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Abstract. Quantitative evaluation of the potential radiation hazards of scanning light sources in medical optical devices is critical. Currently, point scanning light sources of continuous radiation are treated as pulsed sources, where the dwell time at each point is equal to the pulse duration. This study compares the photothermal effects from scanning light and pulsed sources using numerical calculation for scanning without restricting aperture and with various spot sizes. The calculation results show that the thermal damage threshold of scanning source not restricted by measurement aperture does not significantly differ from that of pulsed source. Temporal temperature response and size-dependent photothermal effect also confirm the similarity between scanning and pulsed sources. [DOI: 10.1117/1.JBO.19.4.045004]

Keywords: scanning medical device; optical radiation hazard; photothermal effect.

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1 Introduction

Many optical medical devices use scanning technology and the number of such devices is increasing. Continuous wave (CW) light sources that are scanned (henceforth called scanning sources) have unique characteristics, which distinguish them from stationary CW or pulsed light sources: scanning sources are spatially dynamic but temporally stationary, whereas pulsed sources are spatially stationary but temporally dynamic. Commonly used guidance documents and safety standards suggest evaluating scanning light sources using pulsed source criteria. Details of pulsed source criteria can be found in guidance documents, for example ISO 15004-2:2007.[1] In a previous report using a melanin granule lattice model (MGLM), it was demonstrated that the photothermal effect of scanning source is different from that of pulsed source within restricting aperture.[2] However, the difference reported in the previous study was at maximum 25%, which was not large enough to invalidate consensus use of pulsed source criteria for evaluating scanning source. Also, it was noted in another study that dwell-time and overlap of the adjacent exposure points (EPs) must be considered for worst-case scenario analysis.[3]

A number of questions still remain before it is definitively concluded that photothermal effects from scanning and pulsed sources are comparably equivalent:

1. Previous results comparing photothermal effects from scanning and pulsed sources were confined to the retinal region within a restricting (or measurement) aperture. Actual scanning devices do not operate under such apertures, thus photothermal effects without apertures must be compared.
2. The mechanism for producing a different photothermal response from scanning and pulsed sources is the heat storage and propagation in the tissue. Thus, different scanning spot sizes must be considered.
3. Scanning sources resemble repetitive pulses, rather than single pulse. The additivity of thermal effect depends on temporal temperature characteristics of the scanning source, which must be considered.
4. In addition to temporal temperature characteristics, the temporal change in thermal damage threshold must be considered.
5. Local heat buildup may cause local hotspots in scanning pattern. For scanning devices with two-dimensional (2-D) scanning patterns, the entire scanning area must be considered to find hotspots caused by local heat buildup.

In this study, questions (1)–(4) will be addressed using the MGLM. Question (5) needs rigorous computational calculation, and thus will be discussed qualitatively without numerical calculation results. The main goal of this study is to find the difference (or similarity) between the thermal damage thresholds of linear scanning source and pulsed source. If the thermal damage threshold of scanning source is not significantly different from that of pulsed source, pulsed source criteria can be applied to the evaluation of photothermal effect from scanning source. Actual values of damage thresholds slightly vary depending on the calculation parameters used and will not be discussed in this study because this study aims for numerical calculation of relative differences in thermal damage thresholds between scanning and pulsed sources.

2 Method

The MGLM is a modified version of melanin granule model[4] using uniformly distributed melanosomes in retinal-pigmented

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epithelium and has been proven to be useful for studying photothermal damage of retinal tissue within its limits.[2] The results using MGLM are similar to those using other computational models especially when the pulse duration or dwell-time is longer than 10 μs and shorter than 1 s.[2,4]

