Laser retinal thermal damage threshold: impact of small-scale ocular motion

Brian J. Lund
Northrop Grumman
4241 Woodcock Drive Suite B100
San Antonio, Texas 78228

Abstract. The impact of the small-scale ocular motion that occurs during steady gaze on the retinal thermal damage threshold for long-duration laser exposures is investigated. Exposure durations from 100 msec to 50 sec are considered. Experimentally recorded eye movement data are input into a numerical simulation to calculate the increase in temperature experienced by the retina during an exposure to a continuous wave laser. Calculations are for a small retinal beam spot. An Arrhenius damage integral is used to estimate the thermal damage threshold. The impact of the ocular movements is expressed as a relief factor χ, defined as the ratio of the theoretical damage threshold in the presence of ocular motion to the threshold calculated assuming no eye motion. The relief factor is found to be 1.05 for a 100-msec exposure, increasing to 1.3 for a 50-sec exposure. The relief factor is described well by the equation $\chi = 1.12\tau^{0.037}$ for exposure durations τ in the range 100 msec to 50 sec. © *2006 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.2393091]

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1 Introduction

The current laser safety guidelines, published in 2000[1,2] and 2001,[3] incorporated significant changes to the maximum permissible exposure (MPE) limits for long-duration exposure to laser irradiation. Figure 1 compares the MPE for small-source ocular exposure to a helium-neon (HeNe) laser ($\lambda = 633$ nm) from the previous[4–6] and current guidelines. In the previous guidelines, the MPE corneal irradiance decreases as $\tau^{-0.25}$, where τ is the exposure duration. This decrease continues out to a time T_1, which is wavelength dependent; at $\lambda = 633$ nm, T_1 is 457 sec. For $T_1 < \tau < 10^4$ s, the MPE is given as a constant (but wavelength dependent) value for the corneal radiant exposure, which is equivalent to a τ^{-1} dependence for the corneal irradiance.

Beginning in 2000, the guidelines were changed so that the $\tau^{-0.25}$ dependence of the MPE corneal irradiance continues out only to a break time T_2, which is retinal spot-size dependent. For a small apparent source, subtending less than $\alpha_{min} = 1.5$ mrad, $T_2 = 10$ sec, and increases for extended sources. For exposures longer than T_2, the MPE becomes a constant value for the corneal irradiance. A consequence of this change is that the MPE for very long exposures was increased by about 2 orders of magnitude.

One consideration for making these changes in the MPE for long-duration exposures was provided by the study of Ness et al.,[7] in which ocular movement during steady gaze was recorded. Movement of the eye causes the beam spot to move about an extended region of the retina. As a result, the area of the retina exposed is increased beyond the actual dimension of the beam spot itself. Ness et al. showed that this area increases as the exposure duration increases. The time-averaged retinal irradiance is reduced to less than the actual beam irradiance, and therefore a higher beam power is required to induce damage. This trend is counter to the $\tau^{-0.25}$ decrease in MPE.

Ness et al. examined the eye movement pattern occurring during steady gaze, and the resulting retinal radiant exposure distribution resulting from such a movement pattern. However, the temperature of the retina during an exposure was not considered. The rate of thermal damage processes is strongly sensitive to temperature.[8] Because of the motion of the eye, the retina will experience a complex thermal history during a long-duration exposure. A particular location of the retina will be heated when directly illuminated by the beam, but will cool when the beam spot moves elsewhere in response to eye movements.[9] Ocular movements may therefore be expected to be an important factor in determining the effective thermal damage threshold for a long-duration exposure.

This work presents the results of a study of the thermal damage threshold in the presence of small-scale ocular motion for exposures to the beam from a cw laser. The analysis is carried out for a small retinal beam spot corresponding to a source subtending an angle α_{min} in the field of view. Thermal damage thresholds are estimated for exposure durations in the range of 100 msec to 50 sec. The impact of the ocular motion is assessed by comparing the theoretical thermal damage threshold estimated for the moving eye with the threshold calculated by ignoring the motion of the eye.

Address all correspondence to Brian J. Lund, c/o USAMRD-WRAIR, 7965 Dave Erwin Drive, Brooks City-Base, Texas 78235-5108, USA. Tel: 210-536-4648; Fax: 210-536-3450; E-mail: brian.lund.ctr@brooks.af.mil
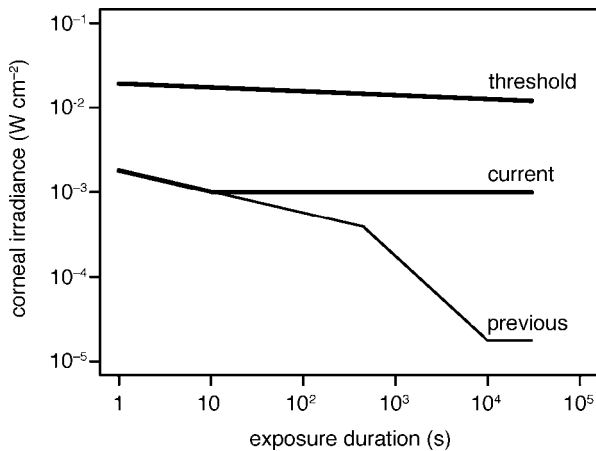
Fig. 1 Comparison of the current[1-3] and previous[4-6] maximum permissible exposure for long-duration, small spot-size exposure to a helium-neon laser ($\lambda = 633$ nm). Also shown is the theoretical thermal damage threshold estimated in this work, which includes the effects of ocular motion.
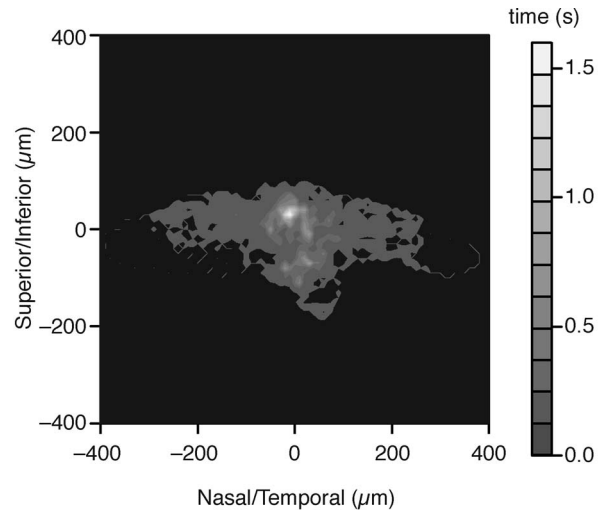

