7 Visible Light and UV Radiation

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7.1 Introduction

The sun is the most important source of visible and ultraviolet (UV) radiation. Even though the distance from the sun to the Earth is large – about 150×10^6 km – the fluence rate of solar radiation on Earth, the solar constant, is about 1 360 W/m^2. Approximately 40% of this radiation is reflected back into space. The remaining 60% is the driving force of all life on Earth. A number of pigments have been developed by life to harvest solar energy: *chlorophyll a* (350-700 nm), *phycoerythrin* (45-580 nm), *phycocyanin* (460-650 nm), *bacteriochlorophyll a* (750-850 nm) and *bacterio-chlorophyll b* (950-1 050 nm) are some of the most important ones. Furthermore, animals have developed visual pigments, the *rhodopsins*, to see light. By its action on DNA, UV radiation from the sun has induced mutations to speed up generation and development of new species. UV radiation acts positively and negatively on the human immune system, *e.g.* induces cancer and takes part in the production of vitamin D.

This chapter reviews some of the basic facts about visible and UV solar radiation: spectra and their variations with the phases of the solar cycle, ozone level, time, latitude, altitude, albedo (reflection), and sky cover. Furthermore, scattering and absorption of optical radiation in the atmosphere and in human skin are discussed. Finally, there is a review of the action spectra for erythema, skin cancer of different types, effects on the human immune system and photoreactivation (light-induced repair of DNA damage). The biology of these phenomena will be dealt with in Chapter 31 'Effects of UV Radiation and Visible Light'.

7.2 The spectrum of the sun

Visible light and infrared radiation constitute the major fraction of solar radiation reaching the atmosphere of the Earth (Fig. 7-1). Approximately 40 % of the radiation energy is visible light of wavelengths between 400 and 700 nm. Ultraviolet radiation is divided into different bands: Radiation of wavelengths between 200 nm and 280 nm is called *UVC*, radiation between 280 nm and 320 nm is called *UVB*, and between 320 and 400 nm is called *UVA*. About 8% of the radiation energy reaching the Earth's atmosphere is within the UV spectrum. At sea level, about 6% of the radiation is UV radiation, about 50% is visible radiation and about 40% is infrared radiation. UVA is 10 to 100 times more abundant than UVB. UVC is practically absent, as it is absorbed in the atmosphere. Due to differences in scattering and absorption, the ratio of UVB to UVA depends on several factors: latitude, zenith angle, cloud-cover and thickness of the ozone layer.

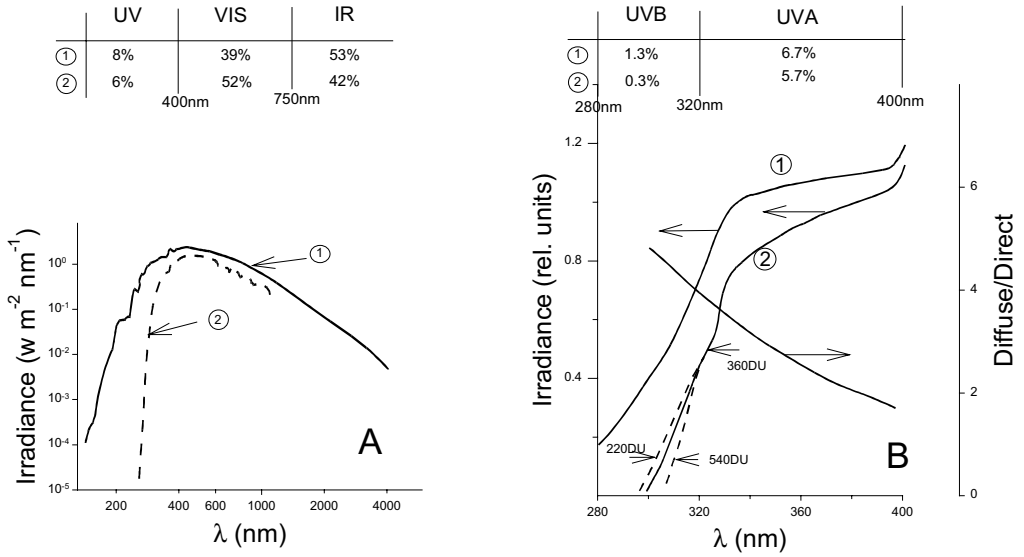

Fig. 7-1. A: Left panel: The spectrum of solar radiation, 1: outside the atmosphere and 2: at sea level. B: Right panel: The UVB and UVA region of the solar spectrum, 1: outside the atmosphere and 2: at sea level. The ratio of diffuse to direct radiation is also shown on the figure referring to the right-hand ordinate. The percentage of the radiation falling within the UVB, the UVA, the visible and the infrared region is given on top of the figure. Spectra for different ozone values are shown.

7.3 Scattering and absorption in the atmosphere – Why are the skies blue?

Scattering plays an important role in the penetration of solar radiation through the atmosphere, since it causes an increase of the path lengths of the photons and thus, makes absorption more likely.

Essentially, atmospheric scattering can be classified as either *Rayleigh scattering* or *Mie scattering*. Nitrogen and oxygen molecules are much smaller than the wavelengths of UV and visible radiation and cause Rayleigh scattering. The probability that a photon will be scattered by an angle θ with respect to its initial path is:

$$I_s = K \cdot \lambda^{-4} \cdot \sin^2 \cdot (\pi / 2 - \theta) \qquad (7\text{-}1)$$

where K is a constant. Thus, the ratio of scattering of blue light (λ = 450 nm) to scattering of red light (λ = 600 nm) is $(450/600)^{-4} \approx 3$ and the ratio of scattering of UVB at 300 nm to that of UVA at 360 nm is $(300/360)^{-4} \approx 2$. The ratio of diffuse to direct radiation decreases with increasing wavelength as shown in Fig. 7-1B. Rayleigh scattering explains why the clear sky is blue since 'blue' photons are more scattered than 'green', 'yellow' and 'red' ones.

With the sun at its zenith, about 10% of the total solar radiation and about 30% of UVB and UVA is diffuse. For a solar elevation angle of 20° about 20% of the total radiation, 70% of UVA and almost 80% of UVB, is diffuse.

Water droplets (in clouds), aerosols and dust particles are much larger than the wavelengths of UV and visible light and scatter light independently of the wavelength like small mirrors. This so-called Mie scattering is predominantly forward scattering, in contrast to Rayleigh scattering, which is isotropic. The grey-white colour of the clouds is due to Mie scattering. The probability that a photon is scattered by a particle is maximal if the particle size is similar to the wavelength of the photon.

7.4 Variations of the spectrum and fluence rate of solar radiation

Variations of the fluence rate and of the spectrum of solar radiation reaching the atmosphere of the Earth

The astronomical variations of the orbit of the Earth (of the tilt of the Earth's axis on the ecliptic, ((period 41 000 years), of the precession of the axis (period 22 000 years) and of the eccentricity (period 100 000 years)) are related to the periodic appearance of ice ages according to the Milankovitch theory, but such considerations are beyond the scope of this text. Of more significance are the variations of the solar energy exposure with the 11-year cycle of sunspot activity, the annual variation of the sun-Earth distance, the 27-day apparent rotation of the sun and occasional solar flares.

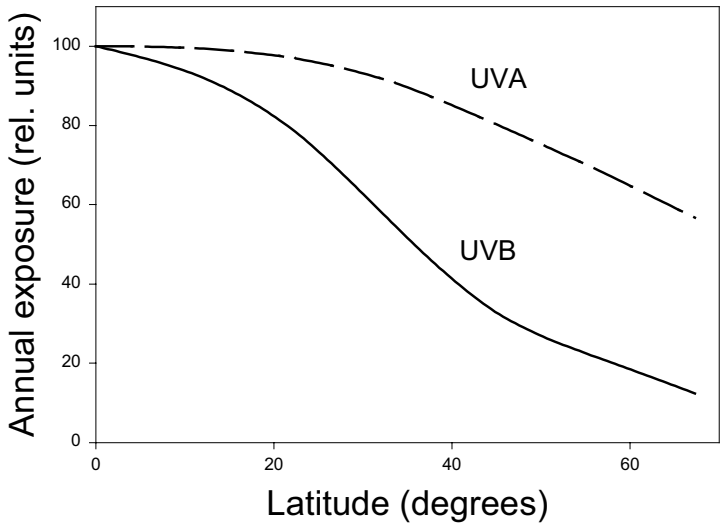

Fig. 7-2. The annual exposure of UVA at about 360 nm (denoted CMM) and of UVB at about 310 nm (denoted CIE) as functions of the latitude.

A number of phenomena, among them a periodic variation in skin cancer incidence rates and longevity of humans, have been related to the sunspot cycle. However, such 'relationships' are usually mere coincidences. Thus, even though the solar irradiance varies over the solar cycle by a factor of 2 at 120 nm, with 10% at 200 nm and with 5% at 250 nm, it varies less than 1% at wavelengths relevant for life on Earth, *i.e.* wavelengths longer than 300 nm. This is far less than variations caused by cloud-cover and ozone.

The sun-Earth distance is 3.4% smaller at perihelion on 3th January than at aphelion on 5th July. Thus, the solar constant is 6.9% larger in the summer of the Southern Hemisphere than in the summer of the Northern Hemisphere. This may be just on the border of significance as far as skin cancer is concerned.

Variations of UV fluences with latitude

The annual fluence of UVB varies more with latitude than annual fluences of UVA and visible light. This is due to absorption of UVB by the ozone layer. The annual fluence of UVB radiation at 310 nm at 60°, 45° and 30° latitude are respectively 20%, 40% and 65% of the annual fluence at the Equator (Fig. 7-2). The corresponding numbers for 60°, 45° and 30° latitude for UVA at 360 nm are 60%, 80% and 92%, respectively.

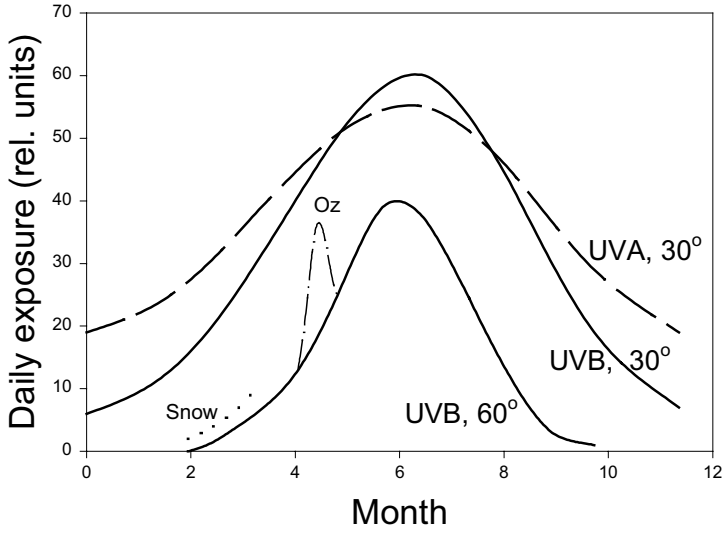

Fig. 7-3. The relative annual variation of UVA and UVB at a latitude of 30°, and that of UVB at a latitude of 60°. An ozone depletion, similar to what has been observed in the Antarctic spring, leads to a peak marked Oz in the UVB curve. Snow doubles the UVB exposure.

Fig. 7-3 shows how the daily UV exposure changes during the year at two latitudes, 30° and 60°. Due to absorption of UVB by the ozone layer, the annual variation of UVB is significantly larger than that of UVA.

For the same reason, UVB varies relatively more at high latitudes than at low latitudes. Furthermore, maximal ozone depletion, similar to that observed around the Antarctic region, leads to a large increase of UVB in the spring. So far, no such depletion has been observed in the Northern Hemisphere. If snow is present on the ground, UV exposure will be almost doubled (Fig. 7-3).

Variations of UV fluence rates during the day – effect on sunburn

Fig. 7-4 shows how UVA and UVB vary during a day in the middle of the summer at 50° latitude. The variation of UVB is more prominent than that of UVA. Thus, UVB is halved about 2.5 hours after noon, while UVA is halved about 4 hours after noon. In the autumn, UVB varies more during the day than at midsummer and is halved about 2 hours after noon.

Clouds have a strong influence on the fluence rates of visible light and UV radiation. Since scattering by air molecules increases with decreasing wavelengths, UVB is more scattered on a clear day than UVA and visible light. Therefore, the effect of clouds, which is added to the scattering by air molecules, is relatively larger for visible light and UVA than for UVB. The effect of a cloud passing the sun at about noon is demonstrated by the arrows (A for visible light and B for UVB) in Fig. 7-4. Since our eyes cannot 'see' UVB, it is impossible to evaluate the effect of clouds and hazy weather on the fluence rate of sunburn (erythemogenic) from UVB radiation without using spectrometers, filter instruments or chemical actinometers.

