Occupational exposure to ultraviolet radiation: the duality dilemma

Michael G. Kimlin\textsuperscript{1,2} and Thomas D. Tenkate\textsuperscript{2}

\textsuperscript{1}Institute of Health and Biomedical Innovation and \textsuperscript{2}School of Public Health, Queensland University of Technology; Brisbane, Australia

Abstract: Human exposure to ultraviolet (UV) radiation is a component of everyday life and a significant hazard for outdoor workers. In addition, a large range of artificial sources also has the potential to provide extreme occupational UV exposure. Even though the human health risks of over-exposure to UV are well documented, to date relatively little is known quantitatively about UV exposure. For example, the evidence indicates that workers who are exposed to particular sources (for example, welding arcs) are exposed to extreme UV exposure, despite the use of current control measures. In contrast, increasing evidence points to significant health impacts resulting from under-exposure to UV, particularly with the production (or more correctly lack of production) of vitamin D in the skin. The latter poses a serious issue for the work-force, with specific risks for workers lacking adequate sun exposure—underground miners, long-haul flight crews, shift workers, and perhaps indoor workers. Using a risk-management approach, this paper provides a comprehensive review of occupational UV sources, health impact of occupational UV exposure, occupational exposure standards, and levels of exposure in various settings, and discusses the appropriate control measures. In addition, the duality aspect of health impacts from overexposure and under-exposure to UV and the associated occupational health implications are specifically explored.

Keywords: vitamin d, eye neoplasms, melanoma, bone health, photodermatoses, photokeratoses

Correspondence: Thomas Tenkate, QUT School of Public Health, Victoria Park Road, Kelvin Grove, QLD, 4059, Australia; e-mail: t.tenkate@qut.edu.au

INTRODUCTION

For most humans, exposure to ultraviolet (UV) radiation is a component of everyday life. For workers, particularly outdoor workers, such exposure has been an important occupational health and safety issue for many years. The risk of overexposure to UV has been well documented in both epidemiologic investigations and laboratory-based experiments proving that excessive exposure to UV is associated with a range of adverse skin and eye conditions, including various types of skin cancer. Consequently, skin-cancer prevention is a significant public health priority for many health agencies. A number of major public health and occupational health and safety initiatives (for example, Sun Smart) have been implemented in an attempt to reduce worker (and the general public) exposure to UV /1-2/. Of concern for human overexposure to UV is the well-documented decline of stratospheric ozone levels over the past two decades, due to anthropogenic emissions of ozone-depleting substances. Such declines are predicted to have significant impacts on the natural UV protection provided by the atmosphere /3/. In particular, an inverse exponential relation has been shown to exist between biologically damaging UV radiation and stratospheric ozone concentration /4/ and between the incidence of skin cancer and UV irradiance as well /5/.

Despite risks of overexposure to UV, very little is known quantitatively about human UV exposure. Interestingly, human exposure to sunlight also has a nutritional impact, namely the development of pre-Vitamin D, which is an important nutrient in bone health. New research
Table 1: Sources of ultraviolet radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>Exposure Potential</th>
<th>Hazard Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Sun</td>
<td>High to Extreme</td>
<td>Direct and reflected UV from the sun and through glass.</td>
</tr>
<tr>
<td></td>
<td>(dependent on location)</td>
<td></td>
</tr>
<tr>
<td>Welding arcs</td>
<td>Extreme</td>
<td>Occupational exposure limit exceeded in seconds within few meters of arc, plus UV-C emitted.</td>
</tr>
<tr>
<td>Germicidal lamps</td>
<td>High</td>
<td>UV-B and UV-C lamps used for sterilization in hospitals and laboratories</td>
</tr>
<tr>
<td>UV lasers</td>
<td>High</td>
<td>Intense UV at a single wavelength</td>
</tr>
<tr>
<td>UV curing lamps</td>
<td>Medium</td>
<td>Usually used inside cabinets</td>
</tr>
<tr>
<td>‘Black’ Lights</td>
<td>Medium to low</td>
<td>UV-A lamps used in non-destructive testing, and in entertainment</td>
</tr>
<tr>
<td>Fluorescent lighting</td>
<td>Low</td>
<td>Limited to no UV emitted</td>
</tr>
</tbody>
</table>

Adapted from: /321/

suggests that low vitamin D status may be a causative factor in the development of selective types of cancer and autoimmune disease, as well as a contributing factor in bone health /6/. This paper presents a comprehensive review of the current literature on occupational exposure to UV from both natural and artificial sources and specifically discusses the health duality aspect of sunlight exposure.

OCCUPATIONAL SOURCES OF UV

Ultraviolet (UV) radiation emanates from many sources, which can be categorized as (a) natural sources (the sun), (b) electrical or gaseous discharge sources (incandescent lamps, fluorescent lamps, welding arcs), and (c) lasers /7/. A summary of sources is shown in Table 1.

Solar UV Radiation

At the earth’s surface, the main source of UV is the sun. The sun is also the main occupational UV source because estimates suggest that up to one-third of the workforce is occupationally exposed to sunlight on a regular basis /8/. Because of its high surface temperature and large size, the sun produces a broad spectrum of electromagnetic radiation that ranges from the very short wavelengths of gamma radiation and X-rays up to radio wavelengths. Around 80% of solar energy falls in the visible 400 to 700 nm spectral range and near infrared 700 to 1500 nm spectral range, with UV making up around 8.3% of the extraterrestrial solar radiation /7/. Yet, solar output is not constant and is subject to temporal variations, due to a 27-day solar rotation and an 11-year cycle of sunspot activity /9/. In addition, the elliptical orbit of the sun results in a variability of ~3.4% in the sun-earth distance. This changeability results in a seasonal variation in intensity of about 7%, causing summer UV levels in the southern hemisphere that are slightly higher than those in the northern hemisphere /10/.

Although the extreme intensity of the solar radiation incident on the earth is considered lethal to most living organisms, the atmosphere provides a large degree of shielding so that the UV levels at the earth’s surface are substantially reduced. The
main factors that contribute to the amount and spectral distribution of solar UV reaching the earth’s surface include the following:

- Atmospheric attenuation. Both the quality and quantity of solar UV are modified when the radiation passes through the earth’s atmosphere. The main attenuation processes occur in the stratosphere (around 10 to 50 km above sea level (ASL)), where essentially all the radiation in the UV-C range (below 290 nm) is absorbed by molecular oxygen and ozone. In addition, a substantial fraction (in excess of 90% of the total energy) of UV-B radiation (290 to 315 nm) is absorbed by ozone, whereas radiation in the UV-A range (315 to 400 nm) is not absorbed in the stratosphere /11/. Therefore, the earth’s surface is exposed only to UVR of wavelengths between 290 nm and 400 nm. Other trace gases and aerosols in the stratosphere, such as sulfur dioxide or particulate matter from volcanic eruptions and pollutant aerosols from industrial sources, can also be important absorbers of UV.

- Clouds. Being made up of either liquid or ice droplets, clouds attenuate UV primarily by scattering. Clouds tend to attenuate UV-B and UV-A to the same degree but attenuate infrared radiation much more than UV, and as such, the risk of overexposure on cloudy days is increased because the warming sensation of heat is reduced /12/. The amount of UV attenuation by cloud cover is on average between 22% and 38% of clear sky values /13/ and can be up to two-thirds of clear-sky values for temperate latitudes and 75% for tropics /14/.

- Surface reflection. When UV reaches the earth’s surface, some is absorbed and some is reflected back up into the atmosphere. Surface reflection can be important for human UV exposure as the reflected radiation can undergo scattering or further reflection from cloud layers back toward the surface, therefore increasing the amount of diffuse radiation incident on the surface. For most ground surfaces, the amount of reflection of solar UV is normally less than 10%, but some surfaces are particularly good at reflecting solar UV, with gypsum sand reflecting about 15% to 30% and snow being able to reflect up to 90% of the incident UVR /12/.

- Surface elevation. The UV incident at any particular location on the earth’s surface varies with the time of day, the time of year, and the geographic position (latitude and longitude). The amount of variation is determined by the solar zenith angle (SZA) (which describes the angle of incidence of incoming radiation), with more attenuation when the sun is low in the sky, namely at larger SZAs /9/. Therefore, UV is highest at the equator and high altitudes, and decreases with increasing latitudes, with UV intensity also considered the highest during the summer months and on a daily basis between 1100 and 1500 hours /15/. These factors are illustrated in Table 2, which displays measured solar UV irradiances at two locations in Australia in both summer and winter.