Fig. 2 Sample ocular movement contour plot. Eye movements were recorded while the individual deliberately stared at a point source produced using a HeNe laser for 50 sec. The z axis shows the total accumulated time that the center of the beam spot was located within 10×10-μm areas of the retina. The minimum contour is at 1 msec. (Data from Ref. 10).

The exposure condition examined is one in which a subject whose head is held stationary (using, for example, a bite bar or a head/chin rest combination) stares directly into the laser beam. This is a scenario in which the effects of the small-scale eye movements are expected to be most significant. Although this is a very specific exposure condition, it represents a situation expected to occur in laboratory and clinical settings and is a worst-case condition for general exposures.

2 Method

Thermal damage thresholds are estimated using recorded eye movement data as the input to a numerical simulation that calculates the increase in temperature occurring in the retina during a cw laser exposure. The search for the threshold beam irradiance is simplified by considering the temperature history at a single point on the retina, specifically the location that, on average, attains the highest temperature during the exposure.

2.1 Ocular Movement Data

Ocular movement data are taken from the study of Lund et al.[10] Eye movements were recorded while a subject deliberately stared at a point-like target produced by a helium-neon laser. A trial lasted 50 sec, during which the subject's head was held steady using a head/chin rest combination. Data were recorded at a rate of 1 kHz.

The contour plot of Fig. 2 shows an example of the ocular movement patterns recorded during the study. The z axis of this plot gives the total accumulated (not necessarily continuous) time during the trial that the center of the beam spot was located at a given position on the retina. The maximum "visitation time" at any single point of this distribution is 1.58 sec. If there was no eye movement, i.e., the eye was completely stationary, the ocular movement contour plot would be a single spike at ($x=0$, $y=0$), with a height of 50 sec. Although ocular movements cause the beam to cover an area several hundred micrometers across, the center of the beam spot generally stays within an area that is 35 to 40 μm in extent.[10]

For this study, five trials from each of seven subjects were used, for a total of 35 ocular movement datasets. The ocular movement pattern of Fig. 2 is used to illustrate the procedure developed here to estimate the thermal damage thresholds.

2.1.1 Retinal radiant exposure

The relevant quantity driving the thermal damage mechanism is the retinal irradiance distribution. The rate at which energy is deposited determines the increase in temperture in the retina. For photochemically induced damage, the total integrated energy dose is the determining factor. It is worthwhile to briefly examine the retinal radiant exposure distribution that results from the eye movement pattern illustrated in Fig. 2. Figure 3 shows the radiant exposure pattern calculated for a 50-sec duration small-source MPE-level exposure to a HeNe laser ($\lambda = 633$ nm). The MPE for exposures longer than 10 sec was used (corneal irradiance of 1 mW cm^{-2}). In this figure, the z axis is the total radiant exposure accumulated during the 50-sec exposure. The definition of the MPE assumes a 7-mm-diam pupil, which means the total intraocular power (TIP) from this exposure is 385 μW. For the calculation, the retinal beam spot was 25 μm in diameter, which corresponds to the minimum angular subtense α_{min} of 1.5 mrad.[1] A uniform, or "top hat," irradiance profile was used. The direct ocular transmission at 633 nm is 0.65.[11] Large angle scattering was assumed to be negligible. The peak total radiant exposure of the distribution of Fig. 3 is 270 J cm^{-2}.

If the eye was motionless, the retinal radiant exposure would be nonzero only over the 25-μm-diam area covered by the beam spot. Within this area, the radiant exposure would have a uniform value of 2500 J cm^{-2}. The ocular movement pattern of Fig. 2 reduces this peak value by about a factor of 10, but spreads the energy over a large area of the retina.
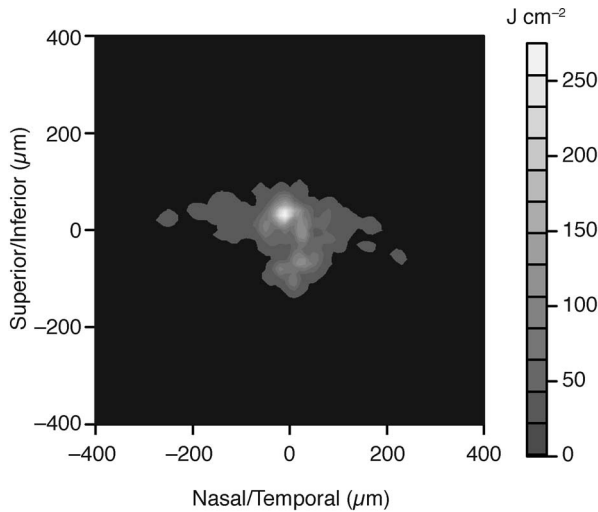
Fig. 3 Retinal radiant exposure pattern resulting from the ocular movement pattern of Fig. 2. The calculation was performed for a maximum permissible exposure to a helium-neon laser. The beam spot is 25 μm in diameter with a "top-hat" irradiance profile. The z axis gives the total radiant exposure accumulated at each point over a period of 50-sec. The minimum contour is at 1 J cm^{-2}.

