Paper

TEMPERATURE RISES IN THE CRYSTALLINE LENS FROM FOCAL IRRADIATION

Tsutomu Okuno,* Masami Kojima,† Ikuho Hata,† and David H. Sliney‡

Abstract—**Many types of ophthalmic instruments produce a concentrated focal irradiance in the lens. Instruments that illuminate large areas of the retina—known as "Maxwellian-view," are but one example, and there are concerns about the potential hazards associated with this optical system. The transfer of the heat generated in the human eye in Maxwellian-view illumination or similar focal-beam situations was simulated using a mathematical model to determine the temperature elevations induced in the human eye. The maximum temperature rise in the lens region was examined to quantitatively assess the potential thermal hazard to the lens. It was shown that Maxwellian-view illumination or similar focal-beam situations can cause thermal injury to the lens under certain conditions, and that this hazard is greater for incident wavelengths of about 320–420 nm than for longer wavelengths. The risk of thermal injury increases as exposure duration increases, and the risk tends to increase as the beam waist diameter or Maxwellian-view angle decreases.**
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Key words: optics; health effects; radiation, nonionizing; lasers

INTRODUCTION

MANY TYPES of ophthalmic instruments illuminate ocular structures by using a converging beam of light that produces a focal zone in the anterior structures of the eye—most typically, in the crystalline lens itself. The most typical example is those instruments that illuminate an area of the retina; this is termed the "Maxwellian-view." There are concerns about the potential hazards to the lens associated with this type of optical system. These ophthalmic instruments include binocular indirect ophthalmoscopes, slit-lamp biomicroscopes for retinal examination, fundus cameras, scanning laser ophthalmoscopes, glucose monitors, and so on.

In Maxwellian-view illumination, a converging light beam is focused at a point inside or adjacent to the crystalline lens such as the center of the pupil or the nodal point of the eye, thereby creating a localized region of high concentration of light (irradiance) in the proximity. Although the lens appears reasonably transparent and little light energy is absorbed, there can be substantial absorption in the near-infrared (IR-A) and near-ultraviolet (UV-A) spectral regions. The lens tissue in the focal region heats up by absorbing some radiant energy and this can lead to injury if the tissue reaches a sufficiently high temperature. In fact, heating of rabbit lenses to more than approximately 43°C has been shown to produce lenticular opacities (Emery et al. 1975; Kramár et al. 1987; Bollenmeijer et al. 1989). Heating of the lens is also widely believed to be responsible for infrared cataracts in glass and steel workers (Sliney and Wolbarsht 1980).

Optical radiation exposure in Maxwellian-view illumination should therefore be limited to protect the lens from thermal injury; however, such injuries have been reported only rarely to date, and generally relate to the use of laser retinal photocoagulators. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is considering guidelines for optical radiation exposure that can be applied to Maxwellian-view illumination as well as other special conditions that occur in the use of ophthalmic instruments. However, there has been a lack of data upon which to base such guidelines.

It is thus necessary to study the thermal conditions experienced by the lens tissues in Maxwellian-view illumination. While it is generally very difficult to quantitatively assess thermal effects of optical radiation upon the eye by conventional laboratory experiments, thermal-model calculations can be used effectively for this purpose. In fact this approach has been used successfully in studying infrared radiation hazards (Scott 1988a, 1988b; Okuno 1991, 1994) and microwave hazards (Emery et al. 1975).

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In the present study, the transfer of the heat generated in the human eye during Maxwellian-view illumination was simulated based upon a mathematical model to obtain the temperature elevations induced in the eye, and the maximum temperature rise in the lens region was examined to quantitatively assess the thermal hazard to the lens.

MATERIALS AND METHODS

The mathematical model assumes that:

- The eye and the incident beam of optical radiation are symmetric about the optic axis of the eye so that only the axis-symmetric cross-section needs to be considered;
- The eye consists of five homogeneous regions: cornea, aqueous humor, lens, vitreous humor and the combined region of retina, choroid and sclera. The dimensions of the eye are the same as those of the standard eye (Sliney and Wolbarsht 1980) (Fig. 1);
- Each region is homogeneous with respect to thermal conductivity, specific heat, density, and absorption coefficients. The values of these physical constants are as shown in Table 1 and Fig. 2;
- Heat transfer occurs only by conduction within the eye. Heat is lost from the cornea to the ambient air with a heat transfer coefficient of 20 W m^{-2} $°C^{-1}$ (Lagendijk 1982). This coefficient takes into account all heat transfer including conduction, evaporation, radiation and convection. Heat is lost from the sclera to the body core with a heat transfer coefficient of 65 W m^{-2} $°C^{-1}$ (Lagendijk 1982); and
- A beam of monochromatic optical radiation with a uniform irradiance enters the eye in such a way that it converges to and diverges from the center of the lens but maintains a small finite diameter near this point, forming a beam waist (Fig. 3). There are no reflections at the surfaces of each ocular region, and there is no scattering within the eye.

