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Optical radiation

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Health-based exposure limits for electromagnetic radiation in the wavelength range from 100 nanometre to 1 millimetre

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GEZONDHEIDSRAAD

Health Council
of the
Netherlands

The Minister and the State Secretary for
Welfare, Health and Cultural Affairs
Sir Winston Churchilllaan 362
2284 JN RIJSWIJK

Subject : Advisory report Submission of recommendation
Your ref. : CDBI/B-U-2705, of 29 May 1990
Our ref. : U 319/WP/MK/259-S
Enclosure(s) : 1
Date : 22 June 1993

In his letter of 29 May 1990 no. CDBI/B-U-2705 the State Secretary for Welfare, Health and Cultural Affairs asked the Health Council, on behalf of the Minister of Social Affairs and Employment, to advise on the consequences of exposure to optical radiation. The relevant request of the Minister of Social Affairs and Employment was made by letter of 16 March 1990, no DGA/GS/90/03135. In the meanwhile the committee appointed for this purpose has submitted its report after having consulted the Standing Committee on Radiation Protection. Copies will also be sent to the Minister of Social Affairs and Employment and the Minister of Housing, Physical Planning and Environment.

Upon request of the committee and after discussing the draft report with the above mentioned standing committee brings the following to your attention.

The recommendations of the committee deviate on several points from the recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH) and of the International Radiation Protection Association (INIRC/IRPA).

With respect to ultraviolet radiation the proposals of the committee are simpler and therefore preferable. The committee feels that, regarding thermal damage to skin and eyes from visible and infrared radiation, the recommendations of the ACGIH and those of the INIRC/IRPA propose a safety margin that is needlessly wide and not necessary from a health point of view. This standpoint is based on sound scientific grounds and is in agreement with the recommendations, dated 1978, on 'Micrometer radiation' of the Health Council. Such measures could wrongly inhibit the development of new sources of radiation. Therefore I should like to ask you to take into consideration the committee's recommendations, not only in the development of Dutch policies related to the exposure of the general population or of groups in the population to optical radiation, but also when the topic is the object of deliberations at the

The Health Council of the Netherlands is a standing advisory body which was set up under the 1956 Health Act to assist the Government.
Its function is to provide the Dutch Government with objective information on scientific developments on all matters realating to health and environmental protection.
Reports are made by ad hoc committees of experts, appointed by the President of the Council.

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European level. An English translation of these recommendations is in preparation which could be of help in ensuring their dissemination.

(signed)

Dr L Ginjaar
President

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OPTICAL RADIATION

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HEALTH-BASED EXPOSURE LIMITS FOR ELECTROMAGNETIC RADIATION IN THE WAVELENGTH RANGE FROM 100 NANOMETRE TO 1 MILLIMETRE

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report from the Committee on Optical Radiation of the
Health Council of the Netherlands

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to

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the Minister and State Secretary of Welfare, Public
Health and Culture,

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the Minister of Social Affairs and Employment,

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the Minister of Housing, Physical Planning and
Environment

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report 1993/09E, The Hague, June 28, 1993

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This report is to be cited as:
Health Council of the Netherlands: Committee on Optical Radiation. Optical radiation. Health-based exposure limits for electromagnetic radiation in the wavelength range from 100 nanometre to 1 millimetre. The Hague: Health Council of the Netherlands, 1993. Report 1993/09E.

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TO THE READER

In this report the Committee on Optical Radiation of the Health Council recommends health-based exposure limits for optical radiation. The report revises and replaces the recommendations of the Health Council from 1978. In presenting this report to the President of the Council the committee considers it mission to be fulfilled.

The Hague, June 28, 1993
on behalf of the committee,

(signed)

Dr WF Passchier, scientific secretary	Dr JJ Vos, chairman

Prof Dr D van Norren,
scientific secretary

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SUMMARY

Optical radiation

Optical radiation comprises infrared radiation, light and ultraviolet radiation. It is a form of electromagnetic radiation with wavelengths between 1 millimetre and 100 nanometres. The main source of optical radiation is the sun. Examples of artificial sources of optical radiation are radiators, halogen heaters and lamps, light bulbs, fluorescent tubes and various types of lasers. Excessive exposure to optical radiation can damage health. The levels at which this happens and the effects that occur are the subject of this report. Possible health-promoting effects of optical radiation are not considered.

Health-based exposure limits

This report, requested by the Minister of Social Affairs and Employment and drawn up by a committee of the Health Council, recommends health-based exposure limits for optical radiation, i.e. the maximum levels of exposure which do not present a health hazard. Keeping radiation levels below this limit prevents damage to health, except perhaps in hypersensitive people. The recommended exposure limits are distinguished according to the type of harmful effect and the effect on skin and eyes. It suffices to consider the effect on these two organs since optical radiation penetrates biological tissues only to a limited extent. Light (visible radiation with wavelengths between 400 and 780 nanometres) is an exception to this rule since it passes through the eye almost without attenuation and is absorbed by the retina.

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Health-based exposure limits, such as recommended in this report, may be used as a basis for protection regulations. The competent authorities, e.g., may establish maximum permissible exposure levels. Also, the recommended limits can be used to establish product standards for radiation sources and personal protection devices, such as safety goggles.

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Earlier Health Council reports

The present report constitutes a revision of the report on micrometre radiation published by the Health Council in 1978. The health-based exposure limits now recommended replace the 'acceptable radiation levels' from the earlier report; in several cases they are identical. The recommendations in the Health Council's 1986 report on ultraviolet radiation are also taken into account.

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Spectral weighting functions

The committee expresses the recommended health-based exposure limits in terms of the total radiant exposure, irradiance, time-integrated radiance or energy influx. In general it assumes that the contributions of radiation of different wavelengths may be regarded as mutually independent. This allows the dependence of the exposure limits on wavelength to be expressed as a spectral weighting function. The equation is as follows:

$$\sum_{\lambda} (A_{\lambda} \times X'_{\lambda} \times \Delta\lambda) \leq X_{A} \, .$$

In this equation X represents the measure of exposure (e.g. the radiant exposure H), in which the health-based exposure limit X_A is expressed. The spectral value of X (X'), averaged over a narrow wavelength band $\Delta\lambda$ at wavelength λ, should be 'corrected' by the weighting function A_λ before a comparison can be made with the exposure limit. The function A_λ represents the spectral dependence of the effectiveness of the radiation to induce the effect considered. The sum comprises the entire relevant part of the radiation spectrum.

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Erythema, damage to the cornea and conjunctiva

The committee recommends one exposure limit for erythema and damage to the cornea and conjunctiva in the eye (keratitis and conjunctivitis). This type of damage is caused by ultraviolet radiation (180 to 400 nm). The health-based exposure limit H_λ for the radiant exposure at a wavelength of 270 nm is 30 J/m^2 for exposure during a maximum of one day. At other wavelengths the exposure limit for the radiant exposure is equal to $30/Y_\lambda$ J/m^2. This limit is expressed in the following equation:

$$\sum_{\lambda} (Y_\lambda \times H'_\lambda \times \Delta\lambda) \leq 30 \text{ J/m}^2 .$$

The values of Y_λ are given in table 7.1. he committee does not make recommendations for wavelengths from 100 to 180 nanometres, as the relevant data are not available. In practice, this has no serious consequences since there are no current sources of radiation in this range which are in common use, and since the radiation is largely absorbed by the air.

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Thermal damage to skin and cornea

For thermal damage to skin and cornea, the exposure limits can be expressed in terms of the radiation dose as follows:

$$H_\lambda = 50/T_\lambda + 5.5 \times 10^3 \ (t)^{0.25} + 10^3 t \ [\text{J/m}^2] \ (t \text{ in s}) .$$

In this equation t is the exposure time. The spectral weighting function T_λ, that represents the wavelength dependence of the recommended exposure limit for the radiant exposure, is given in table 7.2 and is derived from the penetration depth of the radiation in tissue. In the 600 to 1900 nanometre range, different T_λ values apply for skin and eye. These exposure limits agree with those in the 1978 report.

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For short exposure times (less than 1 microsecond), the exposure limit is determined entirely by the penetration depth. For long exposure times (greater than about 1 minute), the exposure limit is independent of the wavelength and is equal to an irradiance of 1 kW/m^2.

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Cataracts

For cataracts, the committee recommends a health-based exposure limit expressed in terms of irradiance. This is a value of 0.25 kW/m^2 for ultraviolet radiation between 350 and 380 nanometres. At other wavelengths λ the recommended exposure limit for irradiance is 0.25/G_λ kW/m^2. The equation is:

$$\sum_{\lambda} (G_\lambda \times E'_\lambda \times \Delta\lambda) \leq 0.25 \text{ kW/m}^2 .$$

The spectral weighting function G_λ is given in table 7.3.

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Damage to the retina

Thermal damage to the retina (retinal burn) occurs mainly in the wavelength range from 300 to 1400 nanometres (1.4 micrometres). Here, also there is a complicated dependence on wavelength and exposure time. In addition, a distinction should be drawn between 'point sources' and 'extended sources', this being done empirically with the help of a critical viewing angle. The relation between the critical angle and exposure time is shown in figure 7.5.

For point sources and short exposure times (less than 1 microsecond), the exposure limit for radiant exposure at the cornea at 550 nm is equal to 0.006 J/m^2. For longer exposure times (greater than 1 s), the committee recommends an exposure limit for irradiance of 20 W/m^2 at the same wavelength. This exposure limit is expressed in the following equation:

$$\sum_{\lambda}(F_{\lambda} \times H'_{\lambda} \times \Delta\lambda) \leq 0.006+20t \quad [\mathrm{J/m^2}] \quad (t \text{ in s}).$$

The function F_{λ}, that represents the wavelength dependence of the recommended exposure limit for the radiant exposure, is given in table 7.4; t is the exposure time.

For extended sources, the exposure limit for time-integrated radiance is 1 kJ/($\mathrm{m^2}$×sr) for short exposure times (less than 1 microsecond) at a wavelength of 550 nanometres; the exposure limit for radiance is 100 kW/($\mathrm{m^2}$×sr) for long exposure times (greater than 1 second) at a wavelength of 550 nanometres. This exposure limit is expressed in the following equation:

$$\sum_{\lambda}(F_{\lambda} \times L{*}'_{\lambda} \times \Delta\lambda) \leq 10^3+5\times10^4 t^{1/3} \quad [\mathrm{J/m^2 \times sr}] \quad (t \text{ in s}).$$

In addition to retinal burn, optical radiation in the ultraviolet and visible ranges can also cause photochemical damage to the retina ('blue light' damage). In this case, the committee recommends a health-based exposure limit for time-integrated radiance of 10^6 J/($\mathrm{m^2}$×sr) at 440 nanometres; at other wavelengths the health-based recommended time-integrated radiance limit is $10^6/B_{\lambda}$ J/($\mathrm{m^2}$×sr). The integration time here is 1 day. This exposure limit is expressed in the following equation:

$$\sum_{\lambda}(B_{\lambda} \times L_{\lambda}{*}' \times \Delta\lambda) \leq 10^6 \quad [\mathrm{J/(m^2 x sr)}].$$

The function B_{λ}, that represents the wavelength dependence of the exposure limit for 'blue light' damage, is given in table 7.5.

People who have had the lens of their eye removed and do not have an implanted lens which absorbs ultraviolet radiation are not protected by this exposure limit. For them, the committee recommends using, instead of the function B_{λ}, a weighting function A_{λ}, which is also given in table 7.5.

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Skin cancer and retina damage in the long term

Two forms of damage have not been included in the recommendations of the committee. It is difficult to give a health-based exposure limit for an increased risk of skin cancer resulting from exposure to ultraviolet radiation. In this case, no threshold can be given below which such an increase could be ruled out for the majority of the population. The committee, however, points out that, as far as exposure to artificial sources is concerned, observing the recommended exposure limits leads to radiant exposures lower than those encountered by people who normally work outdoors or spend their leisure time in the sun.

There is evidence that damage to the retina can also occur from long-term exposure to relatively low radiation levels (especially light). In the committee's opinion, knowledge of this 'visual pigment' damage is not yet sufficient to allow health-based exposure limits to be established.

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Recommendations by other organisations

The committee took into account the proposals made by other organisations, especially the American Conference of Governmental Industrial Hygienists (ACGIH), the International Electrotechnical Committee (IEC) and the International Non-Ionising Radiation Committee of the International Radiation Protection Association (IRPA). It adopted the recommendations of these organisations where it considered them to be scientifically sound. On certain points, however, the committee believed that it had solid arguments for pursuing an independent course. This is discussed in chapters 7 and 8 of the report.

The committee wants to point out that in some instances the recommended exposure limits from the other organisations mentioned imply an excessive safety margin with no scientific basis. This may hamper unnecessarily, at least from a public health point of view, the development of useful radiation sources.

1 INTRODUCTION

1.1 Problem definition and committee

On May 29, 1990 the State Secretary for Welfare, Public Health and Culture, acting on behalf of the Minister for Social Affairs and Employment, asked the President of the Health Council to review the Council's report on micrometre radiation, issued in 1978. The State Secretary's request is reproduced in appendix A to this report.

In response to this request the President of the Health Council appointed the Committee on Optical Radiation on June 19, 1990; this committee will be referred to in this report as 'the committee'. Its membership is listed in appendix B. The chairman of the committee and some of its members had also contributed to the 1978 report on micrometre radiation.

1.2 Background

The advisory report on micrometre radiation of the Health Council

In 1978 the Health Council published a report on the 'acceptable levels for exposure to electromagnetic radiation with wavelengths from 100 nm to 1 mm (micrometer radiation)' (GR78). This report presented an overview of the hazardous biological effects of human exposure to electromagnetic radiation in the wavelength range indicated. As the term 'micrometre radiation', introduced in the 1978 report, did not become generally accepted, the more common term 'optical radiation' is used here.

The 'acceptable exposure levels' from the 1978 report were based on the knowledge of threshold levels at that time. Keeping exposures below these levels was assumed to prevent damage to skin and eyes from unintended exposure. The exposure limits did not apply to the use of ultraviolet sources or lasers for medical treatment. In the present report the term 'health-based exposure limits' will be used; this corresponds to the former 'acceptable exposure levels'.

The committee responsible for the 1978 report proposed that its recommendations be reviewed after a five-year period. This was deemed necessary as the development of optical radiation sources and research into the health effects of exposure to optical radiation were in full swing at that time.

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New data on the effects of exposure to optical radiation

In the 1980s new information indeed became available, especially about the consequences of exposure of skin and eyes to ultraviolet radiation, on heat cataracts in the lens of the eye and on light damage to the retina.

In 1986 a committee of the Health Council published a report on ultraviolet radiation (GR86). This report may be considered as a partial update of the 1978 report on micrometre radiation and outlines the effect of ultraviolet radiation on the human body. The report contains recommendations for the safe use of suntanning equipment, the functioning of which is based on exposure to ultraviolet radiation. The present report will draw heavily on the conclusion in the 1986 report in sofar as radiation with wavelengths smaller than 400 nm is concerned. The interaction between UV radiation and the immune system and the role of UV exposure in the induction of malignant melanoma will be reported on by the Health Council in a separate publication.

New insights in the mechanisms of cataract formation necessitate an update of the 1978 report in this respect. The study of the effects of chronic exposure of the retina to radiation with wavelengths above 400 nm produced new data on no-effect levels and new theoretical concepts.

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1.3 New report

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Nature

In the 1978 report the establishment of 'acceptable exposure levels' for protection against optical radiation was deemed necessary as new and ever more intense sources, lasers in particular, appeared on the market. The sensory warning mechanisms will not always provide sufficient protection against radiation from such sources.

The government has not promulgated official norms for exposure to optical radiation, whether for exposure at the work place, or for environmental exposure. The 1978 report was thus not a basis for setting official protection standards, but was used in the field as an information source about possible health effects and provided a basis for protection measures. The committee expects that the present report will at least play a similar role. Furthermore, an English edition of the 1978 report was used in the international discussion on protection standards (GR79).

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Acceptable levels and health-based exposure limits

'Health-based exposure limit' in the present report is synonymous with the term 'acceptable level' used in the 1978 report. As the latter term is often used for a legal standard, which is the result of not only scientific, but also political judgement, the present committee prefers to avoid this term.

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Structure

The committee restricts its discussion to biological effects of optical radiation that may damage health and may be relevant for determining health-based exposure limits. Effects that promote health (or may be instrumental in this respect) will not be considered here.

The committee will frequently refer for details to the 1978 report on micrometre radiation and the 1986 report on ultraviolet radiation (both reports have been translated into English). This applies especially to those effects and exposure-effect relationships that are essentially unchanged since the publication of the earlier reports.

In chapter 2 the committee starts with definitions of several physical and biophysical quantities. Chapter 3 provides an overview of the interactions of optical radiation with biological tissues. In chapter 4 the committee discusses skin effects in more detail; chapter 5 is devoted to eye effects in general and chapter 6 to retinal damage in particular. Chapter 7 contains the recommended health-based exposure limits. The report ends with a chapter (8) containing some general remarks on the application of the exposure limits and a few examples of safety calculations.

2 QUANTITIES AND UNITS

In this chapter the committee defines several physical and biophysical quantities that will be used in subsequent chapters. Table 2.1 presents an overview of quantities, symbols and units.

Electromagnetic radiation

This reports discusses the possibly hazardous effects of optical radiation on organs and tissues. Optical radiation is a form of electromagnetic radiation. Electromagnetic radiation is characterised by its frequency (f) or its wavelength in vacua (λ). There is a simple relation between the two quantities, as expressed by:

$$f = c/\lambda.$$

in which $c = 3\times10^8$ m/s (velocity of light in vacua). The various types of electromagnetic radiation are grouped according to frequency and wavelength in figure 2.1. Optical radiation has wavelengths between 100 nanometre and 1 millimetre and comprises infrared radiation, (visible) light and ultraviolet radiation. Ionising electromagnetic radiation (X- and gamma rays) has shorter wavelengths and microwaves, radio- and radarwaves have longer wavelengths than optical radiation.

A radiation source usually emits a broad spectrum of radiation with various wavelengths and intensities. The relation between intensity and wavelength is termed radiation-spectrum. Laser radiation consists of radiation with one or a

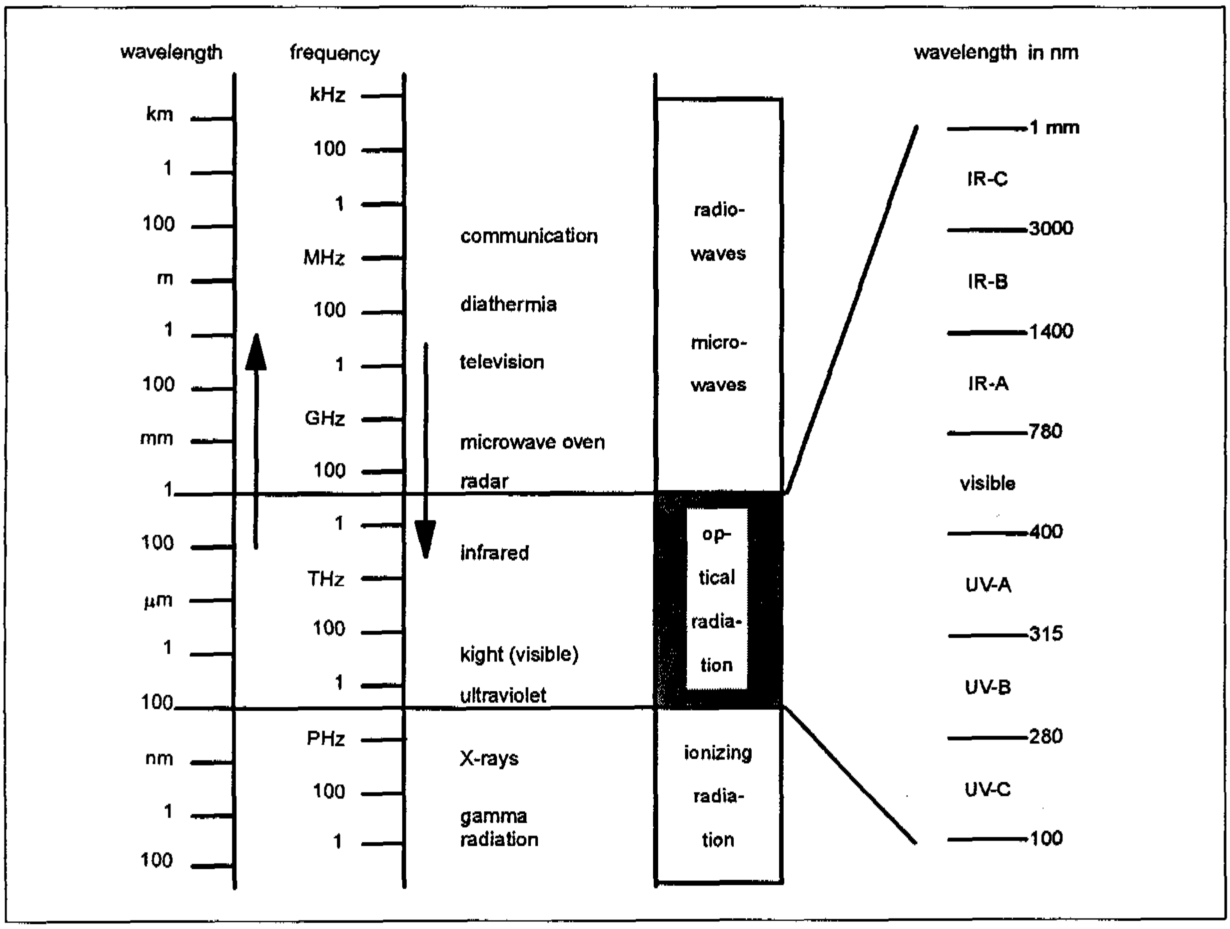

Figure 2.1. The electromagnetic radiation spectrum with some applications (Source: CIE87).

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few wavelengths (line spectrum). The radiation at a given location in space may differ from that near the source, depending on the absorption, scattering and re-emision of the emitted radiation (e.g. in air).

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Scattering, reflection, absorption, fluorescence

When radiation comes into contact with a body (e.g. with skin or eye) its direction of propagation, its intensity and its wavelength may change. After scattering it is usually only the propagation direction that changes. Reflection can be considered as a special case of scattering at surfaces. The amount of radiation energy reflected depends on the wavelength.

Absorption implies transfer of radiation energy. The transferred energy may initiate chemical reactions (at extremely high intensities the molecules may disintegrate), but may also be converted into heat, which may be dissipated as radiation with a wavelength longer than the original one (heat radiation). Also, the radiation may be converted directly into electromagnetic radiation with a greater wavelength (fluorescence).

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Classification

In a discussion of biological effects optical radiation is often classified according the extreme right column of figure 2.1. However, the effects do not change abruptly from one region to another, which means that the classification is a rather arbitrary one.

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Irradiance, radiant exposure and radiance (CIE87)

The intensity of the radiation to which skin or eye is exposed is expressed as irradiance. It is the energy transported by the radiation which reaches a given surface per unit time and unit area. The SI unit is W/m^2 and the commonly used symbol is E. Integration of the irradiance over a given period results in a radiant exposure with the unit J/m^2 and the common symbol H.

The radiance L is the energy transported per unit time by a radiation beam per unit of solid angle in a given direction. Its unit is W/(m^2×sr), where sr is steradian (SI unit of solid angle). The time integral of the radiance will be denoted in this report as the time integrated radiance; symbol L^* and unit J/(m^2×sr).

In the case of lasers the irradiated surface area may be so small, especially in irradiation of the retina, that total energy (symbol Q, unit J) rather than radiant exposure is the quantity that determines the biological effects.