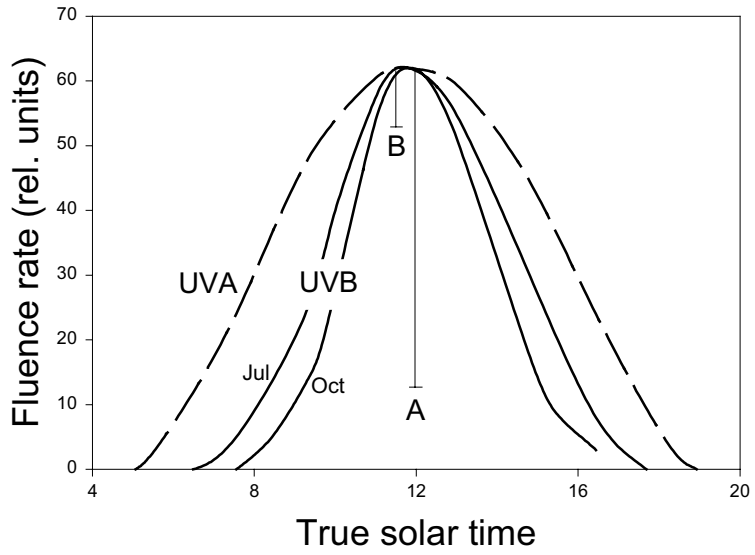

Fig. 7-4. Relative variations of UVA and UVB during a day. For UVB the curves for July and October are significantly different, while for UVA the corresponding curves are almost overlapping. The effect of a small cloud covering the sun is much smaller for UVB than for UVA, as shown by the lines marked B and A.

The effects of altitude and reflection (albedo) on UV fluence rates

The fluence rate of UV radiation changes with altitude. This is related to scattering by water vapour, dust particles and air molecules and to absorption by ozone. The increase is dependent on wavelength and solar elevation. For a solar elevation angle of 20°, the fluence rate of UVA increases by about 12% per 1 000 m and that of UVB at 305 nm by about 20%. For a solar elevation angle of 60°, the fluence rate of UVA increases by about 9% per 1 000 m and that of UVB by about 14%. The percentage of incident radiation reflected by different surfaces, the so-called albedo, is also slightly dependent on the wavelength. Snow reflects between 20 and 100% of all wavelengths (depending on whether the snow is dry, wet, new, old, dirty etc). Water reflects 6-12% of visible light and 4-7% of UVB and grassland reflects 15-30% of visible light but only 2-5% of UVB. The reflection by snow deserves special attention since it may lead to a prominent increase of the fluence rate of erythemogenic UVB radiation. In clear weather, snow with a surface albedo of 80% increases the fluence rate of UVB by a factor of 2 for a solar zenith angle of 45° (Fig. 7-5). On a cloudy day, the fluence rate of UVB may, under otherwise similar conditions, be increased by up to a factor of 4.

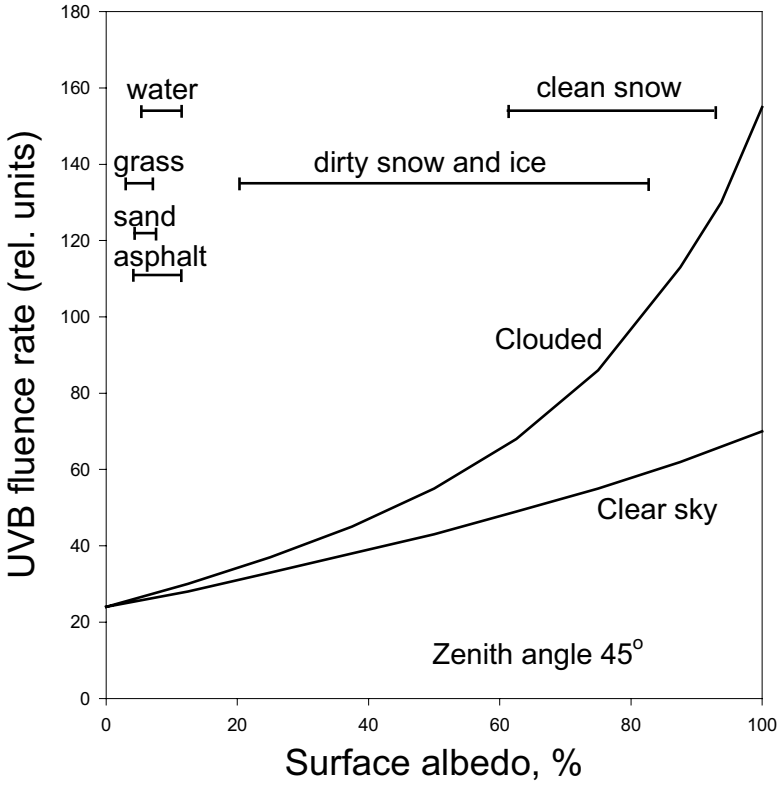

Fig. 7-5. The fluence rate of UVB for a zenith angle of 45° as a function of surface albedo. The albedo plays a greater role on cloudy days than on clear days. Typical albedos for different surfaces are given on top of the figure.

Effects of the ozone layer

Ozone, O_3, is produced when oxygen, O_2, in the upper atmosphere absorbs UVC ($\lambda < 245$ *nm*). This absorption completely eliminates UVC from the solar radiation and dissociates oxygen molecules to oxygen atoms. When an oxygen atom reacts with an oxygen molecule, ozone is produced. More O_3 is produced around the Equator than at high latitudes per unit volume of atmosphere. Nevertheless, because of atmospheric convection, there is more O_3 at higher latitudes than at the Equator as Fig. 7-6 shows. O_3 is measured in *Dobson Units*, *DU*. One DU unit corresponds to an ozone column of 0.01 mm. An O_3 level of 300 DU means that if the O_3 in a vertical column of the atmosphere is collected and brought to sea level at normal air pressure (101 kPa), the column of pure O_3 would be 3 mm high. This small amount of O_3 absorbs a large fraction of biologically damaging solar UVB radiation and is a protective shield for life on the Earth. Its absorption spectrum is located in the same spectral region as that of DNA.

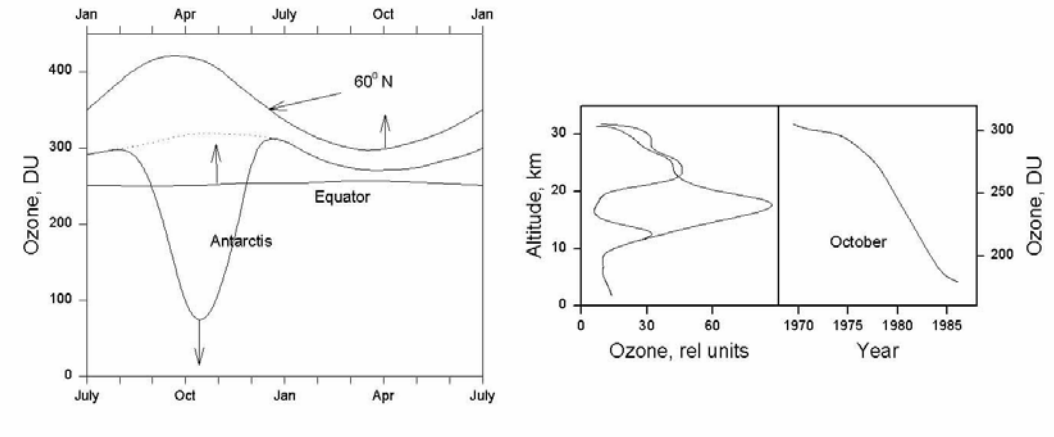

Fig. 7-6. The annual variation of the ozone layer at 60 °N, at the Equator and at Antarctica (top). The dotted curve indicates how the ozone level would vary if no depletion took place. The left lower part of the figure shows the ozone concentration as a function of altitude for no ozone depletion and for a depletion corresponding to what is observed over Antarctica in October. The right lower part of the figure shows the October ozone values for Antarctica for the period 1970-1986.

Variations of the O_3 layer and of UVB

The fluctuations of the fluence rate of UVC reaching the upper atmosphere with the sunspot cycle (with 10% at 200 nm and 5% at 250 nm) cause a fluctuation of the ozone layer. This fluctuation is small, of the order of ±1% and the corresponding fluctuation

of the fluence rate of UVB is hardly observable since the average cloud-cover changes randomly from year to year.

Additionally, there is a random variation of the ozone layer leading to a corresponding random variation of the average annual UVB fluence. The latter O_3 related fluctuation of UVB fluence amounts to about ±3%, while the annual fluctuation of UVB related to the average cloud-cover is significantly larger, of the order of ±10%.

Degradation of ozone layer due to man-made activities

Since about 1970, a significant decrease of the October values of O_3 in the Antarctic region has been observed (Fig. 7-6). The transient depletion of O_3 in October is related to an atmospheric low temperature at an altitude of 15-20 km combined with increasing UV exposure at this time of the year. It is likely that the depletion is related to *anthropogenic chlorofluorocarbons*, *CFCs*. These molecules give rise to chlorine which catalyses the UV induced breakdown of O_3 under conditions where small crystals of ice form in the troposphere between 15 and 20 km. These small crystals in the polar stratospheric clouds provide surfaces for heterogeneous photochemical reactions that release chlorine, Cl_2, into the atmosphere from the reservoir species HCl and $ClONO_2$. F-11 ($CFCl_3$) and F-12 (CF_2Cl_2) used to be two of the major anthropogenic CFCs. The concentrations of these species in the atmosphere were increasing until quite recently. Their lifetimes in the atmosphere can range from years to decades. The concentration of substances containing chlorine in the atmosphere increased from 0.6 ppb (0.6 parts per billion by volume) in 1960 to about 3.5 ppb in 1992 due to human activities. A few of the reactions involved in formation and degradation of O_3 are summarised in Fig. 7-7. CFCs produced at ground level are carried by atmospheric convection to high altitudes, above the O_3 layer, where they are photolysed by UVC and halogen atoms are formed. As these atoms gradually enter the O_3 layer, they catalyse O_3 breakdown. Nitrogen oxides are also present in the atmosphere, partly as a result of human activities, and participate in recovering reactive chlorine back to its reservoir $ClONO_2$: $NO_2 + ClO \Rightarrow ClONO_2$.

Chlorine gas is dissociated photochemically to Cl atoms, which react with O_3 and form ClO. Then dimers (Cl_2O_2) are formed and decomposed to $Cl + Cl + O_2$. In this manner, each Cl atom can catalytically destroy of the order of 100 000 O_3 molecules.

The Arctic stratosphere is slightly warmer than the Antarctic stratosphere (Antarctica is a mountain area and a 'highland' while the Arctic is ice floating on water), and less polar stratospheric clouds are formed. Thus no significant O_3 hole has been observed in the Arctic region so far. In the Antarctic region, the O_3 layer can change quite fast and substantially. For instance, in Punta Arenas, the ozone level was about 210 DU on 15th October 1994. On 16th October, it was only 150 DU and 240 DU on 17th October.

When the O_3 hole appears in the Antarctic spring (in October), the fluence rate of UVB rapidly increases to midsummer values, which are about double the normal spring values. In spring, after the long Antarctic winter, plants, fish and micro-

organisms may be unprepared for high fluence rates of UVB. Protective substances, like carotenoids, may not have had time to be formed. It is too early to say if this will have serious adverse effects.

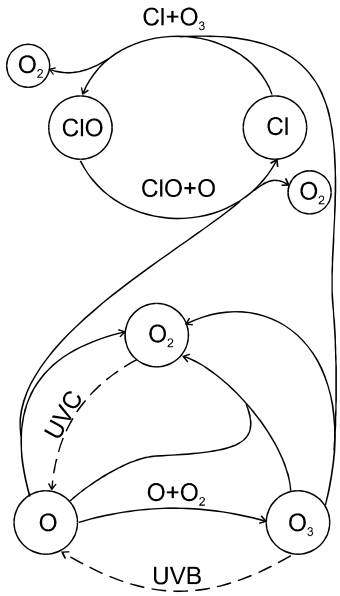

Fig. 7-7 Some of the reactions involved in the production and degradation of O_3 in the atmosphere.

Natural variations of the ozone layer

Not all factors related to O_3 depletion are related to human activities, however. Volcanic eruptions, like El Chichon in 1982 and Mt. Pinatabo in 1991 led to reductions of the O_3 layer by about 20 DU the following year.

As can be seen from Fig. 7-6, there is also some O_3 in the lower atmosphere (the troposphere). With respect to UVB absorption, this tropospheric O_3 plays a larger role than the figure indicates since the troposphere contains much larger concentrations of scattering elements (water vapour, dust, etc.) than the stratosphere. Thus, the photon path length per km of vertical distance is larger in the troposphere than in the stratosphere, and the absorption of UVB per concentration unit of O_3 is larger there as well. Furthermore, in unclean air and in air containing large amounts of nitroxides, increased UVB fluence rates lead to increased O_3 production. Because of its strong oxidative effect, O_3 is poisonous to plants and animals.

7.5 Artificial light sources

Incandescent lamps, halogen lamps and fluorescent tubes are the most commonly used light sources in homes and work places.