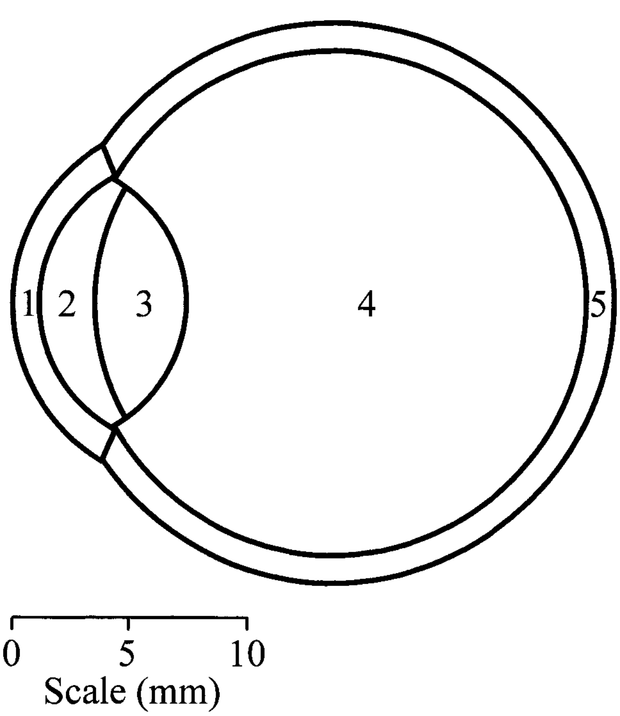

Fig. 1. Cross-section of the model eye. 1: cornea, 2: aqueous humor, 3: lens, 4: vitreous humor, 5: the combined region of retina, choroid, and sclera.

It has been shown analytically that the temperature rises in the eye attributable to optical radiation exposures are predicted by considering only the heat generated by absorbed optical radiation (Okuno 1991). More precisely, the temperature rise is defined as

$$\delta T(x, t) = T(x, t) - T_0(x),$$

where

$\delta T(x,t)$ = temperature rise due to optical radiation exposure;
$T(x,t)$ = temperature in the eye exposed to optical radiation;
$T_0(x)$ = temperature in the normal unexposed eye;
x = position in the eye; and
t = time.

It has also been shown analytically that the temperature rise is linearly related to the power of the incident optical beam in this type of model (Okuno 1991); that is,

$$\delta T(x, t) \propto P, \qquad (1)$$

where P = the power of the incident optical beam.

Most of the values of the physical and thermodynamic constants used in this model are approximations, those of animal eyes or those of water, as there are no reliable data for human ocular tissues.

The optical rays in the beam are assumed to follow the paths shown in Fig. 3 to simplify the calculation of heat generation. Heat generation at a point X in the beam region is given by

$$H_X = \frac{P}{A_X} a_X \exp(-\sum_k a_k d_k),$$

where

H_X = heat generation per unit volume per unit time at X;
A_X = the cross-sectional area of the beam at the axial position of X;
a_X = absorption coefficient at X;

Table 1. Physical constants of the model eye.

Region	Thermal conductivity (W m^{-1} °C^{-1})	Specific heat (J kg^{-1} °C^{-1})	Density (kg m^{-3})	Absorption coefficient (m^{-1})
Cornea	0.500[a]	3,470[b]	1,050[c]	Fig. 2[d]
Aqueous humor	0.623[e]	4,180[f]	994[g]	Fig. 2[d]
Lens	0.430[h]	3,470[b]	1,080[i]	Fig. 2[d]
Vitreous humor	0.623[e]	4,180[f]	994[g]	Fig. 2[d]
Retina/Choroid/Sclera	0.500[j]	3,470[b]	1,050[j]	Fig. 2[j]

[a] Estimated from the water content of the corneal stroma of 75–80% (Moses and Hart 1987) using the relationship between the thermal conductivity and the water content of biological materials (Spells 1960).
[b] The value of the body tissue (Bligh and Johnson 1973).
[c] From Scott (1988a).
[d] From Maher (1978).
[e] The value of water at 37°C (Weast 1986).
[f] The value of water at 20–40°C (Weast 1986).
[g] The value of water at 35°C (Weast 1986).
[h] Estimated from the water content of the lens of 66% (Moses and Hart 1987) using the relationship between the thermal conductivity and the water content of biological materials (Spells 1960).
[i] From Okuno (1991).
[j] Assumed to be the same as for the cornea.