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Spectral effectiveness (action spectrum

The total irradiance in a wavelength range S is given by the expression:

$$E = \int_S E'(\lambda)\, d\lambda\,.$$

In this expression $E'(\lambda)d\lambda$ is the irradiance in a small wavelength interval $d\lambda$ at wavelength λ; $E'(\lambda)$ is the spectral irradiance (commonly used unit: W/(m^2×nm)). The irradiance (or the radiant exposure) is often used to quantify the biological effectiveness of the radiation. However, this effectiveness may vary with the wavelength. This can be taken into account by defining a so-called effective irradiance $E_{eff,g}$ for biological effect g:

$$E_{eff,g} = \int_S s_g(\lambda)\, E'(\lambda)\, d\lambda\,.$$

The function $s_g(\lambda)$ is the so-called spectral effectiveness function or action spectrum for effect g. The above expression is usually written as a sum instead of an integral:

$$E_{eff,g} = \sum_i s_{g,i} E'_i \Delta\lambda_i$$

$s_{g,i}$ is the average value of the function $s_g(\lambda)$ in a wavelength interval $\Delta\lambda_i$ at wavelength λ_i and E'_i is the average irradiance in the same interval.

The function s_g is somewhat arbitrarily normalised to 1 at a given reference wavelength. Describing biological effects of optical radiation by a spectral effectiveness function only makes sense if the effects of radiation at different wavelengths are additive.

The effective radiant exposure $H_{eff,g}$ for effect g can be defined analogously:

$$H_{eff,g} = \int_S s_g(\lambda) H'(\lambda) d\lambda\,.$$

or

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$$H_{eff,g} = \sum_i s_{g,i} H'_i \Delta\lambda_i \,.$$

The introduction of the effective radiant exposure is only meaningful if the effect is independent of the variation of the irradiance with time during a given exposure.

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The committee present its health-based exposure values in terms of spectral weighting functions that are comparable to the spectral effectiveness functions $s_g(\lambda)$. The weighting functions are listed in table 2.1 and further discussed in chapter 7.

Table 2.1. Overview of quantities, units and commonly used symbols discussed in chapter 2.

quantity	symbol	unit
wavelength	λ	m[$]
energy	Q	J
irradiance	E	W/m^2
spectral irradiance	E'_λ	$W/(m^2 \times m)$ [$$]
radiant exposure	H	J/m^2
spectral radiant exposure	H'_λ	$J/(m^2 \times m)$ [$$]
radiance	L	$W(m^2 \times sr)$
spectral radiance	L'_λ	$W(m^2 \times sr \times m)$ [$$]
time integrated radiance	L^*	$J/(m^2 \times sr)$
equivalent penetration depth of skin and eye (table 4.1)[$$$]	d_e	m[$]
weighting functions for		
- photochemical damage to skin, cornea and conjunctiva	Y_λ	
- thermal damage to skin and cornea table 7.2	T_λ	
- cataract table 7.3	G_λ	
- retinal burn table 7.4	F_λ	
- 'blue light'-damage to the retina table 7.5	B_λ	
- 'blue light'-damage to the retina of aphakes and pseudophakes table 7.5	A_λ	

[$] In this report usually in nanometres (nm) or micrometres (μm).

[$$] Instead of per m, usually per nm.

[$$$] See chapter 4.

3 OVERVIEW

3.1 Optical radiation

The wavelength range from 100 nm to 1 mm can be considered as a separate domain within the electromagnetic radiation spectrum (figure 2.1). The nature of the sources and of biological effects of optical radiation gives this domain it special character. Optical radiation on the short wavelength side will affect tissues through photochemical mechanisms, resulting in sunburn as an example. At the longer wavelengths the effect is a thermal one, which may lead to (bio)chemical reactions.

In this report the committee discusses the effects of exposure to optical radiation with wavelengths greater than 180 nm. Data on the effects of exposure to radiation with shorter wavelengths are scarce. Also, there are no common sources that emit radiation in this wavelength region and, furthermore, radiation with wavelengths shorter than 180 nm is strongly absorbed by air. Therefore, absence of exposure limits for the 100 to 180 nm region will have no important consequences for public health.

The optical region is bordered by the X-ray-region on the short wavelength side and the microwave region on the long wavelength side. Both X-rays and microwaves penetrate to relatively great depths in the human body: from a few millimetres to full penetration. Optical radiation, on the contrary, penetrates no further than the superficial tissue layers of the body: from a few micrometres to no more than a few millimetres. This is represented schematically in figure 3.1 for skin. The same applies to the eye, with the exception of the penetration

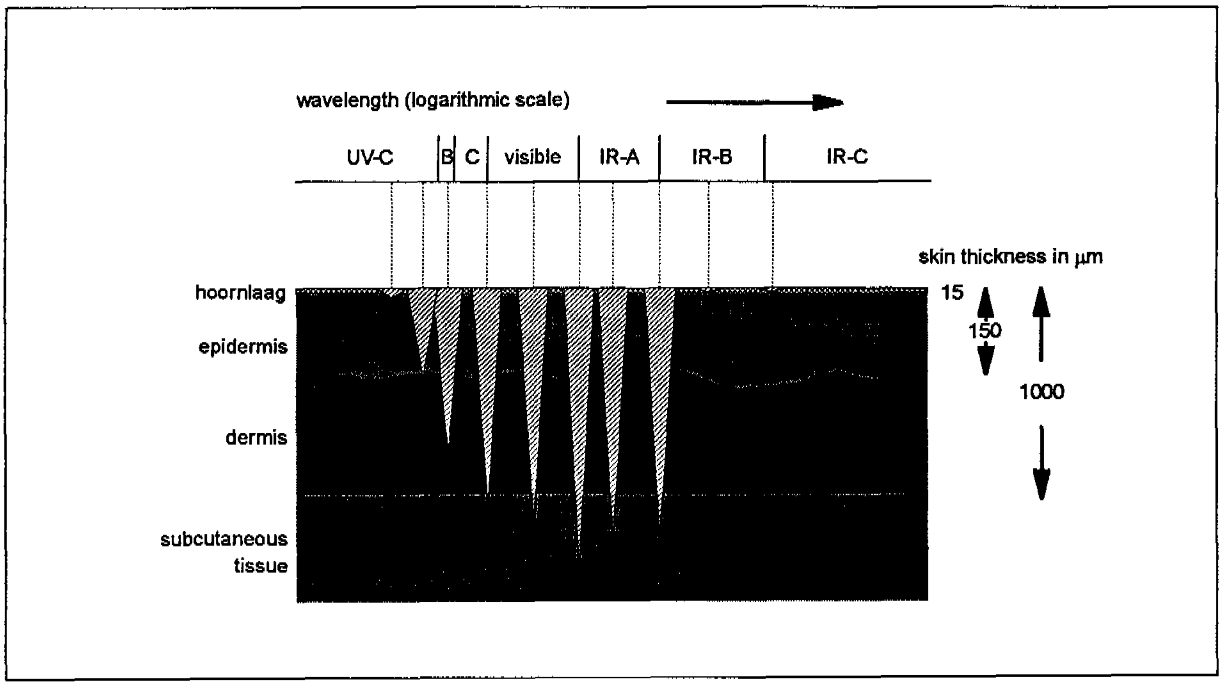

Figure 3.1. Schematic picture of the transmission of optical radiation by the layers of the skin. The penetration depths depicted correspond roughly with an attenuation of 99%. The stratum corneum, epidermis and dermis have not been drawn to scale. (Source: Gie76 and Par78).

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of visible radiation. In this case, however, the retina is to be considered as the effect-determining tissue surface, but with 'ancillary optics' . These 'ancillary optics' - cornea, lens and iris - may also be damaged by radiation exposure.

The most important optical radiation source is the sun. The radiation spectrum at the earth's surface is illustrated in figure 3.2. In the atmosphere, part of the short wavelength ultraviolet radiation is absorbed by ozone. Infrared radiation is absorbed by water vapour and carbon dioxide. Examples of artificial optical radiation sources are: radiation heaters, halogen sources for heating and lighting, incandescent lamps, gas discharge tubes with or without a fluorescent coating (neon lights, sodium street lighting and 'fluorescent lights) and various types of lasers.

All these sources are typical of the optical region. Shorter wavelength radiation is typically emitted by X-ray

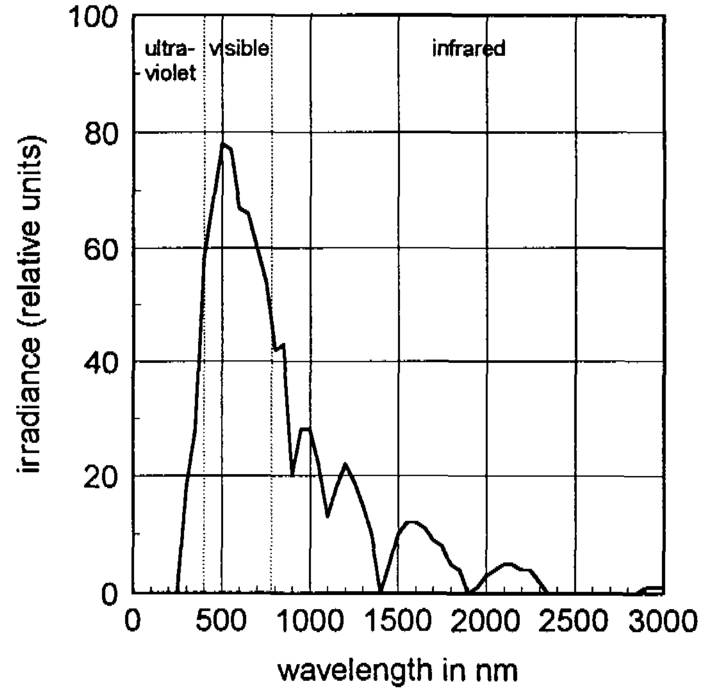

Figure 3.2. Radiation spectrum of the sun at the earth's surface. The irregularities are caused by wavelength-dependent absorption of radiation by ozone, oxygen, water vapour and carbon dioxide in the atmosphere (Source: Gie76).

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tubes and radioactive substances. In the microwave region magnetrons and klystrons are characteristic sources

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3.2 Effects

The transfer of radiation energy to tissue triggers several processes. Their nature depends on wavelength, intensity and exposure time. The subsequent effects can be classified as photomechanical, photochemical and thermal.

Photomechanical effects are induced by very high values of irradiance, such as produced by sub-microsecond laser pulses. Some surgical techniques are based on these effects, but they will not be considered in this report as health damage from photochemical and thermal effects already occurs at much lower levels of exposure. As these effects determine the health-based exposure limits, the limits will therefore also offer protection against photomechanical effects.

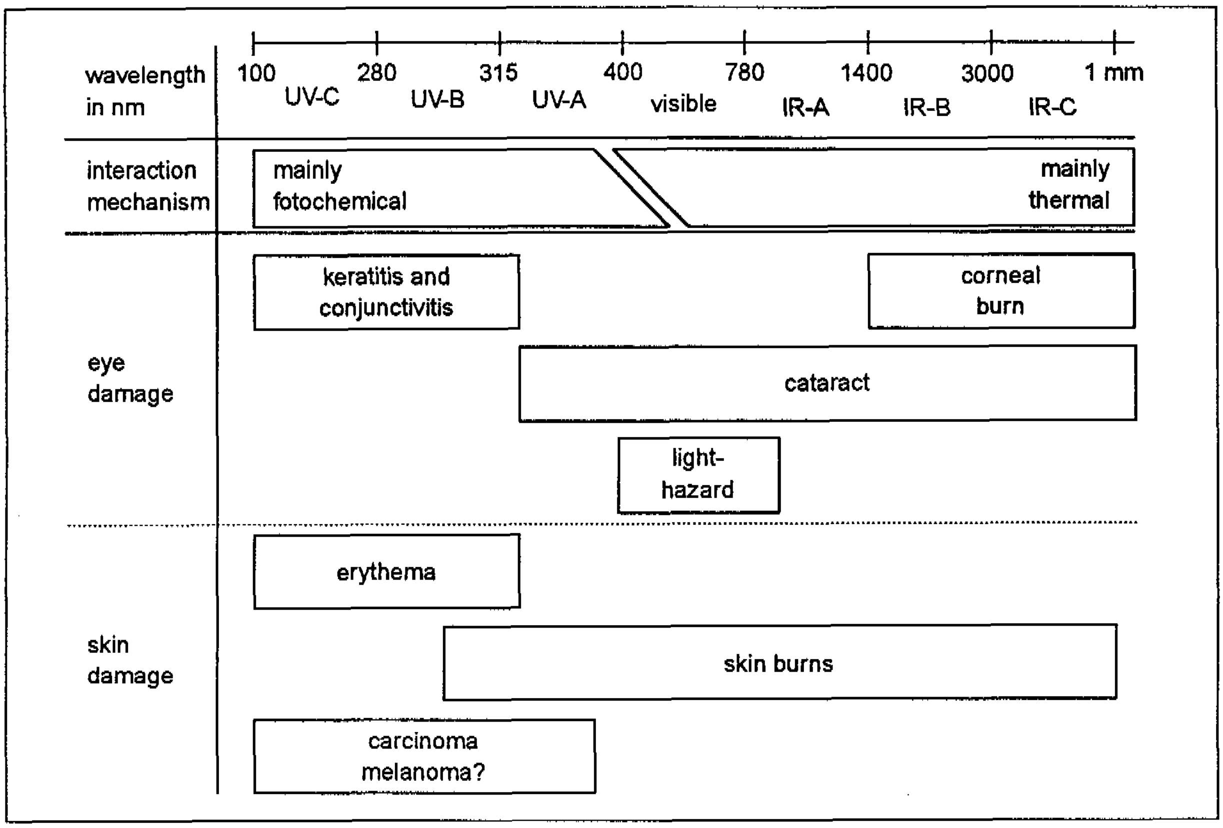

Figure 3.3. Overview of the photochemical and thermal effects of optical radiation in tissue as a function of the wavelength. The role of UV radiation in inducing melanoma is not well understood. (Source: Sli85).

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Photochemical reactions lead to changes in molecular structure through the absorption of radiation energy. Photokeratitis and erythema may result from these changes. Photochemical interaction also plays a role in the production of vitamin D through irradiation of the skin by the sun and by the visual perception of light. The first step in the latter process is the absorption of visible radiation by the light sensitive elements in the retina. Excessive exposure to light can result in permanent damage to the retina.

The absorbed radiation energy may also be converted into heat. The temperature rise of the tissue depends on the amount of energy absorbed and on the irradiated volume and the exposure time. Heat will either be lost to the environment by convection, evaporation and radiative processes or, by conductive processes, to surrounding tissue from which it is carried away by circulating blood. The smaller the irradiated surface and the longer the exposure time, the more important is this effect of conduction loss on the maximum temperature rise. The temperature rise may cause cell death. The death of a few cells, however, need not affect the functioning of the organism as a whole. A prolonged temperature rise of large parts of organs beyond 42 °C can, however, be seriously damaging.

With photochemical effects there is a time lapse between the interaction of the radiation with tissue and the manifestation of tissue damage. Thermal effects, on the other hand, are usually observed directly after the exposure.

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Figure 3.3 presents an overview of the most important effects as a function of the wavelength.

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4 EFFECTS IN THE SKIN

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4.1 Introduction

In this chapter the committee discusses the photochemical and photothermal effects of absorption of optical radiation in the skin. Harmful photochemical effects, predominantly caused by exposure to UV radiation, include erythema (sunburn) and an increased chance skin cancer. Photothermal effects range from a slight heat perception to serious burns and permanent skin damage; the nature of the effect depends on the maximum temperature increase, the exposure time and the area of skin surface exposed.

The interaction of UV radiation with the skin induces thickening of the epidermis and tanning and in this way protects the skin against the effects of subsequent exposures. Furthermore, UV radiation induces the production of vitamin D. Infrared radiation may have a healing effect due to local heating. These and other positive health effects are not dealt with in this report.

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In paragraph 4.2 the committee discusses the induction of erythema by UV radiation. Effects of chronic UV exposure are dealt with in section 4.3. In describing the effects of exposure to UV radiation the committee draws heavily on the Health Council report from 1986 (GR86). Thermal damage is the subject of paragraph 4.4.

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4.2 Erythema

Erythema is commonly called 'sunburn' ('sunburn' includes erythema, skin peeling, pain, itching and possibly blistering due to radiation from the sun). A few hours after a supra-threshold UV exposure the skin reddens because of dilation of the blood vessels in the skin. Radiant exposures that are incurred within an 8-hour period 'add up' with respect to the occurrence of erythema. With longer time intervals between subsequent exposures the effect of earlier exposures is much less or negligible. Moreover, the earlier exposure may result in thickening and tanning of the epidermis, which increase the erythema threshold radiant exposure (skin thickening is especially effective in this respect). Erythema usually disappears within a few days. The phenomenon is accompanied by irritation and a sensation of burning, and may be followed by blistering and peeling. Radiant exposures much greater than the threshold dose - which may occur on a sunny beach - may even be life threatening.

The minimum radiant exposure to induce erythema depends on the wavelength and skin sensitivity. It has been shown that UV-C and UV-B are much more effective to induce erythema than UV-A radiation. Erythema from sun exposure is mainly due to the UV-B component in the radiation from the sun (the amount of UV-C radiation in sunlight at the earth's surface is practically nil).

The 1986 report on UV radiation presents the research data on the minimum erythema dose at different wavelengths (GR86). Little is known as to the extent to which polychromatic radiation is as effective as monochromatic radiation to induce erythema.

Additivity over the spectrum is not inconsistent with the data available. In that case the radiation spectrum can be weighted with a spectral effectiveness function or action spectrum. This allows erythema-effective irradiance and erythema-effective radiant exposure levels to be derived (see chapter 2). The action spectrum is given by the reciprocal value of the minimum erythema dose.

The erythema action spectrum has been discussed extensively in international committees. Figure 4.1 shows the action spectrum recommended by the Health Council of the

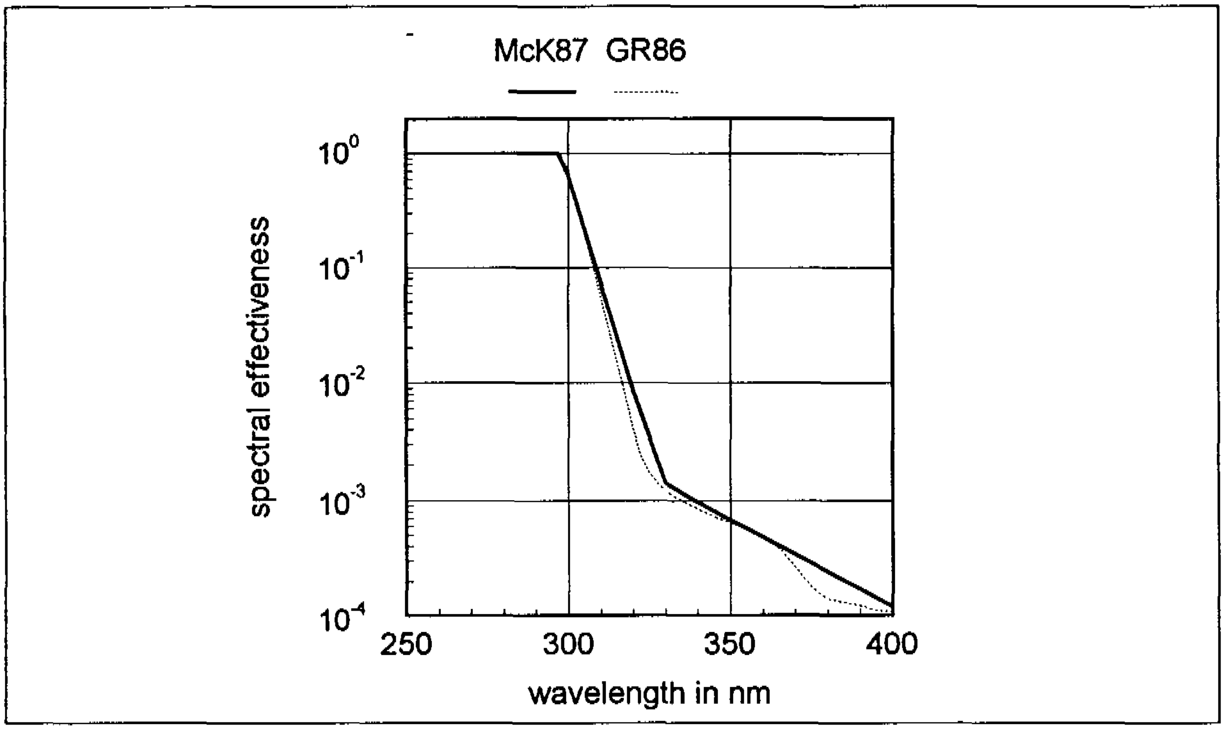

Figure 4.1. Erythema action spectrum, as proposed by the Health Council of the Netherlands (GR86) and by McKinlay (McK87).

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Netherlands in 1986 and that presented by McKinlay (McK87). The latter, that does not differ essentially from the 1986 Health Council recommendation, has been accepted by the Commission Internationale de l'Eclairage and the International Electrotechnical Committee (officially accepted so far only by the IEC; the action spectrum is also incorporated in the European Standard EN 60335-2-27). From a scientific point of view, the committee has no objections to a change to the McKinlay spectrum. The figure shows that the erythema action spectrum was normalised to 1 at a wavelength of 297 nm.

The minimum erythema dose varies between individuals. International commissions have reached consensus on a reference value for this quantity, the so-called MED. The MED based on the McKinlay action spectrum corresponds to an erythema-effective radiant exposure of 250 J/m^2 (this value is in reasonable agreement with the 200 J/m^2 that was proposed by the Health Council in 1986). The MED can be considered as the erythema threshold dose for Caucasians who tan gradually after

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sun exposure. It concerns skin that has not recently been exposed to the sun for longer periods of time. Dark-skinned people have an erythema threshold 3 to 5 times greater than the MED. People who never tan, such as freckled persons of Celtic (Irish, Scottish, Breton) origin, develop erythema at radiant exposures smaller by a factor of 2 to 3 than the MED. It would appear that the minimum erythema dose does not strongly depend on age (Cox92). An erythema-effective radiant exposure of 50 J/m^2 or less will only induce erythema in hypersensitive people.

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4.3 Ageing of the skin and skin cancer

Chronic exposure of the skin to UV radiation may induce irreversible effects: increased ageing of the skin and skin cancer. The induction of skin tumours involves an influence of UV radiation on the immune system. The interaction with the immune system may also lead to other effects on health. The Health Council will discuss in a separate report the effect of exposure to UV radiation on the immune system, both in relation to the induction of skin cancers as well as to an increased susceptibility to other diseases. The committee is of the opinion that such effects and related health risks cannot be quantified at present (Kri91).

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Ageing of the skin

With ageing the skin looses its elasticity and shows increased wrinkling and 'age spots'. Exposure to UV radiation accelerates this process. This is demonstrated by a comparison of the skin of those who are habitually exposed to the sun, e.g. farmers, road workers and seamen, with that of people infrequently exposed to the sun. This effect has been found in experimental animals as well. Skin ageing does not appear to have harmful effect health (other than possibly, psychological effects). The action spectrum for skin ageing is not known. There are indications that both UV-B and UV-A radiation play a role (Kli87, Gil86).

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Skin carcinoma

A carcinoma of the skin is a malignant tumour of the skin epithelium. The most common types of skin carcinoma are basal cell carcinoma and squamous cell carcinoma. The former type is about four times more prevalent than the latter among Caucasians. Both types occur mainly (in more than eighty per cent of cases) on sun-exposed skin parts that are regularly exposed to solar radiation. The probability that skin carcinoma will occur increases with increasing exposure; whites are more sensitive than blacks. Most skin carcinoma can be cured by excision; skin carcinoma mortality is less than one per cent of the incidence.