2.2 Retinal Temperature

The increase in temperature occurring in the retina during a laser exposure was calculated using the retinal heating in a moving eye (RHME) simulation.[9] The RHME model incorporates several simplifying assumptions to reduce the computational effort needed to simulate long-duration exposures. Although it is recognized that there has been a tradeoff in physical accuracy, the model is sufficient for this first investigation of the impact ocular motion has on the effective retinal thermal damage threshold.

The RHME program solves the thermal diffusion equation

$$(\rho C)\frac{\partial \Theta}{\partial t} - k\nabla^2\Theta(\boldsymbol{r},t) = Q(\boldsymbol{r},t), \qquad (1)$$

where Θ is the increase in temperature, in centigrade, above background at the point $\boldsymbol{r}=(x,y,z)$ at time t. The properties of water are used for the specific heat C, the density ρ, and the thermal conductivity k of the ocular medium.

The heat source term Q represents energy absorbed in the retina from the incident laser beam. In the RHME model, this energy is absorbed uniformly through a 10-μm-thick layer representing the retinal pigmented epithelium (RPE). The model is symmetric about the mid-plane of the RPE layer. Therefore, the highest calculated temperature increase will occur in this mid-plane. The beam spot is assumed to have a uniform, or top-hat irradiance profile. The heat source term Q is therefore a cylindrical volume whose position (x,y) within the plane of the RPE is determined, as a function of time, by the input ocular motion data.

The RHME program was used to simulate exposures of 100 msec to 50 sec for each of the 35 ocular movement datasets. The runs simulated an exposure at the MPE

($>$10 sec) to a HeNe laser (1 mW cm^{-2} at λ=633 nm). A 25-μm-diam retinal beam spot was used. For further details, the reader is referred to Ref. 9.

For a motionless beam spot, the maximum temperature increase reached within the model retina during an MPE-level 50-sec exposure is 1.25°C. For the ocular motion data of Fig. 2, the maximum temperature increase is 1.3°C. This unphysical result is an artifact of the numerical simulation. A rapid movement of the source over a large distance causes a transient overshoot in the calculated temperature increase, which rapidly dies out.

2.2.1 Thermal response and average temperature increase

The thermal response of the retina exposed to a small laser beam spot is rapid. The temperature increase at a point of the retina reaches 90% of its maximum value within about 10 msec of being directly exposed to the beam.[9] Cooling, once the beam spot moves to another location, also occurs on this time scale.

The region of highest temperature increase is confined to the area of the beam spot.[9] For a stationary or slowly moving beam spot, the maximum temperature increase occurs at the center of the beam spot. For the 25-μm-diam beam spot, the retinal temperature increase at the edge of the beam is approximately 70% of the temperature increase at the center of the beam spot. At 25 μm from the beam center (12.5 μm from the edge of the beam), the retinal temperature increase falls to 30% of the temperature increase at the center of the beam.

The nature of the thermal response means that the region of the highest retinal temperature increase follows the beam spot as it moves about the retina. Except during flicks, during which the beam spot rapidly moves a large distance on the retina, the maximum temperature increase in the retina is almost equal to the peak temperature increase that would occur for a stationary beam spot.

The time-averaged temperature increase for an exposure duration τ,

$$\Theta_{avg}(\boldsymbol{r},\tau) = \frac{1}{\tau}\int_0^\tau \Theta(\boldsymbol{r},t)\mathrm{d}t, \qquad (2)$$

summarizes the heating pattern experienced by the retina during the simulated exposure. A consequence of the characteristics of the retinal thermal response is that the location of the maximum of the Θ_{avg} distribution corresponds approximately to the point of the retina directly irradiated by the beam for the most accumulated time during the exposure. Figure 4 shows the time-averaged temperature increase calculated from the ocular movement data of Fig. 2 for a 50-sec exposure. The plot shows Θ_{avg} in the plane of the retina reaching the highest temperature during the exposure. At the location of the peak of this distribution, indicated on the figure, Θ_{avg} is 0.31 °C.

2.3 Temperature Versus Time Traces

For the purposes of this study, use of the full 3-D output of the retinal heating model is too unwieldy. Even reducing this to two dimensions by carefully selecting a particular plane along the z direction is impractical, given the need to consider mul-
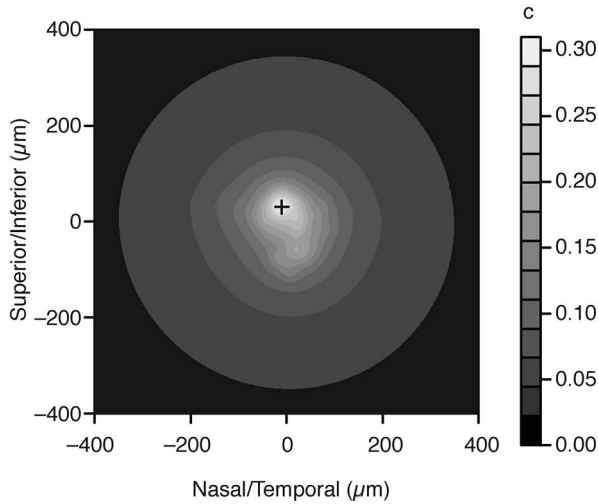
Fig. 4 Time-averaged temperature increase distribution calculated from the eye movement data of Fig. 2. The cross marks the peak of this distribution.

