INTRODUCTION

A retinal condition known as photoretinopathy occurs in people who have stared fixedly at the sun without adequate protection, usually for more than a few minutes (see references [1]). Photoretinopathy is photochemical damage caused by visible light, especially in the wavelength region of approximately 400–500 nm (Fig. 1). Light in this wavelength region appears blue to the eye and therefore is called blue light.

According to the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2] and the American Conference of Governmental Industrial Hygienists (ACGIH) [3], the hazard of blue light is generally measured by blue-light radiance. Blue-light radiance is obtained by weighting the spectral radiance of a light source against the blue-light hazard function (fig. 1) and integrating this in the wavelength range of 305–700 nm. The maximum permissible exposure duration per day is calculated by dividing 106 Jm-2sr-1 by the blue-light radiance. Thus, solar blue-light radiance should be known as a first step toward preventing sun-induced photoretinopathy.
Fig. 1: Blue-light hazard function [2, 3]. The blue-light hazard function shows the relative effectiveness of optical radiation to produce photochemical retinal damage as a function of wavelength.

The intensity of sunlight observed on the earth’s surface generally increases with solar elevation. As solar elevation increases, sunlight travels a shorter distance through the atmosphere to reach the earth’s surface and therefore is less attenuated by atmospheric scattering and absorption. The intensity of sunlight is also expected to be influenced by temporary local atmospheric conditions such as clouds and dust. Thus, these factors should also influence solar blue-light radiance. In this study, solar blue-light radiance was determined for solar elevations up to almost 90° in summer in Ishigaki, Japan (latitude 24°20’N). The effect of solar elevation was studied using a mathematical model of atmospheric extinction.

METHODS

Measurements were made on 10 consecutive days from 21 June (the summer solstice) to 30 June 2006 in Ishigaki from sunrise to sunset at 15-min intervals, except when the sun was completely invisible because of clouds. Since Ishigaki is a small remote rural island, urban atmospheric pollution is expected to be very low.

Spectral radiance in the wavelength range of 380–780 nm at 2-nm intervals was measured at the center of the solar disk with a measuring field of 0.125° (0.0022 rad) diameter by a spectroradiometer (PR-705, Photo Research Inc., 9731 Topanga Canyon Place Chatsworth, CA 91311-4135, USA). Two neutral density filters of about 1% transmittance (ND-100, Photo Research Inc.) were attached to the aperture of the instrument, because solar radiance was too high to measure directly. Corrections for the spectral transmittance of the filters were made automatically by the instrument. The spectroradiometer was calibrated by the manufacturer prior to the measurements. With the use of PC

software (MyPlanet, Japan, Mitsunori Asami), the solar elevation was calculated from the geographic coordinates (longitude and latitude) of the measurement site and the date and time of each measurement.

The blue-light radiance at the center of the solar disk was obtained by weighting the measured spectral radiance against the blue-light hazard function and integrating it with respect to wavelength. In this case, the integration was started at 380 nm instead of 305 nm. This modification is acceptable, because the blue-light hazard function is very small in the wavelength range of 305–380 nm (Fig. 1) and therefore radiant energy in this range is expected to contribute little to blue-light radiance for white-light sources. For example, a simple calculation shows that the contribution of this wavelength range is only 1 % for light sources with a flat spectral distribution.

Data were corrected for the limb darkening of the sun. The central blue-light radiance obtained was multiplied by the ratio of the mean to central radiance at 450 nm of 0.755 [4] to obtain the blue-light radiance of the sun (i.e., the mean of the solar disk).

The blue-light radiance was then multiplied by \((0.0093/0.011)^2\), because the sun subtends an angle of 0.0093 rad, which is less than 0.011 rad [2,3].

According to the ICNIRP [2] and ACGIH [3] guidelines, the maximum permissible exposure duration per day in seconds is obtained by dividing 106 Jm-2sr-1 by the measured blue-light radiance in Wm-2sr-1.

The combined data on blue-light radiance versus solar elevation for all 10 days were compared with the prediction of a model of atmospheric extinction. Assuming that the optical density of the atmosphere that sunlight traverses to reach the earth's surface is proportional to the amount of that atmosphere (air mass), the solar blue-light radiance observed on the earth's surface depends on the solar elevation, as follows:

\[
L(\gamma) = L_0 \exp(-kM(\gamma)),
\]

where:
- \(\gamma\) = solar elevation;
- \(L(\gamma)\) = solar blue-light radiance observed on the earth's surface;
- \(L_0\) = solar blue-light radiance observed outside the atmosphere;
- \(M(\gamma)\) = air mass, which is normalized to 1 at 90°;
- and \(k\) = extinction coefficient per unit air mass.