No threshold for the induction of skin cancer by UV radiation is known. There is always a certain probability that a malignant skin tumour will occur later. This probability increases with increasing UV radiant exposure. The incidence of basal cell carcinoma is roughly proportional to the square, and that of squamous cell carcinoma to the third power of the average annual radiant exposure (Sla86, GR86).

The 1986 Health Council report recommended that the erythema action spectrum be also used as an action spectrum for skin cancer. In the meantime more data have become available on the incidence of skin cancer in UV exposed mice. Sterenborg et al published data from experimental studies on the occurrence of skin carcinoma in 50% and 5% of the experimental animals as a function of the wavelength (Ste87). More recently De Gruijl et al reviewed the entire body of available data and derived an improved action spectrum for skin carcinoma (UNEP91, Gru93); see figure 4.2. The committee recommended to use this new action spectrum for assessing the risk to humans from UV exposure.

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Melanoma of the skin

Melanomas are malignant tumours of the melanocytes. They occur less frequently than skin carcinomas, but are far more aggressive and disseminate to a larger extent. The

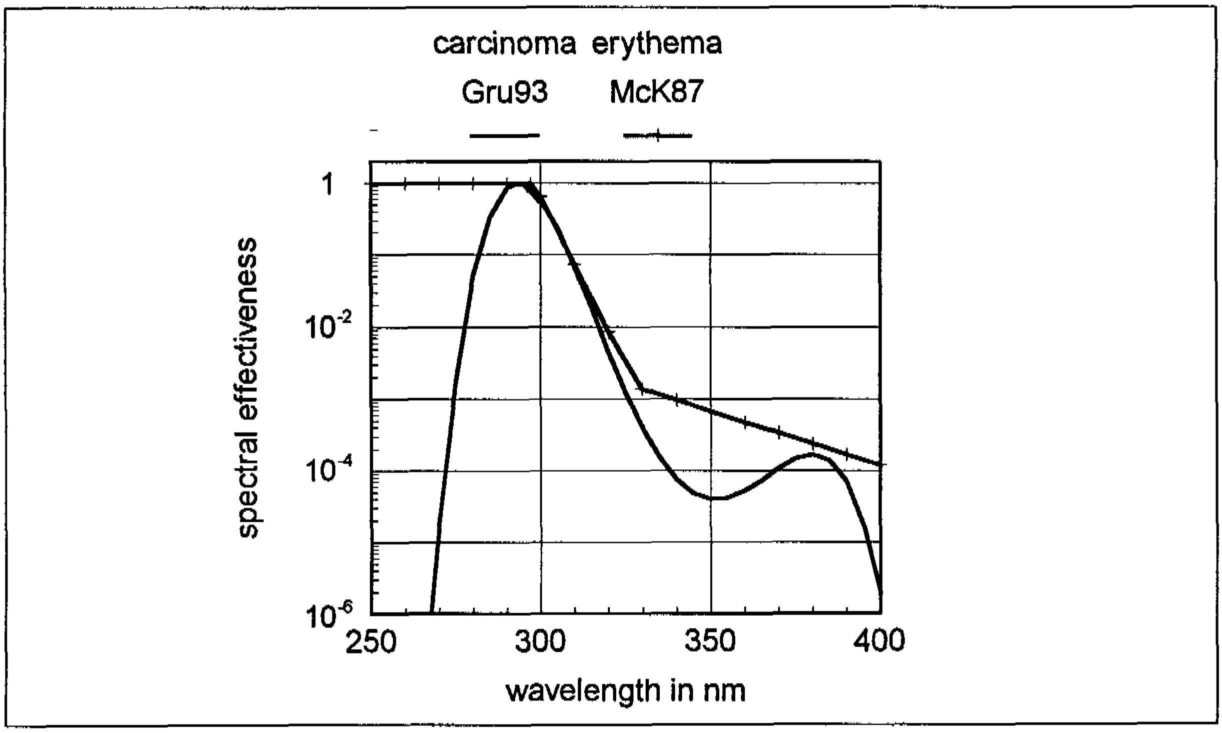

Figure 4.2. Action spectrum for skin carcinoma proposed by De Gruijl et al (Gru93). For comparison purposes the erythema action spectrum according to McKinlay (McK87) has also been drawn.

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melanoma incidence has clearly increased in the last decades. Exposure to solar radiation appears to be a factor in the incidence of certain types of melanoma, because (Kam87):

- the distribution of melanoma across the body seems related to the extent of protection of the skin by clothing
- the incidence of (certain types of) melanoma (e.g. lentigo maligna) is related to the length of sun exposure
- the incidence of (certain types of) melanoma seems to be related to frequent sunburn in the past.

Genetic factors, such as a sun-sensitive skin, and the presence of a number of moles, are also risk factors (Koh91). Melanomas have been induced in two species of experimental animals by exposure to UV radiation (Set89, Ley89).

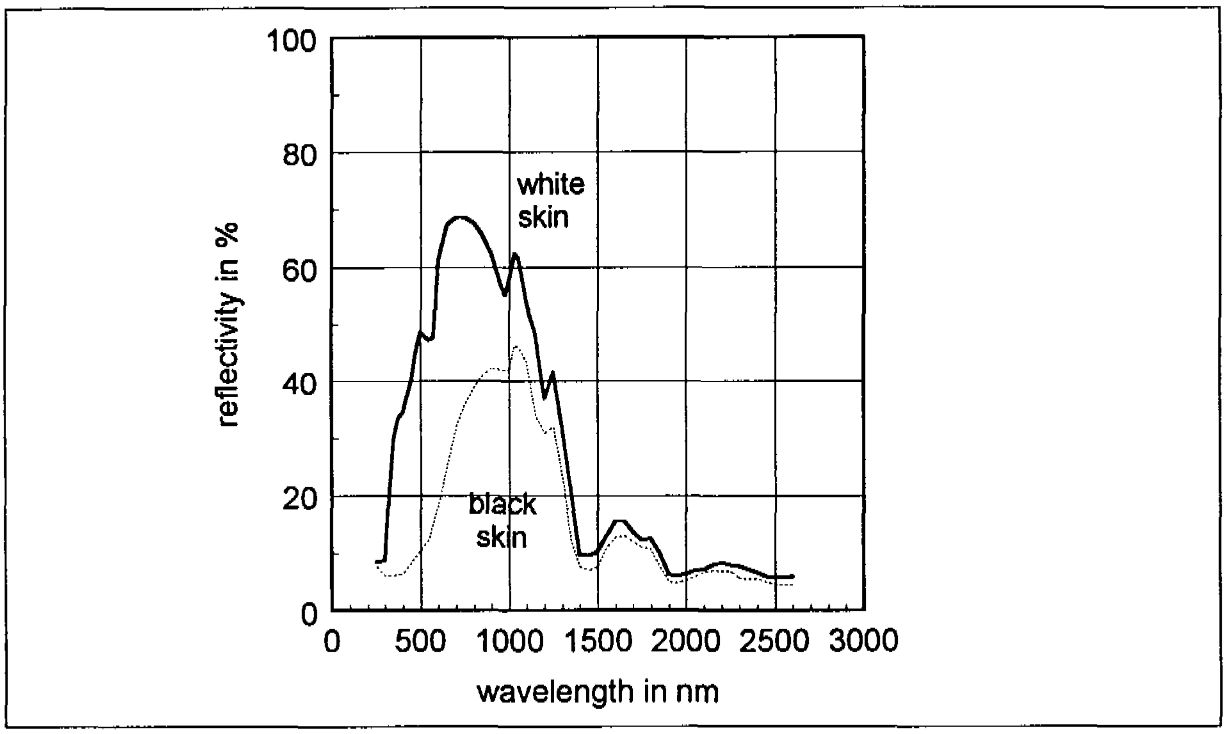

Figure 4.3. Skin reflection (in per cent) as a function of wavelength for white skin and black skin (source: Jac56).

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At present the committee sees no way that health-exposed exposure limits can be derived on the basis of the data available.

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4.4 Thermal damage to the skin

Absorption of radiation energy heats the skin. The temperature may also rise in non-irradiated, neighbouring tissue by heat dissipation. The temperature rise will depend on skin reflection and absorption and heat transport to neighbouring tissues and the environment (and, thus, also depends on the surface irradiated; WHO82, Mar70, Bra88).

The rise in temperature affects the biochemical processes in and between the tissue cells; irreversible changes occur. Above 41.5 °C proteins coagulate, enzymes are inactivated, the permeability of cell walls changes and DNA and protein synthesis slows down. Prolonged periods above 43 °C may even lead to cell death (Mal86).

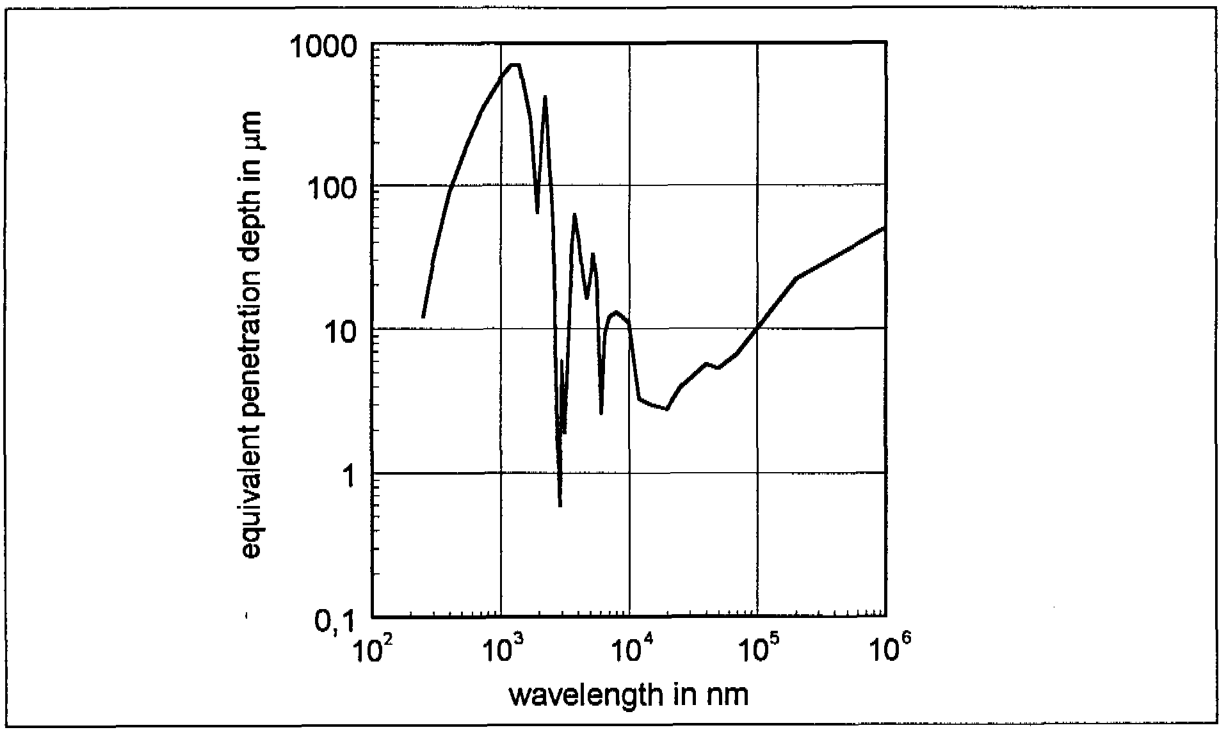

Figure 4.4. Spectral course of the absorption of optical radiation in the skin in terms of the equivalent penetration depth. The equivalent penetration depth is the calculated depth at which 50% of the perpendicularly incident radiation is absorbed. Curve derived from data from Bru84, GR78, Har56, Par78. The values are also presented in table 4.1.

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Skin temperature is usually lower than body temperature. Absorption of radiation in the skin produces a sensation of heat. The pain threshold corresponds to a skin temperature of about 45 °C.

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The reflection of the skin is only noticeable in the visual spectral range. Figure 4.3 presents the spectral reflectance for white and of black skin. Radiation that is not reflected penetrates into the skin; the penetration depth depends on the wavelength (figure 4.4 and table 4.1). The greater the penetration depth, the greater the volume in which the radiation is absorbed. The temperature rise will thus be higher for smaller penetration depths and vice versa. However, at greater depths the dissipation to surrounding tissue is slower. Heat is dissipated by conduction or through transport by the blood. At the skin surface, heat is dissipated by

Table 4.1. Equivalent penetration depth* d_e in skin and eye as a function of the wavelength λ.

	λ (nm)	d_e (μm)	λ (nm)	d_e (μm)	λ (nm)	d_e (μm)	λ (nm)	d_e (μm)
skin								
	250	12	550	200	1200	700	1950	63
	300	30	700	340	1400	700		
	400	90	1000	570	1700	300		
eye								
	600	3036000	850	160000	1100	39900	1500	380
	625	2480000	875	123000	1130	17000	1550	690
	675	1670000	900	102000	1170	6900	1600	1000
	700	1153000	925	48100	1200	6700	1650	1300
	725	437000	950	17900	1250	7700	1700	1300
	750	265000	975	15500	1300	6300	1750	1100
	775	289000	1000	19100	1350	2800	1800	860
	800	353000	1030	37900	1400	560	1850	700
	825	250000	1070	54000	1450	270	1900	84
skin and eye								
	1950	63	3000	0,6	6100	2,6	50000	5,3
	2000	100	3200	1,9	6500	9,1	70000	6,7
	2100	260	3400	9,6	7000	12	100000	10
	2200	420	3600	38	8000	13	200000	22
	2300	290	3800	61	9000	12	500000	35
	2400	140	4100	40	10000	11	1000000	50
	2500	84	4400	23	12000	3,3		
	2600	45	4700	16	15000	3,0		
	2700	7,8	5000	22	20000	2,8		
	2800	1,3	5300	33	25000	3,9		
	2900	0,6	5600	22	40000	5,7		

* The equivalent penetration depth is the depth at which the attenuation of the radiation intensity is 50%, assuming uniform attention following Beer's law. It is a theoretical quantity in which, e.g. the absorption by the lens of the eye is not taken into account.

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convection, radiation emission or evaporation. In general, absorption is restricted to the epithelium.

No new aspects have arisen since publication of the 1978 report. The committee notes that the criteria for thermal damage differ from one study to another; both pain threshold and the occurrence of skin burn are mentioned.

Qualitatively the relationship between the temperature rise and the absorption of radiation energy can be described as follows (it is assumed that the dimensions of the irradiated

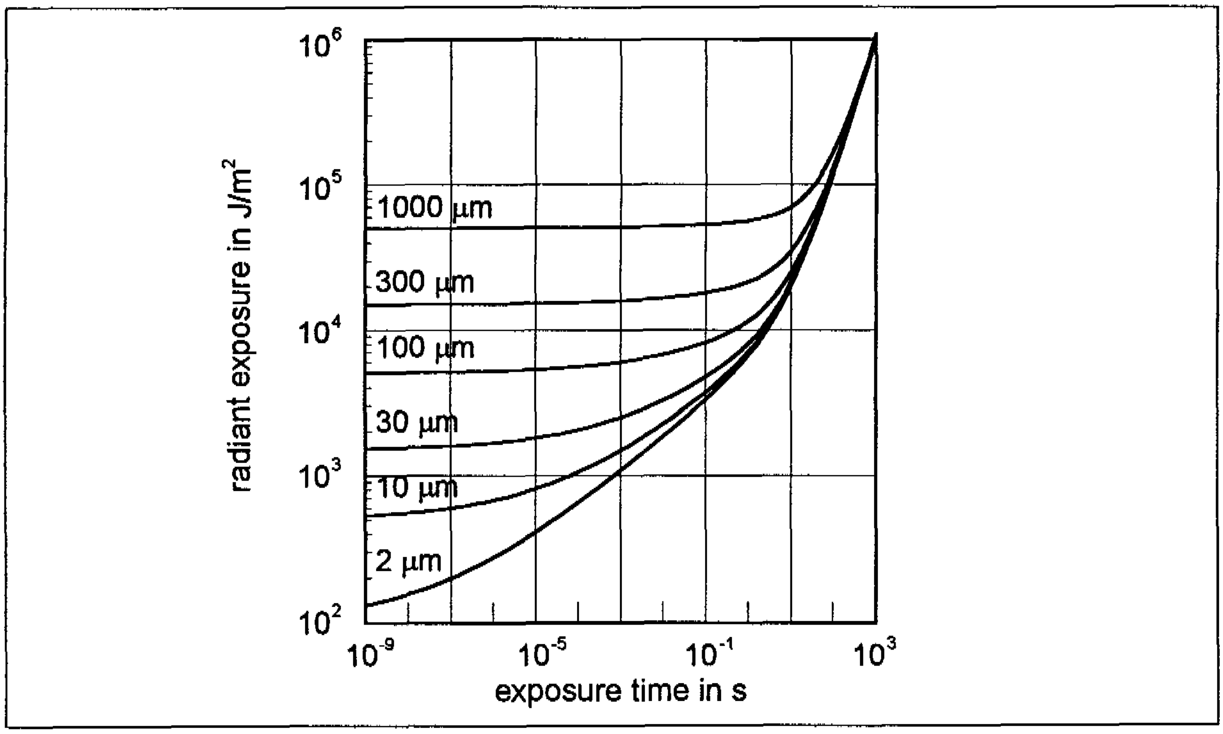

Figure 4.5. Threshold of the radiant exposure for thermal skin damage as a function of the exposure time for different values of the equivalent penetration depth. (Source: GR78).

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surface are much greater than the penetration depth). For short exposure times heat dissipation does not play a role, so that the local temperature rise will be proportional to the radiant exposure, independently of exposure time. For long exposure times heat dissipation will balance the heat generation by radiation absorption, so that the local temperature rise becomes proportional to the irradiance, independently of penetration depth. Hence, all curves in figure 4.5 converge to a threshold of irradiance of 1 kW/m^2; that is the irradiance of a 'burning' sun at high noon in a cloudless sky.

In the 1978 report the threshold for thermal skin damage was presented in the form of the threshold radiant exposure, $H_{threshold,skin}$, as a function of the exposure time, t, for different values of the equivalent penetration depth d_e. The derivation of the curves was based on theoretical considerations, with as boundary condition that the threshold should always be lower than the experimental thermal damage data. The committee is of the opinion that the 1978 approach is still valid and refers to the earlier report for details (GR78). As long as the radiant exposure does not exceed the threshold values (figure 4.5) thermal damage to the healthy skin will not occur.

5 EFFECTS IN THE EYES

5.1 Introduction

When the eyes are exposed to optical radiation the cornea is first encountered. Radiation not absorbed or reflected there reaches the iris and the lens. The radiation may penetrate further into the eye depending on the wavelength and may finally reach the retina to be absorbed there. Visible radiation is the small wavelength band from about 400 to 780 nm that reaches the retina and is absorbed in light sensitive pigments of the retinal cells, resulting in the electromagnetic radiation termed 'light'.

Humans have 'built in' mechanisms that protect the eyes against excessive radiation exposure. The deep embedding of the eyes in their sockets protects the eyes against high sun and against artificial sources shining from above. Intense light triggers the pupil reflex and also make one squint.

Nevertheless, excessive eye exposure may occur. The exposure may be very rapid, in which case the blinking reflex and the pupil reflex are too slow. Furthermore, these reflexes are not triggered by UV and IR radiation. Also some of the effects of radiation are due to chronic, low level exposure, in which case the reflexes do not operate.

In the next paragraph the committee presents a short overview of the structure and the optical properties of the eye. The harmful effects of optical radiation on cornea and lens are then discussed. The thermal and photochemical effects on the retina are dealt with in chapter 6.

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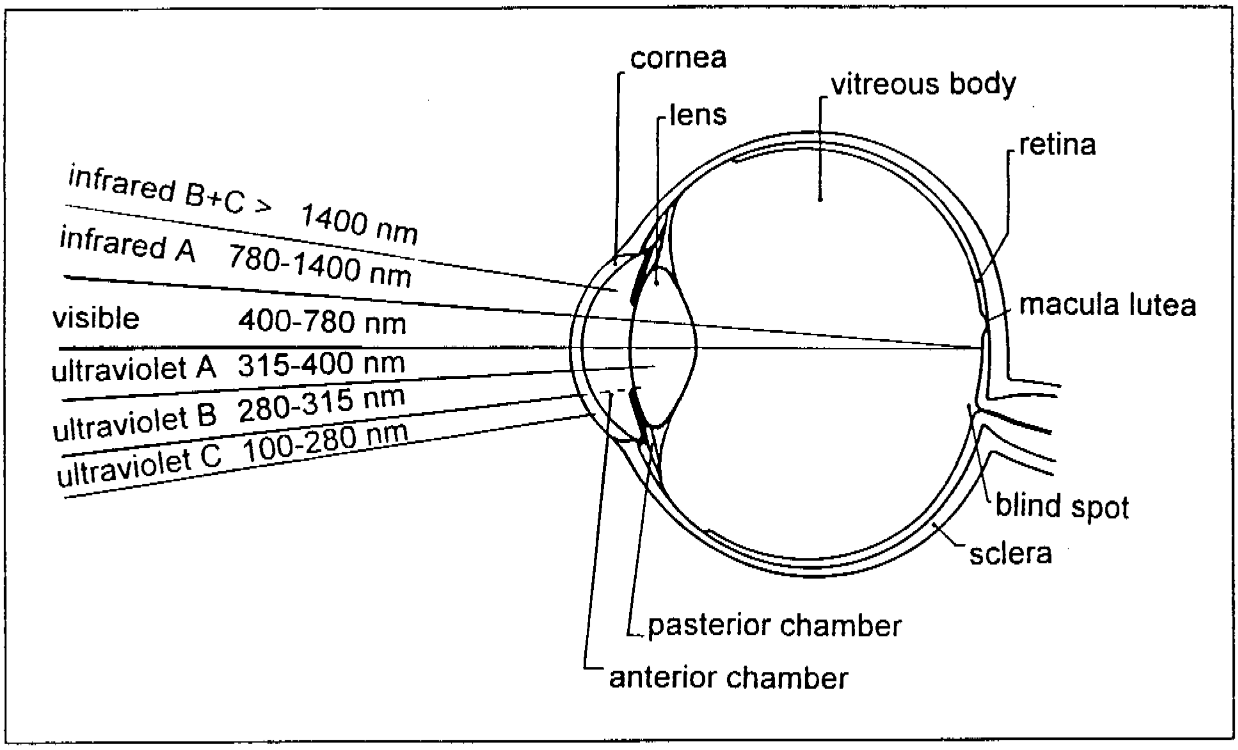

Figure 5.1. Schematic cross-section and spectral transmission of the eye. For radiation with wavelengths above 1400 nm the transmission of the cornea and vitreous humoris less than 1%. Below 400 nm the transmission of the lens decreases to less than 5%. Below 315 nm the transmission of the cornea decreases to less than 5%. This implies that UV-B radiation is partly transmitted by the cornea (dotted line.)

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5.2 Structure of the eye and optical properties

The eye has a spherical shape with a diameter of about 2,5 cm. Figure 5.1 presents a schematic cross-section. The eye is enclosed by a strong membrane, the sclera. Its front part, the cornea, is transparent. The interface between air and cornea is the dominant refracting surface of the eye with a refractive power of about 40 D. The cornea consists of an outer layer of epithelial cells with a thickness of about 75 µm, the stroma (a layer of collagen and keratocytes) about 500-µm thick and a layer of endothelial cells of 5 µm thickness. At the border of the cornea the epithelial cells merge with the conjunctiva; the stroma continues in the form of the sclera. In discussing eye damage it is important to note that the epithelial cells are renewed within a few days (this is not case for the endothelial cells).

