to UVB radiation.[4] When the term MED is used as a unit of exposure dose, however, a representative value is chosen for sun-sensitive individuals. If, in Equation 2, $S(\lambda)$ is chosen to be the reference action spectrum for ultraviolet erythema in human skin[5] and a value of 200 J/m^2 at wavelengths for which $S(\lambda)$ is equal to unity (i.e., $\lambda \leq 298$ nm) is assumed for the MED,[6] the dose (expressed in MEDs) received after an exposure period of t seconds is

$$t\Sigma E(\lambda) \cdot S(\lambda) \cdot \Delta\lambda/200 \qquad (3)$$

Notwithstanding the difficulties of interpreting accurately the magnitude of such an imprecise unit as the MED, it has the advantage over radiometric units of its relationship to the biological consequences of the exposure.

III. Detection of Ultraviolet Radiation

Techniques for the measurement of UVR fall into three classes: physical, chemical, and biological. In general physical devices measure power, while chemical and biological systems measure energy.

The use of chemical methods, which measure the chemical change produced by the radiation, is called actinometry. These techniques usually form the basis of personal ultraviolet dosimeters.

Biological techniques of measurement are generally limited to the use of viruses and microorganisms. Human skin is often used as a UVR dosimeter in phototherapy in an indirect fashion; treatment times are determined by exposing small areas of the patient's skin to increasing exposures from a UV lamp and noting that exposure which produces a given degree of erythema.

A. Physical Ultraviolet Radiation Detectors

A physical UVR detector consists of an element which absorbs the radiation and a means of measuring the resulting change in some property of the element. There are two basic physical types: thermal and photon.

1. Thermal Detectors

Thermal detectors respond to heat or power and have a broad spectral response with near-uniform sensitivity from the ultraviolet to the infrared. The absorption of radiation increases the temperature of the element and this change can be detected in a variety of ways.

In the thermopile the temperature rise of the element causes a small voltage to be generated at the junction of two dissimilar metals. The heat-sensitive element in a pyroelectric detector consists of a slab of ferroelectric material which produces a change in current proportional to the rate of change of temperature of the surface of the slab, which in turn is proportional to the rate of change of irradiance. A bolometer works by sensing the change in resistance of the absorbing element. In the Golay cell the temperature rise is sensed by the expansion of an enclosed gas which presses against a flexible mirror altering its focal length. Finally, photoacoustic detectors use a microphone to detect the small fluctuations in pressure which occur when the heat generated by the radiation absorption is coupled into the gas contained in an acoustic resonator.

2. Photon Detectors

Photon detectors operate on the principle of the liberation of electrons by the absorption of a single quantum of radiation, and consequently tend to have a nonlinear spectral response. Examples of photon detectors include photoemissive types (vacuum phototube, gas

filled phototube, and photomultiplier tube); junction photodetectors (e.g., Si, GaAsP, GaP photodiodes) which may be operated with a "zero bias" (sometimes called "photovoltaic mode") or a "reverse bias" (sometimes called "photoconductive mode"); and photoconductors (e.g., CdS, CdSe, PbS, InAs).

More detailed descriptions of physical optical radiation detectors can be found elsewhere.[7-9]

IV. Spectroradiometry

It is common practice to talk loosely of *UVA lamps* or *UVB lamps*. However such a label does not characterize adequately UV lamps, since nearly all UV lamps will emit both UVA and UVB, and even UVC, visible light and infrared radiation. The only correct way to specify the nature of the emitted radiation is by reference to the spectral power distribution. This is a graph (or table) which indicates the radiated power as a function of wavelength. The data are obtained by a technique known as spectroradiometry. Figure 1 shows the spectral power distribution of UVR emitted by a medium pressure mercury arc lamp (commonly called a "hot-quartz" lamp in the U.S.). This type of lamp has been used for many years for the phototherapy of skin diseases in units such as the Alpine Sunlamp (Hanovia Ltd, Slough, U.K.). In Figure 1a, the relative power emission is plotted on a linear scale. Although lamp spectra are commonly plotted using a linear scale, this representation may not be the most appropriate. Since the erythemal sensitivity of normal skin varies by four orders of magnitude over the spectral region of 200 to 400 nm, it is helpful to be able to discern components of the spectrum which may be of small amplitude in physical terms but nonetheless important in photobiological terms. Figure 1b shows the spectrum from the same lamp with the relative power plotted on a logarithmic scale. We can see now the characteristic wavelengths present in all mercury lamps are superimposed upon a low-level continuous distribution of radiation. The exact shape of the continuum, particularly at wavelengths of less than 300 nm, depends on factors including the lamp envelope material and the vapor pressure of the mercury.

