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CIE RESEARCH NOTE

DETERMINING ULTRAVIOLET ACTION SPECTRA

ABSTRACT:
DETERMINING ULTRAVIOLET ACTION SPECTRA

Background information on photobiological action spectra is provided as a general introduction to the five previously published research notes that appeared in the CIE Journal and are now conveniently republished as a **CIE COLLECTION in Photobiology and Photochemistry**. This note also provides current information on international guidance related to exposure to ultraviolet radiation, which supersedes earlier CIE recommendations regarding action spectra for photokeratitis and photoconjunctivitis.

ZUSAMMENFASSUNG:
BESTIMMUNG ULTRAVIOLETTER WIRKUNGSFUNKTIONEN

Hintergrundinformation über photobiologische Wirkungsfunktionen wird als allgemeine Einleitung zu den fünf Research Notes gegeben, die im CIE Journal erschienen sind und jetzt als **CIE COLLECTION in Photobiology and Photochemistry** neuerlich veröffentlicht werden. Dieser Artikel bietet auch aktuelle Informationen über internationale Richtlinien bezüglich ultravioletter Bestrahlung, die frühere CIE Empfehlungen über Wirkungsfunktionen für Photokeratits und Photokonjunktivitis ersetzt.

RESUME:
DETERMINATION DES SPECTRES D'ACTION ULTRAVIOLETS

D'autres informations sur les spectres d'action photobiologiques sont données comme introduction générale aux cinq Research Notes parus dans le CIE Journal, qui sont maintenant republiés comme **CIE COLLECTION in Photobiology and Photochemistry**. Cet article fournit également une information actuelle sur les guides internationals concernant le rayonnement ultraviolet, remplaçant les recommendations précédentes de la CIE portant sur les spectres d'action pour photokératite et photoconjonctivite.

1 INTRODUCTION

The purposes of this brief introductory note are to provide the reader with the fundamental concepts characteristic of all photobiological effects, to explain the difficulties of obtaining action spectra, to clarify the limitations of biological action spectra, and to update CIE recommendations regarding the use of "standard" photobiological actions spectra. This report is intended to provide background information which should be useful in interpreting the conclusions of two previous CIE research notes (106/2 and 106/3) [1, 2].

2 ACTION SPECTRA

In any quantitative description of a photobiological effect, it is absolutely critical to obtain the *action spectrum*. The action spectrum describes the relative effectiveness of monochromatic optical radiation to elicit a given biological response. The most familiar photobiological action spectrum is the CIE visual response function, V_λ, which forms the basis for the system of photometric units. However, photobiological action spectra exist for photokeratitis (an ultraviolet-induced inflammatory response of the cornea of the eye), erythema (sunburn), etc. In addition, an action spectrum is useful in optimizing the use of ultraviolet radiation (UVR) in any photochemical effect, such as UVR-curing of inks or paints.

This CIE Research Note was prepared by Division 6 Director, D. Sliney [US Army Environmental Hygiene Agency, Aberdeen Proving Ground, MD 21010-5422 USA.

Photochemical (including photobiological) effects have a fundamental characteristic that the interaction at the molecular level results from one photon interacting with one molecule to alter or break the molecule into two new molecular species. Since a certain minimum photon energy Q_v is required to produce the molecular alteration, any photochemical process necessarily will have a long-wavelength cut-off $\lambda_{cut\text{-}off}$ where photon energies are less than a critical value Q_{crit} and insufficient to cause the molecular change of interest, since:

$$Q_v = hc/\lambda \qquad [1]$$

where h is Planck's Constant (approximately $6{,}6 \times 10^{-34}$ J·s) and c is the velocity of light (approximately 3×10^8 m/s).

3 BUNSEN-ROSCOE LAW

A photochemical reaction will also exhibit *reciprocity* between irradiance (exposure dose rate) and exposure duration. This is termed the "Bunsen-Roscoe Law." That is, a given radiant exposure in J/m^2 is required to elicit a given response regardless of exposure duration over a wide range of exposure durations. Repair mechanisms, recombination over long periods and photon saturation for extremely short periods will lead to reciprocity failure. The product of irradiance E in W/m^2 and exposure duration t is the radiant exposure H in J/m^2, i.e.,

$$H = E \cdot t \qquad [2]$$

While both E and H may be defined over the entire optical spectrum, it is necessary only to weight these quantities over the extent of the action spectrum for photochemical effects.

4 EFFECTIVE IRRADIANCE AND RADIANT EXPOSURE

In the same manner that spectroradiometric measurements of a light source can be used to calculate photometric quantities such as illuminance by spectrally "weighting" the spectral irradiance by V_λ, so too can a source spectrum be "weighted" by other action spectra to calculate an "effective irradiance," which may be used to estimate the exposure duration necessary to produce the given effect. With modern computer spread-sheet programs, one can readily develop a method for spectrally weighting a source spectrum by a large variety of photochemical action spectra. These computations can be tedious, but straightforward and take the form:

$$E_{eff} = \Sigma E_\lambda \cdot A_\lambda \cdot \Delta\lambda \qquad [3]$$

where A_λ may be any action spectra of interest. One then can compare different sources to determine relative effectiveness of the same irradiance from several lamps for a given action spectrum.