Going in the direction of incident light we first encounter the anterior chamber, filled with aqueous fluid. We then arrive at the iris, which determines the colour of the eye; the pupil aperture reduces in size with increasing light intensity. A small space, encapsulated between iris and crystalline lens and filled with aqueous fluid, connects the anterior and posterior chambers. The crystalline lens, with its refractive power of some 20 D at a maximum, is the eye's most important optical element; it consists of protein filled fibres with an onion-type layered structure. Behind the crystalline lens comes the vitreous body, a gelatinous, transparent aqueous substance. The retina is the layer in which the incident light is converted to neural impulses. It consists of nerve cells and supporting cells. The interior parts are transparent and contain blood vessels except for the central visual region with which we fixate, the fovea centralis and the macula lutea. The photoreceptors proper (rods and cones) fill the outward-facing parts of the retina. Adjacent to the retina is the retinal pigment epithelium (RPE), which consists of one layer of cells with a thickness of about 10 µm; it contains large amounts of melanin, a pigment that strongly absorbs the residual radiation. Melanin is also abundantly found in the highly vascular choroid plexus, just behind the RPE. Finally, the whole of the eye is encapsulated and thereby made a robust structure, by the sclera. The strongly curved cornea and the crystalline lens, together, form the optical system that images the outside world on the retina.

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The absorption of radiation by the different parts of the eye, as a function of wavelength, is also depicted schematically in figure 5.1. The cornea strongly absorbs UV-C, UV-B, IR-B en IR-C radiation, but is practically transparent to radiation with wavelengths between 300 and 1400 nm (part of the UV-B, UV-A, light and IR-A). The lens of the eye strongly absorbs UV-A radiation; radiation with wavelengths between 400 and 1400 nm penetrates the eye as far as the retina. If the lens has been extracted, UV-A radiation also may reach the retina. This is prevented nowadays by implanting a plastic lens that incorporates an UV-A absorbing material.

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5.3 Keratitis and conjunctivitis

Absorption of UV radiation may damage the cornea and the conjunctiva and cause, respectively, keratitis and conjunctivitis. Keratitis is also popularly known as 'snow blindness' and 'welder's eyes'. The damage manifests itself six to twelve hours after a threshold dose has been exceeded. The symptoms (pain, tears, light avoidance reactions and blinking) usually disappear within two days by regeneration of the epithelial cells. As long as the excessive exposure takes place within a 24 hour period the threshold radiant exposure does not depend on the irradiance. However with protracted exposure, regeneration processes start to play a role. The threshold for exposure periods of a week or more can be better expressed in terms of the irradiance (Zuc80). For exposures that are very much in excess of threshold, the deeper parts of the cornea can also be damaged and vision may be permanently impaired. The data for threshold radiant exposure that were presented in the 1986 report are reproduced in figure 5.2. No new data have been reported since then. Some older data that were not shown in the 1986 report are also given in the figure. These data support the conclusions drawn in 1986.

Recently it has been proposed that the photomechanical interaction of optical radiation with tissue be used for correcting the refractive properties of the eye. The cornea is exposed to short pulses (of the order of magnitude of 10^{-9} s) of excimer-laser radiation with a wavelength of approximately 200 nm which lead to 'evaporation' of a very thin layer of surface cells. The effectiveness and efficacy of this technique are not yet proven.

The processes following 'thermal irradiation' of the cornea do not differ from those in skin at similar penetration depths (GR78, Fle86). The committee thus refers the reader to

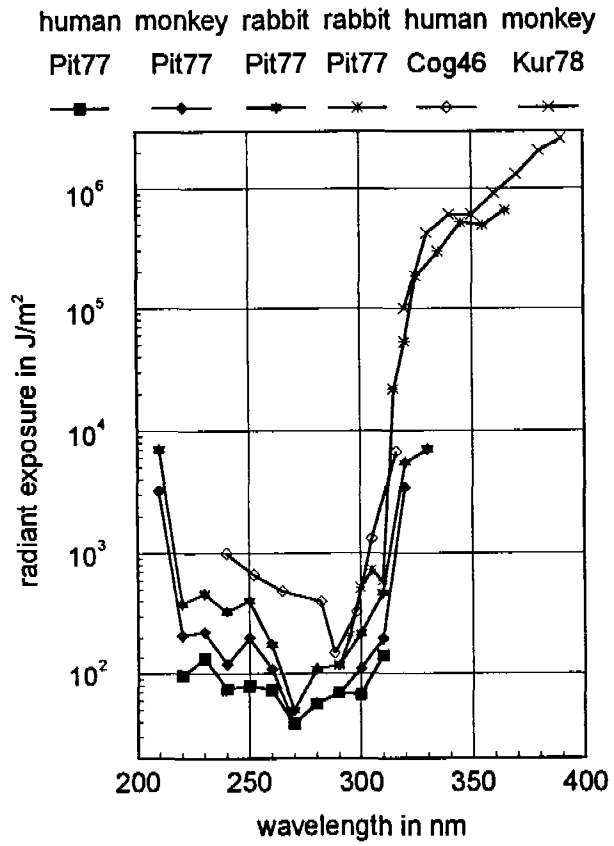

Figure 5.2. Threshold radiant exposure data for keratitis as a function of wavelength. The data marked Pit77 and Cog46 were presented in the 1986 report. The data marked Kur78 only confirm the figure in agreement with the other values.

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chapter 4. However, the spectral course of the penetration depth in the eye differs from that in skin. Figure 5.3 presents the values for the eye and also those for skin for comparison.

Little is known about the effects of chronic exposure to UV radiation. Pterygium and climatic droplet keratitis have been mentioned as such effects, but their relation with exposure time is not evident (Mil87, Gra92). Neither of these conditions is prevalent in The Netherlands. However, ophthalmologists have reported an increasing incidence, especially among immigrants. Some studies mention that carcinoma and possibly melanoma may develop in the cornea, as in the skin; these types of cancer are rare, however (Kop79, Sed90). No data are available about a possible dose-effect relationship between wavelenght and exposure. Because of the similarities between

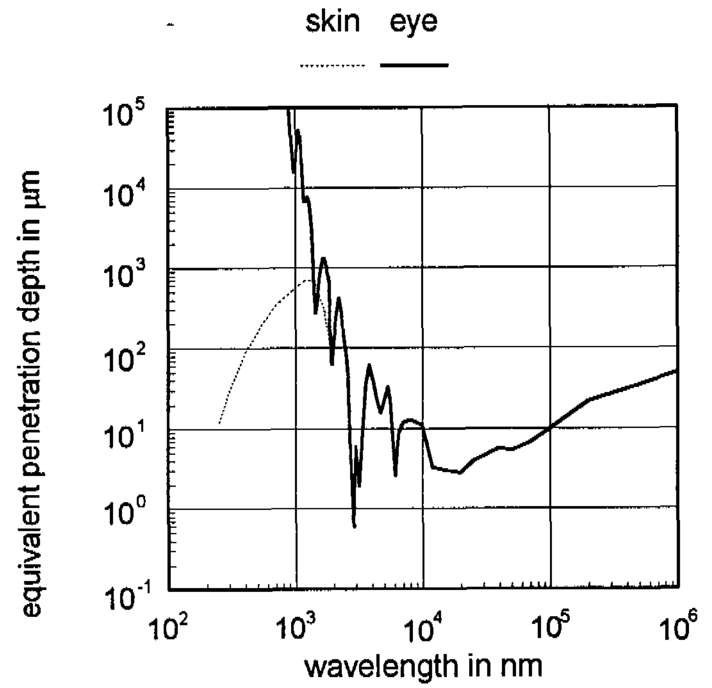

Figure 5.3. Absorption of optical radiation in the skin, represented by the equivalent penetration depth, i.e. the depth at which 50% of perpendicularly incident radiation is absorbed. For comparison purposes the values for the skin are also given (dotted line; cf. figure 4.4); at wavelengths larger than 1900 nm the curves of skin and eye overlap. Curve derived from data presented in GR78.

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the effects in the skin and the cornea after acute exposure, the committee recommends that equal sensitivities be assumed efor these organs (cf. paragraph 4.3).

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5.4 Damage to the lens of the eye

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Photochemical damage

The lens of the eye may be damaged by absorption of UV-B radiation; such damage occurs within a few days after the irradiation. After a threshold exposure is exceeded the damage manifests itself in the form of white grains that may disappear again. Cataracts may occur after larger exposures. Figure 5.4 presents the radiant exposure as a function of wavelength above which damage has been observed; the exposure values apply to the front of the cornea (Pit76). Because of the strong absorp-

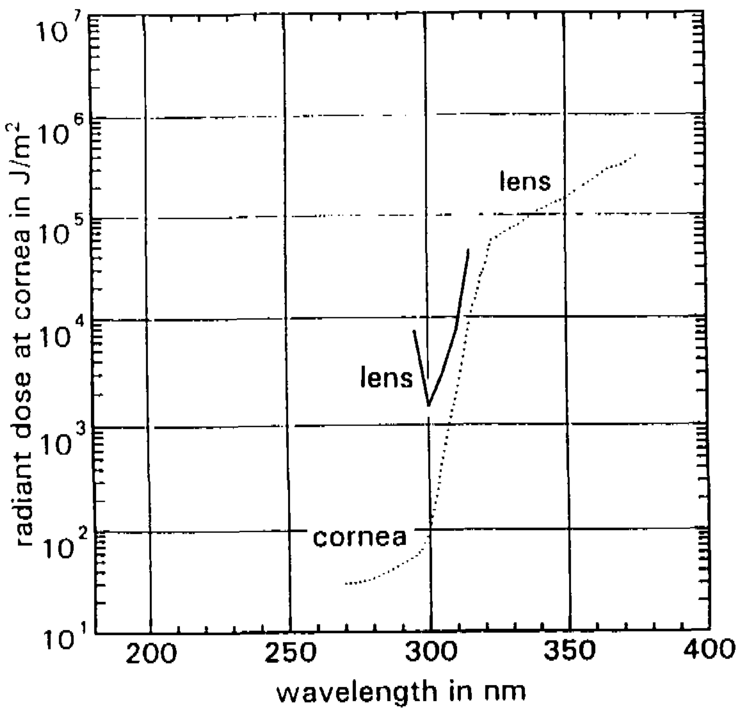

Figure 5.4. Threshold radiant exposure for acute photochemical damage of the lens of the rabbit as a function of the wavelength (Pit76). For comparison part of the threshold curve for damage to the cornea is reproduced from the 1986 report.

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tion in the cornea and the chamber water radiation with wavelengths smaller than 300 nm hardly penetrates to the lens. Converting the threshold radiation exposure to the corresponding value at the front of the lens*, shows that a subthreshold dose for corneal damage will be equally harmless for the lens. This confirms the photochemical character of the lens damage. It also implies that, if the eye is exposed below the threshold for cornea damage, damage in the lens will be prevented.

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With increasing age the colour of the lens becomes more and more yellow; this has been attributed to absorption of UV-A radiation (Gro72). This yellowing has a protective effect, as the lens becomes less transparent for UV-A radiation and violet

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* Some authors incorrectly suggest that the data represented in figure 5.4 apply to the radiant exposure at the front of the lens (e.g. Wax86).

light which, in turn, prevents noxious effects on the retina (cf. paragraph 6.3).

The colouring of the lens may, however, be a precursor of cataract. Other mechanisms may be also instrumental in cataract formation. Epidemiological data point to a relationship between exposure to the sun and the incidence of cataracts (Wax86). A study in the US, in which much attention was paid to accurately determining the radiant exposure of the eye, showed that the cumulative exposure to UV-B was significantly related to the incidence of cortical cataract (Tay88). However, no relationship was found between the cumulative UV-B exposure and nuclear cataract, nor between the cumulative UV-A exposure and cataract. The same study also demonstrated an increased incidence of subcapsular cataract after high UV-B exposures (Boc89). To what extent UV radiation is causally related to the incidence of cataract thus remains controversial.

There are almost no results of animal experiments on the effects of chronic radiation exposure available. Recently a relationship was found in squirrels between chronic exposure to 365 nm radiation (irradiance, 60 W/m^2 during a one-year period) and damage in the lens (Zig91). No action spectrum was published for this type of damage.

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Thermal damage

Excessive heating of the lens may lead to cataract. However, this so-called glassblower cataract often only manifests itself after decades of chronic exposure. But acute heating also may cause permanent opacities in the lens.

Derivation of threshold values for radiant exposure or irradiance is hampered by the lack of both experimental and epidemiological data. The latter only show that furnace workers in glass and steel factories have a higher incidence of cataract than do other workers; a reliable dose-effect relationship cannot be derived from these data (Lyd84). Experimental animals have been exposed to broad band IR-A radiation but the results have provided information on acute eye damage only. Therefore, arrive at a reliable to estimate of spectral exposure threshold one has to rely mainly on model calculations. The committee summarises here the results of such calculations.

Three mechanisms for heating of the lens by optical radiation have been reported in the scientific literature; in chronological order:

- heating by absorption of radiation in the lens itself ('Vogt-mechanism'; Vog19)
- indirect heating through absorption of radiation in the iris ('Goldmann-mechanism'; Gol30)
- indirect heating through absorption of radiation in the cornea ('Okuno-mechanism'; Oku91).

It has been shown that, depending on environmental factors, all three mechanisms may operate (Vos93). The Okunomechanism usually dominates. Glowing objects, both in the form of light sources and of industrial furnaces, emit mainly in the IR-B and IR-C spectral regions; these types of radiations are practically fully absorbed by the cornea. Okuno's (Oku91) model calculations show that the temperature increase in the cornea may lead, through conduction via the vitreous humor, to heating of the lens up to harmful levels (figure 5.5). Only by exposure to radiation with the IR-B and IR-C components removed or by exposure to IR-A lasers, may direct heating of the deeper parts of the eye occur. In this case the lens is heated throughthe Goldmann-mechanism, i.e. by absorption of radiation in the iris. In practice thermal damage via the Vogtmechanism - i.e. via direct absorption in the crystalline lens - will only occur when specialised optical equipment is used that allows local irradiation with narrow beams.

Lens damage does not occur if a lens temperature of 40 °C is not exceeded (Gol30). This value has been used as a parameter in the model calculations; it has also been assumed that absorption in the eye is described by the data given in figure 5.3. Figure 5.6 presents the results of the calculations. This figure shows:

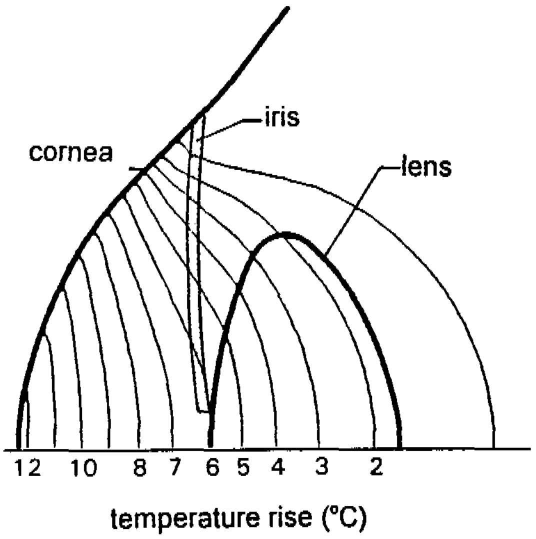

Figure 5.5. Calculated isotherms for heating of the frontal part of the eye through continuous exposure to radiation from a black body source with a temperature of 1473 K (1200 °C) and an irradiance of 2 kW/m^2; the diameter of the pupil is 2 mm and the colour of the iris is brown (Oku91). Protection by the eyelid (not drawn in the figure) causes the temperature decrease in the vertical (upward) direction. The smooth curvature of the isotherms demonstrates that the cornea is the only heat source and that heating via the iris (Gol30) does not play an important role.

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- the spectrum of the threshold according to the Okunomechanism. In the UV-B, IR-C and IR-B spectral regions the calculated threshold for thermal damage is about 1.7 kW/m^2. Radiation from these regions does not pass the cornea. Between 315 en 1150 nm the computed threshold increases sharply and the Okunomechanism cannot play a role in practice with this wavelength region.
- the spectrum of the threshold according to the Goldmannmechanism. Between 315 and 1400 nm the calculated threshold for thermal damage is approximately 2.2 kW/m^2 and it rises sharply outside this region. Roughly speaking the Goldmannmechanism fills the 'gap' in the curve based on the Okunomechanism.

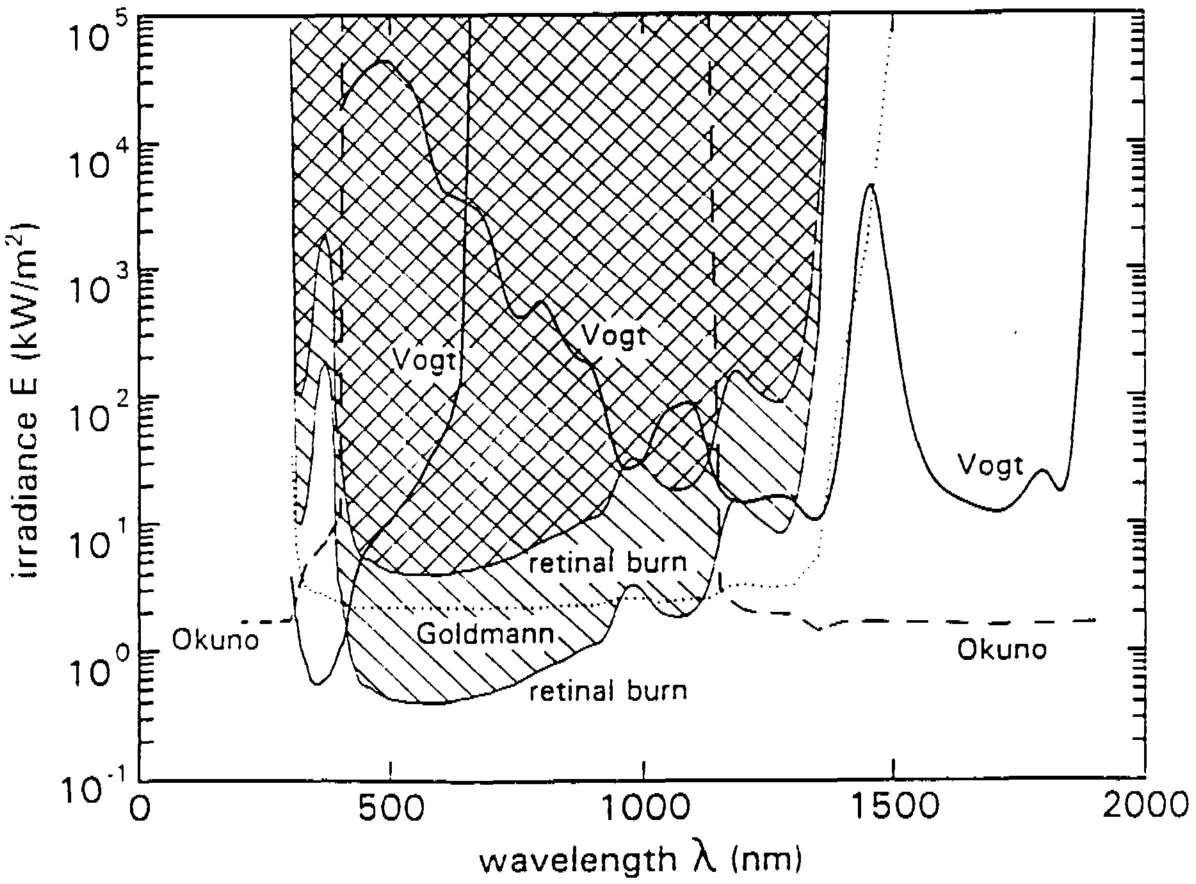

Figure 5.6. Calculated thresholds for thermal damage to the lens of the eye. The thresholds correspond to heating of the lens to 40 °C. The main text of the report explains the Vogt-mechanism (solid line), the Goldmann-mechanism (dotted line) and the Okuno-mechanism (dashed line). In the hatched region retinal burn determines the damage to the eye after exposure to optical radiation (Source: Vos93).

- the spectrum of the threshold according to the Vogtmechanism. The threshold (in terms of irradiance) has two levels. A short wavelength branch determined by absorption of the radiation in the yellow lens pigment, and a long wavelength one determined by absorption in water. Only in the wavelength region from 315 to 420 nm is the Vogt threshold lower than that for the Okuno and the Goldmannmechanisms and it becomes the lower limit for damage. During exposure to narrow radiation beams that do not hit the iris, the Vogtmechanism comes into play. There may be harm to the lens in the 'Goldman' region.
- a hatched area in which retinal burn can occur (the cross-hatching applies to narrow and broad beams, the single hatching to broad beams only). Like Vos and Van Norren (Vos93) the committee emphasises that in this area retinal burn rather than thermal cataract determines the damage to the eye from exposure to optical radiation.

These calculations have not been confirmed experimentally, with one exception. The committee has found one single threshold value for thermal cataract from UV-A exposure in the literature; the value agrees with that computed using the Vogtmechanism (Zuc76).

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6 EFFECTS IN THE RETINA

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6.1 Introduction

Only part of the radiation that impinges on the cornea reaches the retina (see figure 5.1), and of that part only a small fraction is 'seen', i.e. absorbed by the visual pigments. Most of the radiation energy is absorbed and converted into heat by the pigmented cell layers behind the retina, the retinal pigmented epithelium (RPE) and the choroid. During excessive exposure of the retina the local temperature may reach levels at which the tissue is damaged: retinal burn. Apart from this thermal effect optical radiation may also produce photochemical effects and induce a series of chemical reactions that lead to damage.

Retinal damage is a serious affection if it occurs in the center of the field of vision, in particular in the fovea. Foveal damage will decrease visual acuity. Damage at the borders of the retina, on the other hand, will hardly impair vision: one small blind spot more or less will hardly affect visual capability. Slight damage may heal, but true over-exposure may lead to local destruction of the pigmented epithelium and the retina.

In this chapter the committee discusses this photochemical and photothermal damage to the retina. For more detailed discussion of these effects the reader is referred to standard text- and handbooks (Sli80, Wax86, Cro86).