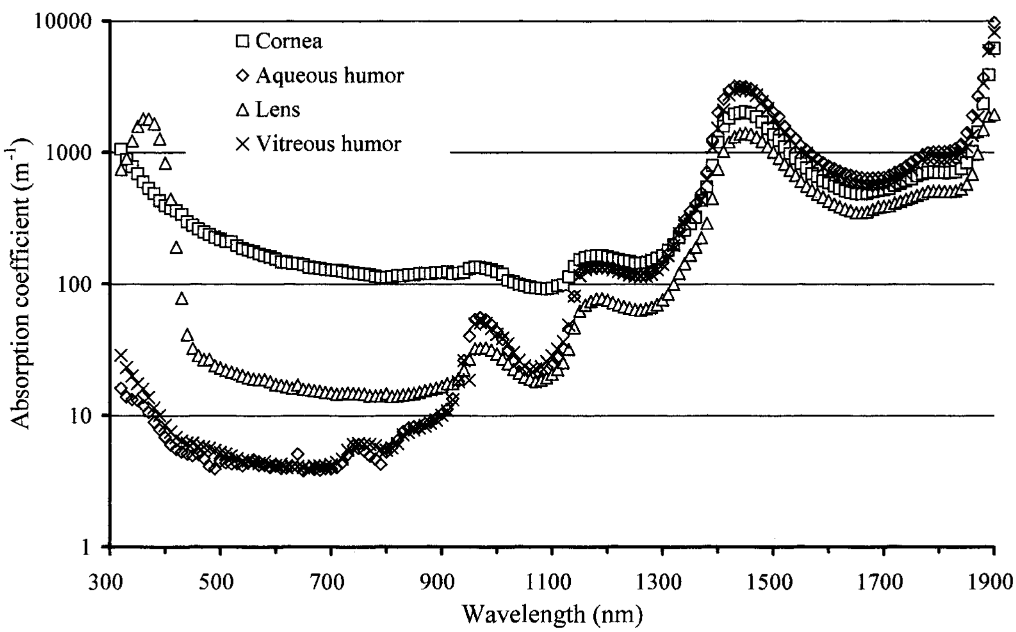

Fig. 2. Absorption coefficients of the cornea, aqueous humor, lens and vitreous humor. These are data for the rhesus monkey eye, which were measured very carefully by Maher (1978) and are considered a good baseline for the primate eye.

a_k = absorption coefficient of region k of the eye; and

d_k = the distance that optical radiation must travel in region k of the eye to reach X,

and the summation is taken for all the media of the eye through which the optical radiation must travel to reach X. Heat generation depends on the wavelength and geometry of the incident optical beam.

To simulate heat transfer numerically, the axis-symmetric cross-section of the model eye was divided into a non-uniform rectilinear grid of 892,621 discrete cells. The grid spacing in the axial direction was 10 μm in the anterior 8-mm region of the eye and was gradually increased toward the posterior end to a maximum of 99.2 μm, and the spacing in the radial direction was 10 μm in the central 6-mm region of the eye and was gradually increased toward the peripheral end to a maximum of 40.4 μm. The 10-μm grid spacing in the anterior, central region of the eye should provide sufficient spatial resolution because it is very small compared with the dimensions of the model eye, the beam waist diameters considered and the optical radiation penetration depths (reciprocals of absorption coefficients) in each ocular region in the wavelength range considered, whereas the

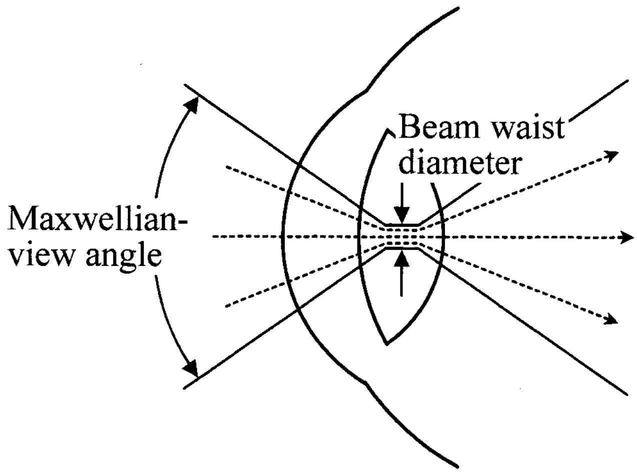

Fig. 3. Geometry of optical radiation beam. Dashed lines show some of the paths of optical radiation on which to base the calculation of heat generation.

wider spacing in the posterior or peripheral region should greatly reduce the computation time by reducing the number of cells.

Each cell i was assigned a value δT_i, which represented the amount of the temperature rise attributable to optical radiation exposure. Each cell i was also assigned a constant value H_i, which represented the heat generated per unit volume per unit time at the center of the cell by absorption of optical radiation. H_i is zero for cells outside the beam region.

δT_i is initially zero and varies with time as heat flows in or out through the faces of cell i or is generated in cell i due to absorption of optical radiation if the cell is in the beam.

When face f of cell i is shared by an adjacent cell j, the heat flux at this face is approximated by a discrete form of Fourier's law:

$$F_{i,f} = -k_{i,j}\frac{\delta T_i - \delta T_j}{\Delta D_{i,j}},$$

where

$F_{i,j}$ = heat flux, taken as positive when heat flows into cell i;
$k_{i,j}$ = the harmonic mean thermal conductivity of the regions of the eye that the two cells belong to; and
$\Delta D_{i,j}$ = the distance between the centers of the two cells.

If face f of cell i forms part of the boundary between the eyeball and the surroundings s (the ambient air or the body core), the heat flux at this face is given by

$$F_{i,f} = -h_s\delta T_i,$$

where $F_{i,f}$ = heat flux, taken as positive when heat flows into cell i, and h_s = heat transfer coefficient from the surface of the eyeball to surroundings s.

Time is measured from the start of the optical radiation exposure and is therefore equal to the exposure duration. Time was also divided into discrete steps as

$$t_n = n\Delta t \qquad n = 0, 1, 2, \ldots,$$

where t_n = discrete time, and Δt = time step size, taken to be 125 μs.