Incandescent lamps give practically no UV radiation, while halogen lamps operate at a higher temperature and give small fluence rates of UVA radiation. It has been speculated that these lamps might have a photocarcinogenic effect, but in view of their small fluence rates of UVA, the risk is probably negligible compared to the carcinogenic effect solar exposure has on people. The same is true for common fluorescent tubes. These tubes contain mercury vapour, which gives a typical line spectrum when current is passed through it. The strongest lines are located at 254 nm, 313 nm, 405 nm, 436 nm, 546 nm and 577 nm. The UV lines are partly filtered out by the glass of the tubes and partly converted to visible radiation with a broad spectrum by a fluorescent layer on the inner surface of the tubes. Some of the tubes that are intended to produce pure visible light give small yields of the mercury lines in the UV region. Different types of fluorescent layer give different emission spectra. Tubes for solaria emit mainly in the UVB and UVA region. Some years ago it was believed that exposure to UVA, leading to a given skin pigmentation, was less carcinogenic and erythemogenic than exposure to UVB leading to the same degree of pigmentation. Thus, a large number of UVA solaria came into use worldwide. However, all UVA solaria also contain some UVB and since UVB is much more potent than UVA in producing both pigmentation and erythema, the effect of UVA solaria is to a large extent a UVB effect. It should be kept in mind that recent research indicates that UVA may be more photocarcinogenic than earlier believed (see the action spectra given in Fig. 7-12). Generally, solaria contain less visible radiation than solar radiation. This may have an adverse effect since visible light removes some of the carcinogenic effect of UV radiation in a process called photoreactivation (see below).

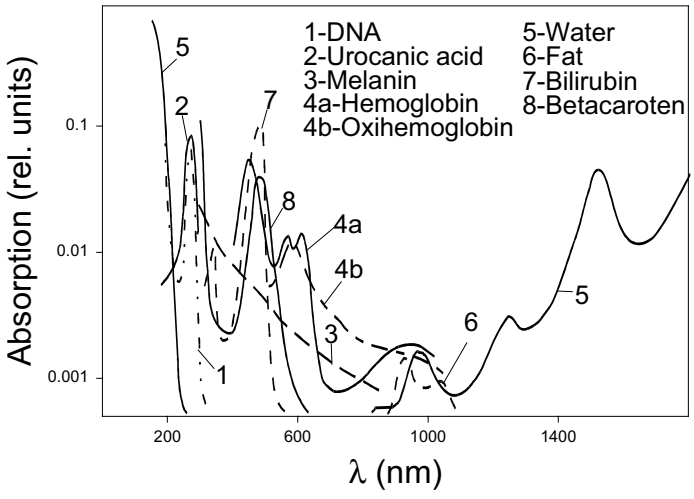

Fig. 7-8. Absorption spectra of some of the chromosphores in human tissue.

7.6 Penetration of light and UV radiation through human skin

The penetration of UV radiation and light into human tissue is limited by scattering and absorption. Just as in the atmosphere, the scattering in tissue follows the rules for Mie scattering (cells, blood vessels, fibres, granules, etc.) and Rayleigh scattering (organelles, molecules). The main absorbers of visible light in tissue are haemoglobin and its degradation products, melanins, flavins and carotenoids. Aromatic amino acids and nucleic acids are absorbers in the UVB region. Fig. 7-8 shows the absorption spectra of some of these chromophores and Fig. 7-9 shows the wavelength dependency of the penetration depth of UV radiation and visible light into human tissue.

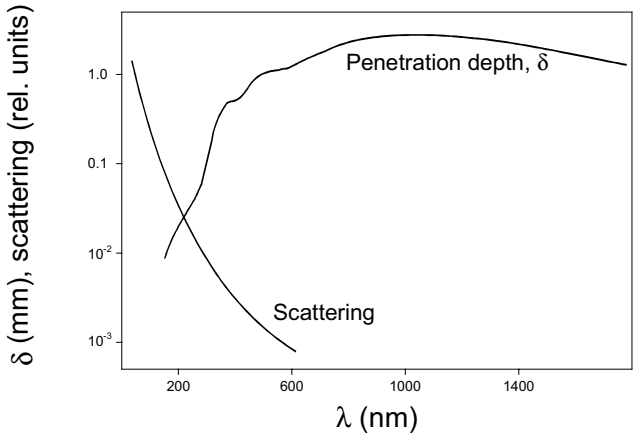

Fig. 7-9. The penetration spectrum of light and UV radiation into human tissue. The scattering increases with decreasing wavelength.

The penetration depth is defined as the distance into the tissue at which the space irradiance of a wide, parallel beam of radiation is reduced to e^{-1} of its value close to (below) the surface.

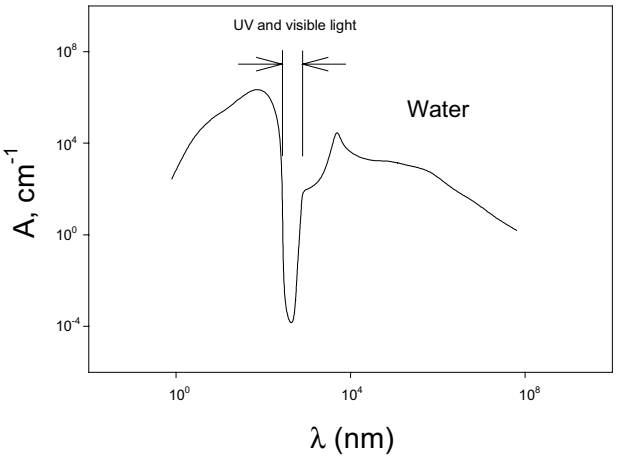

Fig. 7-10. The absorption spectrum of water

Since the absorbing molecules are randomly oriented in biological, scattering media, the space irradiance determines the effect. Space irradiance is defined as the fluence rate falling on an infinitesimally small sphere from all angles divided by the cross section area of the sphere.

Fig. 7-10 shows a curious feature in that the penetration spectrum of water: A window in the UV and visible range. This property of water has certainly played a great role in the development of life on Earth and in sustaining it.

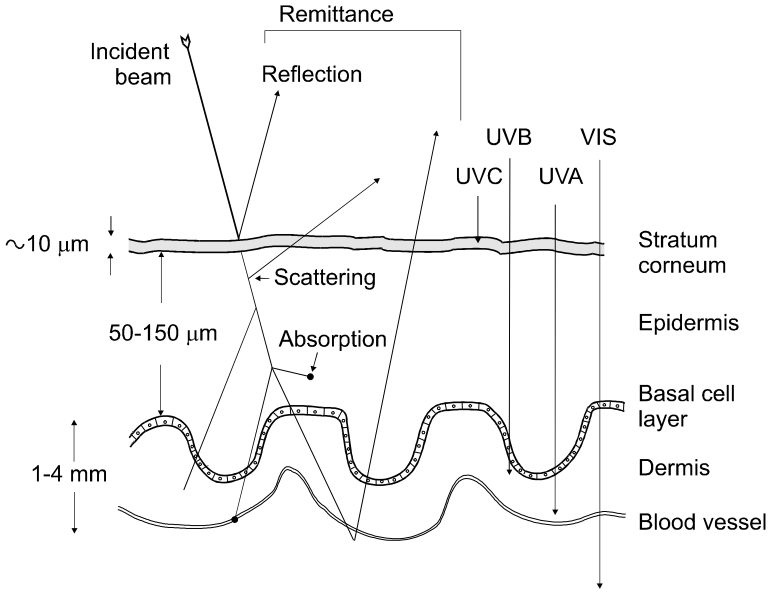

Fig. 7-11. An illustration of absorption and scattering in skin. The penetration depths for different wavelength regions are indicated.

Fig. 7-11 indicates the penetration depths of UV and visible light into human skin. The main action of UVB is believed to take place in the epidermis and in the basal cell layer, while UVA can also have a dermal effect. About 5% of the radiation is reflected from the outer surface of the skin, *i.e.* from the dead layer called *stratum corneum*. The radiation coming back from the skin is composed of reflected radiation and radiation scattered in the epidermis and dermis, and is called remitted radiation. Some of the absorption characteristics of melanin and haemoglobin/oxyhaemoglobin contribute to the shape of the spectrum of the remitted radiation. Because of back-scattering, the space irradiance close to the surface of the tissue is larger than the fluence rate of the incident radiation. Radiation transfer in a scattering and absorbing medium is often approximated by the so-called Kubelka-Munk model. If the inward fluence rate, *i.e.* that in the direction of the incident radiation, is I, and the diffuse, back-scattered fluence rate is J, then:

$$dI = (-KI - SI + SJ)\,dx \tag{7-2}$$

and

$$-dJ = (-KJ - SJ + SI)\,dx \tag{7-3}$$

where S is the scattering coefficient
K is the absorption coefficient
x is the distance into the tissue

Solving these simultaneous differential equations gives:

$$K / S = [(1 + R^2 - T^2) / 2R] - 1 \quad (7\text{-}4)$$

where R is the remittance J_o / I_o
T is the transmission I / I_o

If $K = 0$, *i.e.* the tissue has no absorption, then:

$$R + T = 1 \quad (7\text{-}5)$$

Eq. 7-5 indicates that no radiation is lost.

For a thick sample, where $T \approx 0$:

$$K / S = (1 - R^2) / 2R \quad (7\text{-}6)$$

which means that the remittance of a thick sample depends only on the ratio of the absorption and scattering coefficient.

Melanin plays the major role in penetration of UVB and UVA through the epidermis. Thus, the transmittance at 300 nm is 2-3 orders of magnitude larger for white epidermis than for the darkly pigmented epidermis. Thickening (hyperplasia) of the epidermis is one of the reactions of human epidermis to UV. For UVB, even mild hyperplasia plays a large protective role. However, for UVA and visible light, hyperplasia offers little protection compared to melanogenesis. Melanin is present through the entire epidermis. Negroid *stratum corneum* contains melanin particles, melanosomes, while Caucasian, white *stratum corneum* contains only broken melanosomes, melanin 'dust'. This difference may be significant as far as the K/S ratio is concerned.

Urocanic acid is present in the epidermis of all people. It has an absorption spectrum in the same spectral region as DNA and may play a protective role. Furthermore, it is believed that this substance is a main chromophore for UV effects on the immune system.

Haemoglobin is present only in the vessels of the dermis, but one of its break-down products, the lipophilic substance bilirubin, binds to fat and is present in the whole skin, even in the *stratum corneum*. This is also true for ingested betacaroten. These substances may act in two ways: partly as sunscreens and partly as antioxidants.

For Caucasian skin, the remittance is about 0.1 at 300 nm, 0.2 at 360 nm and about 0.5 at 600 nm. The corresponding numbers for dark, Negroid skin are 0.02 at 300 nm, 0.09 at 360 nm and 0.2 at 600 nm.

7.7 Action spectra

The spectrum of solar light is wide. Radiation of different wavelengths contributes to different degrees in biological processes. Sometimes, it is difficult to identify the chromophores for a given process. The chromophore for a process can be defined as the molecule that absorbs the photon that initiates the process. For instance, in many plants, chlorophyll is the main chromophore for photosynthesis.

Action spectra provide fundamental information about photobiological processes.

Quantum yields

The efficiency of a radiation-initiated process is given by the quantum yield ϕ. The quantum yield ϕ_p for a process P can be defined as ϕ_p = *number of P-events taking place per absorbed photon*. Usually, only one chromophore is involved. It is necessary to determine the number of photons absorbed by this chromophore. When dealing with scattering media, like skin or cell suspensions, the determination of absorption spectra can be quite complicated. Spectrometers with integrating spheres that collect a large fraction of the light transmitted by the sample, are frequently used. Otherwise, spectra can be estimated by use of ordinary spectrophotometers if equal and strongly scattering quartz plates are introduced behind both the sample cuvette and the reference cuvette. Thus, both sample and reference beams are scattered to almost the same extent and the scattering of the sample is 'drowned' in the scattering of the plates.

Sometimes, it is of interest to determine the efficiency of a process per incident photon. This is the case when the chromophore is localised below an absorbing layer.

Action spectroscopy

The action spectrum for a process gives the wavelength dependency of its quantum yield. Conventionally, this is determined as follows: the sample is exposed to $n(\lambda)$ photons at the wavelength λ to produce a given effect, for instance generation of a given concentration of a photoproduct. Then, the wavelength and the photon number are varied in such a way that the same effect is produced at all wavelengths. The action spectrum is then $\Phi(\lambda) = K/n(\lambda)$, where K is a constant.

If only one chromophore is present and if this chromophore is in an unbound and monomeric state, the action spectrum will have a shape identical to that of the absorption spectrum of the chromophore. In samples with many absorbing molecules, action spectroscopy is a powerful tool in identifying the chromophore for the process of interest. For instance, this could be photosynthesis, generation of erythema, melanogenesis, induction of skin cancer etc. If free monomeric chromophore molecules are present together with bound or aggregated molecules, the situation is more complicated. Aggregated or bound molecules usually have distorted or shifted spectra as compared with monomeric molecules, but are usually less efficient in initiating photochemical processes.