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6.2 Thermal retinal damage

Thermal damage to the retina can be observed directly after exposure using the ophthalmoscope; one notices a grey

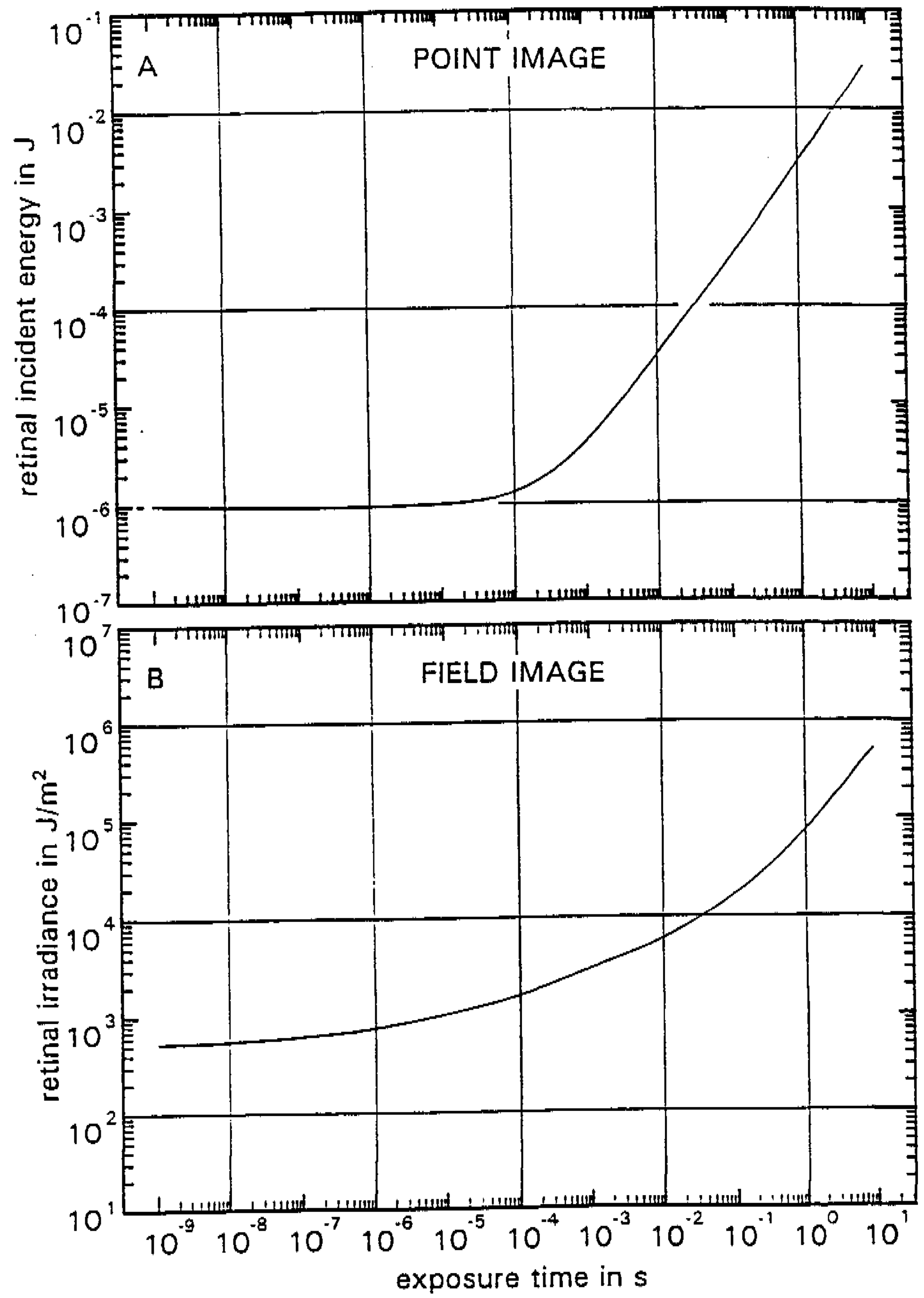

Figure 6.1. Threshold values for thermal retinal damage as a function of exposure time. A: energy *Q* impinging on the retina for point source images. B. radiant exposure *H* at the retina for extended source images. (Source: GR78).

colouring of the fundus. A number of thresholds for retinal damage have been determined this way. With more sophisticated detection instruments, such as the electronmicroscope, damage is observed even at lower exposures. In general the lowest thresholds correspond to radiant exposures that produce a calculated temperature increase of at least 10 °C in the retinal pigmented epithelium (RPE).

With a small retinal image, heat dissipation is much faster than that with a large image, as the surface to volume ratio of the irradiated tissue is greater. This means that the rate of temperature increase, and also the relation between exposure threshold and irradiation time, depends on image size. In practice two classes of images can be distinguished. For small images ('point source images') the quantity that determines the damage in the retina is the impinging radiation energy (in J). For extended images ('field images') it is the radiant exposure that determines retinal damage (in J/m^2).

The experimental threshold vs exposure time data presented in the 1978 report are still valid. The threshold is constant up to exposure times of 10^{-4} s and above this gradually becomes proportional to exposure time, which means that the threshold then becomes constant in terms of irradiance. This dependence of the threshold energy, $Q_{threshold,retina,point\ source\ images}$, on exposure time, t, is shown in figure 6.1A for the center part of the visible spectrum. The following empirical equation gives a valid formal description of this relationship:

$$Q_{threshold,retina,pointsource} = 10^{-6} + 3 \times 10^{-3} t \quad [J], \ t \text{ in s.}$$

The experimental basis for the threshold values for field images also has not changed essentially since publication of the 1978 report. Again, the threshold - in terms of radiant exposure - is constant up to an exposure time of about 10^{-4} s. At exposure times exceeding 1 s the threshold is proportional to exposure time, which means that in terms of irradiance, the threshold is constant. The relation between the radiant exposure threshold, $H_{threshold,retina,extended\ source}$, and the exposure time,

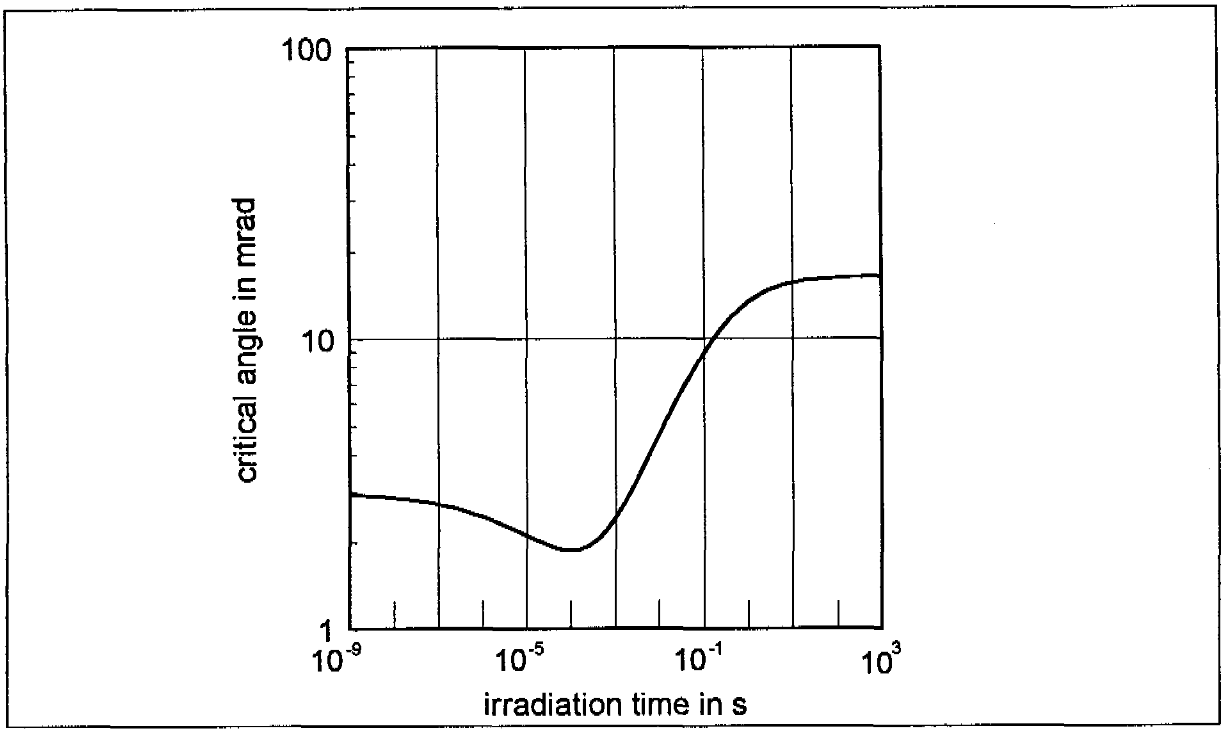

Figure 6.2. Relationship between the critical viewing angle α_{crit} and the exposure time. (Source: GR78).

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t, is given in figure 6.1B for the central part of the visible spectrum. It can also be described by the following empirical expression:

$$H_{threshold,retina,extendedsource} = 500 + 2.5 \times 10^4 t^{1/3} + 5 \times 10^4 t \left[\mathrm{J/m^2}\right],$$
t in s.

Point sources and extended sources are separated by a critical imaging size α_{crit} that is derived from a critical image size, O_{crit}, on the retina. This critical image size is the value at which the radiant exposure thresholds for point and field images are equal. This value can be derived by dividing the first expression (that for point sources) by the second (that for extended sources)

$$O_{crit} = \frac{10^{-6}+3\times10^{-3}t}{500+2.5\times10^4 t^{1/3}+5\times10^4 t} \ [\mathrm{m^2}], \ t \text{ in s.}$$

By using the conversion factor for the standard eye in which an image diameter of 16.7 mm corresponds to an angle of 1 radian (Sli80), the corresponding critical diameter, α_{crit}, is given by the expression:

$$\alpha_{crit} = 3\sqrt{\frac{1+3000t}{1+50t^{1/3}+100t}} \quad [\mathrm{mrad}].$$

This relation is shown graphically in figure 6.2. Its form demonstrates that at high exposure time values the transition from point source to extended source image occurs at greater image sizes because there is more time for heat dissipation.

The expressions are valid for the central part of the visible spectrum, where the cornea and the lens are transparent and the absorption in the RPE is high. With decreasing wavelength (in the blue direction) this transparency of the eye media decreases sharply and with increasing wavelength (in the red direction) absorption in the RPE decreases. In the IR-A spectral region the cornea and the lens are practically opaque (Boe62). With a given radiation exposure of the cornea, radiation away from the central part of the visible spectrum would heat the retina to a (far) lesser degree than visible radiation. In the threshold expressions, this can be taken into account by multiplication with a spectral factor C_λ. The dependence of C_λ on the wavelength λ is given in chapter 7.

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6.3 Photochemical damage to the retina

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Effects of acute exposure

For exposure longer than about 1 minutephotochemical damage is more marked than thermal damage (Mil87, Kre88). Figure 6.3 presents the threshold data from animal experiments on retinal damage caused by white light. To explain these data a distinction is made between the so called 'blue light hazard' and 'visual pigment hazard'.

The 'blue light hazard' is important for high irradiances. It is not known which pigment or group of pigments

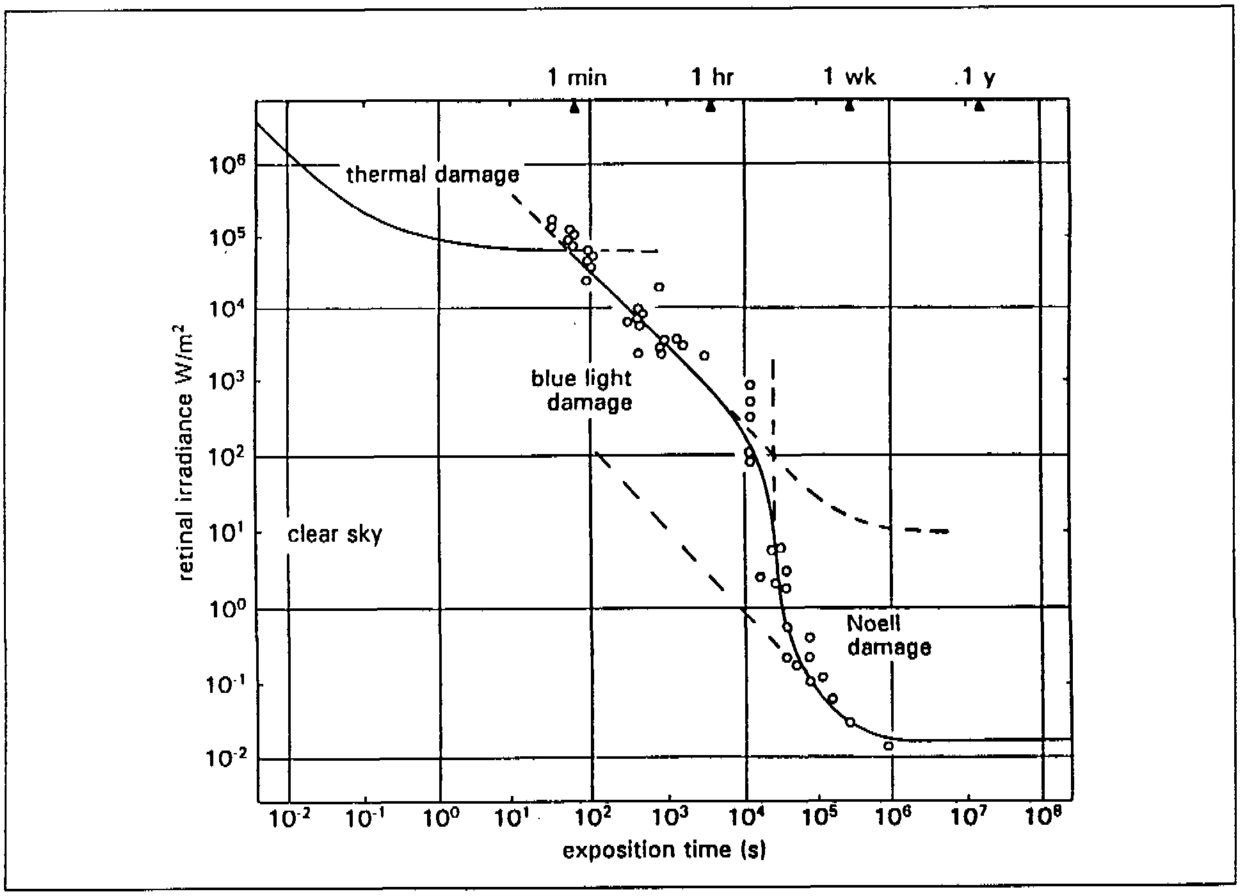

Figure 6.3. Experimental data on the threshold of the irradiance at the retina for retinal damage by white light in several species (Kre88, Kre89, Nor90). The solid curved is based on a model of Kremers and Van Norren (Kre88).

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absorbs the radiation in this case. Damage is usually only observed in the RPE.

The threshold at the retina observed is lowest for 325 nm (Ham82), but no data are available but for shorter wavelengths (figure 6.4). To convert the threshold at the retina to a threshold at the cornea, the one of greatest practical relevance, absorption by the cornea and the lens has to be taken into account. In this case there is a distinct minimum (i.e. maximum sensitivity) in the blue part of the visible spectrum, which explains the choice of the term 'blue light hazard'

People whose lens has been extracted and was replaced by an artificial lens without protective pigment run a greater

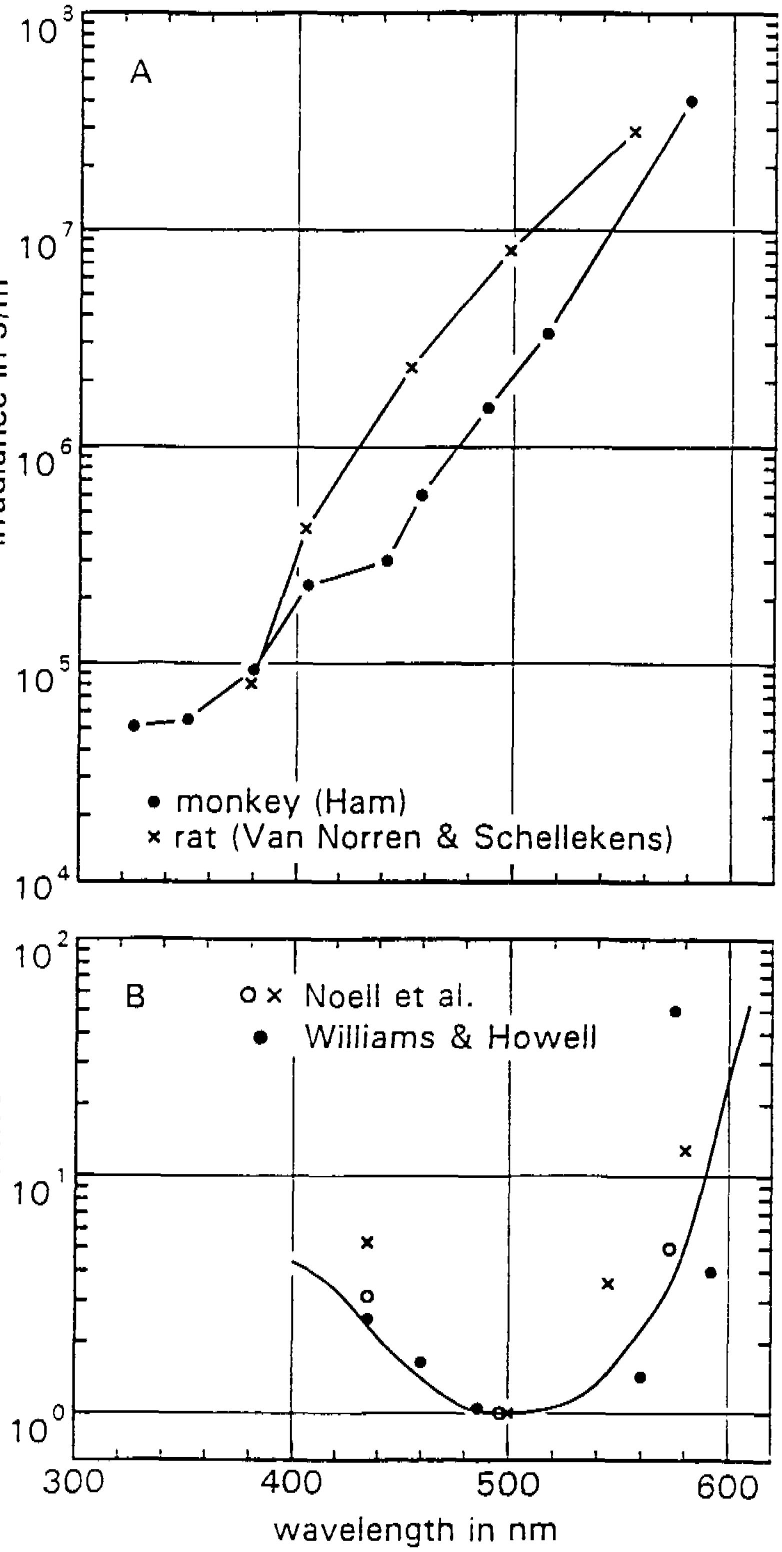

Figure 6.4. Data from animal experiments on the wavelength dependence of the radiant exposure at the retina for photochemical retinal damage. A: 'blue light hazard' (average value from Nor90); B: 'visual pigment hazard' with the rat (Kre88).

risk of retinal damage than do people with a natural lens. Young children also may be at risk as their lens is more transparent to UV radiation than is the adult lens.

At exposure times that exceed 8 hours, retinal damage is observed at relatively moderate irradiance values (see figure 6.3). Noell was the first to report this type of damage from work on rats (1966; Noe66). Later, this same type of damage was observed in other species, among which monkeys (Syk81). This damage is most prominent in the light receptors. The spectral effectiveness function resembles the absorption spectrum of the visual pigments, which explains its name, visual pigment hazard. The absorption maximum for rhodopsin lies around 500 nm (figure 6.4).

While the 'visual pigment hazard' may be relevant for humans, the committee has decided not to discuss this phenomenon. The scientific community still agrees on neither the phenomenology nor the mechanisms underlying this hazard (Kre89). Furthermore, damage does not occur within a working day's exposure whereas the probability of longer exposures is slight.

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Effects of chronic exposure

There is limited evidence that accumulated radiation exposure is related to the incidence of age-related macula degeneration (AMD) (You88, Nor91). This disease of the eye is the leading cause of blindness in old age. In an extensive epidemiological study among a group of 838 fishermen, the integrated radiant exposure over the entire lifetime was determined for UV-A, UV-B and visible radiation. Neither UV-A nor UV-B radiant exposure showed a relation to the incidence of AMD (Wes89), but there was a relation for visible radiant exposure (Tay92). The committee remains cautious regarding acceptance of a relationship between optical radiation exposure and AMD. Recent epidemiological results from Australia, e.g., could not show a relationship between exposure to sunlight and AMD (Mit93).

7 RECOMMENDED HEALTH BASED EXPOSURE LIMITS

7.1 Definition

In chapter 1 the committee explained that the present report would recommend health based exposure limits for optical radiation. For the definition of 'health based exposure limit' the committee refers to the Health Council report on principles for risk assessment and standard setting for chemicals (GR85). The health based exposure limit is the highest level of exposure (in the present case optical radiation) which is acceptable from a health point of view. The health based exposure limits in the present report correspond to the 'acceptable exposure levels' presented the 1978 report.

Straightforward derivation of health-based exposure limits experimental data is not usually possible. Data from animal experiments, e.g., have an inherent uncertainty, because of both flaws in the study design and intraspecies variation. Extrapolation of results from animal experiments to define risks and exposure limits for humans also introduces uncertainty. In most cases, little is known about the possible existence of susceptible groups. The derivation of a health-based exposure limit comprises an assessment of both the scientific data available and the uncertainties attached to the use of these data for risk assessment purposes. I this report the committee will make its assessment of the data and its judgment on the uncertainties explicit.

The recommended exposure limits for optical radiation are usually wavelength-dependent. The committee recommends an exposure limit for a given effect, $X_{A,\lambda}$ stated as follows:

$$X_{A,\lambda} = (1/A_\lambda)\, X_{A,ref}.$$

$X_{A,\lambda}$ is the health based exposure limit at wavelength λ expressed in terms of radiant exposure ($X = H$), the irradiance ($X = E$), the time integrated radiance ($X = L^*$) or the energy ($X = Q$). The weighting function A_λ is standardized to 1 at wavelength λ = 'ref' and is comparable to an action spectrum (cf. chapter 2). At wavelength λ='ref' the exposure limit is equal to $X_{A,ref}$. The committee specifies various weighting functions, e.g. $A_\lambda = Y_\lambda$ for erythema, keratitis and conjunctivitis; cf. table 2.1.

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7.2 Classification

In this chapter the committee distinguishes between early and late damage. Early damage occurs within a few days after the exposure. These effects are relevant for acute exposures, i.e. within one day. Late damage generally manifests itself after chronic exposure lasting several years.

The 'early' effects discussed in chapters 4, 5 and 6 only occur after supra-threshold exposure of skin or eye. The committee will discuss exposure limits related to:

- erythema, keratitis and conjunctivitis (paragraph 7.3)
- thermal damage to skin and cornea (paragraph 7.4)
- cataract (paragraph 7.5)
- retinal damage (paragraph 7.6).

The committee is unable to recommend exposure limits for late damage (paragraph 7.7).

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7.3 Health based exposure limits for erythema, keratitis and conjunctivitis

The skin effect, erythema, and the eye effects, keratitis and conjunctivitis, were treated separately in chapters 3, 4 and 5. However, the differences between the threshold values are so slight that committee feels it is justified to recommend one health based exposure limit for all three effects.

For protection against erythema the committee used the following criteria:

- the exposure limit is set for to people with a sensitive skin (Caucasians who never tan in the sun)
- the exposure limit applies to exposure of less than 24 hours
- the critical effect is erythema that is observable within 8 hours after exposure.

The first criterion warrants further explanation. Dermatologists use a classification of five skin types based on sensitivity to sunburn and tanning (GR86). People who are sensitive to sunburn and never tan have skin type 1, the most sensitive type; people of Celtic origin, as mentioned in paragraph 4.2, often have this skin type. The exposure limit also aims to protect this group. However, this group may include individuals hypersensitive to UV; this enhanced susceptibily may be of genetic origin or caused by certain drugs or natural substances. The latter group of people will not be protected by adherence to the recommended exposure limits.

From the data on the (individual) minimal erythema dose it may be concluded that for exposure to an erythema effective radiant exposure of 50 J/m^2 or less lasting 24 hours no erythema is elicited (paragraph 4.2). The erythema effective exposure is calculated on the basis of the action spectrum proposed by McKinlay (McK87). In determining this value the committee has taken into account both experimental accuracy and the skin types of the experimental subjects. The value of 50 J/m^2 applies to the total UV exposure during a 24-hour period, from both natural and artificial sources. On sunny days this value can easily be exceeded, even without sunbathing. Sensible 'sun behaviour' protects more effectively than enforcement of exposure limits. This behaviour implies adequate information and education about UV habituation of the skin, the need to reduce exposure to the sun and to avoid the sun at certain times of the day, and about the application of appropriate sunscreens.

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The exposure limit for keratitis and conjunctivitis applies to exposure within 24 hours and is based on damage observable with a narrow-beam lamp within 8 hours after the exposure. There is no information available for groups with special susceptibility. The committee follows the practice of the 1986 report in which the recommended exposure limit was based on published data for corneal damage in the 200-370 nm wavelength region. The wavelength dependence was so similar to that for erythema that one spectral course could be adopted. Furthermore the cornea appears to be as sensitive as the most sensitive of the skin types.