Fig. 5 Increase in temperature $\Theta(t)$ at the peak of the time-averaged temperature distribution for a 50-sec exposure. Calculations are for an MPE-level exposure to a HeNe laser (1 mW cm^{-2} corneal irradiance, $\lambda = 633$ nm). Top: $\Theta(t)$ for a motionless eye. The temperature reaches 90% of its maximum value in about 10 msec. Bottom: $\Theta(t)$ calculated from the eye movement data of Fig. 2.

tiple eye movement datasets to avoid statistical anomalies, and the large range of exposure durations to be considered. Therefore, the problem is simplified further by considering the temperature history at a single point of the (model) retina for each exposure duration considered.

The peak of the Θ_{avg} distribution indicates the location on the retina that was at an elevated temperature for the longest accumulated time during the exposure. Because of the nature of the thermal response of the retina to a laser exposure, and the strong temperature dependence of the thermal damage mechanism, it is expected that thermally induced damage is most likely to occur at this location. To estimate the thermal damage threshold, a 1-D temperature-time trace $\Theta(t)$ was produced at the peak of the Θ_{avg} distribution.

In practice, this was accomplished by using a specially modified version of RHME to produce Θ_{avg} distributions in the central plane of the model retina at specified exposure durations. The exposure durations considered were 0.1 to 2.0 sec in 0.1-sec increments; 2.25 to 5.0 s in 0.25-sec increments; 5.5 to 20 sec in 0.5-sec increments; and 21 to 50 sec in 1-sec increments. The peak of the Θ_{avg} distribution was located for each exposure duration. For each duration range listed, typically three to seven points would be selected for each eye movement dataset. These points were located close to each other, unless a large flick or drift occurred during the particular exposure duration range. A second specially modified version of RHME was then run to produce $\Theta(t)$ traces at each of the selected retinal locations. For example, if four retinal locations were identified for the 2.25- to 5-sec exposure duration range, then four temperature increase traces would be calculated. All four traces would be calculated out to five seconds. In subsequent analysis, it was convenient to simultaneously process all the $\Theta(t)$ traces for a given exposure duration range for a particular set of eye movement data. Thus, in practice, multiple retinal locations were considered when estimating the thermal damage threshold for a specific exposure duration.
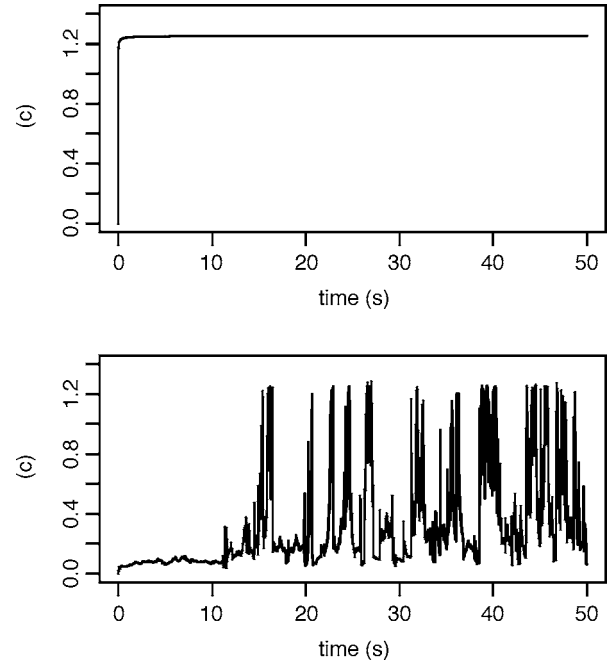
Examples of the $\Theta(t)$ traces extracted for a 50-sec exposure are shown in Fig. 5. If the eye was stationary, the location of the peak of the Θ_{avg} distribution would be at the center of the beam spot. The temperature-time trace for this situation is shown in the top part of Fig. 5. The sampling time increment for the trace is 5 msec. For the simulated MPE-level exposure for this condition, the temperature increase Θ_{stat} reaches a maximum of 1.25°C after 50 sec. Θ_{stat} reaches 90% of this value, 1.13°C, in about 10 msec.

In a moving eye, the situation is quite different. The $\Theta_{move}(t)$ trace constructed for the ocular movement data of Fig. 2 is shown in the bottom part of Fig. 5. The beam spot started some distance from the point at which this temperature trace was extracted, and did not approach this retinal location until about 12 sec into the trial. Periods of elevated temperature occur when the beam directly illuminates this point of the retina. When, because of an eye movement, the beam spot is moved off this point, cooling occurs. Θ_{move} reaches or exceeds 1.13°C for only 2.3 sec of the 50-sec exposure.