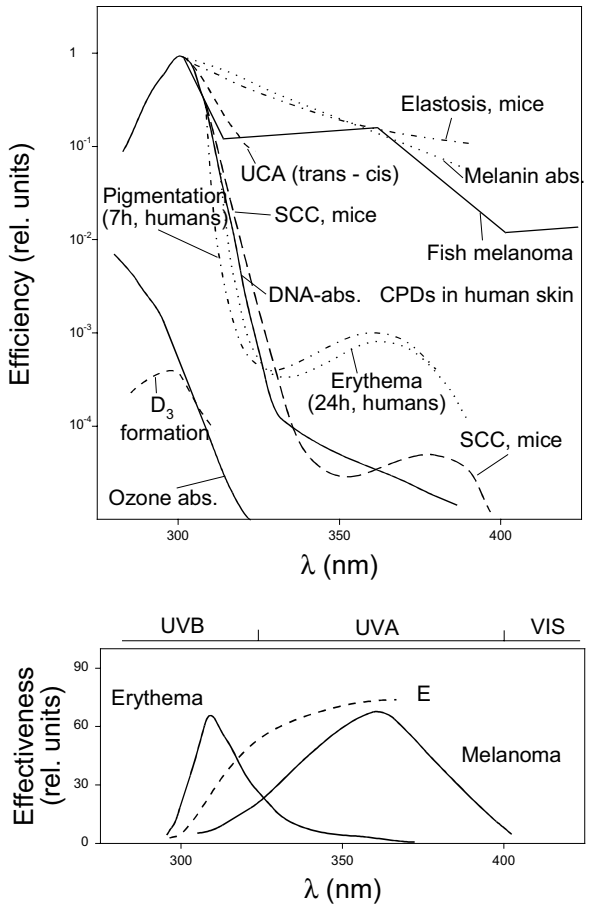

Fig. 7-12. Some important action spectra (upper panel). Effectiveness spectra, are obtained by use of the action spectra for fish melanoma and erythema, respectively, and the emission spectrum for solar radiation, E (lower panel).

Action spectra for some photobiological processes

Action spectroscopy can give the answer to many important photobiological questions, such as:

1. Is skin cancer due to UVA or UVB?
2. Can a light source be constructed that gives skin pigmentation (melanogenesis) without any risk of inducing skin cancer?
3. What light source should be used to stimulate vitamin D synthesis?
4. What is an optimal spectrum for light therapy of infants with hyperbilirubinemia?
5. Do UVA solaria give a UVA or a UVB effect?
6. Do such solaria contain enough visible light to photoreactivate DNA damage that can lead to skin cancer?

The answers to some of these questions can be read from the action spectra sketched in Fig. 7-12. Since the action spectrum of melanogenesis is quite similar to that for erythema (in humans) and for non-melanoma skin-cancer in mice, it is likely that a given melanogenesis is accompanied by a given risk of sunburn and of non-melanoma

skin cancer. The efficiency spectrum of a radiation source producing a given biological effect is constructed by multiplying the spectrum of the light source with the action spectrum for the effect, wavelength by wavelength, as demonstrated in Fig. 7-12. This data indicates that it is mainly the UVB fraction of the solar radiation that gives erythema, melanogenesis, vitamin D synthesis, and non-melanoma skin cancer, while melanoma is likely to be caused by UVA.

Amplification factors

Many photobiological processes are complex and not linearly dependent on the number of photons absorbed. Repair, oxygen depletion, photoninduced movement of chromophores, generation of protecting molecules and skin thickening (hyperplasia) are some of the complicating processes. It is then relevant to ask the question: If the number of incident photons is increased from n to $n + \Delta n$, *i.e.* by a fraction $\Delta n/n$, how large will the increase in the interesting effect be? For instance, if a population has a probability of R (per person and per year) of getting skin cancer when it is exposed to n UVB photons per year, what will the probability be if the number of photons is increased, for instance by ozone depletion, to $n + \Delta n$? In this context, the *biological amplification factor* A_B is introduced and defined by the equation:

$$\Delta R / R = A_B \, (\Delta n / n) \tag{7-7}$$

If A_B is constant throughout the entire relevant range of photon numbers n, then:

$$\ln R = A_B \ln n + constant \tag{7-8}$$

This turns out to be a good approximation of the real relationship between incidence rates R and UV exposure n. For all skin cancer forms, A_B is equal to about 2.

If the ozone amount in the atmosphere decreases, the fluence rate of UVB will increase. The *radiation amplification factor* A_R (by some authors called *RAF*) is defined by the equation:

$$\Delta F / F = A_R \, \Delta C / C \tag{7-9}$$

where F is the fluence rate of UVB
C is the amount of ozone in the atmosphere

A_R is equal to about 1, and thus, if the ozone amount in the atmosphere decreases by 1%, the fluence rate of erythemogenic UVB radiation increases by about 1%. For practical purposes, a more complicated calculation needs to be performed. Instead of considering the UVB fluence rate F, the annual exposure of UVB n has to be calculated or measured. To study erythema, the action spectrum of erythema in the

determination of the annual exposure should be used, and to study skin cancer, the corresponding action spectrum should be used.

A question often asked in the media is – 'how much will the incidence rate of skin cancer increase if the ozone amount (integrated over one year) is reduced by 1%?'

The answer is given by the magnitude of the total amplification factor $A_t = A_B \cdot A_R$. This follows directly from the equations above:

$$\Delta R / R = A_B \, (\Delta n / n) = A_B \cdot A_R \, (\Delta C / C) \qquad (7\text{-}10)$$

Thus, an ozone depletion of 1% will result in an $A_B \cdot A_R$ = 2% increase of the incidence rates of skin cancer using the approximate numbers of A_R and A_B mentioned above.

7.8 Further reading

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31 Effects of UV Radiation and Visible Light

Johan Moan

31.1 Introduction

Almost the entire animal and plant kingdoms are being exposed to UV radiation from the sun and have been so for millions of years. By producing mutations, UV radiation has been an important factor in speeding up the rate of evolution. Just as some mutations are good and some are bad for the survival of species, some of the UV effects are good and some are bad for human health on a much shorter time scale than that relevant for evolution. To cope with the 'bad' effects, repair- and defence mechanisms have been developed. These include a number of modes of DNA repair and synthesis of protective molecules. Repair, as well as defence, is by nature partly constitutive (*i.e.* always existing in an organism) and partly inducible (*i.e.* developing when needed).

Biological effects of UV radiation and light can be classified as either direct effects or indirect effects. Direct effects are those for which the biological alterations take place in the tissue where the photons are absorbed. Indirect effects are those for which signals are transmitted from the organ or tissue where the photons are absorbed via nerves, hormones or other molecules to the organ where the biological effect is manifested. Regulation of circadian rhythms is an example of an indirect effect. Light is absorbed in the retina of the eye, nerve signals are transmitted to organs that control the synthesis of melatonin and other substances involved in maintaining the diurnal circadian rhythms.

The sun is our main source of UV radiation and light. In modern human life, other photon sources such as lamps and solaria play important roles. Humans are exposed to UV radiation and light in outdoor activities like sport, sunbathing and mountaineering.

31.2 Radiation sources

The spectrum of solar radiation has been described in an earlier chapter (Chapter 7: Visible and UV Light). Life on earth is adapted to this radiation and copes with natural variations through seasons, days and varying weather conditions. However, with a low ozone concentration in the spring, the short term UV-variations may be larger than earlier. Some time is needed before adequate protection mechanisms are developed.

Incandescent lamps, including quartz halogen lamps and fluorescent tubes have been used in artificial illumination for a number of years. Some of these sources, notably some commonly used fluorescent tubes and quartz halogen lamps, give small fluence rates of UV radiation, and some investigators have proposed that they may be slightly carcinogenic. However, most people are exposed to much larger fluences of

UV radiation from the sun than from such lamps, so the additional risk arising from them is most likely negligible.

UV sources constructed for use in solaria are of greater concern. They emit UVB and UVA fluences large enough to produce erythema within a few minutes. Because the action spectrum of pigment (melanin) induction, the action spectrum of erythema and the action spectrum for SCC induction in mice are quite similar, a given pigmentation acquired by use of solaria will also give a certain increase in skin cancer risk. For some years, it was anticipated that UVA presented a relatively lower risk of skin cancer than UVB under conditions giving similar pigmentation. Consequently, a number of different fluorescent tubes for UVA solaria were constructed. Some action spectra indicate that strongly pigmented people may gain some benefit from using such solaria compared with UVB solaria. However, no such advantage seems to exist for those really wanting increased pigmentation, *i.e.* people with white skin of types 1 and 2. Furthermore, it should be noted that since UVB is so much more efficient in producing pigmentation than UVA, the small UVB-contribution present in all UVA tubes has a significant browning (and erythemogenic) effect. The situation may be even worse if the action spectrum of fish melanoma is relevant also for humans. This spectrum weights UVA much more heavily than the pigmentation action spectrum does. Thus, UVA solaria may be more appropriate as melanoma generating devices than pigmentation generating radiation sources.

Recently, UV lasers (excimer lasers) have been introduced for therapeutic purposes, notably for eye lens corrections and for dentistry. The possibility that such use may be associated with a small photocarcinogenic risk exists, but the risk is certainly very small.

31.3 Beneficial effects of radiation

Synthesis of vitamin D_3

A large fraction of the white-skinned population is probably exposed to too much UV radiation. Historically, from the industrial revolution until far into the 20th century, the opposite was true. Inhabitants of large industrial cities suffered health problems because of lack of sunshine. They got rickets because of a vitamin D_3 deficiency. At that time, the sun was the main source of this vitamin. Even today, when the food is fortified with vitamin D_3, the sun gives a measurable contribution. Thus, in the Norwegian city Tromsø, where people probably eat a lot of fish with a large content of vitamin D_3 (cod and cod liver), the average content of the vitamin D_3 metabolite 25 OH D_3 in the serum of people is about 50% larger in July-August than in November-March (even though this is the cod season).

Characteristic features of rickets in children are growth abnormalities in the skeleton, notably in the cranium and the backbone. The bones get soft because

inadequate amounts of Ca^{2+} are taken up. In adults, shortage of vitamin D_3 also results in soft bones, osteoporosis.

In 1917, it was proven that cod liver oil contains vitamin D_3, which heals rickets. Before that, however, in 1901 it was shown that radiation from a mercury arc lamp could improve and even heal the disease. It was also shown that UV-irradiated food had increased contents of vitamin D_3 and could prevent rickets.

Not only people living in large cities during the industrial revolution suffered from rickets. Signs of this disease have been found in bones of Neanderthals, and one theory of why they disappeared is that they got rickets and osteoporosis. The time of their disappearance (about 40 000 years ago) was characterised by a worsening of the climate. The Neanderthals probably did not eat fish as did their successors, the Cro Magnons.

Today, vitamin D_3 shortage is a limited problem. However, the frequency of bone fracture among elderly people is increasing. Furthermore, signs of shortage have been noticed in some immigrants, notably people with a dark skin colour, to northern countries. A dark skin colour reduces sun-induced vitamin D_3 synthesis. Vitamin D_3 acts as a hormone rather than as a vitamin since it has to be 'activated' (chemically changed) in two organs (liver and kidney) before it acts on bone metabolism. Its main tasks are to keep the blood content of calcium and phosphate ions at the correct levels, to enhance the intestinal absorption of these ions and to initiate the formation of osteoblasts (cells that remodel bone and mobilise bone calcium stores). This process also requires the presence of parathyroid hormone. In co-operation, these two hormones, 1.25 $(OH)_2$ D_3 and parathyroid hormone, prevent rickets and osteoporosis. There are two major forms of vitamin D – D_2 and D_3. D_2 is formed by UV-exposure of yeast sterols followed by a heat-dependent isomerisation and is added to milk, butter and other foods in many countries. Vitamin D_3 is present in fatty fish and fish liver and is also synthesised in skin during exposure to UV radiation.

7-hydrocholesterol in the skin is transformed by UVB to previtamin D_3, which, by heat, is isomerised to vitamin D_3. During 38 h at 37 °C, about 50% of previtamin D_3 is isomerised. After about 4 days, there is an equilibrium in the skin with 20% previtamin D_3 and 80% D_3. However, vitamin D_3 is transported away from the skin, bound to an α-globulin called DBP (D-binding protein).

In the liver, vitamin D_3 is hydroxylated to 25 OH D_3, which is transported further to the kidneys and hydroxylated to the active hormone 1.25 $(OH)_2$ D_3.

Since previtamin D_3 is retained in the skin for some time before being transformed to vitamin D_3, it can be exposed to solar radiation. This results in the formation of two photoproducts: lumisterol and tachysterol. After a certain exposure, a photoequilibrium is attained. Since the absorption spectra of these substances are different, the composition of the photoequilibrium is dependent on the spectral characteristics of the radiation. At 295 nm, previtamin D_3 dominates, while solar radiation gives most of the lumisterol. Only small exposures to solar radiation are needed to reach a maximum yield of previtamin D_3, and further exposure will degrade the previtamin. Neither lumisterol nor tachysterol have any significant biological activity.