The air mass is approximated as follows [5]:

\[
M(\gamma) = \frac{1.002432 \cos^2(90° - \gamma) + 0.148336 \cos(90° - \gamma) + 0.0096467}{\cos^3(90° - \gamma) + 0.149864 \cos^2(90° - \gamma) - 0.0102963 \cos(90° - \gamma) + 0.000303978}.
\]

The data were least-squares fitted to eqn (1) with \(L_0\) and \(k\) as parameters under the constraint that the solar blue-light radiance measured is lower than that predicted by the model. This constraint was imposed because the solar blue-light radiance may actually be reduced by temporary local atmospheric conditions such as clouds and dust. Fitting was performed using the solver add-in in spreadsheets software (Microsoft Excel).

**RESULTS AND DISCUSSION**

A total of 461 measurements were made of the solar spectral radiance on 10 consecutive days. Although the overall intensity of sunlight varies greatly from measurement to measurement, the spectral features remain basically unchanged (fig.2).

Fig. 2: Solar spectral radiance measured on 23 June 2006. The time and solar elevation at which the measurement was taken are indicated for each line.

The solar blue-light radiance and the maximum permissible exposure duration per day were calculated for each measurement of the solar spectral radiance, according to the ICNIRP [2] and ACGIH [3] guidelines. The solar blue-light radiance generally increases from sunrise to about noon and then decreases toward sunset, but it varies when the sun goes behind a cloud, as shown by the sharp valleys in fig.3. The solar blue-light radiance also fluctuates to some extent, even when no clouds are seen in front of the sun, probably due to invisible moisture or dust in the atmosphere.
Fig. 3: Solar blue-light radiance measured on 22 June 2006, plotted against time of day. The maximum permissible exposure duration per day can be read from the right-hand scale.

The blue-light-radiance data for all 10 days are shown in fig. 4 as a function of solar elevation. Higher blue-light radiances are associated with higher solar elevations. The solar blue-light radiance ranges from 8.39×10 to 1.71×106 Wm-2sr-1 with the median 1.31×106 Wm-2sr-1. The maximum exposure durations per day corresponding to the maximum and median blue-light radiance are only 0.82 s and 1.07 s, respectively, meaning that viewing the sun can be very hazardous. In fact, it is not unusual to view the sun for more than these maximum exposure durations in everyday situations such as scanning the sky for a scenic view. Thus, it is necessary to avoid viewing the sun directly except at very low solar elevations.

Data on blue-light radiance versus solar elevation were well fitted by eqn (1) (fig.4), indicating the validity of this model. The best-fit parameters are L0 = 2.26×106 and k = 0.272. Thus, the maximum solar blue-light radiance at each solar elevation and the corresponding maximum permissible exposure duration per day can be calculated as,

\[
L_m(\gamma) = 2.26 \times 10^6 \exp(-0.272 M(\gamma)) \tag{3},
\]

\[
t_{max}(\gamma) = 0.619 \exp(0.272 M(\gamma)) \tag{4}
\]

where \(L_m(\gamma)\) = maximum solar blue-light radiance at solar elevation \(\gamma\); and \(t_{max}(\gamma)\) = maximum permissible exposure duration per day at solar elevation \(\gamma\).

Eqns (3) and (4) are of practical importance, because the maximum hazard at any time and place can be evaluated by calculating the solar elevation from the geographic coordinates, the date and the
time and substituting it into these equations. This knowledge can be used when discussing measures or strategies to prevent sun-induced photoretinopathy.

Fig. 4: Solar blue-light radiance plotted against solar elevation. The letters A–J represent data for 10 days, respectively, and the line represents the prediction of the best-fit model. The maximum permissible exposure duration per day can be read from the right-hand scale.

CONCLUSIONS

This study demonstrates that the sun is generally very hazardous to view. It is necessary to avoid viewing the sun directly except at very low solar elevations.

This study also presents a mathematical model to predict the maximum hazard at each solar elevation and the corresponding maximum permissible exposure duration per day. This knowledge is important when discussing measures or strategies to prevent sun-induced photoretinopathy.

References

02. ICNIRP (International Commission on Non-Ionizing Radiation Protection), “Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38 to 3 micro m),” Health Phys. 73, 539–554 (1997).
03. ACGIH (American Conference of Governmental Industrial Hygienists), TLVs and BEIs (ACGIH, 2012).