Let $\delta T_i(t)$ denote the temperature rise of cell i at time t. The initial condition is given by

$$\delta T_i(t_0) = \delta T_i(0) = 0. \qquad i = 1, 2, 3, \ldots.$$

The change in the temperature rise of each cell during a time step is determined from the amount of heat flowing into or out of the cell and that generated in the cell during that time step as follows:

$$\delta T_i(t_{n+1}) = \delta T_i(t_n) + \frac{\left(\sum_f F_{i,f}\Delta S_{i,f} + H_i\Delta V_i\right)\Delta t}{\rho_i c_i \Delta V_i}$$

$$i = 1, 2, 3, \ldots, \qquad n = 0, 1, 2, \ldots,$$

where

$\Delta S_{i,f}$ = the area of face f of cell i;
ΔV_i = the volume of cell i;
ρ_i = the density of the region of the eye that cell i belongs to;
c_i = the specific heat of the region of the eye that cell i belongs to;

and the summation is taken for all the faces of cell i.

$\{\delta T_i(t_n)\}$ were calculated from the initial condition and forward in time using the above recursive relation.

The wavelength and geometry of the incident optical beam should be important factors, which affect the amount and distribution of heat generation and the resulting temperature elevations in the eye. Thus, different wavelengths in the range 320–1,900 nm, beam waist diameters ranging from 0.1 mm to 1.6 mm, and Maxwellian-view angles that ranged from 4° to 105° were considered.

$\{H_i\}$ were calculated for each combination of the wavelength, beam waist diameter, and Maxwellian view angle and used for the calculation of $\{\delta T_i\}$.

The temperature rises in the eye were computed with an incident beam power of 1 W only for the sake of convenience. The temperature rises induced by any incident power can be calculated from its result using the linear relationship from eqn (1). Thus a 10-mW beam