**Artificial Sources of UV**

Many artificial sources of UV are used in the occupational environment and can be found in industrial, commercial, cosmetic, and medical settings. These sources can emit UV either deliberately (for example, medical therapy) or as a by-product of a particular process (for example, welding). In addition, these sources often emit other wavelengths of optical radiation, such as infrared radiation and visible radiation /16/. Fortunately, human exposure from most such sources is generally far less than that from the sun, yet, some sources have the potential to be more dangerous than the sun because of the production of high energy UV-C radiation and the capability of such sources to produce high-intensity emissions. As UV-C is highly dangerous to biological systems, usually exposure to artificial sources emitting these wavelengths of radiation is strictly controlled.

For ease of classification, UV-emitting lamps can be grouped under two broad headings: those producing radiation by incandescence and those producing radiation by an electrical (gaseous) discharge. The latter group can be further sub-
Table 2: Comparison of UV emission from various sources

<table>
<thead>
<tr>
<th>Source</th>
<th>$E_{\text{eff}}$ (W/cm²)</th>
<th>Exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TLV</td>
<td>Photokeratitis</td>
</tr>
<tr>
<td>Welding 1 (a)</td>
<td>$1.3 \times 10^{-3}$</td>
<td>2.3 sec</td>
</tr>
<tr>
<td>Welding 2 (a)</td>
<td>$1.25 \times 10^{-3}$</td>
<td>2.4 sec</td>
</tr>
<tr>
<td>Welding 3 (a)</td>
<td>$7.09 \times 10^{-5}$</td>
<td>42.3 sec</td>
</tr>
<tr>
<td>Phototherapy lamp, type A, unenclosed (b)</td>
<td>$2.5 \times 10^{-5}$</td>
<td>120 sec</td>
</tr>
<tr>
<td>UVR curing unit (c)</td>
<td>$4.2 \times 10^{-7}$</td>
<td>120 min</td>
</tr>
<tr>
<td>Solar UVR: (d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darwin, 12.4°, summer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>winter</td>
<td>$5.5 \times 10^{-6}$</td>
<td>9 min</td>
</tr>
<tr>
<td>Hobart 42.8°, summer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>winter</td>
<td>$3.6 \times 10^{-6}$</td>
<td>14 min</td>
</tr>
</tbody>
</table>

Welding 1 = GMAW, steel, 250 A, O₂ + Ar shield; Welding 2 = GMAW, aluminum, 300 A, Ar shield; Welding 3 = GTAW, steel, 250 A, Ar shield; (a) Exposure data from /26/; (b) Exposure data from /322/; (c) Exposure data from /243/; (d) Exposure data from /323/

divided according to the pressure of the filling gas; with low-pressure lamps primarily emitting narrow wavebands (so-called line-emissions), and the higher pressure lamps emitting a broadband (continuum) radiation. Some lamps can also be considered to have a combination of line and continuum emissions due to the pressure of the lamp and to the presence of specific additives (for example, metal halides) /7/.

A representative listing of artificial sources of UV includes the following /17/:

- Incandescent sources, such as tungsten-halogen lamps and oxyacetylene flames;
- Welding arcs;
- Mercury vapor lamps used for curing materials, area lighting, and in germicidal applications (in medicine);
- Fluorescent lamps for phototherapy;
- Laboratory and dental sources, including a range of lamps used in phototherapy and photodermatology, and low-pressure mercury vapor lamps for disinfection; and
- Tanning lamps and booths. The emission spectra of current sunbeds have been found to be similar to the solar spectrum in the UV-B range, but 10 to 15 times higher in the UV-A range /18/.

Of these artificial sources, arc-welding processes are probably the most intense sources of UV radiation. The UV radiation emitted by welding is a by-product of an arc formed between the welding process and the metal, and for most processes, both UV and visible radiation are the main components of the emission /19/. The UV emission from arc welding is particularly complicated and can vary widely from one moment to the next. Some of the factors that influence the overall emission spectrum include the type of electrode; the stage of electrode life; the quantity of fume and
smoke generated; the type of metal being welded (for example, welding highly reflective materials like aluminum produces substantially more UV than other metals do); the arc voltage and arc current (for example, effective UV irradiance varies approximately as a square of the arc current), the arc gap, the shielding flux or gas, and joint geometry /20-27/. In addition, for certain processes like gas metal arc welding (GMAW), UV emission rapidly increases immediately following ignition and then falls to a stable level, with this being as much as a 10 orders of magnitude increase over the stable emission /28/. Despite this range of factors that influence the UV spectrum of a welding arc, the main factors contributing to an excessive UV emission are the combination of shielding gas used and base metal being welded /26/. In addition, UV emission from welding is also responsible for the production of other harmful agents, such as ozone and hexavalent chromium /29/. The gas phosgene is produced when welding is performed in environments containing hydrocarbon-based (degreasing) solvents like trichloroethylene /30/. For comparison, the representative emission levels of a number of UV sources are contained in Table 2.

HEALTH IMPACT

In humans, the adverse effects of UV are limited to the eyes and skin. The latest global burden of disease data from the World Health Organization (WHO) indicate that excessive solar UV exposure caused the loss of approximately 1.5 million Disability-Adjusted Life Years (DALYs - the only quantitative indicator of burden of disease that reflects the total amount of healthy life lost from all causes) (0.1% of the total global burden of disease) and 60,000 premature deaths in the year 2000. The greatest burden of disease results from cortical cataracts, malignant melanoma, and sunburn /31/.

Although UV interacts with a number of cellular components, DNA is the major chromo-phore for damage by UV. The cell accurately and efficiently repairs most of this damage, yet if the amount of damage is too great, certain alterations to the DNA may remain as permanent mutations. DNA damage induced by UV-B is considered the key factor leading to sunlight-induced mutations in cancer-related genes and therefore in initiating the carcinogenic process. UV-induced damage includes single and double stranded breaks, cyclobutane-type pyrimidine dimers, 6-4 pyrophotoproducts, thymine glucols, and 8-hydroxy guanine /32/. In the eye, and particularly the retina, free radicals are produced by metabolic processes involving oxygen and light. The free radicals then attack other molecules, causing peroxidation and possible degeneration /33/. Photochemical reactions such as these are not considered as having to have an exposure threshold, and as such, no level of exposure exists below which a reaction will not occur /34/. This situation therefore presents a ‘duality dilemma’ because a certain amount of UV exposure is necessary for the production of vitamin D and the resulting beneficial effects on immune system and bone health. Indeed, the latest global burden of disease report notes that zero exposure to UV would not result in a minimum disease burden but a rather in a high disease burden resulting from vitamin D deficiency /31/. This duality dilemma is illustrated in Figure 1, and a summary of health impacts associated with UV exposure is shown in Table 3.

Adverse Skin Effects from Solar UV

Erythema (reddening) is a photochemical response of the skin following over-exposure to UV, particularly to UV-C and UV-B. Skin redness, caused by increased blood flow to the capillaries, is a cardinal sign of inflammation and the most widely used clinical endpoints in human skin photobiology. The clinical endpoint is described in terms of the minimal erythema dose (MED), identified as individual sensitivity to UV and assessed 24 hours after exposure. The MED is defined as the lowest UV dose that will cause either a just perceptible redness or redness with a definite border /35/. A related measure to the MED is the standard erythema dose (SED) /36/, a fixed dose of 100 J/m² that is biologically weighted by
Table 3: Health impacts of UV exposure

<table>
<thead>
<tr>
<th>Adverse effects</th>
<th>Beneficial effects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skin</strong></td>
<td><strong>Eyes</strong></td>
</tr>
<tr>
<td>Erythema (S)</td>
<td>Climatic droplet keratopathy (L)</td>
</tr>
<tr>
<td>Chronic sun damage (V)</td>
<td>Pinguecula (L)</td>
</tr>
<tr>
<td>Photodermatoses (S)</td>
<td>Pterygium (L)</td>
</tr>
<tr>
<td>Squamous cell carcinoma (S)</td>
<td>Photokeratitis (S)</td>
</tr>
<tr>
<td>Basal cell carcinoma (S)</td>
<td>Cataract (L)</td>
</tr>
<tr>
<td>Malignant melanoma (S)</td>
<td>Solar retinopathy (S)</td>
</tr>
<tr>
<td></td>
<td>Uveal Melanoma (L)</td>
</tr>
<tr>
<td></td>
<td>Age related macular degeneration (I)</td>
</tr>
</tbody>
</table>

Weight of evidence: S = sufficient, L = limited (i.e. suggestive but not conclusive), I = inadequate, V = variable. Based on data from /77, 324-326/ for adverse effects, and for beneficial effects a=/327/, b=/328/, c= /329/.

the CIE reference action spectrum for erythema /37/ and the emission spectrum of the UV source. Therefore, the SED is independent of the emission spectrum of the UV source /35/.