2.4 Damage Threshold Estimate

Thermal damage thresholds are estimated from the $\Theta(t)$ traces using a rate-process model.[8] An Arrhenius integral

$$\Omega(\tau) = A \int_0^\tau \exp\left[\frac{-E_a}{RT(t)}\right] dt, \tag{3}$$

is used to predict the onset of thermal damage. The parameters $A = 1.3 \times 10^{99}$ sec^{-1} and $E_a = 6.28 \times 10^5$ J mole^{-1} are taken from Welch and Polhamus.[12] $R = 8.314$ J mole^{-1} K^{-1} is

the universal gas constant. For a given exposure duration τ, the value $\Omega(\tau)=1$ indicates the onset of thermally induced retinal damage.

For the present analysis, it is assumed that the damage effects of multiple visits by the beam spot to any point of the retina are additive within the range of exposure durations investigated. In the temperature-time trace shown in the bottom of Fig. 5, for example, it is assumed that no healing takes place during the relatively cool period between the temperature peaks at around 15 and 20 sec. Some evidence to support this assumption of a slow recovery process for retinal tissue is provided by work on multiple-pulse exposures.[13]

The procedure to determine the thermal damage thresholds exploits the linearity of the thermal diffusion equation [Eq. (1)]. If the source term Q is multiplied by a factor β, then the resulting temperature increase is multiplied by the same factor, i.e., if $Q \to Q'(\boldsymbol{r},t)=\beta \cdot Q(\boldsymbol{r},t)$, then $\Theta \to \Theta'(\boldsymbol{r},t) =\beta \cdot \Theta(\boldsymbol{r},t)$.

To estimate the damage threshold, the temperature in Eq. (3) is expressed as

$$T(t) = T_0 + \beta \cdot \Theta(t), \tag{4}$$

where $\Theta(t)$ is the temperature trace extracted from the MPE-level RHME simulation (e.g., Fig. 5). The ambient ocular temperature T_0 is taken to be 310 K. For an exposure duration τ, a search was made, using a specially written computer program, to find the value of β such that $\Omega(\tau;\beta)$ is equal to 1. From the linearity of Eq. (1), to produce a temperature increase of $\beta \cdot \Theta$, the input beam power must be increased by the same factor β. The temperature traces $\Theta(t)$ used here have been calculated for a corneal irradiance of 1 mW cm^{-2}. Therefore the damage threshold for an exposure duration τ is estimated to be $\beta(\tau)$ mW cm^{-2}.

Using this procedure on the temperature traces of Fig. 5, the thermal damage threshold corneal irradiance for a 50-sec exposure to a HeNe laser is estimated to be 12.32 mW cm^{-2} for the stationary eye. The threshold corneal irradiance obtained for the temperature trace shown in the bottom portion of Fig. 5 is 16.16 mW cm^{-2}.

As described in the previous section, multiple temperature increase traces were extracted for each exposure duration range. A value of β was calculated for all of the traces at each exposure duration considered. For example, if four traces $\theta_1 \dots \theta_4$ had been extracted for the 2.25- to 5-sec exposure duration range, then four values $\beta_1 \dots \beta_4$ would be calculated for, say, a 3.0-sec exposure. The smallest of the four values for β would be taken as the thermal damage threshold for a 3.0-sec exposure for that ocular movement dataset.

The method for determining the thermal damage threshold only considers the temperature history at a single point of the retina. There is no requirement that a minimum sized area be damaged. This, plus the simplifying assumptions built into the RHME model,[9] means that the threshold estimates produced here cannot be expected to have a high degree of accuracy. However, the threshold values should agree in the order of magnitude and overall trend of experimentally measured thresholds. The retinal thermal damage threshold estimate for a stationary eye [using the $\Theta(t)$ trace from the top of Fig. 5] is plotted for exposure durations from 100 msec to 50 sec in Fig. 6. The curve is well approximated by the expression
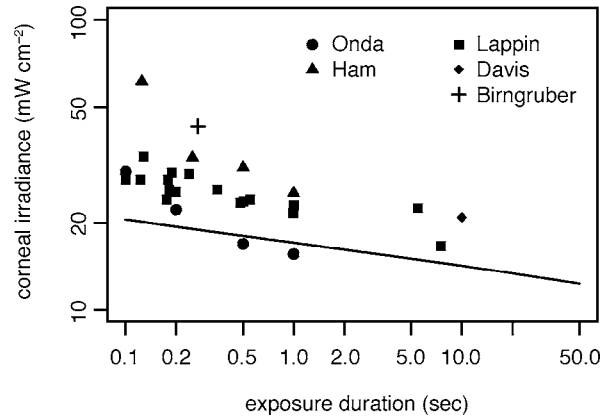

Fig. 6 Comparison of the theoretical retinal thermal damage threshold calculated for a stationary eye (solid line) with experimentally measured thresholds for small spot-size exposures to a HeNe laser. Experimental data were obtained for the rhesus monkey retina.[14–18]

$E_{stat} = 17.08\ \tau^{-0.082}$, where E_{stat} is the threshold corneal irradiance for a stationary eye, in mW cm^{-2}, and τ is the exposure duration in seconds. For comparison, this figure includes the experimentally determined thresholds for small spot-size exposures to a HeNe laser in the rhesus monkey retina.[14–18]

2.5 Relief Factor From Eye Movements

Although the thermal damage thresholds are not expected to be estimated with a high degree of accuracy, all thresholds were calculated using the same retinal heating and damage models. Since real eye movement data were used, a comparison of the threshold estimate for the moving eye with that of the theoretical stationary eye is a valid method to assess the effect of the eye movements.