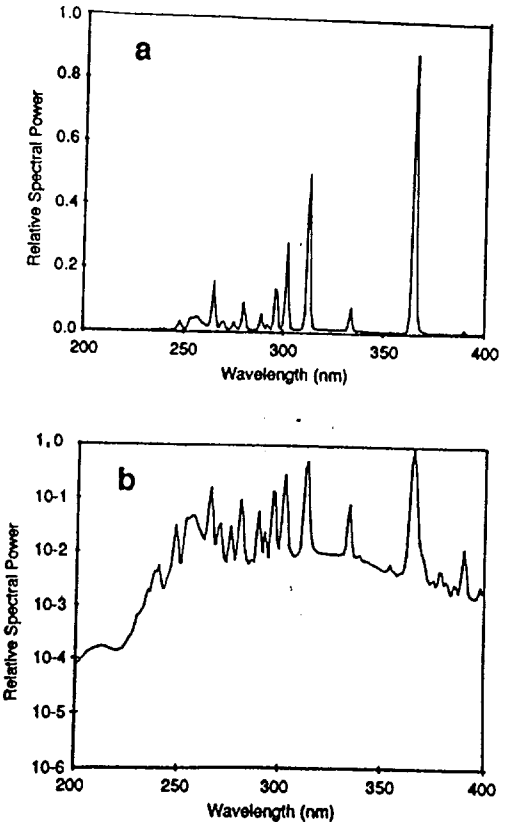

FIGURE 1 The spectral power distribution of UVR from a medium pressure mercery arc lamp (a) linear scale on ordinate and (b) logarithmic scale on ordinate.

A. Components of a Spectroradiometer

The three basic requirements of a spectrometer system are (1) the input optics, designed to conduct the radiation from the source into (2) the monochromator, which usually incorporates a diffraction grating as the wavelength dispersion element, and (3) an optical radiation detector.

1. Input Optics

The spectral transmission characteristics of monochromators depend upon the angular distribution and polarization of the incident radiation as well as the position of the beam on the entrance slit. For measurement of spectral irradiance, particularly from extended sources such as linear arrays of fluorescent lamps or daylight, direct irradiation of the entrance slit should be avoided. There are two types of input optics available to ensure that the radiation from different source configurations is depolarized and follows the same optical path through the system: the integrating sphere or the diffuser. Both these types of input optics produce a cosine-weighted response, since the radiance of the source as measured through the entrance aperture varies as the cosine of the angle of incidence.

2. Monochromator

A blazed ruled diffraction grating is normally preferred to a prism as the dispersion element in the monochromator used in a spectroradiometer, mainly because of better stray radiation characteristics.

High performance spectroradiometers, used for determining low UV spectral irradiances in the presence of high irradiances at longer wavelengths, demand extremely low stray radiation levels. Such systems may incorporate a double monochromator, i.e., two single ruled grating monochromators in tandem, or

laser holographically produced concave diffraction gratings can be used in a single monochromator.

3. Detector

Photomultiplier tubes, incorporating a photocathode with an appropriate spectral response, are normally the detectors of choice in spectroradiometers. However, if radiation intensity is not a problem, solid-state photodiodes may be used, since they require simpler and cheaper electronic circuitry.