An action spectrum is a graphic representation of the relative effectiveness of different wavelengths of radiation in producing the desired biological response. For erythema, the action spectra obtained in the original studies were quite different from those obtained in subsequent studies. The early (‘older’) studies found a maximum effectiveness at 297 nm and a minimum at 280 nm /38-39/, whereas later (‘newer’) studies /40-41/ reported a maximum effectiveness at 250 nm.

The results of the latter studies were pooled to generate a reference action spectrum that was adopted by the Commission Internationale de l’Eclairage (CIE) /37/. This action spectrum, which has a uniform sensitivity between 250 nm and 298 nm, shows that UV-B is orders of magnitude more effective per unit dose (J/m²) than UV-A at producing erythema (Figure 2). For example, the median MED at 300 nm is 0.025 J/m² whereas that at 360 nm is 32 J/m² /35, 37/. The most recent action spectra, produced using ‘mono-chromatic’ radiation (radiation in very narrow wavelength ranges), show a slightly different action spectrum /42-45/. The results of Anders et al /45/, using truly monochromatic laser radiation, show a secondary peak at 362 nm (Figure 2, more recent study).

The level of erythema experienced is highly variable and related to the natural pigmentation of the individual, thickness of the epidermis, UV dose, and the emission spectrum of the source /46-47/. In general, the MED increases with skin type but overlaps considerably among skin types so that the MED is not entirely predictive of skin type /35/. A description of the various skin types is shown in Table 4, with the average MED of skin type IV (eg. Mediterranean, tans well) being about twice that of skin type I (eg. Celtic, does not tan well) /35, 47/.

The exposure required to produce erythema in untanned, lightly pigmented skin (eg. Type I) ranges from 6 to 30 mJ/cm² /40-42/, with this equating to 1.5 SED /36/ or 2.5 SED /35/, and ranging up to 4.5 SED /35/ or 6.0 SED /36/ for skin type IV.
Skin cancers are the most common types of cancer in humans. The three common forms of skin cancer (in order of seriousness) are basal cell carcinoma (BCC), squamous cell carcinoma (SCC) and malignant melanoma (MM). BCC and SCC are also collectively known as non-melanocytic skin cancer (NMSC) and account for around 90% of skin cancers, with BCC being about four times more common than SCC /48/. Even though it is difficult to gain information on the exact incidence for NMSC, as they are generally not recorded in cancer registries, the data indicate that Australia, and particularly the state of Queensland, has the highest incidence of NMSC (and MM) in the world /49-50/. The latest estimates in Australia for NMSC indicate an incidence of ~374,000 cases
each year, more than five times the incidence of all other cancers combined /51/. In addition, estimates suggest that in Australia, 34,000 new NMSCs are identified each year that are related to occupational exposure /52/. Non-melanocytic skin cancers also impose a significant burden on the health system because these types are the most expensive to treat in Australia /53/. Malignant melanomas are the rarest of the skin cancers but recent data indicate that the incidence is continuing to increase in Australia and around the world /54-59/.

The link between UV exposure and skin cancer is strong, with both the International Agency for Research on Cancer /60/ and the United States (US) Department of Health and Human Services (Eleventh Report on Carcinogens) /61/ identifying solar UV as a known human carcinogen. It would therefore seem obvious that outdoor workers would have excess cases of skin cancer as compared with indoor workers, but the evidence is a somewhat contradictory and highlights the complicated nature of risk factor determination for skin cancer.

For example, sunlight or UV exposure was identified as a suspected cause in nearly 96% of cases of occupational skin cancer reported to a British registry over a 6 year period /62/. Another study in England found a significant association between skin cancer (BCC in particular) and outdoor occupation /63/. A study in Australia, however, reported a lack of correlation between skin cancer and outdoor work, possibly because subjects who burn easily were self-selecting for indoor work /64/. In the US, a study found that non-farm outdoor workers had only a slightly elevated risk of skin cancer /65/.

For SCC in particular, the evidence that sunlight is the predominant cause is very convincing. Squamous cell carcinomas occur almost exclusively on sun-exposed skin areas such as the face, neck, and arms; the incidence correlates well with latitude, being higher in areas receiving more sunlight /66/. Additionally, SCCs have been related to cumulative UV dose /67-68/, with an increased risk associated with longer-term total sun exposure /69/. Occupational sun exposure is an important risk factor for SCC /70/, particularly during the 10 years before diagnosis /71/. Even though the relation between BCC and solar UV exposure is more complex than that for SCC, the evidence implicating solar UV is also very clear. For BCC, the relation between cumulative lifetime exposure to UV (including occupational exposure) is not as strong as that for SCC /70, 72-74/; nevertheless, elevated risk is associated with increasing recreational UV exposure below 20 years of age /72, 74/. In addition, lifetime recreational beach exposure and lifetime holiday exposure have been found to be risk factors for BCC /70/, as has beach or beach vacation exposure before the age of 20 years /75-76/. Therefore, exposure during childhood is particularly important in establishing risk for BCC as an adult /70, 72/.

Overall, the evidence is convincing for a causal relation between solar UV and both BCC and SCC /77/, based on both epidemiologic and animal studies for SCC and on epidemiologic data for BCC /78/. In addition, when NMSC is considered as a group, occupational sun exposure has been shown to be a significant risk factor /79-81/. Due to the nature of NMSC, their action spectra cannot be obtained using human subjects, but the results of action spectra produced using hairless mice /82/ have been adapted for humans using an optical model of UV carcinogenesis in the skin. The resulting action spectrum is similar to that for erythema but has a peak efficacy at 299 nm, followed by a dramatic fall in efficacy to a minimum around 350 nm /83/ (Figure 3).

The incidence of malignant melanoma (MM) has increased dramatically in the last few decades and is a significant public health problem for light skin populations. Solar UV exposure has been established as the major environmental risk factor for MM, with individual susceptibility being the principle modifying factor for the effect of this exposure /77/. Even though in virtually all epidemiologic studies, individuals with light skin, hair and eye color have been found to consistently have an elevated risk of MM /84/, the role of solar UV in the development of MM appears to be more complex than that for NMSC, evidenced by an inverse relation between latitude and MM incidence, a low incidence of MM in outdoor
workers, and inconsistencies in sex, age and anatomical distribution of MM /80, 85-87/.

Additionally, an increased risk for MM from chronic (particularly occupational) sun exposure has not been found /84, 86, 88-90/.

Scientific evidence indicates, however, that local (geographic) solar UV exposure, intermittent sun exposure (mainly from recreation activities), and sun exposure as a child are factors associated with an increased risk of MM /84, 85, 90-92/. In addition, increased risk has been found to occur in people with a propensity to burn rather than to tan /93-97/, and in those with either freckling /98-99/ or acquired melanocytic nevi (skin moles) /99-102/.

In addition, the association between skin cancer and solar UV exposure also has major significance due to the discovery of depletion of the ozone layer and the other impacts of climate change. Early studies predicted that for each one percent decrease in ozone, a two percent increase in skin cancer incidence would result /106-107/. The most sophisticated estimate of the impact of ozone depletion on skin cancer incidence was then reported in 1996 by Slaper et al /108/.

Under their most optimistic modeling conditions of complete compliance with the Montreal Protocol and all of its amendments, excess skin cancer incidence was found to peak at nine percent above baseline incidence (at around 2055) and then gradually
decline. In northwestern Europe, this value equates to an additional peak skin-cancer incidence of ~90 cases per million population /109/. The authors did conclude that if compliance could be achieved using the stringent controls specified under the Vienna Convention, any further rise in skin cancer incidence would be limited /108/. When the additional impacts of global warming are included in this analysis, however, the estimates are that for every one degree increase in temperature, the carcinogenic effectiveness of UV will increase by five percent 5/. This estimate has led to a conclusion that the predicted long-term elevation of temperature by 2°C due to climate change would increase the peak excess of skin cancer incidence from the previous nine percent up to eleven percent above baseline, and a 4°C rise would increase the incidence to 13%.