5 PHOTOCHEMICAL VS. THERMAL EFFECTS

It is not uncommon for photochemical effects to be confused with thermal effects. For example, erythema ("sunburn") occurs after a critical radiant exposure as a result of a photochemical injury mechanism, rather than thermal injury, although one frequently senses warmth when exposed to sunlight. Two key factors distinguish a photochemical process from a thermal process. Thermal injury is a *rate process* and is dependent upon the volumic absorption of energy across the spectrum. By contrast, photochemical effects occur only over a given spectral range in accordance with an action spectrum and for a given threshold radiant exposure "dose."

6 PHOTOKERATITIS AND PHOTOCONJUNCTIVITIS

In the first two of the following CIE Research Notes, the action spectra for photokeratitis (inflammation of the cornea) and photo-conjunctivitis (inflammation of the surrounding conjunctiva) arereprinted. These two Research Notes provide a good review of the literature and present the range of published data [1, 2]. Both notes conclude with a recommended action spectrum for use by lighting engineers for each effect based upon these reviews. The Note, *Photokeratitis*, erroneously attributed support for the recommended action spectrum to the World Health Organization [3]. The Note, *Photoconjunctivitis*, proposes an action spectrum based on no biological data from ocular studies, but on an hypothesis that the conjunctiva should behave as the skin debrided of *stratum corneum*. Both notes implicitly assume that each effect has only *one* ("correct") action spectrum. This seems to be a very reasonable first assumption. However, because of different biological (or clinical) endpoints use to define the effect, multiple action spectra actually exist!

The confusion over multiple action spectra arises because the photobiologist must define an observational threshold for the effect in terms of the "grade" or degree of severity of the tissue response and must also specify the time of assessment. Furthermore, different optical examination aids and biochemical markers may be used in the assessment. All of these factors can lead to a different threshold at each wavelength; hence, a different action spectrum [3]. When the physical scientist is faced with what appears to be different action spectra from conflicting sources, he or she is most likely to assume that one action spectrum is in error because of improper radiometric measurements or other physical errors. This variation of action spectra based upon the time of assessment (e.g., 4 hours, 8 hours, 24 hours, 48 hrs, etc.) and intensity of skin redness was first shown very clearly for erythema by Hausser in 1929 [3, 4], and the lack of understanding of differing endpoints led to conflicting action spectra being published in the 1960s by several authors [5, 6]. For this reason, it has been necessary to derive a CIE reference erythema action spectrum [7], which is the third of the following republished notes. On the other hand, CIE Division 6 can no longer recommend the reference action spectra for ocular effects that were published in 1986. Since that time, other international bodies have recommended exposure limits which are more restrictive than in the Research Notes [8].

The differences in action spectra for photokeratitis exist largely because of different biological endpoints and also different responses for human and animal species used in the studies. The endpoint and threshold radiant exposures used by Cogan and Kinsey [9] and Pitts [10] differed. Pitts used a very sensitive threshold criteria which was a slight change in the number of vacuoles in the corneal epithelium (outermost layer of the cornea); whereas, Cogan and Kinsey used a more severe inflammatory response to term "threshold." Hence, it is not surprising that a lower threshold was reported by Pitts compared to Cogan and Kinsey. The latter action spectrum is more indicative of what the average person would sense as an uncomfortable keratitis; whereas, the Pitts' action spectrum probably provides the most sensitive endpoint for showing any effect. Hence the groups which have defined exposure limits (ELs) for safety have used the Pitts' action spectrum and thresholds for defining safety [8, 11]. As noted in the original CIE Research Note [1], the actual exposure of the human eye out-of-doors is frequently very close to the threshold dose reported by Pitts [10], but this does not disprove the data of Pitts. One must consider the eye's squint and the generally low reflectance of most terrain which greatly limit the chances of developing threshold photokeratitis [12].

New sources of UVR now exist which are being used to further define action spectra. The Argon-fluoride excimer laser was recently used to determine the threshold for photokeratitis at 193 nm for the rabbit cornea [12]. The threshold for a very mild form of photokeratitis characterized by a mild superficial corneal haze in the rabbit cornea has been found to lie between 1,0 and 1,5 J/cm^2 at 193 nm.

Further studies regarding repeated ocular exposures of the cornea and studies of lenticular damage all point to the need for limiting UVR exposure of the cornea below the levels cited in the 1986 Research Notes [1, 2], because of potentially additive effects [13-16].

7 CONCLUSIONS

The action spectra recommended previously [1, 2] probably define acute, clinically significant injury of the cornea and conjunctiva, and may be used to estimate the likelihood of experiencing this effect when exposed in a single incident to a source containing UVR. However, the reader is advised to consult other international guidelines for repeated human exposure to UVR. The UVR EL values promulgated by the