A quantitative measure of the impact of the ocular movements on the likelihood of retinal damage occurring during a long-duration continuous-wave exposure is provided by the "relief factor," χ, defined as the ratio of the threshold in the moving eye divided by the threshold obtained for the theoretical stationary eye. The threshold ratio is equal to the ratio of the factors β. Thus,

$$\chi = \frac{\text{threshold in moving eye}}{\text{threshold in stationary eye}} = \frac{\beta_{moving}(\tau)}{\beta_{stationary}(\tau)}. \tag{5}$$

Using the threshold values determined from the temperature traces of Fig. 5, the relief factor provided by the eye movement pattern of Fig. 2 is $\chi=(16.16 \text{ mW cm}^{-2})/(12.32 \text{ mW cm}^{-2})=1.31$ for a 50-sec exposure.

3 Results

The relief factor χ for exposure durations from 100 msec to 50 sec is plotted in Fig. 7. The curve is the result of taking the mean of χ obtained from each of the 35 eye movement datasets used in the analysis. This curve is well described by the equation $\chi(\tau)=1.12\tau^{0.037}$, where τ is the exposure duration in seconds. Several values for χ are listed in Table 1.

For very short exposure durations, χ approaches the limiting value of 1.0. χ initially shows a rapid increase with exposure duration, reaching the value 1.1 (i.e., a 10% effect) for
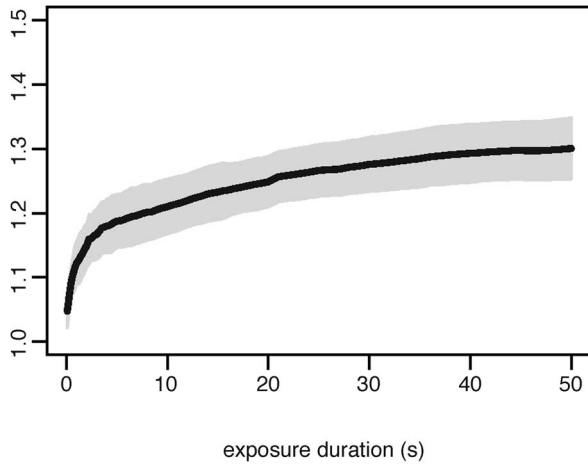
Fig. 7 Thermal damage relief factor χ from small-scale ocular motion for exposure durations from 100 msec to 50 sec. The solid line is the mean value obtained from the 35 ocular movement datasets used in the analysis. The gray band is ±1 standard deviation from the mean.

exposures lasting 0.6 sec. χ is 1.15 for τ somewhat longer than 2 sec, but does not reach χ=1.2 until τ is 8 sec. At 50 sec, χ has only increased to 1.3, a 30% effect.

If the equation describing the threshold corneal irradiance for the stationary eye is multiplied by the equation describing the relief factor χ, an equation for the threshold corneal irradiance for a moving eye is obtained: $E_{mov} = 19.13\tau^{-0.045}$ mW cm^{-2}. This is a theoretical estimate of the thermal damage threshold, incorporating the effects of small-scale ocular motion, for exposures to laser radiation at 633 nm. Assuming this equation can be extended to exposure durations beyond 50 sec (the limit of the ocular movement data), the threshold for a 3×10^4-sec exposure is estimated to be 12.0 mW cm^{-2}, an order of magnitude greater than the

Table 1 Thermal damage relief factor χ for selected exposure durations τ. The average of the value obtained from 35 eye movement datasets is listed. Numbers in parentheses are the standard deviations.

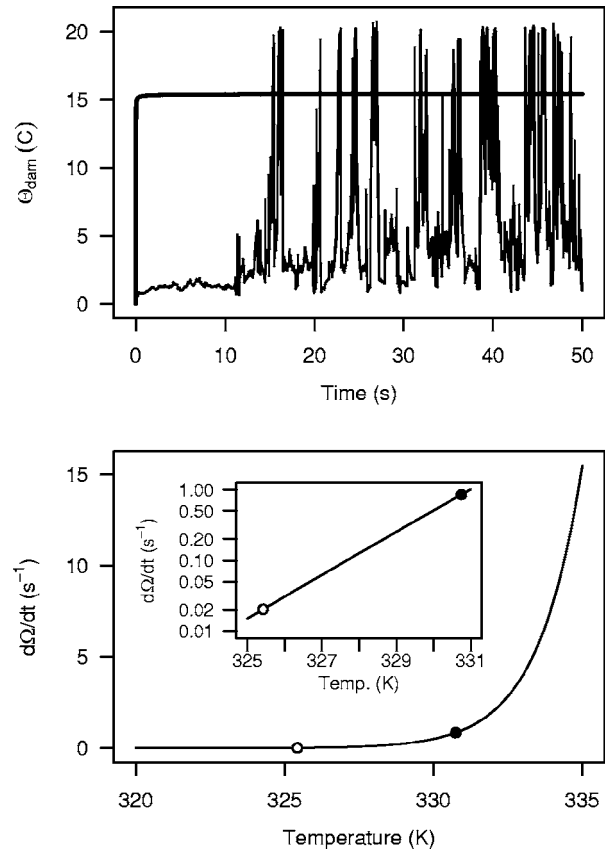| τ (sec)	χ
0.1	1.048 (0.027)
0.2	1.059 (0.025)
0.25	1.068 (0.027)
0.5	1.093 (0.027)
1.0	1.121 (0.034)
2.0	1.148 (0.034)
5.0	1.188 (0.042)
10.0	1.210 (0.043)
20.0	1.249 (0.039)
50.0	1.301 (0.048)

Fig. 8 Top: temperature increase $\Theta_{dam}(t)$ for a damage-level exposure for the sample moving eye data (corneal irradiance=16.16 mW cm^{-2}), and for a stationary eye (corneal irradiance=12.32 mW cm^{-2}). Bottom: damage rate $d\Omega/dt$ as a function of temperature. The solid circle indicates the peak temperature reached by the $\Theta_{dam}(t)$ trace of the moving eye. The open circle indicates the maximum temperature reached in the stationary eye.

current MPE of 1 mW cm^{-2}. The threshold estimate is included in Fig. 1.