In addition, a long-term increase in temperature by 2°C was estimated to result in an increase in baseline incidence of skin cancer by 21% /5/. Therefore, ozone depletion and temperature increases due to climate change seem to interact synergistically to enhance the effects of UV and increase skin cancer incidence. In the UK, such a synergistic effect is expected to result in excess skin cancers increasing to an estimated 6000 cases per year by 2050 /109/.

**Adverse Ocular Effects from Solar UV**

When the eye is exposed to optical radiation, the media of the eye act as a series of filters, with each component absorbing certain wavelengths to varying degrees /110-111/. Actinic UV (UV-B and UV-C) is strongly absorbed by the cornea and conjunctiva, with overexposure resulting in photokeratitis. Following a latent period of generally between 6 and 12 hours, symptoms of photokeratitis include inflammation of the conjunctiva, swelling of the eyelids, a sensation of ‘sand’ in the eyes, and photophobia. Corneal pain may be severe, but discomfort disappears within 48 hours /112-115/. Threshold exposures for producing photokeratitis range from 4 to 14 mJ/cm², with maximum sensitivity of the eye at 270 nm /116-117/ (Figure 3). In addition, photokeratitis can be enhanced by airborne photosensitizers, such as volatilized coal-tar pitch, which has been associated with outbreaks of photo-keratitis among roofers /118/.

Another acute ocular condition associated with overexposure to solar UV is solar retinopathy, also known as eclipse burn or eclipse blindness, which is generally associated with unprotected viewing of solar eclipses or direct sustained viewing of the sun /119/. Sailors and military personnel whose job requires surveying the sky for enemy aircraft have frequently reported this condition /120/; astronomers are considered to be at risk as well /112/.

Epidemiologic studies have also shown support for an association between long-term solar UV exposure and the following ocular conditions: climatic droplet keratopathy /121-122/, pinguecula /121,123/, pterygium /121,124-126/, and cataract (particularly cortical cataract) /127-129/. In addition, circumstantial evidence links ocular (conjunctiva, iris, ciliary body, or choroids) melanoma to UV exposure, with Australian studies finding an increased cancer risk with increasing sun exposure prior to age 40 /133/, and an association between increased risk and residents who may have higher UV exposure /134/. Other studies, however, found no link between cumulative lifetime UV exposure and ocular melanoma /135/. Evidence for a link between SCC of the eyelid and UV exposure has been reported /136/, but the evidence is inconclusive for eyelid BCC, which accounts for up to 90% of eyelid malignancies /137, 138/. Although the evidence for an association between solar UV and age-related macular degeneration (AMD) is limited /139/, experimental and epidemiologic studies indicate that UV reaches the retina and may ultimately cause macular degeneration /140/. A much stronger association has been found between visible radiation and AMD however /141,142/.

**Adverse Effects from Artificial Sources of UV**

*Welding.* As welding arcs produce an intense UV emission and have a broad emission spectrum (including high energy UV-C), one might expect that persons exposed to welding radiation would
report similar (and more prevalent) health effects as those associated with overexposure to solar UV exposure. The evidence to support this assumption is suggestive but not conclusive.

For the acute conditions photokeratitis and erythema and for the chronic outer eye conditions pinguecula and pterygium, the literature is quite conclusive in support of a higher prevalence of these conditions in welders compared with non-UV exposed workers /143-148/. Welders also report a high level of visual discomfort symptoms that can be associated with optical radiation exposure /149-150/. For chronic eye conditions associated with the cornea, however, two studies found that long-term exposure to welding UV did not result in long-term impacts on the corneal endothelium /151-152/.

One study into chronic retinal conditions associated with welding concluded that welders-arc maculopathy seems to be associated with occupational accidents and negligence of safety regulations rather than improper safety practices /153/. On the other hand, a recent case report identified a history of repeated and extreme exposure to welding UV as the proximal cause of spheroidal degeneration /154/.

Regarding other chronic health effects, the literature varies. Two case reports indicated that UV from welding (particularly UV-C) resulted in the exacerbation of atopic dermatitis /155/ and in the development of hyperpigmentation on the face of a patient following laser surgery /156/. Exposure to UV from welding is considered a risk factor for ocular melanoma /157-163/, with a recent meta-analysis (using exposure to welding as a surrogate measure for intermittent UV exposure) finding a significantly elevated risk of ocular melanoma /164/. Cortical cataracts have also been shown to be more prevalent in welders than in non-welders /165/. Regarding skin cancers, surprisingly only a few case reports have emerged of an association between NMSC and long-term welding exposure /166-169/. Other studies found welders to be at no increased risk of NMSC or MM /94, 170-171/. Overexposure to UV from lasers can also cause photokeratitis and contributes to cataracts. In addition, lasers have an enormous potential to cause retinal injury due to the laser beam producing a small retinal image that is of an intensity far greater than that from conventional sources /6/. Ultraviolet radiation from lasers predominantly produces photochemical effects on the skin (for example, erythema) /184/, with the risk of skin cancer from excimer lasers and lasers used in the laboratory environment being minimal /185/. Accidents involving lasers have resulted from direct and reflected beam exposure, with ocular injuries particularly occurring during beam alignment and when eye protection was not worn /8/.

**Beneficial Effects**

A new emerging area of research is the positive impact of UV exposure, that is, the synthesis of
vitamin D in the skin. In the plasma membrane of keratinocytes in the epidermis, UV radiation interacts with a cholesterol metabolite, 7-dehydrocholesterol (also known as provitamin D). After UV exposure, the B ring of 7-dehydro-cholesterol opens to form an unstable molecule known as previtamin D (cholecalciferol), an unstable molecule that is then stabilized through a series of thermal reactions in the skin. Previtamin D is then transported through the blood where it is first hydrolyzed in the liver and then undergoes a second hydroxylation in the kidneys (and other tissues possessing vitamin D receptors), where the active form of vitamin D, 1-25 dihydroxyvitamin D₃ is produced /186-188/. In this paper, broad references will be made to Vitamin D, with this terminology referring to the photo product produced in the skin (previtamin D), rather than the active form of vitamin D (1,25 dihydroxyvitamin D₃).

Low status of blood serum Vitamin D (25 Di-hydroxyvitamin D) has traditionally been considered a modifiable risk factor for bone metabolic diseases such as rickets, osteomalacia, and osteoporosis /189-190/. More recently, low Vitamin D status has also been considered as a risk factor for breast, prostate and colon cancer /191-195/, which is an intriguing area of research as such associations are counter intuitive to current public health policy on sun exposures. Over time, it has become evident that the Vitamin D receptor (VDR) can be found not only in cells and tissues involved in calcium and bone metabolism but also in a variety of other cells and tissues, including cancer cells. Many studies have investigated Vitamin D in tumor-cell growth regulation, cancer treatment, and the development of synthetic analogs.

Understanding that sunlight, specifically UV radiation, can have both positive and negative impacts on our health, the need for quantifying the exposures to the population is an important part of any well-structured public health campaign. Population assessment of exposure is a very difficult task and one that requires significant resources and planning to obtain reliable results. Several research groups have begun this long process of measurements of exposures to small, localized groups /196-201/. These studies, however, lack sufficient geographic diversity in the populations sampled to provide global estimates of personal UV exposure.

The photo production of vitamin D is a complex process. A sample of the photo-activation of 7-dehydrocholesterol in vitro is shown in Figure 4 showing the change in optical absorbance pre and post solar UV irradiation.

---

**Fig. 4:** In *Vitro* photo activation of 7-D-hydrocholesterol (Y-axis = relative effectiveness)
Fig. 5: Spectral sensitivity of Pre-Vitamin D production (X axis = wavelength [nm], Y-axis = Vitamin D UV Irradiance [mW/cm²])
Upper line = Hawaii; Lower line = Denali.