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Figure 7.1 presents three relations: the spectral course for an erythema-effective irradiance of 50 J/m^2 (based on the McKinlay action spectrum, see paragraph 4.2), the spectral course proposed in the 1986 report, based on an erythema-effective irradiance of 30 J/m^2 and finally, the McKinlay relation at a reduced erythema-effective level of 30 J/m^2. As the curves appear rather similar, and in view of the spread in the experimental data (see GR86), the committee proposes that the three curves be combined. A question yet to be answered is: which exposure limit should be recommended below 300 nm? In the 1978 report a constant value of 30 J/m^2 was recommended for the UV-C region. The committee supports this recommendation and, will not follow the 1986 report on UV radiation regarding this point. A constant value for the exposure limit is the simplest course and, use of such a value, should not present aproblem, given the limited number of sources and the rather strong absorption of UV-C radiation in air.

The absence of experimental data for wavelengths below 180 nm led the committee to refrain from making a proposal for the 100-180 nm wavelength domain. There are no commonly used

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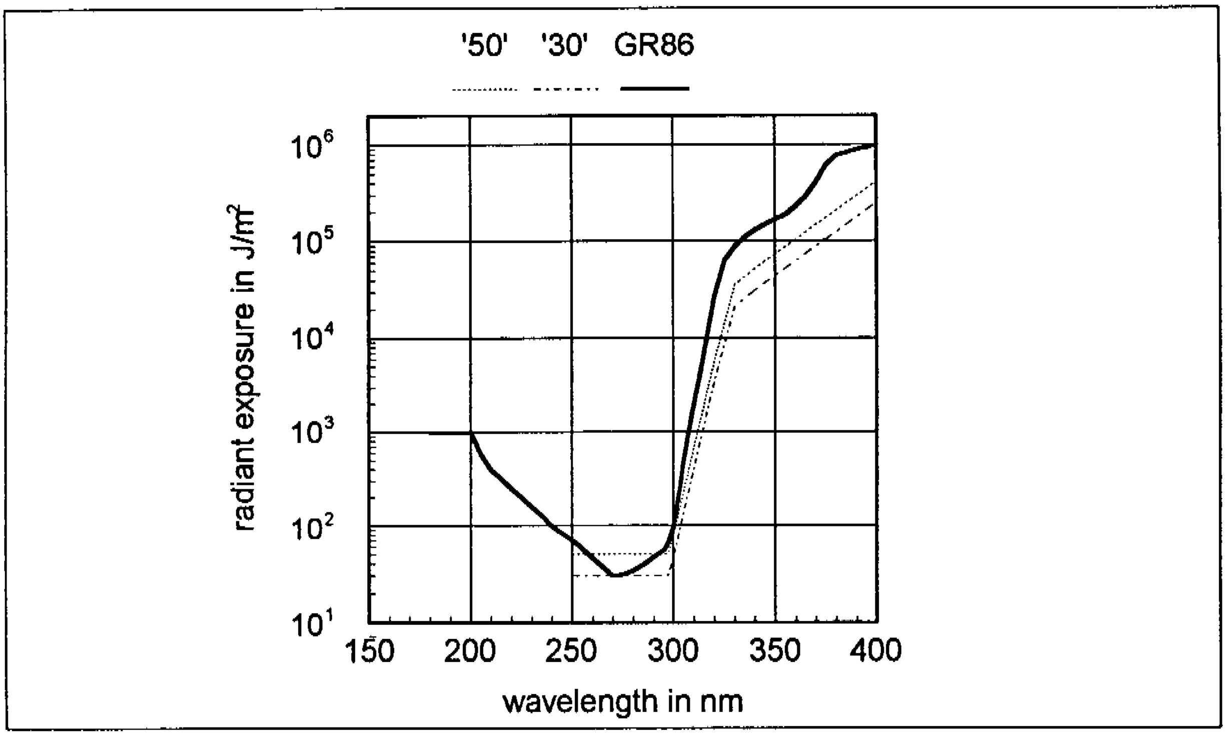

Figure 7.1. The wavelength dependence of the radiant exposure that corresponds to an erythema effective radiation exposure of 30 ('30') and of 50 J/m^2 ('50') and to a 'skin-eye'-effective radiant exposure of 30 J/m^2 ('GR86'). The erythema-effective exposure is based on the McKinlay action spectrum (McK87); the 'skin-eye' action spectrum is taken from GR86.

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sources in this range, and moreover radiation in this range is heavily absorbed by the air.

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Taking these considerations into account, the committee recommends a health based exposure limit for erythema, keratitis and conjunctivitis of 30 J/m^2 in the wavelength range from 180 to 270 nm, a 'skin-eye'-effective radiant exposure of 30 J/m^2 from 270 to 300 nm and an erythema-effective radiant exposure of 50 J/m^2 from 300 to 400 nm. In figure 7.2 this recommendation is compared with the exposure limit proposed by the International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA). The recommended health based exposure limit applies to exposure within a 24 hour period. The values of the weighting function Y_λ, that describes the wavelength dependence of the exposure limit, are presented in table 7.1. The committee follows the

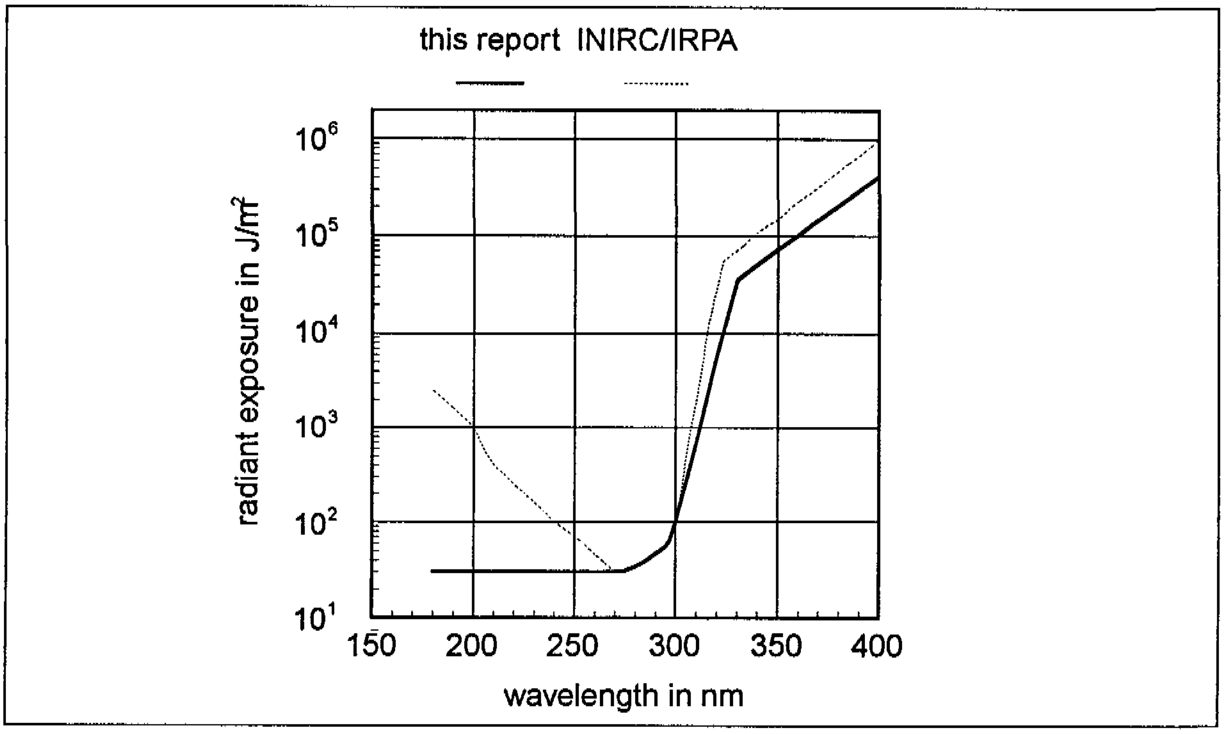

Figure 7.2. The health based exposure limit for the radiant exposure within 24 hours related to erythema, keratitis and conjunctivitis as proposed in this report. For comparison purposes the exposure limit proposed by the INIRC/IRPA for exposure to non-coherent UV radiation is also given (dotted line; IRPA91).

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1986 report in not proposing a separate exposure limit in terms of the irradiance for protection against acute effects.

Differences between the recommendation of the committee, the proposals of the INIRC/IRPA and those in the 1986 report arise mostly for wavelengths smaller than 270 nm. The committee points out that the INIRC/IRPA does recommend a constant exposure limit of 30 J/m^2 for laser radiation (IRPA91). The authors of the 1978 report saw no reason to differentiate between lasers and other optical radiation sources, and the present committee is of the same opinion. Such a differentiation only complicates the recommended exposure limit and has no scientific basis. The committee took note of the recommendation of the ACGIH (ACG91) and of the INIRC/IRPA (IRPA91) to apply an additional exposure limit of 5600t$^{1/4}$ for exposure times of 10 s or less. The basis of this

Table 7.1. Weighting function Y_λ that describes the dependence of the wavelength λ of the recommended health based exposure limit of the radiation exposure for erythema, keratitis and conjunctivitis. The exposure limit $H_{A,\lambda}$ is equal to $30/Y_\lambda$ $\mathrm{J/m^2}$.

λ (nm)	Y_λ	λ (nm)	Y_λ	λ (nm)	Y_λ
180	1	280	0.88	325	0.17×10^{-2}
190	1	285	0.77	328	0.91×10^{-3}
200	1	290	0.64	330	0.82×10^{-3}
205	1	295	0.54	333	0.74×10^{-3}
210	1	297	0.46	335	0.69×10^{-3}
215	1	300	0.39	340	0.58×10^{-3}
220	1	303	0.20	345	0.49×10^{-3}
225	1	305	0.13	350	0.41×10^{-3}
230	1	308	0.69×10^{-1}	355	0.35×10^{-3}
235	1	310	0.45×10^{-1}	360	0.29×10^{-3}
240	1	313	0.23×10^{-1}	365	0.24×10^{-3}
245	1	315	0.15×10^{-1}	370	0.21×10^{-3}
250	1	316	0.12×10^{-1}	375	0.17×10^{-3}
254	1	317	0.98×10^{-2}	380	0.15×10^{-3}
255	1	318	0.79×10^{-2}	385	0.12×10^{-3}
260	1	319	0.64×10^{-2}	390	0.10×10^{-3}
265	1	320	0.51×10^{-2}	395	0.87×10^{-4}
270	1	322	0.33×10^{-2}	400	0.73×10^{-4}
275	0.98	323	0.27×10^{-2}		

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recommendation is unclear and the committee was unable to obtain further clarification from the INIRC/IRPA.

The committee has expressed the wavelength dependence of the exposure limit as a radiant exposure weighting function Y_λ that was standardized to 1 at a wavelength of 270 nm (see table 7.1). For exposure time t, erythema, keratitis and conjunctivitis will be avoided if the exposure conforms to the condition:

$$\sum_{180\,\mathrm{nm}}^{400\,\mathrm{nm}} (Y_\lambda \times E'_\lambda \times \Delta\lambda)t \le 30 \quad \mathrm{J/m^2}.$$

in which E'_λ is the average spectral irradiance in wavelength band $\Delta\lambda$.

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7.4 Health-based exposure limits for thermal damage in the skin and the cornea

The 1978 report presented a model for the derivation of exposure limits for thermal damage (cf. paragraph 4.4). The committee deems this model still valid and recommends that the values proposed in 1978 report as health-based exposure limits for the protection against thermal effects in the skin and the cornea still be used. When these limits were derived skin reflection was assumed to be zero. Figure 4.3 shows that reflection is only of importance in the visible part of the spectrum, but even there it remains below 50% for the darkest skins. The exposure limits are less by about a factor of three than the observed damage thresholds, including those for reversible effects.

The health based exposure limits recommended by the committee depend on exposure time t (paragraph 4.4). The wavelength dependence is represented by the weighting function T_λ standardised to 1 at 3000 nm and is equal to $2/d_e$ for values of the equivalent penetration depth d_e that are greater than 2 μm, and equal to 1 for values of d_e less than or equal to 2 μm (see table 7.2). The health based exposure limits are given by the following expression (GR78; see also figure 4.5):

$$H_{A,\lambda} = 100/T_\lambda + 5.5 \times 10^3 t^{0.25} + 1000t\,[\mathrm{J/m^2}]\ (t \text{ in s, } d_e \text{ in } \mu\mathrm{m}).$$

Separate exposure limits for d_e less than 2 μm are not required. The reason is this: in that case radiation is absorbed in the superficial layers of the cornea and the skin, i.e. in non-living tissues (tears or the dead cuticle). From a health point of view such an exposure requires no special protection.

For exposure times less than roughly 1 microsecond the exposure limit for the radiant exposure practically equals $100/T_\lambda$ J/m^2, for exposure times greater than 1 s it approaches $1000t$ J/m^2, i.e. an irradiance of 1 kW/m^2.

Table 7.2. Weighting function T_λ that describes the wavelength dependence of the health based exposure limits of the radiant exposure for thermal damage in the skin and the cornea. λ is the wavelength.

λ (nm)	T_λ	λ (nm)	T_λ	λ (nm)	T_λ
skin					
250	0.17	550	0.10×10^{-1}	1200	0.29×10^{-2}
300	0.67×10^{-1}	700	0.59×10^{-2}	1400	0.29×10^{-2}
400	0.22×10^{-1}	1000	0.35×10^{-2}	1700	0.67×10^{-2}
eye					
600	0.66×10^{-6}	925	0.42×10^{-4}	1350	0.71×10^{-3}
625	0.81×10^{-6}	950	0.11×10^{-3}	1400	0.36×10^{-2}
675	0.12×10^{-5}	975	0.13×10^{-3}	1450	0.74×10^{-2}
700	0.17×10^{-5}	1000	0.10×10^{-3}	1500	0.53×10^{-2}
725	0.46×10^{-5}	1030	0.53×10^{-4}	1550	0.29×10^{-2}
750	0.75×10^{-5}	1070	0.37×10^{-4}	1600	0.20×10^{-2}
775	0.69×10^{-5}	1100	0.50×10^{-4}	1650	0.15×10^{-2}
800	0.57×10^{-5}	1130	0.12×10^{-3}	1700	0.15×10^{-2}
825	0.80×10^{-5}	1170	0.29×10^{-3}	1750	0.18×10^{-2}
850	0.13×10^{-4}	1200	0.30×10^{-3}	1800	0.23×10^{-2}
875	0.16×10^{-4}	1250	0.26×10^{-3}	1850	0.29×10^{-2}
900	0.20×10^{-4}	1300	0.32×10^{-3}	1900	0.24×10^{-1}
skin and eye					
1950	0.32×10^{-1}	3200	1	7000	0.17
2000	0.20×10^{-1}	3400	0.21	8000	0.15
2100	0.77×10^{-2}	3600	0.53×10^{-1}	9000	0.17
2200	0.48×10^{-2}	3800	0.33×10^{-1}	10000	0.18
2300	0.69×10^{-2}	4100	0.50×10^{-1}	12000	0.61
2400	0.14×10^{-1}	4400	0.87×10^{-1}	15000	0.67
2500	0.24×10^{-1}	4700	0.13	20000	0.71
2600	0.44×10^{-1}	5000	0.91×10^{-1}	25000	0.51
2700	0.26	5300	0.61×10^{-1}	40000	0.35
2800	1	5600	0.91×10^{-1}	50000	0.38
2900	1	6100	0.77	70000	0.30
3000	1	6500	0.22	100000	0.20

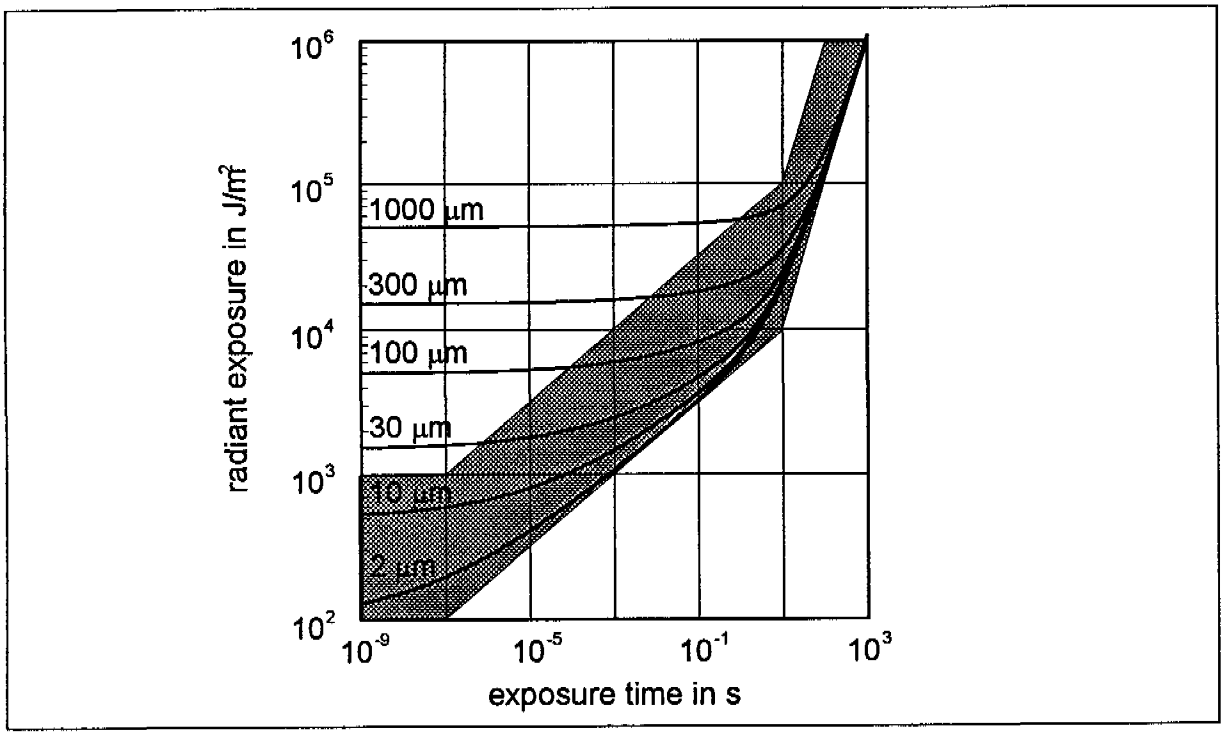

Figure 7.3. The health-based exposure limit for thermal damage in skin and eye. The curves are given for various values of the penetration depth d_e (= $2/T$; T is the weighting function that describes the wavelength dependence of the exposure limit). The shaded area contains maximum exposure levels according to the ACGIH and the INIRC/IRPA(IRPA91).

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Exposure at constant irradiance during an exposure time t will be safe when:

$$\left(\sum_{900nm}^{1mm} (E'_\lambda \times \Delta\lambda)/H_{A,\lambda}(t)\right)t \leq 1 .$$

in which E'_λ is the average irradiance in a wavelength band $\Delta\lambda$ at wavelength λ and $H_{A,\lambda}$ is the appropriate health based exposure limit for exposure time t

Figure 7.3 is a plot of the recommended exposure limit for various values of the penetration depth d_e (= $2/T$), together with the proposals of the ACGIH (ACG91, ACG92) and the INIRC/IRPA (IRPA91) for comparison: the values derived by those committees fall in the shaded area. In figure 7.4 the weighting function T_λ is drawn and compared with the corresponding function recommended by the ACGIH. The vertical line at 1540 nm represents a recent change proposed by the ACGIH. The figure

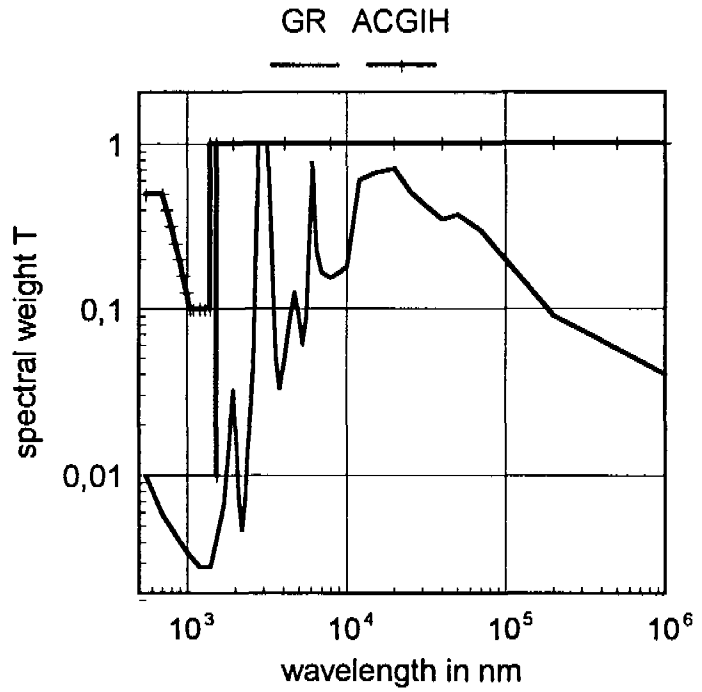

Figure 7.4. The spectral weighting function T_λ for thermal damage in the skin as a function of the wavelength λ as recommended by the committee and by the ACGIH (ACG91, ACG92). The ACGIH proposes to change the earlier value at 1540 nm of 1 to 0.01. The function T represents the wavelength dependence of the recommended exposure limit for very small exposure times.

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shows clearly that the INIRC/IRPA and the ACGIH apply a much greater margin of safety for exposure times less than about 1 s and an equivalent penetration depth greater than roughly 30 µm. This difference was already apparent in the 1978 report. The committee feels that applying such a broad safety margin is not justified from a health point of view.

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7.5 Health based exposure limits for cataract

Limiting exposure of the eye to the health based exposure limits for corneal damage generally also provides protection against cataract. This will apply for both photochemical and thermal cataract. In paragraph 7.4 the committee concluded that for exposure times of more than 1 s thermal damage to the skin and the cornea is prevented if irradiance is limited to 1 kW/m^2. This value is somewhat less than the threshold value for thermal cataract discussed in

Table 7.3. Weighting function G_λ that describs the wavelength dependence λ of the recommended health based exposure limit of the irradiance for cataract. The exposure limit $G_{A,\lambda}$ is equal to $0,25/G_\lambda$ kW/m^2.

λ (nm)	G_λ	λ (nm)	G_λ	λ (nm)	G_λ
<315	0.25	350	1	390	0.63
320	0.5	360	1	400	0.5
330	0.63	370	1	410	0.36
340	0.83	380	1	>420	0.25

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paragraph 5.4.2. Exposure to UV-A radiation is an exception: the threshold in this spectral region may be lower by a factor of 4. The committee therefore proposed that an irradiance of 0.25 kW/m^2 divided by the weighting function G_λ listed in table 7.3 be taken as an exposure limit for cataract. Limiting the exposure to the recommended exposure limit corresponds to the following conditions:

$$\sum (G_\lambda \times E'_\lambda \times \Delta\lambda) \leq 0,25 \text{ kW/m}^2.$$

in which E'_λ is the average irradiance in wavelength band $\Delta\lambda$ at wavelength λ and G_λ is the spectral weighting function describing the wavelength dependence for the cataract exposure limit. The sum covers, at least in principle, the full UV-A wavelength range (see table 7.3).