In this study, MGLM was adapted for calculating temperature and thermal damage threshold from scanning sources. Temperature at a given location (r) and time (t) can be analytically calculated using temperature function $T(r,t)$, which depends on the thermal diffusivity of the tissue (D), thermal conductivity (k), granule radius (a), heat capacity (c_p), absorption coefficient of melanosome (α_m), and melanosome number density (ρ_m). Parameters for calculations are summarized in Table 1.[2] The radiant exposure at the cornea (I_c) was set to 10 μJ/cm^2, and the retinal radiant exposure (I_0) was approximated by multiplying I_c by a factor of 10^5.[4] Each melanosome shown as filled circles in Fig. 1 has radius (a) 1.0 μm, and the melanosomes were placed in close proximity with each other. Melanosome number density (ρ_m) is the inverse of the volume containing one melanosome, which is a cube with 2.0-μm sides. A total of five layers of melanosomes without gap between each layer were used in this study. More details can be found elsewhere.[2]

The Arrhenius integral calculations were performed on locations $z = 1.5\,\mu$m above the top melanosome layer, to avoid excessively high temperature inside the melanosome itself while obtaining lowest damage thresholds possible. Also, different from the previously reported results, restricting aperture of size D has been removed in this study. The calculation without restricting aperture can be simply implemented by enlarging the size of the restricting aperture within which scanning light source is moving. Figure 1 illustrates laser spot sizes (d_x, d_y) and scanning lengths (D_x, D_y) used for the calculation. Scanning lengths in x- and y-directions, D_x and D_y, can be considered as restricting aperture with same dimensions. Also, the spot size d was varied from 30 μm, which was the only value used in the previous study. Square tophat source profiles were used in this study due to its advantage over circular spots: Circular and Gaussian source profiles, although they are realistic profiles of actual optical devices, exaggerate geometrical effect from the source itself.[2] Calculations were performed for different scanning speeds which correspond to 0.1, 1, 10, and 100 ms of dwell time. All dwell-times are well within the range where

Table 1 Summary of parameters for calculation.

Variable	Symbol	Value
Thermal conductivity	κ	5.0323×10^{-3} J/cm/K/s
Tissue density	ρ	1.0 g/cm^3
Melanosome radius	a	1 μm
Heat capacity	c_p	4.186 J/g/K
Melanin absorption coefficient	α_m	2000/cm at 532 nm
Melanosome density	ρ_m	1.25×10^{11}/cm^3
Frequency factor	ln A	228.22
Activation energy	E_a	627.6 kJ/mole

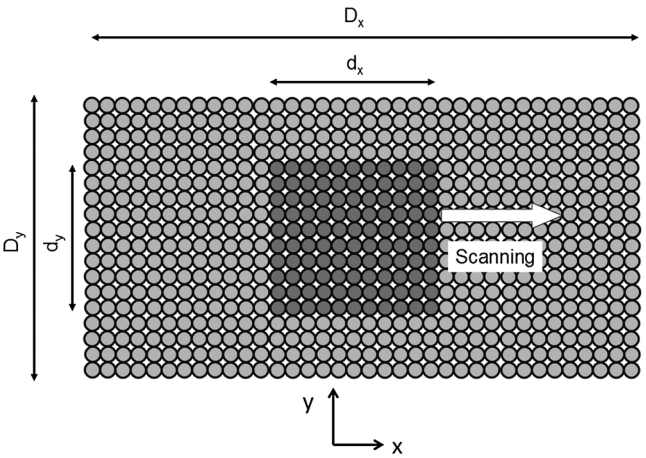

Fig. 1 Illustration of melanosomes (gray circles) and scanning light source. Irradiated melanosomes are marked with darker gray circles.

MGLM produces calculation results that are comparable to those found using other numerical methods.