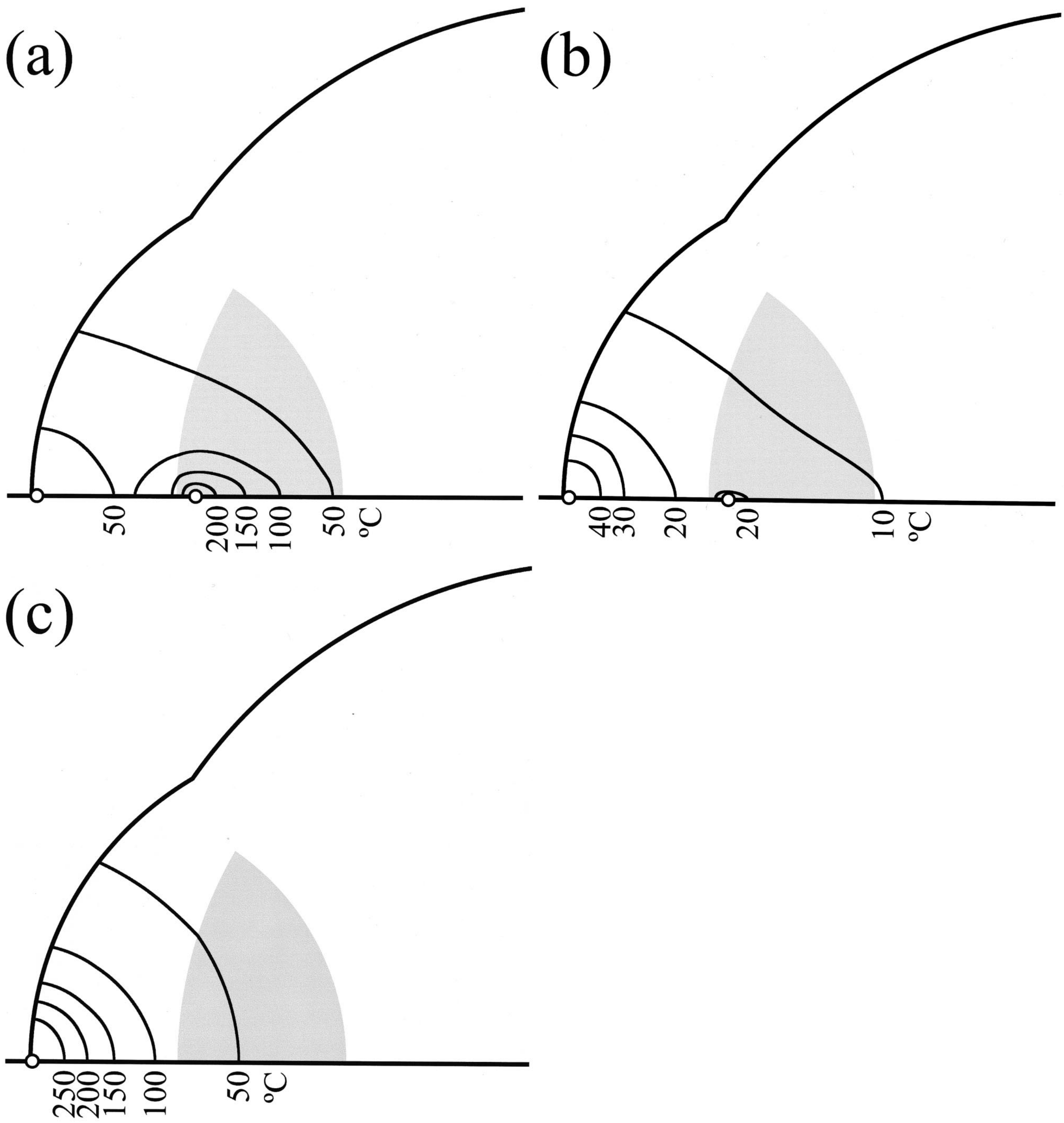

Fig. 4. Temperature rise distributions on the axis-symmetric cross-section for incident wavelengths of (a) 400 nm, (b) 700 nm, and (c) 1,500 nm. The exposure time is 10 min, the beam waist diameter is 1 mm, the Maxwellian-view angle is 30°, and the incident beam power is 1 W. Open circles on the symmetry axis indicate the positions of (local) maxima.

would, under these assumptions, produce a temperature rise of only 1% of the 1-W beam.

RESULTS

The calculated temperature rises in the eye vary with exposure time and conditions. Figs. 4 and 5 show examples of their spatial distribution and time evolution.

The temperature rise distributions have a peak just under the center of the corneal surface and, depending mostly on the wavelength of optical radiation, have another peak or a small increase in or near the beam waist in the lens (Fig. 4), which means that a considerable amount of the incident optical radiation is absorbed around these positions and converted into heat.

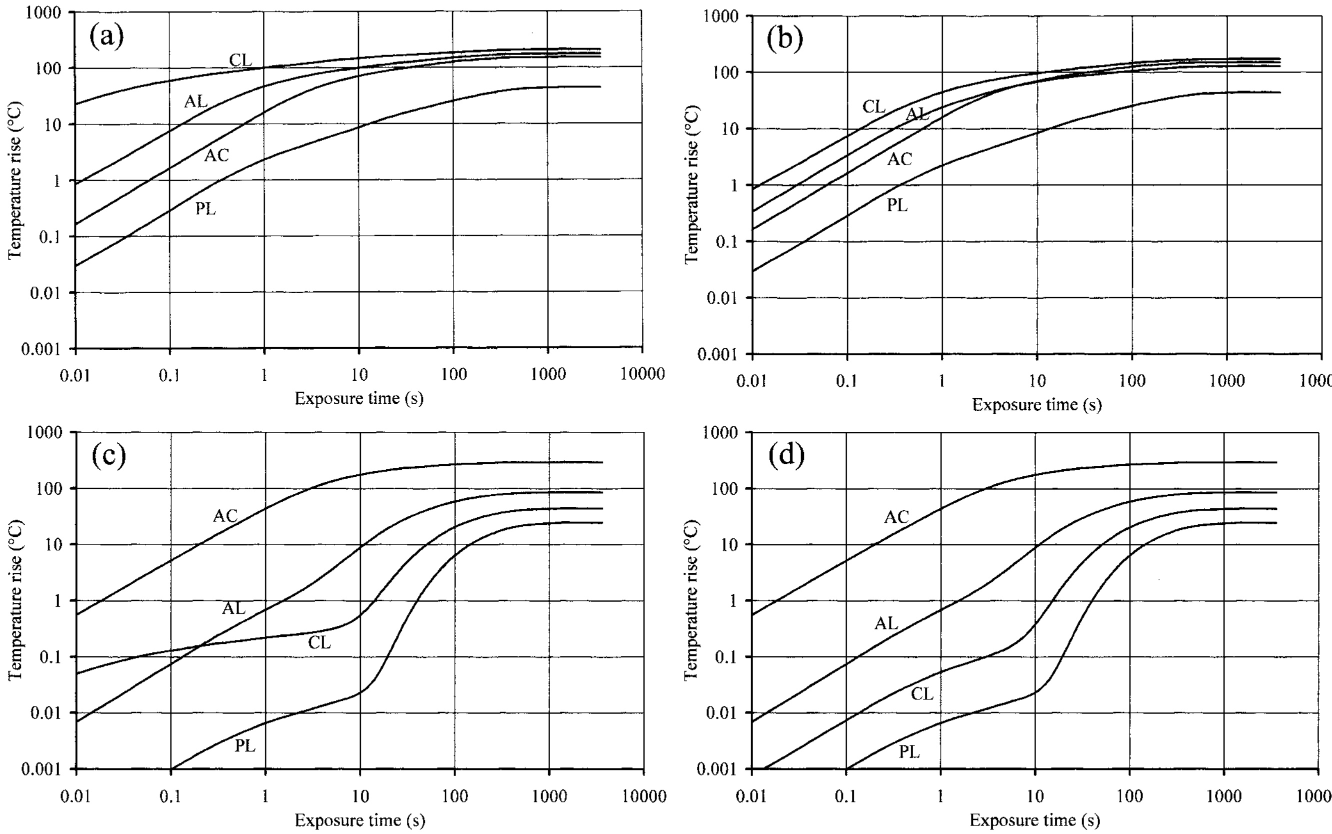

Fig. 5. Time evolution of the temperature rises at the center of the anterior corneal surface (AC), the centers of the anterior and posterior lens surfaces (AL, PL) and the center of the lens (CL) for incident wavelengths and beam waist diameters of (a) 400 nm and 0.1 mm, (b) 400 nm and 1 mm, (c) 1,500 nm and 0.1 mm, and (d) 1,500 nm and 1 mm. The Maxwellian-view angle is 30°, and the incident beam power is 1 W.