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7.6 Health based exposure limits for retinal damage

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Thermal damage

In chapter 6 the committee distinguished between point and field images with respect to retinal damage. The transition between both types could be expressed in terms of a critical angle, α_{crit}, that depends on the exposure time t (in s):

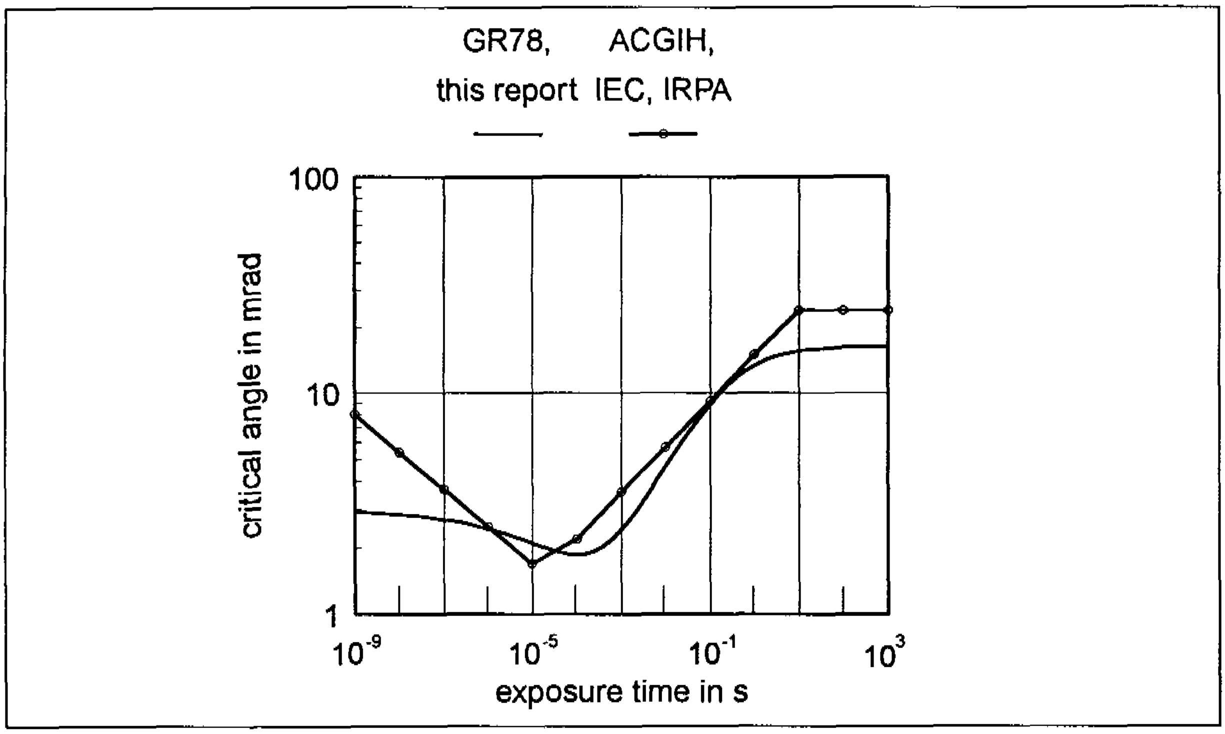

Figure 7.5. The relationship between the critical angle α_{crit} and exposure time t as given in the 1978 report (GR78) and in this report (figure 6.2). For comparison purposes the relationship used by the ACGIH (ACG91), the IEC (IEC84) and INIRC/IRPA (IRPA91) is given.

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$$\alpha_{crit} = 3\sqrt{\frac{1+3000t}{1+50t^{1/3}+100t}}\ \text{[mrad]}.$$

This relationship is plotted in figure 7.5 and compared with the dependence of α_{crit} on t as proposed by other international groups.

The committee bases its derivation of exposure limits for retinal burn in the case of point images, on the threshold energy, and in the case of field images, on the threshold radiant exposure (see chapter 6). These thresholds were determined in animal experiments in which the animals had a sensitivity greater than that of humans by about a factor of 3.. This means that these 'animal thresholds' may be used as human health based exposure limits. In the 1978 report an extra 'conditional safety factor' was nevertheless introduced because of the rather limited experimental database. Little new

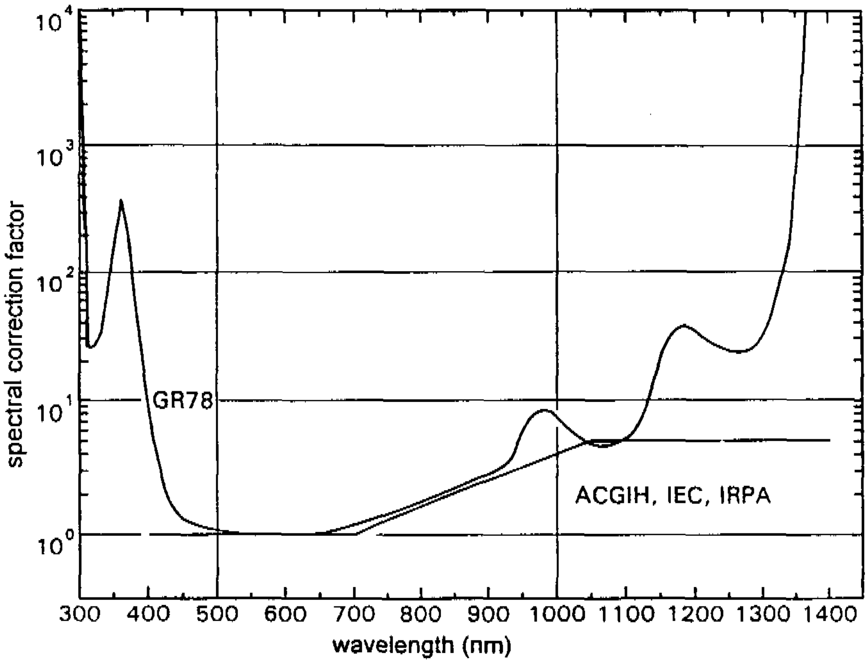

Figure 7.6. The wavelength dependence of the correction factor $C_\lambda=1/F_\lambda$ (see table 7.4). For comparison the relationship proposed by the ACGIH (ACG91), the IEC (IEC84) and the INIRC/IRPA (IRPA(91) is also given.

information has become available since then. As the values recommended in the 1978 report were consistent with internationally used 'threshold limit values', the committee proposes that the 1978 values be to retained as recommended health based exposure limits for retinal burn.

The exposure limits are specified at the cornea. This means that the expressions given in chapter 6 have to be converted from application to the retina to use for the cornea. For the threshold of the energy in the case of exposure for point images this means division by the factor F_λ (F_λ is the inverse of the correction factor C_λ that was given in the 1978 report and mentioned at the end of paragraph 6.2 and also features in international recommendations, e.g. in IRPA91). Values of F_λ are presented in table 7.4 and in graphical form in figure 7.6. For comparison the wavelength dependence of F_λ = $1/C_\lambda$ as proposed by international committees is also given in the figure.

Table 7.4. Weighting function F_λ that describes the spectral course of the wavelength λ of the recommended health based exposure limit for retinal burn.

λ (nm)	F_λ	λ (nm)	F_λ	λ (nm)	F_λ
300	0.00001	670	0.91	1040	0.21
310	0.038	680	0.83	1050	0.21
320	0.040	690	0.83	1060	0.21
330	0.029	700	0.83	1070	0.21
340	0.014	710	0.77	1080	0.21
350	0.0048	720	0.77	1090	0.20
360	0.0026	730	0.77	1100	0.19
370	0.0054	740	0.71	1110	0.17
380	0.019	750	0.71	1120	0.15
390	0.053	760	0.67	1130	0.11
400	0.14	770	0.63	1140	0.071
410	0.26	780	0.63	1150	0.045
420	0.43	790	0.59	1160	0.036
430	0.59	800	0.56	1170	0.029
440	0.71	810	0.53	1180	0.026
450	0.77	820	0.53	1190	0.027
460	0.77	830	0.48	1200	0.029
470	0.83	840	0.45	1210	0.033
480	0.83	850	0.45	1220	0.036
490	0.91	860	0.43	1230	0.038
500	0.91	870	0.40	1240	0.042
510	0.91	880	0.38	1250	0.043
520	0.91	890	0.37	1260	0.043
530	1	900	0.36	1270	0.043
540	1	910	0.33	1280	0.042
550	1	920	0.32	1290	0.038
560	1	930	0.29	1300	0.031
570	1	940	0.23	1310	0.023
580	1	950	0.17	1320	0.017
590	1	960	0.14	1330	0.010
600	1	970	0.12	1340	0.0050
610	1	980	0.12	1350	0.0014
620	1	990	0.13	1360	0.0010
630	1	1000	0.14		
640	0.91	1010	0.15		
650	0.91	1020	0.17		
660	0.91	1030	0.19		

NB. For the light of an incandescent lamp the weighting function F has an effective value of 0.2 and that for sunlight, 0.5 (GR78).

If the eye with a wide pupil (worst case) with a diameter of 8 mm (area about 50 mm^2) is irradiated the relationship between the radiant exposure at the cornea and the energy at the retina is:

$$H_{cornea,pointsource,\lambda} = 2 \times 10^4 \, (1/F_\lambda) \, Q_{retina,pointsource}$$

H in J/m^2, Q in J.

The exposure limit for extended sources is recommended by the committee in terms of the time integrated radiance L^*. Here again the 8 mm pupil is taken as a reference. The viewing angle of such a pupil aperture from the retina is 0.15 sr. This yields:

$$L^*_{extendedsource,\lambda} = 6.7 \, (1/F_\lambda) \, H_{retina,extendedsource}$$

L^* in J(m^2×sr), H in J/m^2.

The resulting exposure limit for thermal retinal damage can be written as:

$$H_{A,cornea,pointsource,\lambda} = (0.006 + 20t)/F_\lambda \quad \text{for } \alpha \leq \alpha_{crit}$$

H in J/m^2, t in s.

$$L^*_{A,extendedsource,\lambda} = (10^3 + 5 \times 10^4 t^{1/3} + 10^5 t)/F_\lambda \quad \text{for } \alpha > \alpha_{crit}$$

L^* in J/(m^2×sr), t in s.

The values of F_λ are given in table 7.4. The relationship between $Q_{A,cornea,pointsource}$ and $L^*_{extendedsource}$ on one hand and the exposure time t on the other is given in figure 7.7. For a source emitting radiation of various wavelengths, the equations can be written as:

for point sources

$$\sum_{300\text{nm}}^{1360\text{nm}} (F_\lambda \times E'_\lambda \times \Delta\lambda)\, t \leq 0.006 + 20t \quad [\text{J/m}^2]$$

E' in W/(m^2×nm), t in s.

for extended sources

$$\sum_{300\text{nm}}^{1360\text{nm}} (F_\lambda \times L'_\lambda \times \Delta\lambda)\, t \leq 10^3 + 5 \times 10^4 t^{1/3} + 10^5 t \quad [\text{J/(m}^2\times\text{sr)}]$$

L' in W/(m^2×sr×nm), t in s.

A few additional remarks may be made. In the first place these recommended health based exposure limits are generally in agreement with international standards, but at some wavelengths there are serious discrepancies (as there are between the various international standards). The committee draws attention to the conversion of the recommendation of the ACGIH that necessitates additional hypotheses (cf. the legend of figure 7.7). A constant value of the weighting function $F_\lambda = (1/C_\lambda)$ at wavelengths greater than 1050 nm, as proposed by the ACGIH, is theoretically incorrect and not justified by some rather unreliable experimental data (Lun86). The background documentation provided by the ACGIH is not very enlightening in this respect (ACG92). The committee has decided to adhere to the course of the 1978 report (GR78).

The second comment concerns the problem of intermittent sources, such as pulsed lasers. The experimental data for damage from such sources are scarce. Again like the 1978 report the committee has decided to choose the simplest of the international recommendations. It proposes to follow the ACGIH and recommend the use of the exposure limits for one pulse after division by $N^{1/4}$, in which N is the number of pulses to which one is exposed (ACG91).

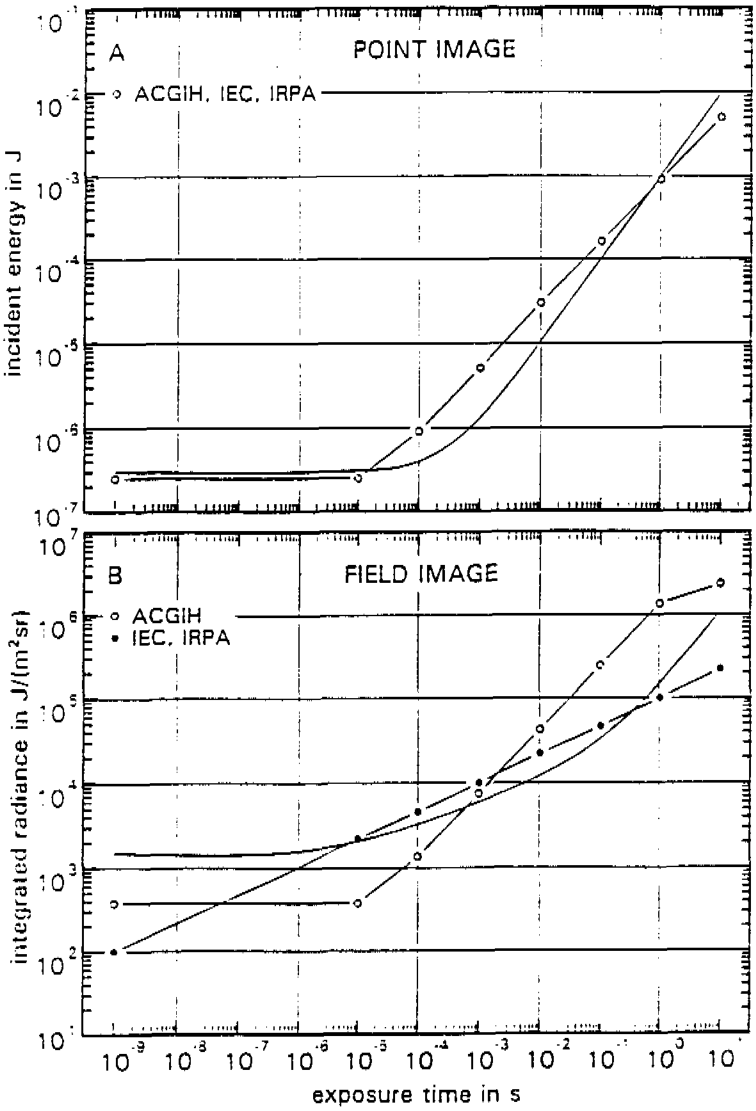

Figure 7.7. Health based exposure limits for thermal retinal damage as a function of the exposure time for exposure to point images(A). For comparison the functions proposed by the ACGIH (ACG91), the IEC (IEC84) and the INIRC/IRPA (IRPA91) are also presented. The radiant exposure values in J/cm^2 proposed by these organisations have been multiplied by 0.5 cm^2 (the area of maximum pupil size). In (B) the exposure limit in terms of the time integraded radiance for field images is given, again together with values of the ACGIH, the IEC and the INIRC/IRPA. The ACGIH has specified its limit value in terms of the radiant exposure at the cornea in J/cm^2. The conversion to radiance depend on the image size of the sun (0.5° in diameter), the conversion factor is 3×10^8 (to J/cm^2×sr); the final result is that the ACGIH more or less coincides with that of the IEC and the INIRC/IRPA, and with that of the committee.

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Photochemical damage to the retina

The data on the thresholds for 'blue light'damage have been obtained from experiments with monkeys (Ham82) and with rats (Nor90); additional data were obtained from studies with other animals. The similarity between the various results has led to the conviction that the observed action spectrum is also relevant for human exposure, provided a correction is applied for absorption by the eye media. The committee agrees in general with the recommendations of the ACGIH (ACG91), that were primarily based on the studies of Ham et al (see figure 6.4A). There are two differences, however, between the American recommendations and those of the committee. The committee does not recommend a constant exposure limit at the cornea for wavelengths greater than 600 nm, as use of such a plateau is contrary to photochemical laws. This constant value was most probably based on one observation of Ham (Ham79), that related to thermal damage and was incorrectly interpreted as being related to photochemical damage. Also the committee has 'smoothed' the ACGIH curves, because it could find no argument for the 'irregularities' in the ACGIH values.

The committee again follows the ACGIH in defining an additional 'blue light'-hazard limit for aphakes (people with the lens of the eye extracted). The same exposure limit applies to pseudophakes who have an implanted lens without UV absorbing pigments. Both exposure limits are tabulated as a function of wavelength in table 7.5 and are shown graphically in figure 7.8a. Figure 7.8b presents the values recommended by the ACGIH. The main differences are found between 600 and 700 nm.

The committee has derived the reference value for the exposure limit as follows. Ham observed a radiant exposure threshold 2.5×10^5 J/m^2 at the retina after exposure to 442 nm radiation (average value of observations with exposure times between 100 and 1000 s). The value corresponds to a radiance of 3.3×10^7 J/(m$^2\times$sr) taking a narrow pupil (diameter 2.5 mm, i.e. a solid viewing angle from the retina of 0.015 sr) and a transmission of 0.7 by the eye media (table 6.1.). The ACGIH

Table 7.5. Weighting function B_λ that describes the spectral course of the recommended health based exposure limit of the radiance for photochemical retinal damage for people with their natural lens intact. A_λ is the corresponding value for people with their natural lens extracted and without a coloured implant lens (aphakes and pseudophakes).

λ (nm)	B_λ	A_λ	λ (nm)	B_λ	A_λ
305	-	6.0	410	0.64	2.0
310	-	6.0	415	1.20	1.8
315	-	6.0	420	1.25	1.6
320	-	6.0	425	1.20	1.4
325	-	6.0	430	1.10	1.2
330	-	6.0	435	1.07	1.1
335	-	6.0	440	1.0	1.0
340	-	5.9	445	0.92	0.92
345	-	5.7	450	0.84	0.84
350	-	5.5	455	0.75	0.75
355	-	5.3	460	0.65	0.65
360	-	5.0	465	0.55	0.55
365	-	4.7	470	0.45	0.45
370	-	4.4	475	0.36	0.36
375	-	4.0	480	0.28	0.28
380	-	3.6	485	0.23	0.23
385	-	3.3	490	0.16	0.16
390	-	3.3	495	0.12	0.12
395	-	2.8	500-700	$10^{[(450-\lambda)/50]}$	$10^{[(450-\lambda)/50]}$
400	0.17	2.5	>700	0	0
405	0.34	2.2			

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(ACG91) recommends a threshold limit value at 442 nm of 10^6 J/(m^2×sr) and thus implicitly chooses a rather larger safety factor of 33. However, given the large uncertainties due to the limited experimental data, the difference in damage criteria used in the experiments, and the differences in transmission values and pupil size, the committee feels justified in supporting the ACGIH recommendation. It proposes that this value be adopted as a reference for the exposure limit curve.

What integration period should be used in evaluating the 'blue light'hazard after exposure to optical radiation? Kremers observed that, with monkeys, the threshold values were independent of exposure times up to 12 hours (Kre89). In order to err on the side of safety the committee recommends

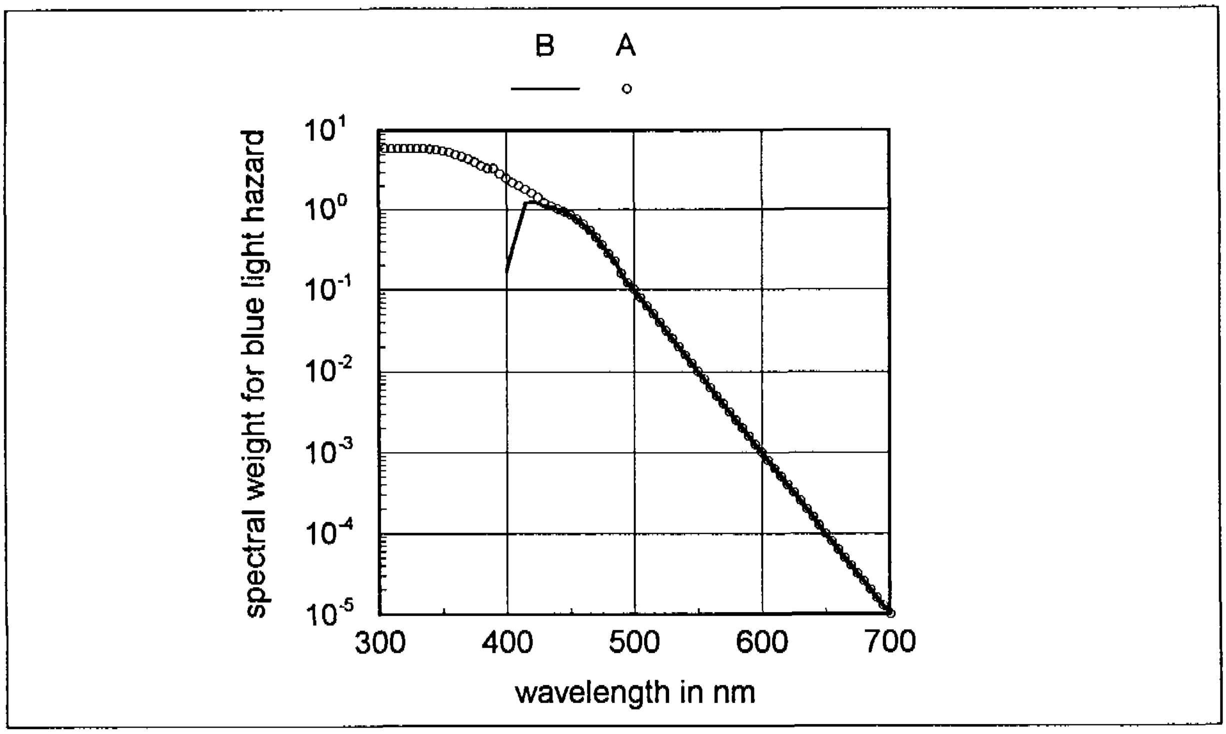

Figure 7.8a. Weighting function B_λ that describes the spectral course of the health based exposure limit of the radiance for photochemical retinal damage in people with a natural lens. A_λ is the corresponding function for people without a natural lens.

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application of an integration period of 10^5 s (ca 27 hours, consistent with a 24-h period) to the irradiance. This recommendation differs from that of the ACGIH of 10^4 s (about 3 hours). In the case of occupational exposure the committee proposes that the irradiance be integrated over a full working day.

The recommended exposure limit is presented in figure 7.9 as a function of exposure time for three different wavelengths. The committee points out that, in deriving the exposure limit, 'visual pigment'damage was not taken into account, as has been mentioned in chapter 6.