4 Discussion

The impact of the ocular motion during deliberate fixation is to increase the effective thermal damage threshold by 30% for an exposure lasting 50 sec. This increase is relative to the threshold calculated, assuming the eye is motionless. The impact on the retinal radiant exposure pattern is certainly more significant. As Fig. 5 shows, any point on the retina may spend relatively little time during the exposure at an elevated temperature. A 30% increase in the thermal damage threshold may seem surprisingly small. However, the damage process, as modeled by Eq. (3), is highly sensitive to temperature.

The top portion of Fig. 8 shows the damage level temperature increase traces $\Theta_{dam}(t)$ for a stationary eye, and for the eye movement data of Fig. 2. These traces were obtained by multiplying the MPE-level traces of Fig. 5 by the appropriate factor β found using the procedure developed in Sec. 2. The trace for the moving eye therefore represents a 50-sec exposure at a corneal irradiance of 16.16 mW cm^{-2}, while the corneal irradiance for the stationary eye trace is 12.32 mW cm^{-2}. The peak temperature increase reached in

the moving eye trace at threshold is 20.7°C, while the maximum temperature increase attained in the stationary eye is 15.4°C. While the moving eye trace reaches a peak temperature that is 5.3°C higher than the stationary eye, the temperature in the moving eye trace equals or exceeds the temperature in the stationary eye for only 4.2 sec of the 50-sec exposure.

The damage rate [the integrand of the Arrhenius integral, Eq. (3)]

$$\frac{d\Omega}{dt} = A \exp\left[\frac{-E_a}{RT(t)}\right], \tag{6}$$

is plotted as a function of temperature in the bottom portion of Fig. 8. The maximum temperatures reached by the two Θ_{dam} traces are indicated. The damage rate at the peak temperature of the stationary eye is $d\Omega/dt=0.02$. At the peak temperature of the moving eye, $d\Omega/dt=0.85$. A 30% increase in temperature leads to more than an order of magnitude increase in the damage reaction rate, which compensates for the fact that the moving eye trace is at an elevated temperature for less than 10% of the exposure duration.

The results presented were derived using a retinal beam spot diameter of 25 μm. The impact of the ocular motion on the thermal damage threshold will be largest for such a small beam spot, which is smaller than the extent of the peak of the eye movement pattern (typically 35 to 40 μm). An eye movement is frequently large enough to completely remove the beam spot from a previously directly illuminated point on the retina, affording that retinal location an opportunity to cool. This leads to the alternating hot-cold temperature trace seen in the bottom of Fig. 5. If the diameter of the beam spot is increased to a few hundred micrometers, then an eye movement will rarely be large enough to completely uncover a point in the center of the movement pattern. This location will have few opportunities to cool during the exposure—the temperature trace for this point of the retina will look more like the motionless eye trace from the top of Fig. 5. χ is expected to be largest for small beam spots, and decrease toward a value of 1 as the size of the beam spot increases.

The RHME simulation used to calculate retinal temperature increases incorporates several simplifying assumptions. In particular, absorption of energy is taken to be uniform through the thickness of the RPE. Heating due to absorption by melanin within the choroid is assumed to be negligible. The model does not include any cooling effects from blood flow (primarily in the choroid). The simulation therefore has a symmetry about the mid-plane of the model RPE layer, which was used to reduce the computational effort needed to simulate long-duration exposures. Improvements to the model would include these factors.

Welch, Wissler, and Priebe[19] have investigated the impact of blood flow on calculations of the temperatures occurring in laser irradiated tissue. Using a model in which blood perfusion is assumed to occur uniformly throughout the tissue, they estimate that, as an upper limit, blood flow will reduce the peak temperature increase by 10% for exposures lasting longer than 8 sec. For the stationary eye, the temperature increase $\Theta(t)$ of Eq. (4) may be approximated as a constant Θ_0 for such long-duration exposures. By using this approximation in the Arrhenius integral [Eq. (3)], after some manipulation, it is found that $\beta \sim 1/\Theta_0$. Thus, a 10% reduction in the

peak temperature increase leads to a 10% increase the thermal damage threshold estimated for the stationary eye. Blood flow is expected to have a smaller impact on the moving eye calculation, as the beam spot rarely directly irradiates a particular retinal location for as long as 8 sec before moving to another location (Fig. 5). The threshold calculated for the moving eye will be increased by a factor smaller than the 10% increase in the stationary eye threshold. The relief factor χ will be smaller than the value calculated neglecting blood cooling effects. Since the Welch, Wissler, and Priebe model gives an upper limit, it is expected that a thermal model accurately incorporating cooling of the retinal tissue by blood flow will yield a value for χ that is a few percent smaller than the values presented in this work.