The action spectrum commonly used for Vitamin D is that of Webb et al /202/, which provides an adequate baseline for an order of magnitude estimate of Vitamin D synthesis in human skin, but more important, offers clues to the wavelengths responsible for Vitamin D formation. Forewarned with this information, should we not investigate the sun’s capability to produce Vitamin D? No. We must be fully conscious, however, that this action spectrum may change after biologically validated experiments are conducted, and that multiple systems are in play when discussing the production of previtamin D in human skin.

The impact of the Vitamin D action spectrum on measured spectra is illustrated in Figure 5. The spectral UV data used for this figure were obtained from the United States Environmental Protection Agency (US EPA) Brewer network. The measured spectra at a large solar zenith angle (84°) from the Brewer instrument were weighted with the Vitamin D action spectrum to produce the biologically weighted action spectra for Vitamin D production. The peak response of the action spectra is around 300 nm with a sharp decrease to a nadir at 315 nm. The high sensitivity of the action spectra to the shorter wavelengths of the solar UV spectrum coupled with increased ozone absorption in these wavelengths impacts on previtamin D production. This figure highlights for the same large solar zenith angle, previtamin D production can be impacted significantly between two locations, due to local atmospheric composition. As the entire Vitamin D action spectrum exists in the UV-B, such changes are far more sensitive than action spectra with a UV-B and UV-A component, for example, erythema.

The issues surrounding vitamin D and UV are further highlighted in the recent WHO report on the global burden of disease, which reviewed the health impacts of underexposure and overexposure to ultraviolet radiation /31/. The results estimated that 1.5 million DALYs were lost in the year 2000 due to excessive UV exposure, whereas, under a scenario of zero exposure, 3,304 million DALYs would have been lost due to vitamin D deficiency diseases /31/.

The WHO results therefore indicate a potentially a significantly greater burden of disease as a result of underexposure to UV radiation than for overexposure to UV radiation.
EXPOSURE LEVELS

Exposure Standards

The structure of an exposure standard is usually derived from an understanding of the injury mechanisms involved, such as photochemical and photothermal reactions in the case of radiation hazards. The actual values for the exposure limits are derived from experimental results, such as the erythema and photokeratitis action spectra and damage thresholds. The determination of a damage threshold may, however, be complicated by such factors as an unclear damage threshold, difficulty in measuring damage criteria, and biological variability and uncertainty in measurement. For these reasons, the concept of an exposure standard as separating safe from unsafe exposures should be modified into one of relative safety or possible damage.

The most widely used UV exposure standard was initially developed by the American Conference of Governmental Industrial Hygienists (ACGIH) in 1971. This value was based on a ‘single envelope action spectrum’, in which the threshold data for erythema and photokeratitis were combined on one graph and an envelope curve drawn around the collective data (Figure 3). The limiting value of the curve is 0.003 J/cm² at 270 nm. The standard is based on protecting individuals from the acute effects of UV exposure, with the assumption that chronic exposure at subthreshold levels would contribute slightly to long-term health risks. A built-in safety factor also ensures that certain exposures above the exposure limit should not result in any acute effects. The standard is considered to provide a limiting value for the eye, as repeated exposures do not result in increased protection, whereas conditioned (tanned) persons are able to tolerate skin exposures above the exposure limit without acute effects. When evaluating the UV emission of a source, the effective UV irradiance for the source (at a location representative of worker exposure) is determined using the following equation:

\[ E_{\text{eff}} = \sum E_{\lambda} S_{\lambda} \Delta \lambda \]

where, \( E_{\text{eff}} \) = effective irradiance, relative to a monochromatic source at 270 nm in W/cm² [J/(s.cm²)]; \( E_{\lambda} \) = spectral irradiance of the source in W/(cm²·nm); \( S_{\lambda} \) = relative spectral effectiveness (unitless), is a biological weighting function and is based on the UVR hazard curve (Figure 3); and \( \Delta \lambda \) = bandwidth in nm.

To determine the permissible exposure time (in seconds), the limiting value of the curve (0.003 J/cm²) is divided by the \( E_{\text{eff}} \) in W/cm².

The original standard was widely adopted by many organizations including the National Institute for Occupational Safety and Health (NIOSH), WHO, and the International Radiation Protection Association (IRPA). In 1988, the standard was revised to provide for more appropriate protection in the UV-A region, with the current guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2004. Most recently, these guidelines have been included as part of the risk management approach adopted in the draft Australian Radiation Protection Standard for Occupational Exposure to Ultraviolet Radiation.

An interesting issue regarding the application of this standard is that it was originally intended for occupational exposure only, and this is still the intention of the ACGIH, whereas the IRPA/ICNIRP considers the standard applicable for both general (public) and occupational exposure. The ICNIRP guidelines state that the exposure limits represent conditions under which it is expected that nearly all individuals may be repeatedly exposed without adverse effect. Those persons not covered by the standard include highly photosensitized individuals and persons exposed to photosensitizing agents. It would seem that this interpretation is based on the exposure limit being at a level that is below the threshold for acute effects and on the assumption that public exposure is significantly less than occupational exposure. In contrast, the ACGIH exposure limit is defined in narrower terms and is presented as a threshold limit value (TLV), which is a time-weighted average exposure for an 8-hour workday and 40 hour workweek, to which it is believed that nearly...
all workers may be repeatedly exposed, day after day, without adverse effect /207/.

**Solar UV Exposure**

Because for most individuals, the sun is the largest source of UV exposure, the main factor influencing overall exposure is whether the person is an indoor or outdoor worker. The development of personal dosimetry techniques, particularly the use of polysulphone film (PSF), has enabled the study of personal exposure levels for various situations. When the results of a range of studies are combined, outdoor workers (such as gardeners, lifeguards, physical education teachers, farmers, and fishermen) generally receive around three times the solar UV exposure than do indoor workers /215-218/. The UV exposure can vary quite dramatically, however, and is influenced by many factors, including occupation, personal behavior, the use of personal protective equipment, and varies significantly among different body sites as well. As a percentage of the ambient UV level, outdoor workers generally receive at least 10% of ambient as a personal UV exposure with indoor workers receiving around 3% as a personal UV exposure. As Table 5 highlights, such UV exposures can be highly variable, mainly depending on occupation and can be more than 100% of ambient in some cases due to working around highly reflective surfaces.

**Table 5: UV Exposure of outdoor workers as a percentage of ambient UV level**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Category</th>
<th>Percent of ambient</th>
</tr>
</thead>
<tbody>
<tr>
<td>/216/</td>
<td>Outdoor workers</td>
<td>10 to 70</td>
</tr>
<tr>
<td>/215/</td>
<td>Physical education teachers</td>
<td>30 to 50</td>
</tr>
<tr>
<td></td>
<td>Gardner, carpenter, bricklayer</td>
<td>44 to 85</td>
</tr>
<tr>
<td>/221/</td>
<td>Construction workers (median, all workers)</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Pavers-tilers</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>Traffic controllers</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Roofer</td>
<td>45</td>
</tr>
<tr>
<td>/330/</td>
<td>Farmers</td>
<td>13</td>
</tr>
<tr>
<td>/222/</td>
<td>Arctic field scientists (under clear sky)</td>
<td>35</td>
</tr>
<tr>
<td>/331/</td>
<td>Car driving (windows closed)</td>
<td>3 to 4</td>
</tr>
<tr>
<td></td>
<td>Car driving (windows open)</td>
<td>25 to 31</td>
</tr>
<tr>
<td>/332/</td>
<td>Physical education teachers, gardeners, lifeguards</td>
<td>27 to 36</td>
</tr>
<tr>
<td>/232/</td>
<td>Indoor workers</td>
<td>2 to 4</td>
</tr>
<tr>
<td>/216/</td>
<td>Indoor workers</td>
<td>6</td>
</tr>
<tr>
<td>/215/</td>
<td>Classroom teacher</td>
<td>7 to 11</td>
</tr>
<tr>
<td>/221/</td>
<td>Cabinet makers</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Painters</td>
<td>3</td>
</tr>
</tbody>
</table>
For comparison, personal UV levels of around 10% of ambient have been recorded during such activities as sailing and sightseeing, with higher exposures recorded for skiing (20%) and sunbathing at the beach (80%) /219-220/.