For incident wavelengths shorter than about 420 nm (ultraviolet–violet wavelengths), there is a pronounced peak in the lens region (Fig. 4a) due to the high absorption coefficients of the lens in this wavelength range (Fig. 2). For wavelengths greater than about 1,400 nm (IR-B wavelengths), there is no peak or "bump" in the lens region (Fig. 4c). This is because the cornea, as well as other ocular structures, has high spectral absorption coefficients in this wavelength range (Fig. 2) due to water absorption; and the cornea absorbs most of the incident optical radiation before it reaches the lens. For intermediate wavelengths of about 420–1,400 nm (blue–IR-A wavelengths), there is a small peak or temperature "bump" in the lens (Fig. 4b).

The temperature elevations increase generally in proportion to exposure duration for the first 1–10 s, although they increase more slowly in or near the beam waist in the lens region for smaller beam waist diameters (Fig. 5). Then the temperature elevations gradually level off and reach a maximum after 100–1,000 s of exposure.

The maximum temperature rise in the lens, which is directly related to the potential hazard to the lens, varies with exposure time and conditions.

The maximum lens temperature elevation increases for the first 1–10 s in proportion to exposure duration for larger beam waist diameters but increases more slowly for smaller beam waist diameters (Fig. 6). Then the maximum lens temperature rise gradually levels off and reaches a maximum after 100–1,000 s of exposure.

The maximum lens temperature elevation is generally larger for ultraviolet–violet incident wavelengths than for longer incident wavelengths (Fig. 7) because of the high absorption coefficients of the lens in this wavelength range (Fig. 2).

The maximum lens temperature rise tends to increase as the beam waist diameter or Maxwellian-view angle decreases (Figs. 8 and 9), because irradiance becomes higher in the beam waist region or in the other beam region. This tendency with the beam diameter is pronounced for blue–IR-A wavelengths but is weak or

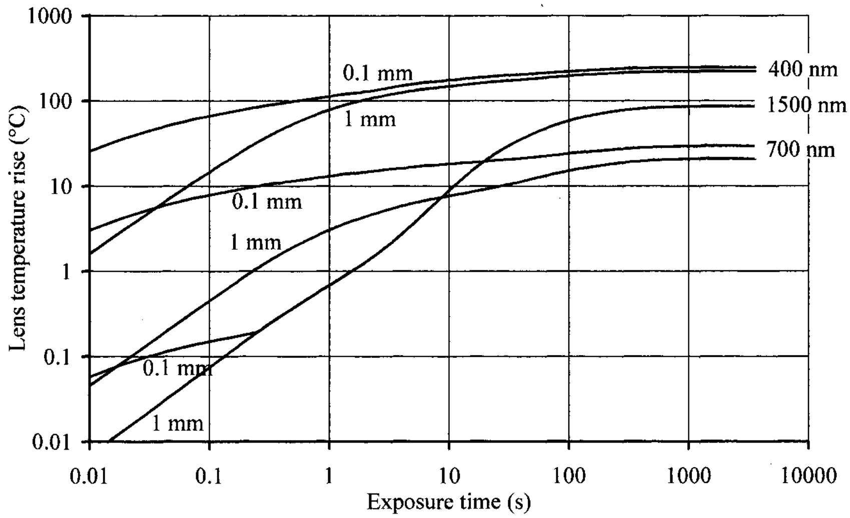

Fig. 6. Time evolution of the maximum temperature rise in the lens region for incident wavelengths of 400 nm, 700 nm, and 1,500 nm and beam waist diameters of 0.1 mm and 1 mm. The Maxwellian-view angle is 30°, and the incident beam power is 1 W.