Vitamin D_3 is itself photolabile and gives rise to transvitamin D_3, suprasterol I and suprasterol II upon irradiation. 1.25 $(OH)_2$ D_3 has anti-proliferative effects and has been used to treat psoriasis. It is possible that transvitamin D_3 and its hydroxylated derivatives have a similar effect and may be involved in the healing effects of UV-radiation on psoriasis. Two hours exposure to the sun at noon in midsummer degrades about 80% of the vitamin D_3 in the skin. Even UVA reaching the dermis with its capillaries may degrade circulating DBP-vitamin D_3. Photodegradation of vitamin D_3 may protect against toxic overdoses of vitamin D_3. 25 OH D_3 and 1.25 $(OH)_2$ D_3 have biological activities twice and ten times larger than that of vitamin D_3 itself. While the blood level of vitamin D_3 is strongly increased (by factors of 4 to 6) after whole-body exposure to 1 to 2 MEDs, the level of 25 OH D_3 is much less affected, and that of 1.25 $(OH)_2$ D_3 is very tightly regulated and practically remains constant.

Need for vitamin D_3

The human need for vitamin D_3 can probably be covered by solar radiation even at high latitudes (> 60 °N). The daily need is about 2.5 µg/day, but vitamin experts recommend an intake of 10 µg/day for children and pregnant women. Exposing 1 m^2 of white skin to 1 MED of solar radiation yields about 30 µg vitamin D_3. Vitamin D_3 may protect against some forms of cancer. Because of this, some investigators have proposed that sun-exposure may, in fact, have an anti-carcinogenic effect. Since ozone and 7-dehydrocholesterol have similar absorption spectra in the UVB range, ozone depletion may reduce the incidence rates of these cancers.

Biological clocks and circadian rhythms

Practically all plants and animals have, during their evolutionary history, developed endogenous rhythms with periods ranging from seconds to years. These rhythms are driven by biological 'clocks', self-sustained oscillators. The best known rhythm is the circadian rhythm, which has a period of about one day. For some strange evolutionary reason, the human circadian rhythm has a period that is longer than 24 hours. Exceptionally, it can be up to 48 hours. The light of the day and the darkness of the night are believed to be the main signals keeping the period locked to 24 hours, *i.e.* synchronising the clock to a period of 24 hours. Usually, this period is independent of the environment so that the biochemical reactions underlying the rhythms are in some way temperature compensated. However, abrupt changes of the temperature cause phase shifts and can be applied to study the dynamic properties of the oscillators. Similarly, phase changes of the light/dark cycle, such as those experienced during long east-west or west-east flights (jet lag), can disturb the circadian rhythms. Changes of the ratio of the light intensity of day and night, as well as the length of the day, and even spectral changes, can cause profound physiological changes, trigger sexual behaviour of animals (and humans?) and elicit mental disturbances. The most common disturbance of this kind is a type of depression called 'seasonal affective disorder', SAD. SAD is most common in the dark period of the year, notably at high latitudes, and has been

associated with disturbances of the temporal organisation of endocrine hormone systems. Jet lag, as well as SAD, can be treated with bright, artificial light. A commonly used treatment regime is a daily exposure of about 2 500 lux at eye level for 2-6 hours or 10 000 lux for 0.5 hours. 10 000 lux of cool white light from fluorescent tubes correspond to about 1.5 mW/cm^2 at corneal level and about 9×10^{-3} mW/cm^2 at retinal level. About 80% of SAD patients show clinical remission after one week. The treatment is effective for other disorders than SAD, such as jet lag, shift work sleep disturbances, age-related insomnia, and advanced and delayed sleep phase syndromes. Provided that all UV radiation is filtered away from the light and that the patients do not take photo-sensitising drugs, the treatment does probably not cause any eye damage. This treatment is believed to act by influencing the circadian clock. However, the mechanisms are complicated: the anti-depressive effects of light are probably not only mediated by circadian phase shifts or prolongation of the winter days since the treatment is effective even when given in the middle of the day. In contrast, bright light exposure in the middle of the day has no effect on the phase of the circadian rhythm. When a light pulse of a couple of hours is given at night, before the time of the circadian minimum of body core temperature (which, for most persons occur between 3 and 5 a.m.), it delays the phase of the circadian rhythm. When given after this time point, it advances the phase of the rhythm. Thus, the mechanisms of the effect of light on SAD and circadian rhythms are probably different.

Antidepressants

The tryptophan derived neurotransmitter serotonin, 5-HT, is involved in circadian rhythmicity as well as in depressive illness. Thus, 5-HT can advance the phase of the circadian clock when given during the day and block the phase-shifting effect of light when given during the night (a time when 5-HT has little effect on the circadian rhythm). Further, 5-HT re-uptake inhibitors are among the most widely used anti-depressants. Even though light given during the day has no effect on the circadian clock, it can, in fact, block the expected phase-shifting effect of a serotonin antagonist (*i.e.* of a drug eliminating the effect of serotonin).

'Sleeping pills'

To localise the main circadian clock in humans has been a subject of intense research. It seems likely that this clock is located in the suprachiasmatic nuclei, SCN. The SCN are two small assemblies of about 10 000 neurones localised in the hypothalamus about 3 cm behind the eyes and close above the optical nerve from the retina to the brain. People with pituitary tumours that exert pressure on the SCN lack circadian rhythms. The same is true for animals having their SCN surgically removed. The SCN get direct signals from the retina as well as 5-HT signals from the raphe nuclei in the brain stem. SCN control another gland, the pineal gland or the epiphysis as it is also called. In this gland, melatonin, the 'hormone of darkness', is produced from 5-HT and sent out into the body to control many other hormone systems including sex hormones, prolactin, adrenal hormones and many others. Melatonin

peaks at night, and, when given exogeneously, is an efficient circadian phase modulator. Melatonin pills can be effective as sleeping pills, notably in connection with jet lag.

Is the retina the only receptor of light for circadian phase control or shifting?

Certainly not. In the house sparrow, three different input pathways have been found. Retinally degenerated mutant mice, as well as totally blind humans, also have receptors that can modulate the circadian rhythmicity of melatonin. Light exposure of the popliteal region (the region behind the knee) of humans to light during the night shifts the circadian phase just as exposure of the retina does. It seems that neuroactive gases, like NO and CO in the blood, may be involved in this extra-ocular light effect. Both have a vasodilating effect and NO can shift the circadian phase. Light can dissociate these gases from heme (which is then the chromophore for the effect) and can also increase the activity of NO synthase.

Possibly, most of the cells in our body have a circadian clock built in. Thus, if cells are removed from the SCN or from the pineal gland of a mammal and grown in culture, they continue their circadian rhythm for weeks. Even cell lines that have been immortalised and grown in culture for 25 years can have genes like per (see below) activated by serum deprivation followed by serum supplementation. Such oscillatory genes are well preserved in the evolution since similar genes operate in single-celled organisms, in algae, in Drosophila (a fruit fly) and in humans.

Mutations

The recent study of the circadian clock molecules in Drosophila is an extremely fascinating story. Mutations in genes coding such protein molecules result in flies with different lengths of the circadian rhythm or totally lacking the rhythm. Early in the night, the genes 'per' (for period) and 'tim' (for timeless) are active in producing m-RNA and then generate their proteins ('Per' and 'Tim', respectively). Per is rapidly degraded in the cytoplasm, but is stabilised upon binding to Tim. The Per-Tim hetero-dimers enter the nucleus and suppress the activity of their own genes, per and tim. Then, the synthesis of Per and Tim is stopped and the two proteins are gradually broken down. Two other genes, 'clock' and 'bimal', encode proteins that are involved in the initiation of the next cycle of activation of per and tim. Another gene, called 'double-time', encodes an enzyme that phosphorylates Per, whereby its lifetime is reduced. Human and mouse genes equivalent to the Drosophila per and tim genes have been identified.

Stimulation of the immune system

While scientists in the Western world have been active in identifying the negative effects of UV-radiation and light, scientists in East Europe have been looking for positive effects. It seems quite likely that small exposures stimulate the immune system in a hormetic manner. (The expression 'hormetic' is derived from 'hormone'. Hormones

are catalysts of biochemical reactions. Small amounts of them are necessary for the body to exist, while large amounts often are toxic.) Furthermore, moderate exposures can probably increase the physical performance of humans, but the mechanisms behind this remain obscure.

31.4 Adverse effects

Effects on the eye

Snowblindness (photokeratitis) is damage to the outer layers of the cornea causing severe pain and reducing vision. Photokeratitis appears a few hours after exposure to intense UV radiation and disappears within a couple of days.

Another form of eye damage is the cataract, which implies loss of the transparency of the lens. It is the main cause of blindness in the world. The incidence of cataracts increases with age and the process is accelerated by prolonged UV exposure.

UV exposure may also cause damage to the retina, such as age-related macular degeneration. This disease is a common cause of blindness in the developed world.

Erythema

UV-induced erythema is caused by vasodilatation leading to increased blood content of the dermis. A single UV-exposure causing a barely perceptible erythema after 24 hours is called one minimum erythema dose, 1 MED. The MEDs are different for different wavelengths. Furthermore, the MED-value for a given light source is dependent on a number of factors (see Table 31-1):

1. Skin pigmentation. Caucasians have 3-5 times smaller MEDs than moderately pigmented races and up to 30 times smaller MEDs than Africans.
2. Season. MEDs are about 50% larger in summer than in winter.
3. Age of the subject. Children and persons over 70 years have significantly lower MEDs than middle-aged people.
4. Irradiationsite. MEDs for face, neck and trunk are 2-3 times smaller than for limbs.

Table 31-1. Minimum erythema doses (MEDs) for different skin types.

Skin type	Colour	MED (UVB, mJ/cm^2)	Time in the sun (minutes) (midsummer, midday)
1	white	20	10-30
2	white	30	15-45
3	white	40	20-50
4	light brown	50	25-75
5	brown	80	40-120
6	black	100-200	50-300

The action spectrum for erythema in humans resembles the DNA spectrum in the UVB region, but has a small peak in the UVA region. The MED value is independent of fluence rate over 7 decades.

Skin has a biphasic erythema response to UV radiation: an immediate response and a delayed response.

In humans, UVB- or UVC exposure causes erythema, probably as a result of damage to epidermal cells. Following UVA exposure, the erythema is of a different nature and probably originates from dermal damage. Vasopermeability caused by UV exposure has been studied in laboratory animals. In guinea pigs, it occurs about 1 minute after irradiation and reaches a maximum in 10 minutes. The affected vessels are venules. These immediate vascular responses may result from direct effects on endothelial cells and/or from effects induced by chemical mediators. Direct irradiation of dermal arterial blood vessels in dogs, rabbits, and humans with about 3-5 MEDs of UVB or UVC produces immediate arteriolar vasodilatation, which rapidly recovers.

Histamine, a substance stored in mast cells, may play a role in the immediate phase of UV inflammation. Mast cells release histamine after UV exposure. Histamine produces erythema and edema.

Serotonin is also present in mast cells and may be released by UV radiation. Its role in the immediate phase of UV inflammation in humans is not certain. Furthermore, prostaglandins (PGs) are released in human skin in vitro, possibly from membrane receptor sites, immediately following UVB irradiation.

After the immediate phase of inflammation, there is a period of quiescence before the onset of the delayed phase. Several structures are involved in this response: blood vessels, blood cells, and plasma proteins as well as skin cells.

Erythema after UVB irradiation appears in about 8 h, reaches a maximum at about 12-24 h and fades in a further few hours to several days depending on the exposure. Increasing exposures progressively shortens the time before the appearance of the delayed erythema, lengthen its duration, and increase its intensity. UVA irradiation leads to an immediate erythema followed by a delayed phase lasting for hours or days. Arterioles, capillaries, and venules all seem to be affected in the delayed vasodilatation. The increased vascular permeability permits passage of leukocytes and plasma into the exposed tissue. As in the immediate phase, it is possible that direct damage to endothelial cells contributes to the delayed phase of UV inflammation.

Prostanglandins are cyclic oxygenated 20-carbon fatty acids, which induce vasodilatation and enhance the vasopermeability of other mediators, like histamine. Mast cell histamine and plasma polypeptides may be important in delayed erythema, causing pain, vasodilatation, increased vascular permeability, and increased leukocyte migration.

UV irradiation may cause lysosomal rupture in epidermal cells. This may play an important role in the delayed phase of UV inflammation. However, even lethally damaged cells may contain completely normal lysosomes. No products of lysosomal breakdown are detectable in epidermal suction blister fluid until at least 11 hours after irradiation, and maximal levels occur at 4-7 days. Thus, released epidermal lysosomal contents probably do not initiate UV inflammation, but may accentuate it.

The chromophores responsible for the mentioned process are unknown. Nucleic acids are likely to be involved. The similarity of the erytherma action spectrum and the DNA absorption spectrum as well as the fact that some photoreactivation may occur, strengthen the arguments for DNA as an important chromophore.

During the first hours after UV-exposure, apoptotic cells, so-called sunburn cells, are seen in the epidermis. Apoptosis is one defence mechanism by which potential cancer cells are eliminated. UV-induced damage to elements of the apoptotic mechanism may allow mutated cells to grow and develop into tumour cells. Many therapies have been attempted to reduce erythema: anti-inflammatory agents, cortico-steroids, antihistamines, antioxidants, vitamin A, anti-malarials, DNA repair enzymes and beta-carotene.