It is worth noting (Fig. 1) that the thermal damage thresholds estimated here for long-duration cw exposures are at least an order of magnitude larger than the MPE corneal irradiance of 1 mW cm^{-2} set in the current safety standards.[1–3] The results of this work support the increased MPE values for the visible wavelengths incorporated in the current laser exposure guidelines.

5 Conclusion

This work presents an analysis of the impact of the small-scale ocular motion occurring during steady gaze on the retinal thermal damage threshold for long-duration exposure to a continuous-wave laser. The analysis is performed for a small retinal beam spot. In the exposure condition considered, an individual, whose head is held steady, stares directly into the beam.

A quantitative measure of the impact of the ocular motion occurring during steady gaze is provided by the relief factor χ, defined as the damage threshold in the moving eye divided by the threshold for a motionless eye. χ is 1.05 for a 100-msec exposure—the threshold corneal irradiance is 5% higher than it would be if there was no ocular motion. χ increases to 1.3 for a 50-sec exposure. For exposure durations τ in the range 100 msec to 50 sec, the relief factor is found to follow the expression $\chi(\tau)=1.12\tau^{0.037}$.

The theoretical estimate of the thermal damage threshold for a long-duration exposure for a subject deliberately staring into the laser beam is found to be at least an order of magnitude larger than the maximum permissible exposure corneal irradiance contained in the current laser safety guidelines. The large increase in the MPEs for visible wavelength exposures incorporated in the current safety guidelines is supported by this work.

5.1 Disclaimer

References

1. American National Standards Institute (ANSI), *American National Standard for Safe Use of Lasers, Z136.1*, Laser Institute of America, Orlando, FL (2000).
2. International Commission on Non-Ionizing Radiation Protection (IC-NIRP), "Revisions of guidelines on limits of exposure to laser radiation of wavelengths between 400 nm and 1.4 μm," *Health Phys.* **79**(4), 431–440 (2000).
3. International Electrotechnical Commission (IEC), "*IEC 60825-1 safety of laser products, part 1: Equipment classification, requirements and user's guide*," 1.2 ed., Geneva (2001).
4. American National Standards Institute (ANSI), *American National Standard for Safe Use of Lasers, Z136.1*, Laser Institute of America, Orlando, FL (1993).
5. International Commission on Non-Ionizing Radiation Protection (IC-NIRP), "Guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1,000 μm," *Health Phys.* **71**(5), 804–819 (1996).
6. International Electrotechnical Commission (IEC), "*IEC 60825-1 Safety of laser products, part 1: equipment classification, requirements and user's guide*," 1.1 ed., Geneva (1998).
7. J. W. Ness, H. Zwick, B. E. Stuck, D. J. Lund, B. J. Lund, J. W. Molchany, and D. H. Sliney, "Retinal image motion during deliberate fixation: Implications to laser safety for long duration viewing," *Health Phys.* **78**(2), 131–142 (2000).
8. J. Pearce and S. Thomsen, "Rate process analysis of thermal damage," Chap. 17 in *Optical-Thermal Response of Laser-Irradiated Tissue*, A. Welch and M. van Gemert, Eds., pp. 561–606, Plenum Press, New York (1995).
9. B. J. Lund, "Computer model to investigate the effect of eye movements on retinal heating during long-duration fixation on a laser source," *J. Biomed. Opt.* **9**(5), 1093–1102 (2004).
10. B. J. Lund, H. Zwick, D. J. Lund, and B. E. Stuck, "Effect of source intensity on ability to fixate: Implications for laser safety," *Health Phys.* **85**(5), 567–577 (2003).
11. E. A. Boettner and J. R. Wolter, "Transmission of the ocular media," *Invest. Ophthalmol.* **1**, 776–783 (1962).
12. A. J. Welch and G. D. Polhamus, "Measurement and prediction of thermal injury in the retina of the rhesus monkey," *IEEE Trans. Biomed. Eng.* **BME-31**(10), 633–644 (1984).
13. J. A. Zuclich and M. F. Blankenstein, "Additivity of retinal damage for multiple-pulse laser exposures," USAF School of Aerospace Medicine Technical Report USAFSAM-TR-88-24 (1988).
14. Y. Onda and T. Kameda, "Studies of laser hazards and safety standards (part 2) retinal damage thresholds for helium neon lasers," Tech. Rep., Technical Research and Development Institute, Japanese Defense Agency (1979). English translation: US Army Medical Intelligence and Information Agency Translation No. USAMIIA-K-9991 (1980).
15. W. T. Ham, W. J. Geeraets, H. A. Mueller, R. C. Williams, A. M. Clarke, and S. F. Cleary, "Retinal burn thresholds for the helium-neon laser in the rhesus monkey," *Arch. Ophthalmol. (Chicago)* **84**, 797–809 (1970).
16. P. W. Lappin, "Ocular damage thresholds for the helium-neon laser," *Arch. Environ. Health* **20**, 177–183 (1970).
17. T. P. Davis and W. J. Mautner, "Helium neon laser effects on the eye," Tech. Rep. C106-59223, EG&G Inc., Los Angeles (1969).
18. R. Birngruber, V. P. Gabel, and F. Hillenkamp, "Experimental studies of laser thermal retinal injury," *Health Phys.* **44**(5), 519–531 (1983).
19. A. J. Welch, E. H. Wissler, and L. A. Priebe, "Significance of blood flow in calculations of temperature in laser irradiated tissue," *IEEE Trans. Biomed. Eng.* **BME-27**, 164–166 (1980).