Clearly, personal UV exposures of outdoor workers can be considerable, with a range of studies indicating that such exposures substantially exceed current occupational exposure standards/guidelines. For example, in a comprehensive study conducted in Queensland, Australia, during spring, daily UV exposures of construction workers were at 4.5 SED (median for all workers), with the highest median UV exposure of 9.9 SED recorded for pavers-tilers /221/. In addition, when compared with the current occupational exposure limits (OELs) /207, 213/ only 10% of the construction workers in this study (n = 493) received UV exposures that were below the OEL, with almost half recording exposures that were more than 4 times the OEL and 7% of workers having UV exposures over 10 times the OEL /221/. Similarly, high personal UV exposures have also been recorded for a range of other outdoor workers, including artic field scientists /222/, mountain guides /223/, professional cyclists /224-225/, gardeners /196/, postal workers, and physical education teachers /226/. In contrast, the UV exposure of international pilots has been found to be relatively low and comparable to those received by indoor workers /227/. When also considering that outdoor workers have been found to spend significantly more time outdoors on days-off and weekends as compared with indoor workers /228-230/, the total UV exposure of outdoor workers as a group is considerable.

The solar UV exposures of indoor workers are also quite variable, with measured values ranging from 0.7 SED (in Denmark in summer) /231/ to 3 SED in winter and 7 to 10 SED in spring for indoor workers in Australia /196/. For this group of workers, around 20% of their exposure is received when traveling to and from work and going outside for lunch, 30% from vacation exposure, and about half from weekend exposure /48, 232/. Several recent studies have found that indoor workers can receive more than 5 times their regular exposure while on holidays /231/ and around 3.5 times their weekday exposure on the weekends /196/.

Such exposure assessment studies play a key role in the assessment of health risks, with the following representative UV exposure values being previously used when undertaking risk calculations: outdoor worker = 270 MED, indoor worker = 90 MED, and sunbathing two weeks per year = 100 MED /233/. The ocular UV dose of outdoor workers has also been investigated and was found to range between 2% and 17% of the ambient UV level, and to be significantly reduced by wearing hats /137, 234-235/. The accurate determination of ocular UV exposure is, however, difficult because such exposure is influenced by behavioral, anatomic, and environmental factors. For example, an individual seldom looks directly at the sun when it is overhead and at its most hazardous, whereas the sun is not very hazardous to view when lower in the sky and within the normal field of view. Therefore, ground reflectance is a major factor in determining ocular UV exposure.

Squinting also decreases the field of view and limits ocular UV exposure. When the sun is overhead, the brow ridge and upper lid also shield the cornea, and if the eye is turned away from the sun, the overhead rays strike the cornea at an oblique angle of incidence and are mainly reflected /236-237/. To account for these factors, contact lens dosimeters have been developed. In these studies, the ocular to ambient UV exposure has ranged between 4% and 23%, depending on the amount of cloud cover /238/. Further studies using dosimeters would be beneficial to determine UV exposure accurately at the surface of the eye and the variables influencing this exposure.

Regarding solar UV exposure and vitamin D, the debate is an increasing on what an appropriate minimum level of UV exposure is for healthy bone growth and development while not increasing skin cancer risk /239-240/. Recently, an Australian working group from several professional societies published a recommendation that ‘exposure of hands, face, and arms to one-third of a MED of sunlight most days is recommended for adequate endogenous vitamin D synthesis’ /241/. This value,
however, is based on limited data indicating that about 1 MED of sun exposure is comparable to taking 15000 IU of vitamin D orally /242/. As such, more research is needed in this area to provide an evidence base for appropriate public health messages.

**Artificial UV Exposure**

Occupational exposure measurements for a range of artificial UV sources have been reported, with these often described in terms of allowable exposure times at various distances/locations from the source (refer to Table 2). For example, in the furniture industry, UV lamps are used to cure paints and lacquers, and high UV levels have been recorded close to the entry and exit openings of curing units. At these locations, the OEL can be exceeded in around one minute, but at regular working positions, the OEL is reached in about two hours /243/. The UV emission from photoflood lights used in television studios and theaters has also been measured, with direct viewing of these lights discouraged because for the most intense lights, the OEL can be reached in only a few minutes /244/.

A range of artificial UV sources are used in laboratories, with many of these sources providing negligible exposure when following normal safety procedures /245/. Yet, a number of such sources have been found to present a significant safety risk under normal operating conditions. For example, the OEL can be exceeded in less than one minute for certain transilluminators /245-246/ and within a few minutes for a number of other lighting systems and viewing systems /245/. The UV hazard potential of operating microscopes has also been investigated and found to be acceptable only if various eyepiece filters are used /247/. Low-pressure mercury vapor lamps used for UV disinfection in laboratories have also been evaluated and at one facility, 16 of 76 measurements made at normal worker locations exceeded the OEL, with the highest up to twice the OEL /248/. Personal UV exposures of workers in a hospital have also been evaluated, with only some workers in particular phototherapy areas recording exposures in excess of the OEL. These UV sources were generally fluorescent lamps emitting UV-A or UV-B radiation, and in areas where UV lamps were not used, worker exposures were under the OEL /249/. For workers in a car manufacturing plant, personal UV exposures were evaluated in an area that used fluorescent lamps to aid in the inspection of paintwork. In this case, very low personal UV exposures were recorded, with no measurements exceeding the OEL /250/.

The UV emissions from arc-welding processes have been assessed using radiometric, spectroradiometric, and personal dosimetry techniques. Obtaining accurate spectroradiometric and radiometric measurements can however be difficult for welding arcs, due to the instability of the arc and interference by electromagnetic radiation. Optical radiation emission spectra and effective irradiance values have been obtained under laboratory conditions for many welding processes to control for these factors /24-25; 251-252/. From these measurements, acceptable exposure times have been calculated indicating that at regular working positions for welders, the OEL can be exceeded in a matter of seconds for a large number of welding processes /24, 252/. With increasing distance from the arc, however, longer exposure times can be achieved /253/.

Personal UV exposures of welders have been assessed only in a few studies. In one study, exposure levels were measured for a welder who suffered from severe facial dermatitis, with UV exposures found to range from 4 to 9 times the TLV on the patients cheeks and up to 128 times the OEL for the site on the outside of the welding helmet /254/. In another study, UV exposures on the outside of clothing were measured for seven non-welders who worked in a welding workshop. The UV exposures of these workers were found to be around eight times the OEL /255/.

In the most comprehensive assessment of personal UV exposure of workers in a welding environment /256/, personal UV measurements were obtained for both welders and non-welders (total of 20 subjects). In that study, dosimeters were placed on the subjects clothing, on the exterior of welding helmets, on the inside of welding helmets,
and on the bridge and side-shields of safety spectacles. Ambient UV levels were also measured using dosimeter placed at a large number of locations throughout the work area. Within the welding helmets, UV exposures of welders were found to exceed the OEL by up to 5 times, and facial exposures of non-welders were found to be between 9 and 12 times the OEL, with exposures of supervisory workers being the highest. The measurements on the subjects clothing were also substantially higher than the OEL, with the following mean exposure levels: welders = around 3000 times OEL, boilermakers = around 60 times OEL, and non-welders = around 13 times OEL. Ambient UV levels were also above the exposure limit (mean = 5.5 times OEL). Despite such high UV exposure levels, the workers did not display adverse effects /256/.

CONTROL MEASURES

When attempting to manage any occupational hazard, the following is an accepted hierarchy for control measures: elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment (PPE). Noteworthily, the higher control priorities (for example, elimination and substitution) are usually considered more efficient than the lower priorities (for example, PPE) and therefore should be given greater consideration and attention /214/. As such, when a potential exists for overexposure from UV, then the most appropriate control technology should be applied in order of priority. Obviously, the measures that can be applied to control exposure from either solar UV or artificial UV can be quite different and have to be determined following a comprehensive risk assessment. In addition, if they are included within an employer-based safety policy, then the effectiveness of such control measures is increased /257/. Many countries have occupational health and safety legislation providing legal obligations on both employers and employees, and these equally relate to UV exposure as to any other workplace hazard. The legal obligations/duties of care include requirements for employers

- to assess and manage the risks posed by hazards in their workplace, and
- to protect employees from excessive exposure by limiting exposure to within recognised exposure limits/guidelines /258/.