Elastosis and ageing

Chronic exposure to UV radiation leads to accelerated skin ageing. This can be observed as wrinkling, loss of elasticity, irregularities of pigmentation and thinning of epidermis. The melanocytes may lose their dendrites, and even their ability to produce melanin. Sometimes, giant binucleated melanocytes are formed. Normally, there are about 1 000-2 000 melanocytes per mm^2 in facial skin and about 500-1 000 in thigh skin. The numbers of melanocytes is decreased in sun-damaged skin. Also, the antigen presenting Langerhans cells is reduced in number and changed in appearance by UV radiation. They lose their dendrites and probably their immunological function.

The sebaceous glands in sun-damaged skin secrete less sebum and the skin gets dry. Such skin is wrinkled because of damaged connective tissue. The fibres in this tissue are made up of the proteins collagen and elastin, which are secreted by the fibroblasts in the dermis. The flexible collagen fibres consist of fibrils of about 0.5 μm diameter and show bands of about 0.05 μm length. Sun-damaged, elastotic skin shows tangled collagen fibrils with little or no banding structure.

In the lower dermis, elastin fibres form networks between the collagen fibres. The elastin fibres are normally elastic but get less so when sun-damaged. They thicken, clump and fragment. Lumps of elastin fibres, together with the oxidation product lipofuscin, give the skin a yellowish colour. Elastotic skin has lost its flexibility and returns to its original state slower than healthy young skin after being stretched. While thickening of the epidermis (due to cell proliferation and inflammation) is an early, transient reaction to UV exposure, elastotic skin is thinner than healthy skin. The normal wavy pattern of the border between dermis and epidermis, where the basal cells reside, is flattened out. Elastotic skin is permanently damaged, although transplantation of such skin to a non-damaged skin area makes it to some extent regenerate.

Elastosis develops from about the third decade of life. In sun-exposed skin of type 1, elastosis is maximal in the sixth decade. The resistance to elastosis increases with pigmentation, and in black skin of type 6 it is far from complete even at an age of 80 years.

The action spectrum of elastosis weights UVA quite heavily, and, since reactive oxygen species seem to be involved, it is likely that other chromophores than DNA are involved.

Permanent UV-induced alteration of the skin is certainly related to DNA damage and reduction of DNA repair capacity.

With time, skin cells accumulate damage. Non-dividing cells eject 'ageing' factors into the blood, into basal cells and into fibroblasts. If the DNA in basal cells is altered, other epidermal cells derived from them will also change. Injured fibroblasts produce abnormal fibres. After long-term sun exposure, blood vessels become loose as their connective tissue is damaged. Such vessels are capable of accommodating more blood than normal blood vessels in skin. The skin of sailors, farmers and other outdoor workers is frequently sun-damaged. The pink or reddish colour of such skin partly results from tinned epidermis and partly from enlargement of blood vessels.

Immune suppression

Photoimmunology

Photoimmunology is the science of the interactions of optical radiation, notably UV, with the immune system. It combines three fields of science: photobiology, immunology and dermatology. The initiating processes in photoimmunological responses take place in the largest organ of the body, the skin.

All cells of the immune system originate from pluripotent stem cells in the bone marrow. The progeny of the stem cells are released into the blood stream and are called white blood cells, leukocytes. Differentiation of these cells gives rise to T-lymphocytes, B-lymphocytes, monocytes and granulocytes. There are two main lineages of such cells: the lymphoid lineage, producing lymphocytes and the myeloid lineage, producing monocytes, macrophages, neutrophils (stained with neutral dyes) and mast cells. Because of their granular morphology, these cells are also called granulocytes. Whether the NK cells (natural killer cells, cells that can lyse tumour cells in vitro) and Langerhans cells belong to the myeloid or the lymphoid lineage is uncertain.

The immune system is of a systemic and dynamic nature, and its main task is to fight foreign pathogenic organisms (vira, bacteria and paracites). Upon interfection, granulocytes, macrophages and NK cells try to destroy the pathogen in a rather non-specific way. If this strategy fails, specific immune responses are triggered. These are more efficient but need time (4-7 days) to become fully active. Antigen presenting cells (APCs, Langerhans cells in the skin), antibody producing cells (B cells) and effector cells (NK cells, macrophages, cytotoxic T cells (T_c), helper T cells (T_H) and suppressor T cells (T_s)) are active in this battle. The antigen, which can be a protein or a peptide specific for a virus or a bacterium, is caught by the Langerhans cells which then migrate out of the epidermis to the lymph nodes, present the antigen to T_H cells which proliferate and send out signals (cytokines) that stimulate B cells to produce antibodies

against the antigen, T_C cells to proliferate and attack the intruder and provoke inflammatory responses. Inflammatory responses involve lysis of mast cells in the skin. Histamine is released and causes increased blood flow as well as increased capillary permeability. Different types of leukocytes can then migrate out of the vessels and into the tissue to fight the intruder. In some cases, T_H cells emit signals that reach suppressor cells, T_S, which then become activated and reduce the immune response.

When Langerhans cells present the antigen to T_H cells, the latter need to know whether the antigen is foreign and dangerous or belongs to the host itself. To do this they use class II 'major histocompatibility complex' molecules (MHC class II). MHC class I and II proteins act as guidance systems for T cells. T cells possess on their surface different types of receptor molecules (TCR molecules) which recognise complexes of antigen fragments (peptides originating from pathogens) and MHC molecules. One of these tries to keep track of marker molecules on the surface of T cells by the CD system (CD = cluster differentiation, referring to clusters of monoclonal antibodies, each cluster binding to a particular marker molecule). CD4 markers and CD8 markers are found on T_H and T_C cells, respectively. T_H cells (with CD4) react when antigens + MHC class II molecules are presented to them, while T_C cells react on presentation of antibodies + MHC class I proteins. When a T_H cell binds to an APC cell, interleukin-1 (a signal molecule) is released from the APC. This signal activates T_H cells. T_H cells then release cytokines that activate B cells to produce antibody or T_C cells to attack and destroy the intruder. Furthermore, effector cells are activated by cytokines released from T_H cells. Memory cells are also produced. These cells amplify and accelerate the immune response to an antigen that is encountered at a later time. The immune system has a memory of antigens it has fought earlier.

Hypersensitivity

Effector cells may cause so-called delayed type hypersensitivity (DTH), of which the contact hypersensitivity reaction (CHS) is most familiar in dermatology. The foreign substance is a small molecule, called a hapten, which binds to a protein in skin to form the antigen. Langerhans cells present this antigen to T_H cells in the regional lymph nodes. Memory T cells are activated, proliferate and migrate into the bloodstream together with activated T_H cells. These cells reach the skin area where the hapten was applied. When encountering the antigen (hapten + protein), they release lymphokines that activate effector cells and lyse mast cells. Because the antigen is partly made up of a host substance (protein), some destruction of host tissue occurs.

UV radiation has profound effects on the immune system in the skin. First of all, the number of Langerhans cells decreases upon UV exposure. Application of a contact sensitising hapten to skin after low, non-erythemal exposures fails to induce CHS and instead induces hapten – specific T_S (suppressor T cells).

It is probably alteration of the activity of Langerhans cells that initiates this. These APCs bring incorrect signals to the T_H cells in the lymph nodes. Small UV exposures reduce the CHS reaction only locally in the UV exposed skin. Larger UV exposures

can also impair distant immune effects and therefore act systemically on the immune system.

There are three ways to induce T_C by UV:

1. By injecting an antigen subcutaneously at an unirradiated site in mice exposed to large UV doses
2. By applying a hapten to the skin exposed to low UV doses
3. By applying the hapten to unexposed skin of mice given large UV exposures

The systemic response to UV-radiation can be demonstrated by transfer of cells from exposed to unexposed mice. It appears to result from the release of immunoglobulin molecules from UV irradiated skin, either from the stratum corneum or from the keratinocytes. Keratinocytes produce a variety of interleukins and other signal molecules for immune and inflammatory responses.

The chromophores for the immune effects of UV may be either trans-urocanic acid, or DNA or both. UV isomerises trans-UCA to cis-UCA. Application of cis-UCA on mouse and human skin mimics UV exposure with respect to immunological effects. However, in some experimental animals, the immune effects of UV can be photoreactivated, *i.e.* reduced by subsequent exposure to visible light. This argues for DNA as the main chromophore. The absorption spectra of UCA and DNA are quite similar although UCA has a slightly more pronounced UVA-tail in its spectrum. Since UVA provokes immune responses and, since pure UVB sunscreens do not eliminate the immune effects of solar radiation, UCA seems to play a significant role.

Why should UV induce suppressor cells? Large exposure introduces a large number of antigenic changes in the skin. An intact immune system is powerful enough to eliminate all these changed skin cells. This may lead to unacceptably large skin damage, and the purpose of the suppressor mechanism may be to 'keep the battle on a proper scale'.

Skin cancer

There are three main forms of skin cancer in humans: basal cell carcinoma (BCC), squamous cell carcinoma (SCC) and cutaneous malignant melanoma (CCM). In addition to these, are Bowen's disease, a localised, non-spreading form of SCC, and keratoacantoma, which probably develops from hair follicles. Some preneoplastic lesions should also be mentioned: actinic keratosis (AK), also called solar keratosis, which in about 25% of the cases develops into BCC or SCC, and melanocytic dysplastic nevi, which is considered a precursor of CMM.

AK and melanocytic nevi are both related to solar exposure while the etiology of Bowen's disease is more uncertain. On the whole, about 80-90% of SCCs, BCCs and CMMs in white populations are related to UV exposure, and as most populations seem to have increased their exposure, this percentage is increasing.

Genetic factors play a major role in the susceptibility of a person to skin cancer from UV exposure: the incidence rates are highest for people with blue eyes, red hair,

freckles and sun-sensitive skin (type 1 and 2). Typically, the risk for people that burn and never tan is twice as large as that for people that burn and gradually tan. For people that always burn and never tan the risk is 3-4 times larger than that for people who never burn and always tan. Furthermore, people with some inherited diseases like Xeroderma Pigmentosum (XP) (a disorder related to deficient DNA excision repair), are more prone to get skin cancer than others. The same is true for immune suppressed people. These observations demonstrate the significance of a functional DNA-repair and an intact immune system in the prevention of skin cancer development.

Typical incidence rates in white populations like those in the Nordic countries are 1 000-2 000 BCCs, 100-200 SCCs and 150-300 CMMs per million inhabitants per year. Since the chances of getting skin cancer increases with age, it is possible that more than 30% of people over 70 years old suffer, or have suffered from skin cancer.

Mutation is likely to be an inevitable step in skin carcinogenesis. UVB produces mutations through direct absorption in DNA followed by generation of cyclobutyl pyrimidin dimers and 6-4 photoproducts. UVA is not absorbed by DNA, but can nevertheless induce mutations, supposedly through absorption in other chromophores (so far unidentified), generation of reactive oxygen species like singlet oxygen and OH radicals, which can damage DNA by producing 8-hydroxy-2-deoxyguanosine, giving rise to G→T transversions. The genetic map of mutations relevant for skin cancer is far from being complete. However, it appears that mutations of the p53 gene are important for non-melanomas. The p53 protein, the 'guardian of the genome', normally arrests damaged (mutated) cells in the cell cycle, gives them time for repair or leads them to elimination through apoptosis. If the p53 protein is mutated itself, damaged and mutated cells can divide and proceed towards carcinogenesis. Once a mutation in a cell has been 'fixed' in this way, clonal expansion and promotion to tumours may occur. An impaired immune system will facilitate this process. UVA generates reactive oxygen species that may be involved in the promotion and progression of steps towards carcinogenesis.

As a first and very crude approximation of the relationship between age specific incidence rates of non-melanoma, age and UV exposure, the following formula can be given:

$$\ln R = K_1 + K_2 \ln(age) + K_3 \ln(UV\ exposure)$$

where K_1, K_2 and K_3 are constants.

In the following, the three major forms of skin cancer will be considered more closely. A term that will be frequently used is the relative tumour density, RTD, which is the relative incidence rate per cm^2 on a given body localisation.

Basal cell carcinoma, BCC

BCC is clearly related to solar exposure. Its RTD is largest for body localisations frequently exposed to the sun (face, neck). Furthermore, the incidence rate increases uniformly with age, which might indicate that the risk is related to total, lifelong UV

exposure. However, recent findings indicate that episodes of intense UV exposure may be particularly risk elevating.

BCC arises from malignant transformation of the basal cells. These cells are normally dividing and give rise to the keratinocytes in the upper skin layers. An interesting clinical observation is that BCCs almost never arise on skin devoid of hair. This might indicate that basal cells in the hair follicles are particularly prone to developing into tumour cells upon UV exposure. Pigmentation obviously protects against BCC since the incidence rate among Africans is about 60 times lower than that among Caucasians living in the same area. Albinos and immunosuppressed patients have an increased risk of getting BCC. Surprisingly, some studies indicate that vitiligo (pigment loss) does not predispose sufferers to BCC. Increased risks are also seen after exposure to ionizing radiation. In most epidemiological studies, the male to female ratio of the incidence rate of BCC is in the range 1.3-1.9. Patients with multiple basal cell nevus syndrome (Gorlin's syndrome) have a lifelong elevated risk of developing multiple BCCs.