Adhering to the recommended exposure limits implies that the following condition should be fullfilled:

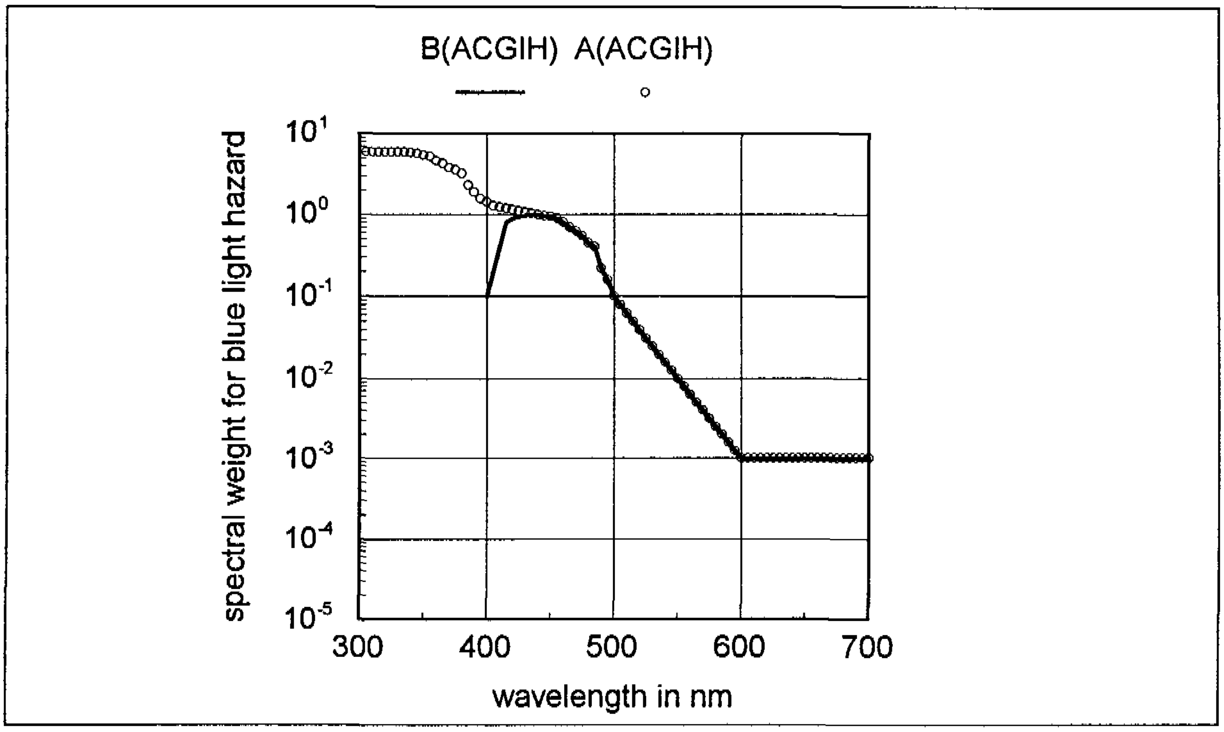

Figure 7.8b. Recommendation of the ACGIH (ACG91) for the weighting function B_λ that describes the wavelength dependence of the health based exposure limit of the radiance for photochemical retinal damage in people with a natural lens. A_λ is the corresponding function for people without a natural lens. See also figure 7.8a.

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$$\sum_{400\text{nm}}^{700\text{nm}} (L'_\lambda \times B_\lambda \times \Delta\lambda)\, t \le 10^6 \text{ J/(m}^2\text{×sr)}$$

L'_λ in W/(m^2×sr×nm), t in s and less than 24 hours

In this expression B_λ is the blue light'-hazard function (see table 7.5). When protection of pseudophakes without a coloured implant lens and aphakes is involved the function A_λ from table 7.5 should be used instead.

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7.7 Effects of chronic exposure to optical radiation

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Skin cancer

Exposure of the skin to ultraviolet radiation increases the risk of skin cancer (basal cell and squamous cell carcinoma; the committee refrains from making a statement about

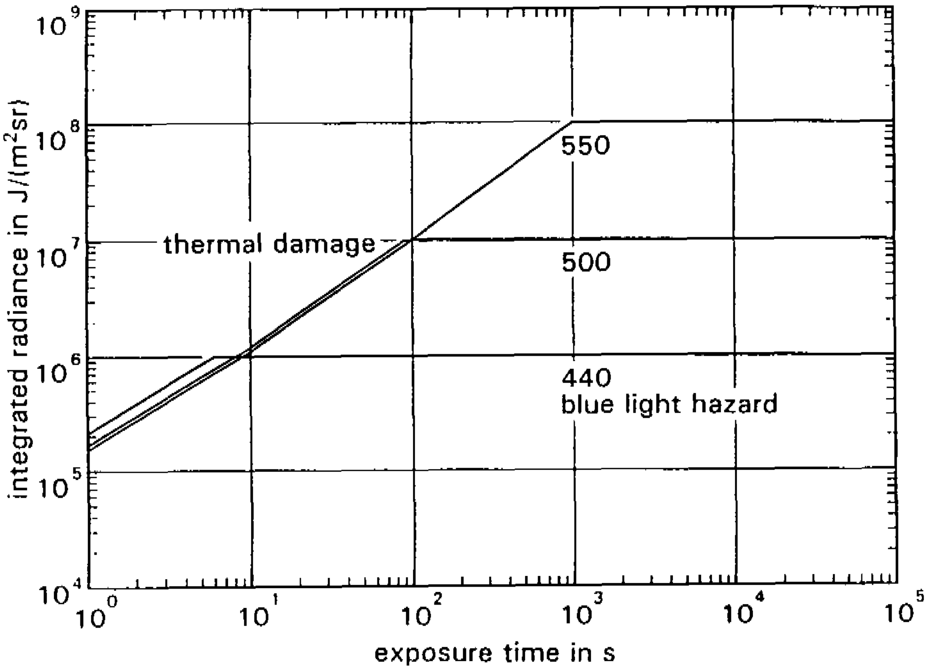

Figure 7.9. Exposure limits for photochemical and thermal damage (combined) at wavelengths of 440, 500 and 550 nm.

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the risk of melanoma; see chapter 4). An exposure level below which an effect on health effect cannot be defined is absent. To prevent damage to health it is therefore advisable to simply reduce chronic exposure as far as possible. Information about the risks of occupational exposure to ultraviolet radiation should consequently also refer to the contribution of cumulative exposure to the sun. It should be pointed out, however, that UV radiation also stimulates the production of vitamin D in the body (GR86).

The 1986 report presented some estimates of the risk of skin cancerk. A 40 year occupational exposure to an erythema-effective radiant exposure of 20 J/m^2 per working day increases the risk of skin cancer by a factor of 1.3. This exposure corresponds roughly to the exposure limit in terms of the 'skin/eye'-effective radiant exposure of 30 J/m^2 per working day that was recommended in the earlier report. It was noted in the 1986 report that outdoor workers are exposed to a daily erythema-effective exposure that is about 200 J/m^2

greater than that of indoor workers. Such a difference corresponds to an about 5-fold increase in skin cancer risk.

The calculations that yielded these estimates were based on the erythema action spectrum recommended by the Health Council in 1986. Recalculation with newer action spectra (Ste87, UNEP91, Gru93) are not expected to produce drastically different values.

The committee does not recommende an exposure limit to reduce the risk of skin cancer. It does, however, recommend that the chronic total exposure to UV radiation should be reduced as much as possible.

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Cataract

The committee has discussed cataract resulting from chronic exposure to optical radiation in paragraph 7.5.

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Retinal damage

The committee discussed the 'visual pigment'hazard in chapter 6. This type of damage is caused by chronic exposure to visible radiation. Knowledge about the 'visual pigment'hazard is still too limited to provide the basis for an exposure limit.

The same applies to age related macular degeneration (AMD).

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7.8 To conclude

The committee has recommended four sets of health based exposure limits for acute damage from exposure to optical radiation. These limits were derived for erythema, keratitis and conjunctivitis, for thermal skin and cornea damage; for cataract; and for photochemical and for thermal retinal damage. In practice, in order to prevent acute effects on health, the exposure should be less than all recommended limits at the same time.

8 EPILOGUE

The committee's task was to investigate in how far new insights made it necessary to review the 1978 report of the Health Council. The recommendations of the committee were given in the preceding chapter as health-based recommended exposure limits for acute damage to skin and eye due to optical radiation. In this final chapter the committee compares its conclusions with the limits earlier recommended and with relevant international recommendations. Some points are raised that may be helpful in putting the present recommendations into practice. The chapter ends with examples in which the present recommendations are applied to situations of practical interest.

8.1 Differences in recommended exposure limits

The recommendations from international bodies such as the International Non-ionising Radiation Committee of the International Radiation Protection Association (now the International Commission on Non-Ionising Radiation Protection), the International Electrotechnical Committee and the American Conference of Governmental Industrial Hygienists, do agree to a large extent. This is not surprising, as these organisations recruit their experts from the same, narrow group of scientists. Differences between the various proposals are mostly due to differences in speed of adjustment, rather than differences in insight. The regulations that are now being discussed with the European Commission (EG92) are based on the recommendations of the organisations mentioned.

The committee takes the point that international agreement about health based exposure limits is desirable and this is reflected in the recommendations of chapter 7. However, it is of overriding importance that these limits be founded on experimental and epidemiological data. When the committee did decide to deviate from the international proposals, considerations based on these data were the reason.

The exposure limits for protection against retinal damage recommended by the committee, differ here and there from what prevails internationally. This was already the case in 1978; the earlier Health Council report differed as to essential points from the recommendations of the American National Standards Institute; the same holds true for the present recommendations as compared to those of the ACGIH and the INIRC/IRPA. This was to be expected for photochemical retinal damage as the data are limited and research on the topic is being actively carried out.

One may wonder, however, why the various recommended exposure limits for protection against retinal burn have not converged during the last two decades. No new developments have occurred since the publication of the 1978 report and one would expect that consensus had been reached. However, the present committee saw no reason to deviate essentially from the 1978 recommendations. The international recommendations are in general unchanged, with only few, and somewhat obscure modifications. The discrepancies between the Dutch and the international recommendations thus still persist (Vos93a).

The wavelength dependence of the radiant exposure threshold for retinal burn given here follows the absorption characteristics the eye media. The international standards have a much more schematic wavelength dependence, probably because the experts who formulated them preferred simple curves. This leads to rather large differences at wavelengths greater than 1100 nm (figure 7.6). The effect of such differences may be that the development of types of radiation sources will be hampered because of a not obviously valid health protection argument. At the wavelength of the Nd:YAG-laser of 1.32 μm, for example, the spectral weighting factor for retinal burn, *F* (= 1/*C*), proposed by the ACGIH, differs by a factor of more than 10 from the value recommended by the committee (ACGIH: 0.2; present and 1978 Health Council report: 0.017). This results in an, according to the committee, unnecessary increase by a factor of 3,4 in the minimal safety distance.

A second notable difference is the way in which exposure to point images is distinguished from that to extended field images (figure 7.5). Physical arguments dictate that the critical viewing angle approaches a constant value with decreasing exposure time and not a sharp increase as the international standards suggest.

Another example is provided by the comparison of the spectral dependence of the limit for thermal skin damage (figure 7.4). The intended change in the ACGIH Threshold Limit Value by a factor of 100 (which would bring it to near coincidence with the value recommended by the committee) especially shows the degree of arbitrariness of some of the international proposals. In these cases, the committee deems the scientific basis of its own recommended exposure limits sufficiently sound to justify steering its own course.

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8.2 Preventive action comes first

When possible, the committee has recommended health based exposure limits for optical radiation exposure. It is made clear in chapters 4, 5 and 6 that keeping exposures below these limits does not provide a guarantee that damage will never occur. This is obvious in the case of skin cancer, because a no-effect-level cannot be determined. With respect to melanoma, pterygium or macula degeneration, not enough is known about optical radiation as a risk factor moment. Furthermore, lack of knowledge about groups specially at risk is still a problem. An example of the latter is the controversial effect of light on premature babies (Rob92). Faced with all these uncertainties the committee cannot but recommend avoidance of unnecessary exposure to optical radiation: prevention should come first.

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8.3 Practical examples

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8.3.1 Translating exposure limits into practical measures

Secondary limits, more directly applicable in practice, should be derived. The limits also have to be translated into applicable technical measures. This is not always easy, as the limits themselves are rather complicated and also because the language of industrial specifications often is not suited for a direct translation. Some examples are given below to illustrate the difficulties, and a possible way out in the form of product norms is presented in paragraph 8.4.

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8.3.2 Nd:YAG-laser

What is the minimal distance from a Nd:YAG-laser with a wavelength of 1.32 µm at which the recommended exposure limit is not exceeded? (laser power 15 W; exit diameter 3 mm; beam divergence 2 millirad, $1/e^2$-values).

The intensity distribution, I, that follows from the laser specifications is given by the expression:

$$I=2.4\times10^6\exp\ (-\phi^2/2\mathrm{x}10^{-6})\,[\mathrm{W/sr}]\quad(\phi \text{ in rad}).$$

At a distance R [m] in a forward direction the irradiance, E, is given by:

$$E=2.4\times10^6/R^2\ \ [\mathrm{W/m^2}].$$

If the laser can be taken as a point source, retinal damage during exposure time t is prevented by:

$$H=Et\leq H_A=(0.006+20t)/F_\lambda.$$

or

$$R^2\geq(2.4\times10^6t)/((0.006+20t)/F_\lambda).$$

At a wavelength of 1.32 µm $F_\lambda = 0.017$, which means that for all exposure times of practical interest (t > 3 ms), one should keep a distance of 45 m or more ($R \geq 45$ m). Whether the condition for point sources is satisfied at this distance must be verified. The viewing angle at this distance is 2/45 = 0,044 millirad, which is indeed smaller than α_{crit}.

However, the exposure limit for an irradiance E_A = 1 kW/m^2 for the prevention of damage in the skin, the cornea and the lens should be satisfied simultaneously:

$$E \leq E_A = 1000\,.$$

or

$$R \geq \sqrt{2400} \approx 50 \text{ m.}$$

In this case both distances happen to be approximately equal. This is sheer coincidence, which can be demonstrated by using the 'international' value of 0.2 for F_λ instead of 0,017. Using the former value would increase the minimal distance to 150 m.

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8.3.3 Halogen-filled incandescent lamp

Can erythema be induced by exposure to unfiltered light from a halogen filled incandescent lamp and is it safe to view straight into the lamplight?

The following calculation is based on the specifications of the GY6.35 lamp with a power of 50 W. The manufacturer specifies the intensity distribution, i'_λ, only up to 780 nm. Using Planck's law for a source temperature of 3100 K this intensity distribution has been extended beyond this wavelength.

Assuming the use of the lamp as a desk light, an illuminance of 1000 lux on the desk seems appropriate. This means:

$$680 \sum_\lambda E'_\lambda V_\lambda \Delta\lambda = 1000 \quad \text{lux.}$$

in which V_λ is the relative sensitivity of the eye (V_{550nm} = 1) and the value 680 (lumen/watt) converts irradiance into illuminance. The manufacturer specifies an illuminance of 1000 lux at a distance of 50 cm. Standardizing irradiance E'_λ in this way enables one to calculate the Y-weighted irradiance:

$$\sum_\lambda E'_\lambda Y_\lambda \Delta\lambda = 8.24 \times 10^{-5} \mathrm{W/m^2}.$$

The condition that the weighted radiant exposure should be less than the exposure limit is expressed by:

$$\left(\sum_\lambda E'_\lambda Y_\lambda \Delta\lambda\right) t \leq 30 \quad \mathrm{J/m^2}.$$

This leads to a maximum exposure time of t_{max} = 12000 s = 3.3 hours. The halogen lamp may thus induce erythema within a working day. However, filtering out the UV-B radiation will prevent erythema without significantly affecting illuminance.

What about the possibility of retinal burn as a result of viewing directly into the lamplight? The light emitting element has a length of 3.6 mm and can be considered to be a point source at a distance of about 1 m or more. The irradiance at 1 m can be derived by multiplying the E'-values given earlier by 0.25. The F_λ-weighted irradiance is computed from:

$$\Sigma_\lambda E'_\lambda F_\lambda \Delta\lambda = 4.3 \quad \mathrm{W\ m^2}.$$

Application of the exposure limit requires:

$$\left(\sum_\lambda E'_\lambda F_\lambda \Delta\lambda\right) t \leq 0.006 + 20t \quad \mathrm{J/m^2}.$$

which in this case, appears to be satisfied for all exposure times t, *so that* there is no retinal burn hazard from this lamp at a viewing distance of 1 m.

Halogen lamps are also used in operation microscopes, for example, in ophthalmology. According to the literature, these sources produce an irradiance at the retina of about 4 kW/m^2, which corresponds to a radiance of L = 3×10^4 W/(m$^2\times$sr). To avoid retinal burn the following condition for the time integrated radiance should be satisfied:

$$Lt \leq 10^3 + 5 \times 10^4 t^{1/3} + 10^5 t \quad [\mathrm{J/(m^2 \times sr)}].$$

This condition is fulfilled for all exposure times *t*. Operation microscopes incorporating the lamp as specified here do not produce retinal burn.

'Blue light' hazard is a different case, however. Again starting from the irradiance, weighted for retinal burn, of 4 kW/m^2 at the retina:

$$\sum_{\lambda} E'_{\lambda} F_{\lambda} \Delta\lambda = 4000 \ \mathrm{W/m^2}.$$

Irradiance, weighted by the 'blue light'-hazard weighting function B_{λ} can then be calculated:

$$\sum_{\lambda} E'_{\lambda} B_{\lambda} \Delta\lambda = 153 \ \mathrm{W/m^2}.$$

For an open pupil with a diameter of 8 mm (0,15 sr) this yields:

$$\sum_{\lambda} L_{\lambda} B_{\lambda} \Delta\lambda = 1000 \ \mathrm{W/(m^2 \times sr)}.$$

The condition to be satisfied to avoid the 'blue light'-hazard is in this case:

$$\left(\sum_{\lambda} L_{\lambda} B_{\lambda} \Delta\lambda\right) t \leq 10^6 \ \mathrm{J/(m^2 \times sr)}.$$

This means that looking into the lamp should be restricted to 1000 s ≈ 17 minutes.

This implies that the retina of a patients who must look into an operation microscope during treatment, may be damaged. This can be prevented by applying a yellow filter with a cut-off wavelength of 500 nm, as roughly 90% of the damage is caused by radiation with wavelengths of less than 500 nm. Use of such a filter means that viewing time can be extended to 170 minutes, i.e.. about 3 hours.

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8.3.4 Solaria

Is there a risk that personnel in a suntanning parlour will develop erythema as a result of occupational exposure?

In this third example the calculations are based on data for a solarium with TL09-tubes and spectral data (i'_λ) supplied by the manufacturer. The intensity spectrum is bell-shaped and covers roughly the full UV-A spectral region. It is presumed that personnel is exposed to an averaged irradiance of 1 W/m^2 on the skin (value obtained during actual practice). This exposure, together with the intensity spectrum yields an erythema-effective irradiance of:

$$\sum_{\lambda} E'_{\lambda} Y_{\lambda} \Delta\lambda = 5.6 \times 10^{-4} \text{ W/m}^2.$$

To prevent erythema the condition for erythema-effective radiant exposure is:

$$\left(\sum_{\lambda} E'_{\lambda} Y_{\lambda} \Delta\lambda\right) t \leq 30 \text{ J/m}^2.$$

It can be derived from this condition that exposure time should be limited to 54000 s, i.e. about 15 hours. Personnel will thus not experience problems involving erythema from their occupational exposure (other sources are not considered in this calculation)

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8.4 Product standards

All three examples illustrate the complexity of translating industrial specifications into maximum permissible exposure times. Safety instructions for users of optical radiation sources should be formulated in appropriately simple terms. One way of achieving this is the introduction of product standards. The committee gives the following examples.

It is internationally accepted that lasers be classified from 'not dangerous' to 'very dangerous on viewing into diffuse reflected light'. In the case of sunlamps and solaria, the standards contain protocols for courses of irradiation that are related to irradiance and exposure time. Such protocols were proposed in the 1986 Health Council report on UV radiation. The product standards for (e.g.) halogen lamps and fluorescent tubes should focus on irradiance in the UV spectral region.

Standards can also set requirements for products aimed to personal protection. Examples of personal eye protectors are: welding goggles, UV and sun glasses. Product information in these cases should contain data on UV transmission, visual density and, depending on the intended use for the glasses, on IR transmission. Sunscreen creams and lotions are used for protection of the skin against UV radiation. It is common to characterise a sunscreen by its sun (erythema) protection factor. In the 1986 report it was noted that this factor does not necessarily indicate the degree of protection against skin cancer. Standards for implant lenses should include specifications for use of UV absorbing material so as to provide requirements of the UV transmission in view of retinal protection.

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Recommendations for product standards are, however, outside the scope of the present report.

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8.5 To be continued?

The Health Council committee that produced the 1978 report suggested a revision of its recommendations after a 5-year period. This revision, i.e. the present report, was prepared 15 years later. The present committee refrains from recommending a revision period. However, any other revision should be performed in a European context, given the present development to set EC-regulations for optical radiation exposure in the worksituation.

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APPENDICES

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A Request for advice of the Minister of Social Affairs and Employment

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B Membership of the committee

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A REQUEST FOR ADVICE OF THE MINISTER OF SOCIAL AFFAIRS AND EMPLOYMENT

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In his letter of March 16, 1990 the Minister of Social Affairs and Employment asked the Minister of Welfare, Public Health and Cultural affairs for an advisory report of the Health Council. The Minister's request runs as follows:

....

Dated March 30, 1978 the Health Council published an advisory report on 'Recommendations concerning acceptable levels of electromagnetic radiation in the wavelength range between 100 nm and 1 mm (micrometre radiation)'. In this report a committee of the Council describes the possible biological effects in humans and recommends maximum permissible exposure levels ('exposure limits').

On June 10, 1986 the Health Council report on UV radiation was published. In that report a committee of the Council slightly revises the exposure limits for UV radiation and in addition proposes measures to protect skin and eyes. In that report exposure to laser radiation was left out of consideration, although the committee states that, in any case in the wavelength region from 100 to 400 nm, the recommended limit for unintentional exposure is also applicable for laser radiation

In the course of the last decade new data have become available on exposure to micrometer radiation and on the health damage that such exposures may entail. The data relate both to very high doses during extremely short periods (as may the case with laser radiation, and to relatively low doses spread out over longer periods of time (light damage). Also in the latter years new information has become available about the mechanisms that lead to such effects.

The rapid development of lasers and laser applications and of increasingly intense radiation sources, e.g. in hospitals and in industry, lead to more frequent exposure of workers to high doses of micrometre radiation.

These new data stimulated many (international) committees (among others INIRC/IRPA, IEC, ACGIH) to revise the standards and exposure limits recommended by them. The present activities of the CEN (Committee European de Normalisation) TC76 to establish a European standard for the radiation safety of laser products based in the IEC825-standard are an example.

In its 1978 report the committee recommended to evaluate the proposed exposure limits after a period of 5 years, in order to determine if revision is required.

Given these considerations I would appreciate it if the Health Council would revise its report on exposure to micrometre radiation. In a new report I expect the description of the biological effects, the mechanisms behind them and the exposure risks to figure prominently.

(signed)
The Minister of Social Affairs and Employment

(B. de Vries)

....

....

B MEMBERSHIP OF THE COMMITTEE

....

The membership of the committee was as follows:

- Dr JJ Vos, chairman
  Bilthoven, retired, former senior scientist at the Department of Visuology, TNO Institute for Human Factors, Soesterberg
- Dr TJTP van den Berg
- Professor of medical physics and information sciences, The Netherlands ophthalmic research Intituut. Royal Netherlands Academy of Arts and Science, Amsterdam.
- Dr BFM Bosnjakovic, advisor (untill 1 April 1990)
  Department of Radiation, Directorate-General of Environment, Ministry of Housing, Physical Planning and Environment, The Hague.
- Ing F Hooft
  Ermelo, former chief of the Department of Safety and Environment, University of Utrecht. Utrecht.
- Prof dr JC van der Leun
  Professor of the physics of the skin, Department of Dermatology, University of Utrecht. Utrecht.
- Dr CCE Meulemans
  Former scientist at the Laboratory of Optics and Application, Philips Lighting BV, Eindhoven
- Prof dr JA Oosterhuis
  Wassenaar, retired, professor of ophthalmology, Leiden University.
- Dr ir HJCM Sterenborg
  Scientist at Lasercentre, Academic Medical Centre, Amsterdam
- Prof dr D Suurmond
  Leiden retired, professor of dermatology, Leiden University.
- Dr JWM Visser
  Scientist at the Department of Cell Biology, Institute for Applied Radiobiology and Immunology TNO, Rijswijk (ZH)
- Drs L van Vliet, advisor
  Directorate-General of Labour, Ministry of Social Affairs and Employement, The Hague.
- Drs GJ Eggink, scientific secretary (until 1 January 1991)

The Health Council of the Netherlands, The Hague.
- Dr WF Passchier, advisor (until 1 januari 1991),
  Scientific secretary (from 1 January 1991).
  The Health Council of the Netherlands, The Hague.
- Prof dr D van Norren, scientific secretary (from 1 June 1991).
  TNO Institute for Human Factors, Soesterberg.

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