3 Numerical Calculations

3.1 *Photothermal Damage without the Aperture*

As shown in Fig. 1, when a scanning source with size d_x and d_y is moving in x-direction, the range of melanosomes that are irradiated by the scanning source can be specified by D_x and D_y. Setting D_y equal to d_y, the scanning is restricted to a linear scan. When D_x equals to d_x, the scanning irradiation is restricted only within the aperture of size equal to the source spot size. When D_x is larger than d_x, the scanning source is irradiated over a wide range of retinal tissue. Figure 2 shows the damage thresholds for 30×30 μm^2 tophat laser spot scanned for different D_x. The damage thresholds for scanning speeds corresponding to 0.1-, 1-, and 10-ms dwell times are almost identical to those of scanning laser with ($D_x = 30$ μm) and without aperture ($D_x > 30$ μm). This is in agreement with the previous findings that the damage thresholds for scanning sources do not differ from those for pulsed sources,[2] and it further confirms that the discrepancy remains insignificant even without restricting

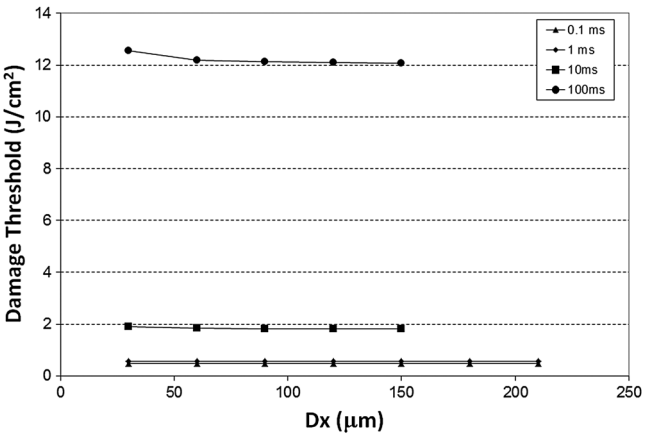

Fig. 2 Damage threshold of scanning source calculated using melanin granule lattice model (MGLM) for different scan lengths with 30-μm laser spot.

aperture. The damage threshold decreased from 12.55×10^{-5} J/cm^2 to 12.07×10^{-5} J/cm^2 for the 100-ms dwell time, which is a slightly greater decrease compared with shorter dwell times. The longer the dwell time, the more thermal energy is deposited on the irradiated volume of tissue, and thus requires less energy to induce photothermal damage. However, a 4% decrease in damage threshold for 100 ms is still not significant. Considering the fact that a 100-ms dwell time corresponds to a scanning speed of 0.3 mm/s for a 30-μm beam spot, which represents a lower limit on the scanning speed for practical imagers, consideration of a larger decrease in damage threshold for dwell time larger than 100 ms would not be practical. As a matter of fact, some modern fast scanners used in medical imaging devices can achieve frame rate as high as 60 frames-per-second, which produce 1000 pixels $\times$ 1000 pixels images in total 1×1 mm^2 image sizes. The dwell time of such devices is as short as 500 ns, at which photothermal damage from scanning and pulsed sources are equivalent.

3.2 *Spot-Size Dependence*

As described in the previous section, a small difference in thermal damage thresholds between scanning and pulsed sources exist and is mainly caused by the dynamic dissipation of moving heat generated by scanning light source. The greater the heat stored in the tissue, the more the effect of dynamic heat dissipation contributes toward thermal damage. Previous calculation results used a 30-μm spot size because this is considered to be the smallest achievable focal spot size at the retina without incorporating adaptive optics.[4] Larger spot sizes must be considered because not all ophthalmic devices generate diffraction-limited spot on the retina, and they may generate a larger discrepancy in thermal damage thresholds between scanning and pulsed sources. For numerical calculation, larger d_x (>30 μm) was used and more dramatic change in damage thresholds were observed from increased spot size.

Figure 3 shows the damage thresholds for square laser spot of size d_x ($= d_y$) scanned over square aperture of size D_x ($= D_y$). The damage thresholds for 0.1- and 1-ms dwell-time were almost identical regardless of d_x and D_x. However, damage threshold decreased from 12.55×10^{-5} to 7.42×10^{-5} J/cm^2 for 100-ms dwell time as the d_x ($= D_x$) increased from 30 to 120 μm. This represents a 40% decrease in damage threshold.