B. Calibration

It is important that spectroradiometers are calibrated over the wavelength range of interest using standard lamps. A tungsten filament lamp operating at a color temperature of about 3000 K can be used as a standard lamp for the spectral interval 250 to 2500 nm, although workers concerned solely with the ultraviolet region (200 to 400 nm) may prefer to use a deuterium lamp.

C. Sources of Error in Spectroradiometry

Accurate spectroradiometry, even where only relative spectral power distributions are used, requires careful attention to detail. Factors which can affect accuracy include wavelength calibration, bandwidth, stray radiation, polarization, angular dependence, linearity, and calibration sources.[10]

V. Narrow Band Radiometry

Although spectroradiometry is the fundamental way to characterize the radiant emission from a light source, radiation output is normally measured by techniques of narrow band radiometry. Narrow band radiometers generally combine a detector (such as a vacuum phototube or a solid-state photodiode) with a wavelength-selective device (such as a color glass filter or interference filter) and suitable input optics [such as a quartz hemispherical diffuser or polytetrafluoroethylene (PTFE) window].

A. The Problem of Spectral Sensitivity

Naive users of narrow band radiometers often gain the impression from commercial literature that instruments are readily available to measure UVA, UVB, or UVC. In order to meet the criterion for a UVB radiometer, say, the sensor should have a uniform spectral response from 280 to 315 nm (the UVB waveband) with zero response outside this interval. In other words, the electrical output from the sensor should depend only on the total power within the UVB waveband received by the sensor and not on how the power is distributed with respect to wavelength. In practice no such sensor exists with this ideal spectral response (neither does one exist that measures UVA or UVC correctly for that matter). All radiometers that combine a photodetector with an optical filter have a nonuniform spectral sensitivity within their normal spectral band. This problem is discussed more fully in the next section using the calibration of dosimeters used in PUVA therapy as an example.

B. Calibration of Ultraviolet A Dosimeters Used in Psoralen Photochemotherapy (PUVA)

PUVA therapy — the combination of oral psoralens and long-wave ultraviolet radiation (UVA) — is widely used in the treatment of a variety of skin diseases, particularly psoriasis.[11] Most dermatology departments in the U.K. have PUVA units incorporating UVA fluorescent lamps.[12] The spectral emission (i.e., a plot of the intensity of radiation at each wavelength) of these lamps is remarkably similar no matter which make of PUVA unit is used. This spectrum is shown in Figure 2.

Shortly after the introduction of PUVA therapy in the early 1970s, the protagonists of the treatment stressed that "... *careful attention to dosimetry is essential and ... the dosimetry system is a key to both the effectiveness and safety of PUVA*". These authors[13] recommended that UVA exposure of the patient be expressed in radiometric units; the intensity (or irradiance) of the radiation beam is measured in milliwatts per square centimeter (mW/cm^2) and the prescribed dose (or radiant exposure) is expressed in Joules per square centimeter (J/cm^2). It is important to realize that all sensors that are used to measure UVA irradiance show a wavelength-dependent response (Figure 3) and so produce an electrical signal that depends not only on the irradiance from the optical source but also on its spectral emission.[14]

Despite these early recommendations subsequent intercomparisons of UVA dosimeters carried out in the U.K.,[15] Belgium,[16] and France[17] have shown wide variations in accuracy, with threefold differences in sensitivity at the extreme ends of the range. It is likely that inconsistencies in UVA dosimetry are a major factor in the tenfold range of doses prescribed at the start of treatment found in the U.K.[12]

So what do users do about calibration? Many dermatology centers with UVA dosimeters rely upon the initial calibration provided by the manufacturer. Yet it is not clear from the literature provided by some suppliers of UVA dosimeters used in PUVA therapy exactly *how* they calibrate their dosimeters — so what the meter reading in mW/cm^2 actually means is unclear. Other manufacturers calibrate their dosimeters with narrow band radiation around the peak spectral sensitivity. For the dosimeter with the spectral sensitivity shown in Figure 3 this would be at 360 nm. This means that the calibrated dosimeter would record the correct irradiance from a source emitting monochro-