Solar UV Exposure

In controlling overexposure to solar UV, elimination of the hazard is not possible as indoor workers still receive varying levels of exposure. Nevertheless, each of the other control measures is available to some degree. For example, certain evidence indicates that outdoor workers are less likely to have sun-sensitive skin because of self-selection of indoor occupations by people with fairer skin types /64, 230/, thereby passively implementing the substitution control measure. Examples of engineering controls include the provision of shade (for example, shade structures, trees, cabins for tractors) to limit direct sun exposure. Administrative controls include workplace sun protection policies and incorporation of sun protection in occupational health and safety legislation, training of staff, and scheduling of work activities to minimize exposure during peak UV periods (11 am to 2 pm). The most widely used control measure, however, is PPE and even though quite effective, should be considered the least favored approach. To enhance the efficacy of PPE, the various personal protective measures should be used in combination, and should be used in combination with engineering and administrative measures as well.

Clothing: the appropriate use of clothing is one of the simplest means of reducing exposure. A number of factors affect the degree of protection provided by fabrics, with the most important being the tightness of the weave /259-260/. Color is also important, with darker colors absorbing more strongly than lighter colors. Additionally, when fabrics become wet, they generally transmit more UV, with cotton in particular showing an increased transmission. Other factors include the stretch-ability of the fabric, laundering and use, and the
quality of the garment /261-262/. To assist workers and the public choose clothing providing suitable UV protection, a scheme of ultraviolet protection factors (UPF) was developed /263/. In this scheme, the higher the UPF the greater the UV protection provided by the garment. A UPF of 40+ provides maximum protection and has a UV transmission of less than 2.5%. Further development of the scheme will involve recommendations for design that provide maximum body coverage /262, 264-265/.

**Hats:** the wearing of a hat can also provide a substantial degree of protection to the face and eyes /137, 234/. The amount of protection is determined by hat design, with baseball-style caps providing good protection to the nose but negligible protection to the rest of the face, ears, and neck. As expected, hats with wide-brims (>7.5 cm) provide the best protection to the face, neck, and ears /266-267/.

**Sunglasses:** sunglasses and spectacles provide excellent ocular protection from exposure to solar UV, with most lenses allowing for little UV transmittance /268/. The amount of protection provided, however, can be related more to the design and wearing position than to the transmission properties of the lenses. The design that offers the best protection is the wrap-around style of sunglasses, and all glasses should be worn so that the frame is against the forehead of the wearer to eliminate infiltration around the lens /269-270/.

**Sunscreen:** despite the ongoing controversy regarding the adequacy of protection afforded by sunscreen and its role in preventing melanoma /271-272/, broad-spectrum sunscreens having an SPF of 15+ or more are considered an effective means of personal protection /273/. For example, a recent meta-analysis found no association between sunscreen use and melanoma /274/, and other studies have concluded that sunscreen ingredients do not pose a human health hazard /15/. This controversy is understandable as before the early 1990s, sunscreen formulations generally provided little protection from UV-A, but good UV-B protection, and when combined with the lower SPF sunscreens available at this time, they provided only minimum levels of protection. During the 1990s, however, new UV filters became available that provide a high level of protection in both the UV-B and UV-A regions /273/. The actual effectiveness of sunscreens is determined by many factors, including the following:

- thickness of the application /275/—most users applying between one-quarter and one-half of the recommended amounts and therefore result in a level of protection which is between 20% and 50% of that expected /276-277/;
- application technique—most users do not apply sunscreen uniformly and therefore do not provide protection to large parts of their bodies, particularly the ears, neck, feet and legs /278-279/;
- sunscreen type—many sunscreens contain inorganic chemicals like titanium oxide, which make the creams more difficult to spread and therefore result in reduced coverage /277, 280/;
- substantivity—most sunscreens are quite water resistant but they are readily removed through various activities (eg. rubbing, sand, lying on a towel) /281/; and
- re-application time—given the factors of cost, convenience, and human nature, the expectation that many users will reapply sunscreens as regularly as required is unlikely /275/. The recommendations identify that initial application should occur 15 to 30 minutes before sun exposure and then reapplication 15 to 30 minutes after sun exposure begins, with further reapplication as needed /282/.

Given all of the foregoing considerations, the use of sunscreens should form only one part of an overall sun protection strategy /275/.

**Scheduling:** as approximately two thirds of the daily UV is received in the two hours before and after solar noon, when UV levels are at their highest, the undertaking of work activities that have direct solar exposure during these times should be minimized or avoided, if possible, with these activities rescheduled for less UV intense
times /2, 214, 257/. For example, as compared with no meal-break or a meal-break taken outdoors, a one-hour meal-break indoors (or adequately protected from the sun) sometime between 11:30 and 13:30 has been found to provide a daily reduction in erythemal UV exposure of around 17% in summer and 20% in winter. In addition, up to a 40% reduction in daily erythemal UV exposure can be gained by totally avoiding sun exposure between 11:00 and 13:00 /283/. An indoor break taken during peak UV times has also been suggested as a key factor in substantially reducing the personal UV exposure of gardeners /284/.

Shade provision: workers and the public have also been encouraged to seek protection from the sun by sheltering under trees and other shade producing structures. Personal UV exposure has been shown to decrease when shade from trees is used /285/. Yet, the amount of protection provided by trees is variable and depends on the density of the foliage and the diameter of the foliage canopy. Intrusion into shaded areas by scattered and reflected UV can dramatically decrease the effectiveness of this protective measure /286-288/. Shade structures can provide some protection from solar UV as well, but the level of personal protection depends on the UPF rating of the material used to provide the shade and the amount of scattered and reflected solar UV, both of which can significantly reduce its effectiveness /214/. Recommendations for effective shade structures indicate that they should (a) provide maximum protection from UV year-round, (b) provide suitable side-on protection to reduce the impact of scattered UV, (c) provide adequate thermal comfort for different weather conditions, and (d) be appropriately positioned with respect to the outdoor activities undertaken /289/. For workers who spend a significant proportion of their day in motor vehicles, laminated windscreens and clear or colored window tinting can dramatically reduce the amount of UV entering the vehicle. Most tints have a UV transmittance of around 5%, and as such provide adequate protection over an 8-hour workday /290/.

Personal behavior: the use of protection measures by outdoor workers has been investigated in a number of studies. In general, it appears that only about 50% of outdoor workers take adequate protections against solar UV /291-293/, with the face and lower arms being the least protected sites /293- 294/. In particular, the use of sunscreen and wide-brimmed hats is low /228, 292, 295-296/. Factors that influence sun-protective behavior include the following: (a) workers forgetting to implement protective actions, (b) workers feeling that sun protection is inconvenient, (c) wanting to get a tan, and (d) being unconcerned about sun exposure /292/; with ethnicity influencing the use of sunscreen and sunglasses (non-Latino white employees had higher rates of sun safety behavior) /296/.

Gender, family history, sun sensitivity, and time spent outdoors influence sunscreen or wide brimmed hat use—females are more likely to use sunscreen but less likely to wear hats, a family history of skin cancer or having sun sensitive skin increases sunscreen use, and the longer people spend outdoors the more likely they are to use sunscreen or wear a hat /228/. As these studies indicate, a major factor in providing effective protection from solar UV is related to personal behavior. As such, the effectiveness of protection measures can be reduced by their lack or inappropriateness of use, adherence to particular fashion trends, and purposeful exposure during peak periods of solar UV.

Education and training: workplace health education campaigns/interventions have included such activities as sun-safety training, sun-protection, skin cancer-education sessions and skin exams, promotion of covering-up behaviors, role-modeling, provision of sun-protection measures (sunscreen, hats, sunglasses), and provision of educational brochures /291, 297-303/. All these attempts have reported mixed results in improving worker behavior. Even though a range of reports have demonstrated a certain amount of evidence for the effectiveness of their interventions /291, 294, 300, 304/, a systematic review of skin-cancer
prevention interventions found insufficient evidence to determine the effectiveness of these interventions in occupational settings /305/.

**Artificial UV Exposure**

The protection of workers from exposure to artificial UV generally consists of a combination of administrative controls, engineering controls, and the use of PPE. Administrative controls include a pre-purchase review to identify hazards and correct operating procedures, to restrict unauthorized or photosensitive workers from certain work areas, increasing the distance and decreasing duration of exposure, and to place warning signs and labels. Engineering controls include isolating or enclosing high intensity sources, using non-reflective paints, and using interlocks and alarms on access panels and enclosures /17/.