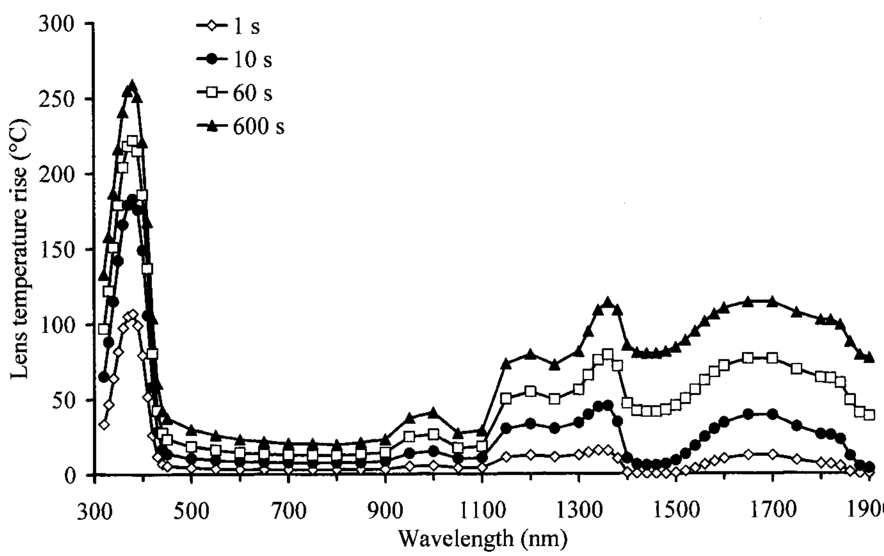

Fig. 7. The maximum lens temperature rise as a function of the incident wavelength for exposure times of 1 s, 10 s, 60 s, and 600 s. The beam waist diameter is 1 mm, the Maxwellian-view angle is 30°, and the incident beam power is 1 W.

absent for other wavelengths. In contrast, the tendency with the Maxwellian-view angle is strong for ultraviolet–violet and IR-B wavelengths but is weak or absent for blue–IR-A wavelengths.

The maximum lens temperature rise is the largest when optical radiation of wavelength 370–380 nm enters the eye with a beam waist diameter of 0.1 mm and a Maxwellian-view angle of 4°, reaching about 700°C for longer exposure times.

DISCUSSION

This study demonstrates that Maxwellian-view illumination or similar focal-beam situations can cause thermal injury to the lens under certain conditions. Assuming this model is correct, incident beams of optical radiation with a power of 1 W can cause a lens temperature rise of 700°C. This implies that even a reduced power of 10 mW can produce a lens temperature elevation of 7°C, which exceeds an estimated threshold for cataract formation of 5°C (Okuno 1991).

This study also shows that the thermal hazard to the lens in Maxwellian-view illumination or similar focal-beam situations varies with exposure time and conditions. Thus, this hazard can be reduced in practical situations by reducing exposure duration, increasing the beam waist diameter or Maxwellian-view angle or by

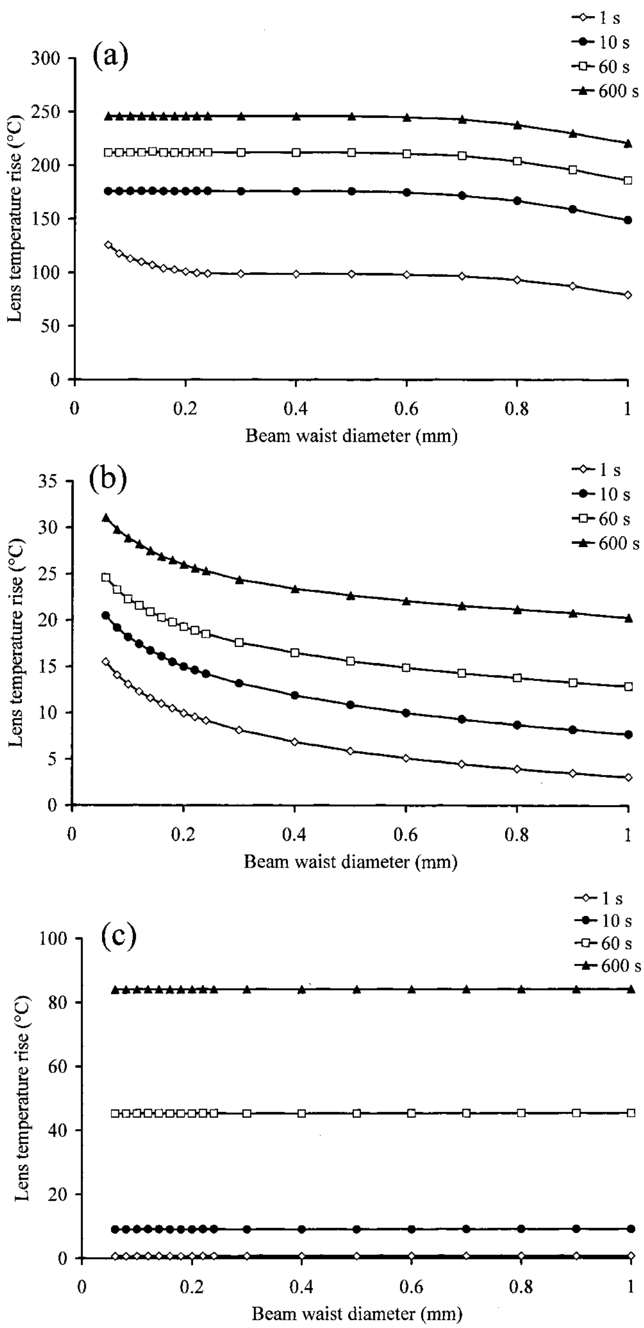

Fig. 8. The maximum lens temperature rise as a function of the beam waist diameter for exposure times of 1 s, 10 s, 60 s, and 600 s for incident wavelengths of (a) 400 nm, (b) 700 nm, and (c) 1,500 nm. The Maxwellian-view angle is 30°, and the incident beam power is 1 W.