Squamous cell carcinoma, SCC

Many of the biological and epidemiological features of SCC are similar to those of BCC: high levels of mutant p53 proteins are found in the vicinity of BCCs and SCCs. XP increases the risk with a factor of 1 000-5 000. The incidence rates of both cancer forms, in the period 1950 to 1995, increased by 30-70% per decade in most white populations. The risk of getting BCC or SCC increases monotonously with age and with accumulated exposure. While cells in normal skin are almost always diploid, cells in BCCs and SCCs are frequently aneuploid. The same is true for epidermal pre-cancers like actinic keratosis, Bowen's disease and keratoacantoma. A larger fraction of the cells are in S and G_2M phase in BCCs and SCCs than in normal skin. The frequency of metastasis is low for SCCs ($\approx$ 0.3-4%) and possibly even lower for BCCs.

However, there are also differences between SCC and BCC: immunosuppression increases the risk of SCC more than of BCC. In a typical white population, the incidence rates are 5-10 times larger for BCC than for SCC while among immuno-suppressed patients, SCC may be twice as common as BCC. Thus, impairment of the immune system may seem to play a greater role in the development of SCC than of BCC.

Episodes of sunburn seem to play a greater role in BCC than in SCC induction, although in both cases, accumulated UV exposure appears to be a main determinant. PUVA treatment increases the risk of non-melanoma skin cancer, as observed a couple of years after the treatment, with a factor of 4-12 and it seems that the risk of SCC increases more than that of BCC. The male/female ratio of incidence rates is 1.3-1.9 for BCC and somewhat larger, about 2-3 for SCC. While BCC is the most common skin cancer amongst Caucasians, SCC is the most common one in Africans. Thus, pigmentation appears to protect more against BCC than against SCC, which is not surprising since SCC is initiated in keratinocytes in the skin layers above the basal cells where BCC arise. Burn scars are risk areas for SCC more than for BCC.

Arsenic, soot, tar and petroleum products appear to be carcinogens for SCC.

Cutaneous malignant melanoma, CMM

CMM arise from melanocytes, which are of neural crest origin. A few cases (about 10%) of melanomas arise in the eye, and even fewer arise in the mucosa of the gastrointestinal and genital tracts. Lentigo maligna melanoma (Hutchinson's melanotic freckle) has epidemiological characteristics similar to those of BCC and SCC. Acral lentigous melanoma arises on the skin of palms and foot soles. In the following, the two main forms of CMM, superficially spreading melanoma and nodular melanoma, will be considered.

CMM has a much higher mortality rate than the other skin cancers. Typically, the 5 year survival is 60-90% depending on site of origin, type of CMM and time of diagnosis. During the last decades, the incidence rates of CMM have increased at a similar rate as those of BCC and SCC. In most populations, CMM has an age-distribution different from that of BCC and SCC, being relatively more frequent among the young and middle aged. Furthermore, the distribution of CMM on different parts of the body (*i.e.* the site-specific, relative tumour density, RTD) is significantly different from that of BCC and SCC. Thus, for younger generations, the RTD of CMM is not always greatest on the head and neck, but rather on the back. It is believed that this indicates that CMM is not related to the total, accumulated UV exposure, but rather to episodes of intense exposure obtained in sunbathing, like vacations and weekends. This is in agreement with the observation that in many populations, CMM is relatively more common among people with indoor work than among farmers, fishermen and other outdoor workers. PUVA therapy of patients with psoriasis leads to an increased risk of BCC and SCC but apparently not of CMM. Most cases of CMM are probably due to solar exposure. This is indicated by the increase in incidence rates with decreasing latitude. Furthermore, before the era of topless sunbathing, CMM rarely occurred on the breasts of women, while over recent years, the incidence rate on this body localisation has been sharply increasing.

The genetic predispositions to CMM are generally similar to those for BCC and SCC: a fair skin that easily burns, freckles, red hair and blue eyes.

The incidence rates of CMM among people with black skin (type 6) and white skin living in the same country are widely different: for BCC and SCC, the incidence rates are about 60 times greater among white people and for CMM, the incidence rates are about 10 times greater for white people. Similarly, albino Africans have a much higher risk of getting BCC and notably SCC than normally pigmented Africans. The CMM risk, however, does not seem to be much elevated among the albinos. Albinos have melanocytes, but their ability to produce melanin is impaired. These findings may indicate that melanin is a photocarcinogen for CMM. Free radicals are generated when melanin is exposed to UVA or UVB in a test tube. When produced in the stratum corneum, these radicals may not reach the DNA of the melanocytes, while when produced inside the melanocytes, they may attack and mutate DNA. Unlike DNA, melanin absorbs UVA. Thus, one might expect – if the above model of melanin in

melanocytes as a photocarcinogen is correct – that UVA exposure can cause CMM. This is in agreement with the action spectrum of CMM in the fish Xiphophorus, one of the few animal models suited for melanoma induction. Furthermore, the latitude gradient of CMM incidence rates is much smaller for CMM than for BCC and SCC, and so is the gradient of UVA compared with that of UVB. The model needs further epidemiological and experimental work if it is to be verified. If it is correct, it will have the following consequences: a possible ozone depletion will have little influence on the CMM incidence rates, use of UVA solaria may lead to increased CMM rates, UVB sunscreens, protecting against erythema, may not protect adequately against CMM.

31.5 Protection against adverse UV effects

Cells, tissues and organisms are equipped with permanent or inducible mechanisms that protect against UV damage. The presence of such mechanisms is certainly of great importance for the development of life on earth since life has seen periods of considerably more UV stress than now. Inducible mechanisms need some time to become fully active. As the summer approaches with more solar radiation, they are gradually activated. It has, therefore, been speculated that an ozone depletion, which is manifested early in the spring and can give midsummer values of UVB in April, is particularly damaging because defence mechanisms have not had time to develop.

In addition to the endogenous defence mechanisms, humans can adopt protective behaviour: avoid sunbathing at noon midsummer, apply sun-lotions and wear hats and protective clothes.

Cell defence systems

UVB- induced CPDs and 6-4 photoproducts are the most important types of DNA damage. Most cells have different enzymatic repair systems for this kind of damage. The most important is excision repair, which eliminates the photoproducts. When enzymes of the excision repair pathway are missing, like in the disease Xeroderma Pigmentosum, normal cells are frequently transformed to cancer cells. In addition to excision repair, most animal cells possess photoreactivating enzymes for both CPDs and 6-4 photoproducts. These enzymes bind to damaged DNA regions. They contain one or more chromophores and absorb UVA and visible light. This provides energy to cut out the damaged DNA. Whether photoreactivating enzymes exist in human skin is a matter of debate since some experiments have failed to detect them. However, visible light can remove CPDs and 6-4 photoproducts from human skin, so some kind of photorepair must be present. It has been proposed that applying lotions containing repair enzymes after sun exposure helps the skin repair UV damage.

Reactive oxygen species are formed in normal biochemical processes. Since such species may induce damage, all cells are equipped with protection systems against oxidative stress. UVA exposure adds to this stress since singlet oxygen and other

reactive oxygen species are formed. Three different (partly inducible) defence systems exist:

1. Anti-oxidant molecules
2. Detoxifying enzymes
3. Redox metal ions

UVA induced oxidative species include singlet oxygen, hydroxyl, peroxyl, alkoxyd and alkyl radicals. These species can initiate and/or propagate the chain reactions of lipid peroxidation, leading to cell inactivation or cell damage. The yellowish age pigment lipofuscin is a typical product of their action. Any product that can quench these radicals can be considered an antioxidant. Lipid-soluble antioxidants include a-tocopherol, quinons (coenzyme Q, ubiquinone), bilirubin and beta-carotene. Beta-carotene is of particular interest. It has a long, conjugated double-bond system that makes it an excellent radical and singlet oxygen quencher. Additionally, it can deactivate triplet states that are intermediates in most photooxidative reactions. Water-soluble antioxidants include ascorbic acid, metal-binding proteins, uric acid and albumin. These molecules normally act extracellularly.

Of the de-oxifying, antioxidant enzymes, examples include superoxide dismutase (SOD), catalase and glutathion peroxydase. SOD transforms O_2^- to H_2O_2, and catalase converts H_2O_2 to O_2. In the absence of SOD and catalase, OH radicals can be generated from O_2^- whenever iron or copper ions are present. Glutathion peroxidase acts on UVA-induced, damaging phospholipid peroxides in cell membranes.

Tissue specific defence systems

Melanogenesis, the production of melanin by melanocytes in the skin, is an adaptive and inducible defence mechanism. Melanin is formed from thyrosine. Two kinds of melanin are found in human skin: the brown/black eumelanin and the red/brown sulphur – containing pheomelanin. Melanin has a number of functions: it can act as a camouflage pigment, as an antioxidant, as a radical scavenger, as a UVB and UVA-absorbent (natural sunscreen) and, in fact, as a photosensitiser (see the section on melanoma above). Pheomelanin in particular has the latter negative effect.

Melanins are generated in organelles called melanosomes of about 1 μm diameter in melanocytes, transferred to kerationocytes and further to the stratum corneum. In Africans, the melanosomes are large and melanin is found in all skin layers. In Caucasians the melanosomes are smaller and melanin is mainly found in the cells of the 'melanin unit'. A melanin unit is a melanocyte and about 36 keratinocytes surrounding it.

UV radiation of a limited skin area seems to have a systemic melanin-generating effect: some pigmentation is also induced outside the exposed area. Melanin is partly constitutive and always present in skin, and partly inducible. About 7 days after UV exposure, the content of pigment in the skin is maximal. During and immediately after

sun exposure, the constitutive melanin darkens (immediate pigment darkening, IPD). IPD is transient and lasts for a few hours.

UV radiation is a mitogen. Thus, it induces cell proliferation and epidermal thickening. This is protective with respect to the melanocytes and the dividing basal cells. However, in the long run, after decades of sun exposure, the skin becomes thinner. Pigment loss, vitiligo, in patches can also occur as a result of life-long sun damage.

Protective behaviour

Since the fluence rate of UVB in solar radiation is about 50% of noon values two hours before and two hours after noon, it is efficient protective behaviour to avoid the sun for a few hours around noon. Wearing sunglasses protects against eye-damage (snow-blindness and cataracts) and wearing clothes efficiently protects against skin damage. Sun lotions containing UVB filters efficiently protect against erythema and development of non-melanoma skin cancer. Since UVA may induce melanomas as well as lead to skin ageing and immune suppression, one should apply sun lotions containing both UVB and UVA filters and, preferably, neutral absorbing, scattering or reflecting compounds like iron oxides. Some of these substances may be taken up by cells and also enter the circulation. As long as the effect of this is not fully understood, the safest protection against sun damage is to limit the exposure time. However, people that feel they 'have to' sunbathe should be encouraged to use light clothes and apply sun-protective lotions and creams in adequate amounts.

31.6 Further reading

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Innhold

Når er det sunnest å være ute i sola?

Johan Moan, Arne Dahlback og Asta Juzeniene

Johan Moan (f. 1944) er forsker ved Radiumhospitalet og professor II ved Fysisk Institutt, Universitet i Oslo, medlem av Det Kongelige Norske Videnskabers Selskab og av Det Norske Videnskaps-Akademi. Mer spesifikt har han arbeidet med karsinogenese, fotodynamisk terapi, kreft-epidemiologi, og fotobiologien av folsyre og vitamin D. Moan har publisert mer enn 400 internasjonale vitenskapelige artikler og mange populærvitenskapelig artikler. Han har fått både Bergesenprisen og Birkelandprisen.

Arne Dahlback (f. 1954) er professor ved fysisk institutt, Universitetet i Oslo. Hans forskningsfelt er måling av UV-stråling og ozon, samt modellering av spredning og absorpsjon av elektromagnetisk stråling i atmosfæren.

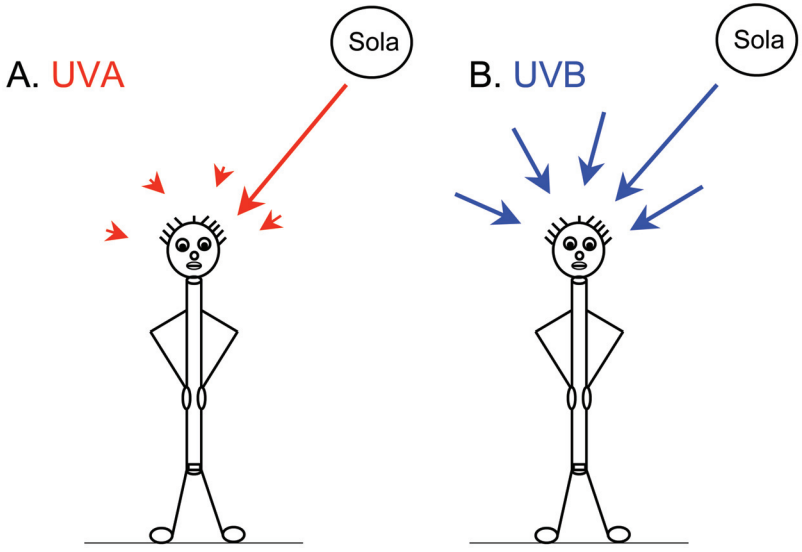
Asta Juzeniene (f. 1971) er biofysiker utdannet i Vilnius, Litauen. I 2001 ble hun medlem av gruppen til Prof. Johan Moan (Norge). Hennes forskningsaktivitet er fokusert på fotodynamisk terapi og på fotobiologien av folsyre. Hun forsvarte sin doktorgrad ved Universitetet i Oslo i 2007, og fortsetter nå sine fotobiologi studier som postdoc i den samme gruppen. Hun har publisert 44 vitenskapelige artikler.