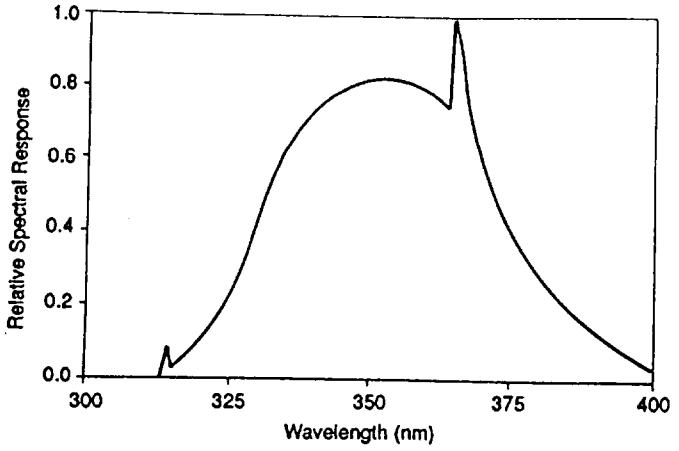

FIGURE 2 The spectral power distribution of UVA fluorescent lamps used in PUVA therapy. Lamps which have this spectrum include Philips TL85/100W/09, Philips TL100W/09 R-UVA, Philips UVA 100W-P, Sylvania F85/100W-PUVA, and Thorn UV 75/85W.

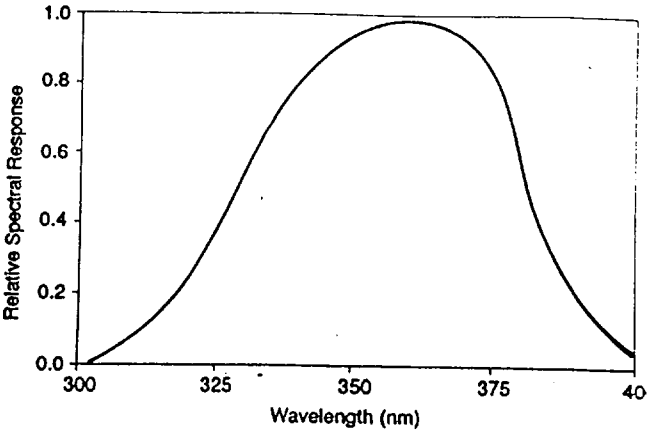

FIGURE 3 The spectral sensitivity of a typical UVA dosimeter Dosimeters with similar sensitivity include[9] the IL135 phototherapy radiometer (International Light Inc, Newburyport) PUVA meter, and UV meter (H Waldmann GmbH & Co. Schwenningen, Germany), Blak-Ray J221 and UVX-36 (Ultra Violet Products, Inc., San Gabriel), and Uvichek (Rank Hilger Margate, U.K.).

matic radiation at 360 nm but when irradiated with any other spectral power distribution, such as that shown in Figure 2, would indicate an irradiance that was different from the true UVA irradiance. Expressed mathematically, the true UVA irradiance is

$$\int_{315}^{400} E(\lambda)d\lambda \quad mW/cm^2 \tag{4}$$

whereas the meter would indicate

$$\int_{0}^{\infty} E(\lambda)S(\lambda)d\lambda \quad mW/cm^2 \tag{5}$$

$E(\lambda)$ is the spectral irradiance in $mW/cm^2/nm$ and $S(\lambda)$ is the relative spectral sensitivity normalized to unity at the wavelength (in this case 360 nm) where the dosimeter is most sensitive. Clearly these two quantities are numerically different unless $E(\lambda)$ is zero at all wavelengths other than 360 nm.

More enlightened users might ask national standards laboratories, such as the National Physical Laboratory in the U.K., to calibrate their UVA dosimeter. Unfortunately, a similar problem can exist. When UVA dosimeters are sent to standards laboratories for calibration, an optically filtered medium pressure mercury arc lamp is often used as the source. The spectral power distribution of this source is confined to a narrow band of radiation centered at 365 nm (one of the characteristic lines present in the mercury spectrum) and is very different from that shown in Figure 2. The consequence is that dosimeters calibrated in this way will underestimate the true UVA irradiance from UVA fluorescent lamps by about 25%.