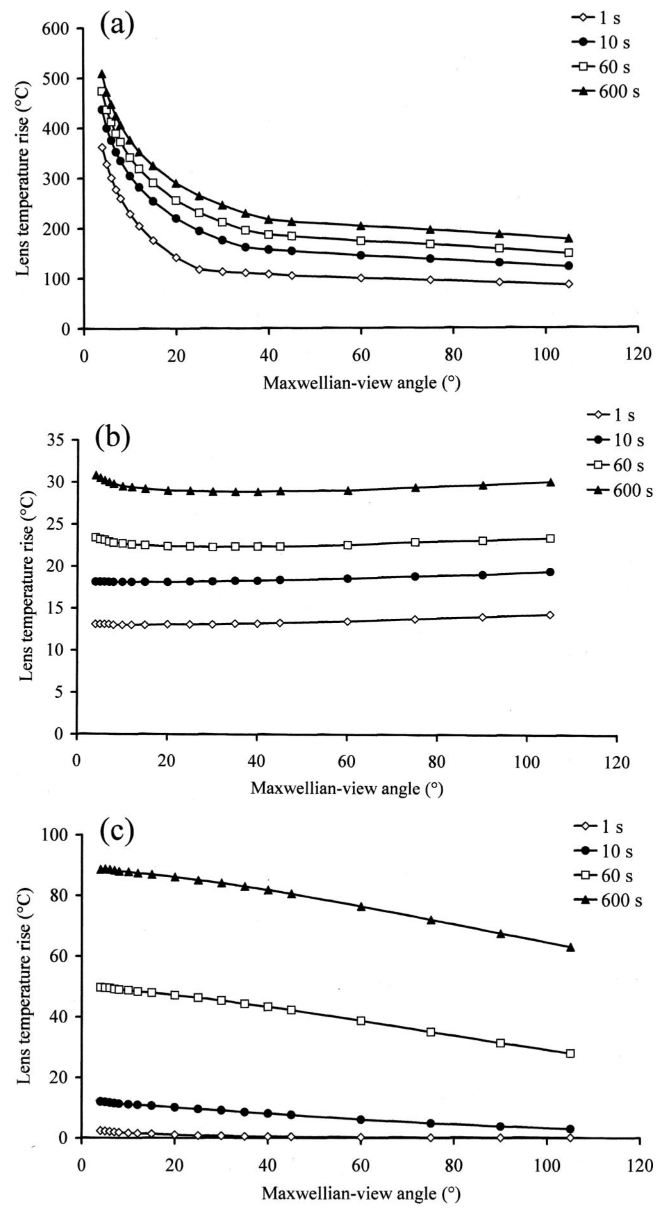

Fig. 9. The maximum lens temperature rise as a function of the Maxwellian-view angle for exposure times of 1 s, 10 s, 60 s, and 600 s for incident wavelengths of (a) 400 nm, (b) 700 nm, and (c) 1,500 nm. The beam waist diameter is 0.1 mm, and the incident beam power is 1 W.

removing the ultraviolet–violet component from the incident optical beam. These factors should also be considered in developing guidelines for optical radiation exposure that can be applied to Maxwellian-view illumination. In this case the data of this study can be used as a basis.

The model used in this study, like all models, is an approximation based on simplifying assumptions and estimated parameter values. Unfortunately, the results cannot be validated because it is almost impossible to measure internal temperatures of the human eye and therefore there are no experimental data available with which to compare the computed results. In order to indirectly validate the model, temperature measurements and similar model calculations are planned for the rabbit eye as future work. The present model is, however, expected to be a good approximation, because a very similar model with a parallel optical radiation beam has predicted a reasonable range of threshold incident irradiance for cataract formation (Okuno 1991, 1994).

Still, this model may not make good predictions in situations where the temperature becomes very high in the eye, because the properties of ocular structures or the physiological conditions of the eye may be different from those assumed in the model. For example, since the thermal conductivity of water increases from 0.623 W m^{-1} $°C^{-1}$ at 37°C to 0.680 W m^{-1} $°C^{-1}$ at 97°C (Weast 1986), those of ocular structures are expected to increase to a similar degree. The absorption coefficients of the lens should also differ due to opacities at high temperatures. In fact, lenticular opacities were observed in rabbit lenses at temperatures higher than about 43°C (Emery et al. 1975; Kramár et al. 1987; Bollenmeijer et al. 1989). Moreover, the eye may respond to high temperatures by increasing the blinking rate, the evaporation from the corneal surface and the blood flow in the choroid. These responses are equivalent to increased heat transfer coefficients from the surface of the eyeball to surroundings. Thus the very large temperature rises predicted by this model for an incident beam power of 1 W are in themselves meaningless, although they are valuable to calculate temperature rises induced by a beam of much lower power.

CONCLUSION

The results of this study show that Maxwellian-view illumination or similar focal-beam situations can produce temperature elevations that can cause thermal injury to the lens under certain conditions; this hazard is greater for incident wavelengths of about 320–420 nm than for longer wavelengths, and the hazard increases as exposure duration increases and tends to increase as the beam waist diameter or Maxwellian-view angle decreases.

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