Personal protection includes equipment for the skin and eyes. Most industrial clothing provides good attenuation of UV (maximum transmittance of 1%) /260/, with the design of the clothing important in providing adequate coverage. Safety spectacles and goggles that use glass or plastic lenses provide good protection for the eyes of workers. The UV transmittance has been found to be variable between the types of eyewear, but most provide near total UV protection /268, 306/. The type of eyewear should be compatible with the emission spectrum and the intensity of the sources, and should be of a design and fit that prevents infiltration /17/.

Workers exposed to UV from welding arcs require particular protection measures. Areas in which welding is conducted can be designed to reduce exposure by positioning welding stations as far apart as possible /253/, using non-reflective materials and paints /307/, and positioning permanent, temporary, and semitransparent screens to localize the hazards /308-309/. Guidelines for appropriate protective clothing are contained in various national standards, such as *American National Standard Z 49.1-2005* /309/. These standards provide for extra protection for welders in the form of gloves, aprons, leggings, and shoulder covers. General eye protection from UV is provided by safety spectacles and goggles, which are considered the minimum protection against optical radiation from welding /310/. Welding helmets and hand-shields designed to protect the eyes and face from optical radiation and to make an impact on hazards associated with welding are considered secondary protectors and should be used in conjunction with primary protectors (safety spectacles) /310/. Many welders do not follow this recommendation because the spectacles are uncomfortable to wear (in addition to the welding helmet) and because of a continual ‘fogging’ of the lenses from heat and perspiration /311, 312/.

The design of welding helmets has remained relatively unchanged for some time with recent designs providing extra protection to the side of the head. The design criteria contained in the standards comprise mainly transmittance and impact requirements, and do not address dimensional issues for the shield. Some have suggested that the helmet design could allow radiation to infiltrate around the shield and reflect off the filter plate into the welder’s eyes /28, 313/. Recent reports have indicated that UV is able to infiltrate into welding helmets from the top and sides /314/, and that UV exposure beneath welding helmets can be at levels above the exposure limits /254, 256/. Whether such exposures come from infiltration into the helmet or from when then helmet has been raised is unclear, however. The results do suggest that further investigation into welding-helmet design is warranted.

**Vitamin D and Protection Measures**

As stated previously, over 95% of the body’s requirements for Vitamin D derive from solar UV exposure. In a high UV environment, such as that in Australia and New Zealand, Vitamin D deficiency was thought to be nonexistent. Recent research conducted in Australia, however, suggests that certain groups of the population are at risk of Vitamin D deficiency, in particular those who are confined to the indoors (eg. nursing home and hostel residents) and women who wear traditional
clothing (for example, veils) that provides substantial skin coverage /315-317/.

Public health campaigns surrounding skin-cancer prevention focus on the use of hats, sunscreen, and sun avoidance as protective measures that individuals can undertake to reduce their risk of skin cancer. Yet, the use of such UV-protection strategies could reduce an individual’s capability to synthesize Vitamin D in the skin. This situation is therefore perplexing because recommending sun exposure to maintain healthy Vitamin D levels would be a dangerous message /318/. In contrast, the monitoring of an individual’s Vitamin D status, through a simple blood test, is an important tool for monitoring the health impacts of sun exposure /242/. We therefore recommend a discussion with a medical practitioner to plan for treating (typically oral supplements) Vitamin D deficiency and maintaining the use of UV protective measures /319/.

RISK MANAGEMENT

Based on the extensive discussion above, both solar UV and artificial UV clearly present a significant occupational hazard and, as such, they must be managed in a way that minimizes the risk to all workers. The consultation draft of the Radiation Protection Standard: Occupational Exposure to Ultraviolet Radiation recently released by the Australian Radiation Protection and Nuclear Safety Agency /214/ identifies the following key elements (in order of implementation) of a risk management process for occupational UV exposure:

- Identification of the hazards: this includes the identification of the sources of UV.
- Assessment of the risk: this includes the estimation of exposure levels, comparison to the relevant limits, and consideration of both the likelihood and severity of the consequence/s of the hazard. Assessment of the UV hazard posed by an artificial source is identified as being achieved through (a) knowledge of the source emissions and power (for example, manufacturers data sheets on spectral emission), (b) dosimetric assessment using photosensitive polymer film (for example, PSF), or radiometric or spectral assessment of the source output. Unfortunately, the last two of these approaches are generally out of the reach of most employers because they require specialized training and equipment. Therefore, without access to such equipment or expertise, the risk-management process is severely hampered. Regarding risk assessment for outdoor workers, a number of qualitative risk assessment checklists have been developed to guide employers or employees when undertaking exposure assessment and to help them identify appropriate control measures /320/.
- Choice of the most appropriate control measures to prevent or minimize the level of risk, with the control/s chosen not able to cause any other hazards.
- Implementation of the chosen control measures, including maintenance requirements to ensure the ongoing effectiveness of the control/s and training on the control measures for potentially exposed workers.
- Monitoring and review of the effectiveness of the control measures: the monitoring and review process needs to assess whether the chosen controls have been implemented as planned, that the control measures are effective, and that they have not introduced new hazards or worsened existing hazards.

The above risk management process needs to be incorporated in a workplace policy that expresses a commitment by all parties. This policy should identify the specific UV risks that are faced by the workplace, specify the procedures that must be implemented to control and manage the risks, and identify those responsible for implementation. In addition, all workers exposed to UV should be trained in safe work practices and supervised when appropriate. Such a process will therefore ensure that safe systems of work are implemented to minimize risk from UV exposure /214/.
CONCLUSION

Outdoor workers and workers exposed to certain artificial sources are frequently exposed to UV levels that are well above the current exposure limits. Such workers are clearly at an additional risk of developing non-melanocytic skin cancer and possibly malignant melanoma, along with a range of other acute and chronic eye and skin conditions. A large range of control measures is available for both indoor and outdoor workers, and these generally provide substantial protection from over-exposure to UV. Many workers, however, particularly outdoor workers, do not take adequate precautions and therefore place themselves at substantial risk of developing adverse effects. In addition, the evidence shows that workers exposed to particular sources (for example, welding arcs) are exposed to high levels of UV despite current control measures being implemented. Therefore, the implementation of a comprehensive risk management program is critical if the hazard posed by over-exposure to UV radiation is to be assessed accurately and controlled appropriately to ensure that workers are adequately protected.

In contrast, no risk-management processes are currently in place to manage underexposure to UV radiation and the subsequent health impacts (Vitamin D deficiency). With a recent WHO report on the global burden of disease indicating that the impact (death and disability) of underexposure to UV is probably thousands of times higher than for overexposure to UV /31/, this problem is a serious issue for the workforce and must be addressed. Specific risks therefore exist for workers without ‘adequate’ sun exposure, such as underground miners, long-haul flight crews, shift workers, and perhaps even indoor workers. As large-scale surveys of the workforce have not been undertaken to assess the impact of the work environment on Vitamin D production, the level of risk remains unknown and therefore unmanaged.

REFERENCES

6. Lucas RM, Ponsonby A-L. Considering the potential benefits as well as adverse effects of sun exposure: Can all the potential benefits be provided by oral vitamin D supplementation? Prog Biophys Mol Biol 2006; 92: 140-149.


1995; 61: 200-205.


99. Marrett LD, King WD, Walter SD, From L. Use of host factors to identify people at high risk for


123. Hiller R, Sperduto RD, Ederer F. Epidemiologic


152. Oblak E, Doughty MJ. Chronic exposure to the ultraviolet radiation levels from arc welding does not result in obvious damage to the human corneal endothelium. Photochem Photobiol Sci 2002; 1: 857-864.


192. Grant W. An estimate of premature cancer mortality


205. Slinsky DH. Unintentional exposure to ultraviolet radiation: risk reduction and exposure limits. In: Passchier WF, Bosnjakovic BF, eds, Human exposure to ultraviolet radiation: risks and


207. American Conference of Governmental Industrial Hygienists. 2006 TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents, Biological Exposure Indices, Cincinnati, OH, USA: ACGIH, 2006.


236. Riechrath J. The challenge resulting from positive and negative effects of sunlight: how much solar UV exposure is appropriate to balance between risks of vitamin D deficiency and skin cancer? Prog Biophys Mol Biol 2006; 92: 9-16.
242. Akbar-Khanzadeh F, Jahangir-Blouchian M.