If the purpose of UVA dosimetry is to measure the UVA irradiance to which patients are exposed and to record the UVA doses that patients receive, the logical approach is to calibrate dosimeters using lamps with the same spectral power distribution of radiation as those used for treatment.

The technique used in the author's laboratory is to measure the spectral irradiance at 20 cm from a bank of eight UVA fluorescent lamps (Philips TL20W/09N) using a spectroradiometer. It is important that users of spectroradiometers have their own standard lamps (either deuterium or tungsten) regularly calibrated by standards laboratories so that these can be used to provide an absolute spectral sensitivity calibration of the spectroradiometer. By summing the spectral irradiance across the UVA waveband (315 to 400 nm) the absolute UVA irradiance can be derived. Calibration of a UVA dosimeter simply involves removing the spectroradiometer, placing the entrance aperture of the sensor at the same point as the input optics of the spectroradiometer, and adjusting the meter display so that it reads the UVA irradiance determined spectroradiometrically.

VI. Broad Band Radiometry

Broad band radiometry uses a detector which responds equally to all wavelengths of optical radiation. The most common detector used is the thermopile and this is especially useful in measuring the irradiance from an irradiation monochromator used in the investigation of

skin photosensitivity.[18] Until a few years ago, commercial thermopiles were hand-made, expensive, and fragile devices. A major advance came with the production of multiple junction thermopiles based on thin-film technology. These devices are rugged and much less expensive and typified by the Dexter range of thermopiles (Dexter Research Center, Michigan) which have found a role in dermatological photobiology.[19,20]

A. Calibration

Thermopiles measure absolute radiant power and calibration can only be achieved satisfactorily by national standards laboratories, such as the National Physical Laboratory in the U.K.[21,22]

VII. Radiometer Stability

It should be remembered that the sensitivity of all radiometers will change with time; frequent exposure to high-intensity sources of light will accelerate this change. For this reason it is always a sound policy to acquire two radiometers, preferably of the same type, one of which has a calibration traceable to a national standards laboratory. This radiometer should be reserved solely for intercomparisons with the other radiometer(s) used for routine purposes. A measurement of the same source is made with each radiometer and a ratio calculated. It is the stability of this ratio over a period of months and years which indicates long-term stability and good precision.

VIII. Personal Ultraviolet Radiation Dosimetry

We have seen that UVR is generally measured with thermal or photon detectors, often used in conjunction with optical filters. A different yet complementary approach is the use of various photosensitive films as UVR dosimeters. The principle is to relate the degree of deterioration of the films, usually in terms of changes in their optical properties, to the incident UVR dose. The principal advantages of the film dosimeter are that it provides a simple means of integrating UVR exposure continuously and that it allows numerous sites, inaccessible to bulky and expensive instrumentation, to be compared simultaneously. Personal ultraviolet dosimetry can be useful in establishing the effect of photoprotective agents in the treatment of photosensitivity.[23]

A. Requirements of Personal UV Dosimeters

Ultraviolet dosimeters designed for personal use should have the following characteristics:

1. The physical or chemical change produced in the dosimeter (e.g., increase in optical absorbance) should, ideally, increase linearly with UV dose. If not, the dose response curve should at least be monotonic, that is, any given dosimeter response is effected by only one radiation dose.
2. The dosimeter should exhibit photoaddition; each wavelength acts independently and the effect of polychromatic radiation is the sum of the effects of all wavelengths involved.
3. The dosimeter response should depend only on dose and be independent of dose rate.
4. The spectral sensitivity of the dosimeter should, ideally, match the action spectrum of the photobiological effect being monitored.
5. The dosimeter response should be independent of temperature and humidity; it should exhibit no "dark effect" (continuing response when radiation exposure terminated); it should be stable on long-term storage.
6. The dosimeter should be easy to handle and not impose restrictions on the activities of the wearers.
7. The dosimeter should not require laborious processing and should be easy to convert the physical or chemical response to a measure of ultraviolet exposure dose.
8. The cost per dosimeter should be low so that large-scale monitoring is feasible.