I mange år har vi hørt at vi bør vente med å være i sola til ettermiddagen. Hvis vi er ute midt på dagen, er sjansen til å få hudkreft stor. Evolusjonsmessig kunne man argumentere for slike solingsvaner ved å si at nær Ekvator, der de første menneskene antakelig oppholdt seg, er det så varmt midt på dagen at man må krype inn i skyggen. Men en tvil på om dette er riktig melder seg når vi tenker på at menneskene, tross alt, har utviklet seg i sola, og at mange forskere mener at huden deres ble lysere og lysere når de beveget seg nordover fra Ekvator-områdene (se vår tidligere artikkel om hudfargene her i Naturen 2008, 1: 2-12). Det er til og med sannsynlig at vi ble lyse her nord fordi vi trengte mer sol! Sola er hovedkilden til D-vitamin. Beinskjørhet og rakitt resulterte av for lite sol og D-vitamin. Men menneskenes levetid har økt, og kreft av alle slag har blitt et økende problem. Ingen tviler på at sola er den viktigste grunnen til hudkreft. Vi bestemte oss derfor for å gå problemet litt nærmere inn på klingen: Er det sunt eller usunt å sole seg litt mer, og er middagssola mest uheldelig?

Helsemessig sett er den ultrafiolette (UV) delen av solstrålingen viktigst. UV fra sola deles i to: UVB med bølgelengder mellom 280 og 320 nm (1 nm = 10^{-9} m), og UVA med bølgender mellom 320 og 400 nm. D-vitamin dannes utelukkende av UVB stråling, mens UVA-stråling etter all sannsynlighet er en viktig årsak til den mest ondartede formen for hudkreft: føflekk-svulstene, eller melanomene, som de også kalles. Nå er det slik at den relative mengden av UVA og UVB varierer ulikt med solhøyden. Det er to hovedgrunnene til dette:

1) Ozon-laget absorberer UVB, men ikke UVA. Når solhøyden avtar, får solstrålene lenger vei gjennom ozonlaget. Dermed blir det absorbert mer UVB-stråling enn UVA-stråling, og UVB/UVA-forholdet avtar.

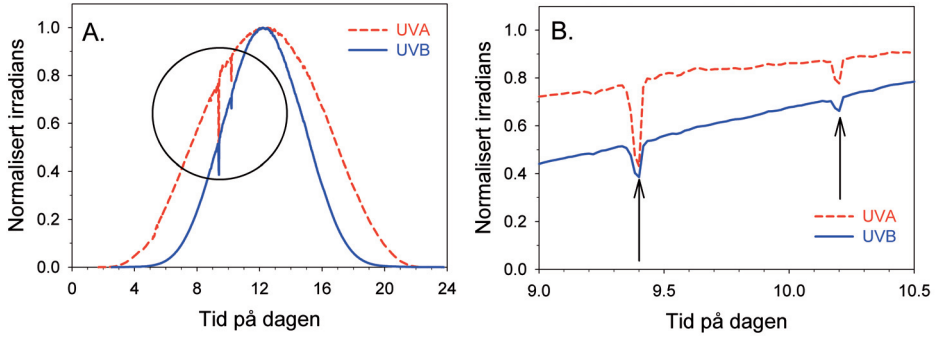
2) UVB spres mye mer i atmosfæren enn UVA (figur 1). Dette skyldes at de spredende partiklene i klar luft er små. Fysikerne kaller denne spredningen Rayleigh-spredning. På grunn av Rayleigh-spredning blir UVB med bølgelengde rundt 305 nm spredd omkring 2.4 ganger mer effektivt enn UVA med bølgelengde rundt 380 nm. Populært kan vi si at UVB kommer fra alle himmelretninger, mens UVA kommer i større grad rett fra sola. Bevis på at dette er rett, kan vi få ved å måle UVA og UVB gjennom en solklar dag med et par små skyer som passerer sola. Den



Figur 1
Forenklet skisse for spredning av UVA (A) og UVB (B) med direkte solstråling for en klarværssituasjon om sommeren. Pilenes lengde gjenspeiler at UVB spres i større grad enn UVA-stråling. For andre solhøyder, innføring av skyer, etc. vil situasjonen bli en helt annen en vist i figuren.

9. juni 2002 var en slik dag, og målinger fra denne dagen er vist på figur 2. Vi ser at de to små skyene reduserer UVA-strålingen mer enn UVB-strålingen. Altså kommer det relativt mest UVB-stråling fra andre romvinkler enn den lille hvor sola og skyene er. Figuren 2B illustrerer også noe annet, nemlig at forskjellene er større jo lavere solhøyden er: Skyen som kom 2 timer og 40 minutter før største solhøyde reduserte UVB og UVA med henholdlvis 27 og 45%, mens skyen som kom en times tid senere reduserte UVB og UVA med henholdsvis 8 og 12%, altså betydelig mindre. Begge skyene reduserer UVA mer enn de reduserer UVB, fordi, som sagt, mye UVB kommer fra andre himmelretninger enn der sola og skyene er.

UVB er mye mer spredt i atmosfæren enn UVA



Figur 2
Relativ variasjon av UVA (305 nm) og UVB (380 nm) irradians som funksjon av tid på dagen. UV-strålingen ble registrert i Oslo den 9. juni 2002.

En liten sky demper UVA-strålingen mer enn den demper UVB-strålingen.

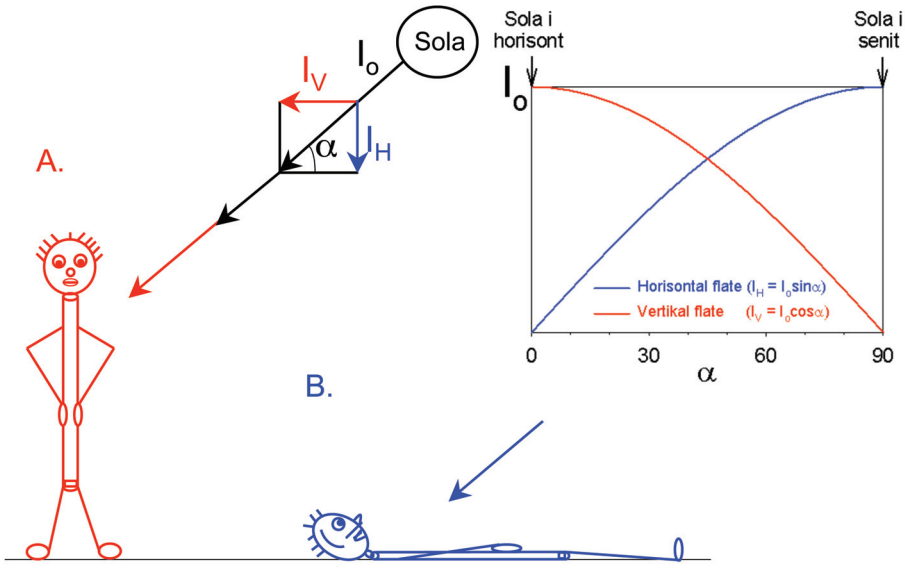
Vi ligger bare en begrenset del av tiden vi er ute i solen. Derfor ligner vi mer en vertikal sylinder enn en horisontal, liggende pepperkake.

Er vi flate, horisontale pepperkakemennesker, eller er vi vertikale sylindre?

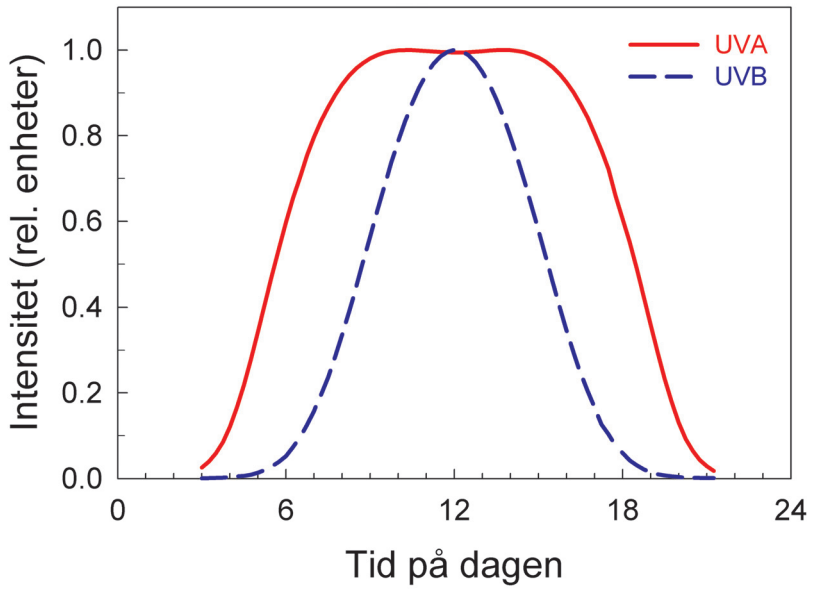
Hittil har de fleste modellregnere sagt at når menneskene soler seg, er de oftest liggende som flate pepperkaker. At et liggende menneske også har vertikale hudflater, har de oversett. Men vi tror at de fleste faktiske er oppegående det meste av den tiden de er i sola (figur 3). Derfor har vi modellert menneskets hudflate som sideflaten av en vertikal sylinder. Vi kan argumentere for dette med å si at de fleste ligger bare korte stunder nakne i sola, og ved å ta i betraktning at mest hudkreft oppstår på ansiktet. Hadde man fått det meste av solen liggende i badedrakt, ville hudkreft ha oppstått med lik hyppighet per kvadrat centimeter hud på alle kroppsdeler, untatt de som er dekt av badedrakter. Slik er det altså ikke.

UVA varer mye lenger utover dagen enn UVB

Vi er nå klare til å beregne hvordan UVA- og UVB-strålingen fra sola varierer gjennom en klar midtsommersdag i Oslo. Beregningene er nylig publisert i et internasjonal tidsskrift Advances in Experimental Medicine and Biology 624, side 86-8, 2008. Figur 4 er en skisse av disse funnene. UVB er vist for et spektrum rundt 305 nm (”D-vitaminspekteret”) mens UVA er vist for et spektrum rundt 360 nm (”melanomspekteret”). UVB-intensiteten er halvert 3 timer og 20 minutter etter største solhøyde. På dette tidspunktet er faktisk UVA-intensiteten ennå uforandret. Den er ikke halvert før 6.5 timer etter største solhøyde.



Figur 3
Er vi vertikale sylindre (A), eller er vi flate, horisontale pepperkakemennesker (B)?



Figur 4
Døgnvariasjonen av solstråling midtsommers i Oslo for UVB (D-vitamindannelse i hud) og UVA (induksjon av føflekksvulster i Xiphophorus). Beregningene er utført for en vertikal sylinderflate med eksklusjon av topp og bunn. Alle kurver er normalisert til 1 ved største solhøyde. Et ozon-nivå på 350DU, en overflatealbedo på 0.05, skyfrie forhold, samt gjennomsnittelig aerosolnivå ble brukt i beregningene, her vist for 21. juni i Oslo.

Konklusjoner

Ludvig i Flåklypa sier: "Det blåser nordavind fra alle kanter". I en omskriving av dette sier vi: "Det skinner UVB fra alle himmelretninger".

Vi har antatt at UVA er en viktig årsak til at føflekk-svulster dannes. Denne antakelsen er bygd på en rekke vitenskapelige argumenter gitt i referansen vår. Hvis den er viktig, må vi konkludere med at sola kan forårsake føflekksvulster lenge ut over ettermiddagen og tidlig på formiddagen. D-vitamin-dannelsen, derimot, er sentrert mye mer rundt midten av dagen.

I lys av dette er det sunnest å sole seg noen minutter midt på dagen, uten solkremer med UVB-filtre. Men vi bør ikke være for lenge i sola. Solbrenheten kan medføre betydelig hudkreftrisiko.

Videre lesning

Moan J, Juzeniene A. Hudfargene våre – Utvikling og betydning. Naturen 2008; 1: 2-12.

Moan J, Dahlback A, Porojnicu A.C. At what time should one go out in the sun? Advances in Experimental Medicine and Biology 2008; 624: 86-8.

UVA-strålingen varer lenger ut over ettermiddagen enn UVB-strålingen gjør. Derfor gir solstrålingen lite D-vitamin ved lav solhøyde, mens hudkreftfaren kan være betydelig.