B. Types of Personal UV Dosimeters

1. Polysulfone Film

Perhaps the most commonly used material for studies of personal UV dosimetry has been the thermoplastic, polysulfone, which was first suggested as a possible dosimeter for UVR by Davis et al.[24] Since then, the use of polysulfone film as a personal UV dosimeter has been exploited for monitoring both environmental and artificial UVR.[25] The basis of the method is that, when film is exposed to UVR at wavelengths less than 330 nm, its UV absorption increased. The increase in absorbance measured at a wavelength of 330 nm increases with UV dose. In practice the film (40 μm thick) is mounted in cardboard photographic holders and normally worn on the lapel site.

2. Plastic Films Incorporating Photosensitizing Drugs

In field studies of drug-induced photosensitivity the possibility of using a dosimeter which incorporates the relevant drug is an attractive proposition. To this end, several drugs which are known to have photosensitizing effects in humans have been incorporated as the chromophore in a polyvinyl chloride (PVC) film. Photoactive drugs which have been used in this way include phenothiazine,[26] 8-methoxypsoralen,[27] nalidixic acid,[28] and benoxaprofen.[29]

3. Diazo Systems

Diazo systems, which are based on diazonium compounds, are one of the oldest photochemical non-silver processes. The two fundamental properties of the diazo type process which make it suitable for use as a UV dosimeter are

1. the ability to be decomposed by ultraviolet radiation
2. the ability of the undecomposed diazonium compound to couple with a color former to produce a stable image

Diazonium compounds are sensitive principally to the UVA and blue regions of the spectrum. Their spectral sensitivity, together with the simplicity, economy, and convenience of the diazo system, have led to their use as film badge dosimeters for UVA and blue radiation.[30,31]

4. Photosensitive Papers

One drawback of the film dosimeters described above is that they require laboratory equipment to facilitate readout. An alternative approach is to use a system whereby the photochemical process initiates a color change so that visual comparisons with stable printed color standards enable the user to obtain a reasonably accurate and continuously readable integrated measure of his exposure to UVR. An example of a dosimeter based on this principle has been described by Zweig and Henderson.[32] This dosimeter is a polycarbonate film matrix incorporating a chromophore which converts to a red photoproduct following exposure to UVR of wavelengths less than 350 nm. The depth of red color developed depends solely on the radiant exposure.

Another type of photodosimeter is based on the reversible color change of photochromic aziridine formulations.[33] The colorless aziridine undergoes isomerization following ultraviolet exposure to form the blue-colored azomethine slide.

Photosensitive papers form the basis of dosimeters designed for consumer use while sunbathing.[34]

5. Thermoluminescent Materials

Several thermoluminescent (TL) materials have been investigated as possible UV dosimeters. Many materials (e.g., LiF:Mg; $CaSO_4$: Tm; CaF_2: natural) require pre-irradiation with high doses of gamma radiation and partial annealing before showing sensitivity to UVR (so-called "transferred thermoluminescence"), whereas other materials (e.g., MgO; Al_2O_3:Si; CaF_2:Dy) have proved to be directly sensitive to UVR. It is probably true to say that TL materials have yet to find an established role as dosimeters for UVR.

6. Polycarbonate Plastic

On exposure to UVR the transparent plastic, CR-39 (allyl diglycol carbonate), alters its optical properties. These changes are the basis of its use as UVR dosimeter.[35] After exposure the plastic is etched in 6 *N* KOH at 80°C for 3 hours, rinsed, and allowed to dry. The degree of UV dose-dependent front surface damage, visible as opacification, is quantified by measuring the transmission at 700 nm. A novel use of this material has been to construct CR-39 contact lenses which can be used for measuring ultraviolet exposure to the front surface of the eye.[36]

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