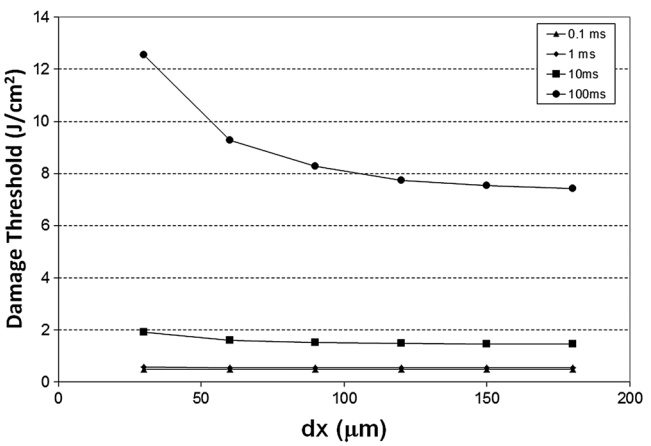

Fig. 3 Damage threshold of scanning source calculated using MGLM for different spot sizes.

The damage threshold curve in Fig. 3 can be approximately fitted to $(1/d_x)$ curve. The $(1/d_x)$ dependency of the thermal damage threshold is similar to what was observed for spot-size dependency of retinal irradiations.[5,6] The spot-size dependence study of scanning source also suggests that thermal damage threshold of larger scanning spots demonstrate similar tendency in spot-size dependence of pulsed source.

3.3 *Temporal Thermal Characteristics*

Scanning sources resemble repetitive pulses, rather than single pulse. It is particularly true for scanning sources in imaging medical devices, such as those used in scanning laser ophthalmoscopy and optical coherence tomography. For repetitive pulse irradiations of N pulses, the correction factor $N^{-1/4}$ was adopted in many consensus standard documents. Clark et al.[7] recently performed a comprehensive study on the multiple-pulse thermal damage thresholds of the retina and pointed out the importance of interacting pulses for temperature rise and thermal damage threshold. For short pulses with the pulse duration in the range of 100 μs, the temperature from a single pulse does not reach steady state, thus the damage threshold not only depends on N but also depends on the duty cycle. When the duty cycle is high, the pulses are similar to a single long pulse with the total pulse duration approximated by total-on-time (TOT). When the duty cycle is low, the pulses are noninteracting thus the temperature returns to the initial value before each new pulse arrives, giving the highest damage threshold. Multiple-frame scanning irradiation resembles repetitive pulse irradiation, because multiple repetitive optical exposures are delivered to a certain location. It is very important to know whether temporal temperature change from scanning irradiation is similar to that of pulsed irradiation.

Figure 4 shows the numerical calculation results on normalized temperature rise versus normalized time for a 30-μm square spot both for scanning and pulsed sources. As can be seen in Fig. 4(a), the temporal temperature rise of a scanning source is quite different from that of a pulsed source shown in Fig. 4(b) for certain dwell times. In scanning, the normalized time origin ($t = 0$) indicates the moment where laser spot started to irradiate a certain location. Negative normalized time means that the laser spot did not reach the specific location yet. The scanning light source itself is not turned on and off like a pulsed source, thus the temperature at time origin starts to rise before the light source reaches the region. The temporal temperature characteristic is similar for scanning and pulsed sources with a 0.1-ms duration, whereas it is dramatically different for the 100-ms duration. Although the temperature reaches steady state for a 100-ms pulsed source, it widely spreads out into negative-normalized time range for scanning source. A similar calculation was performed for larger spot sizes. The larger the irradiated area, the longer it takes for the temperature to reach steady state. Figure 5 shows normalized temperature rise versus normalized time for 300-μm square spot both for scanning and pulsed sources. Scanning source showed temporal temperature rise similar to that of a 30-μm spot, as can be seen in Fig. 5(a). However, pulsed source exhibited quite different response compared with a 30-μm spot, showing no steady state in Fig. 5(b).

Numerical calculation of temporal temperature response of scanning irradiations exhibited almost no steady state even for long dwell time of tau100 ms. Thermal additivity of longer pulses is the key mechanism of reduced thermal damage threshold of repetitive pulses, and thermal additivity is stronger when

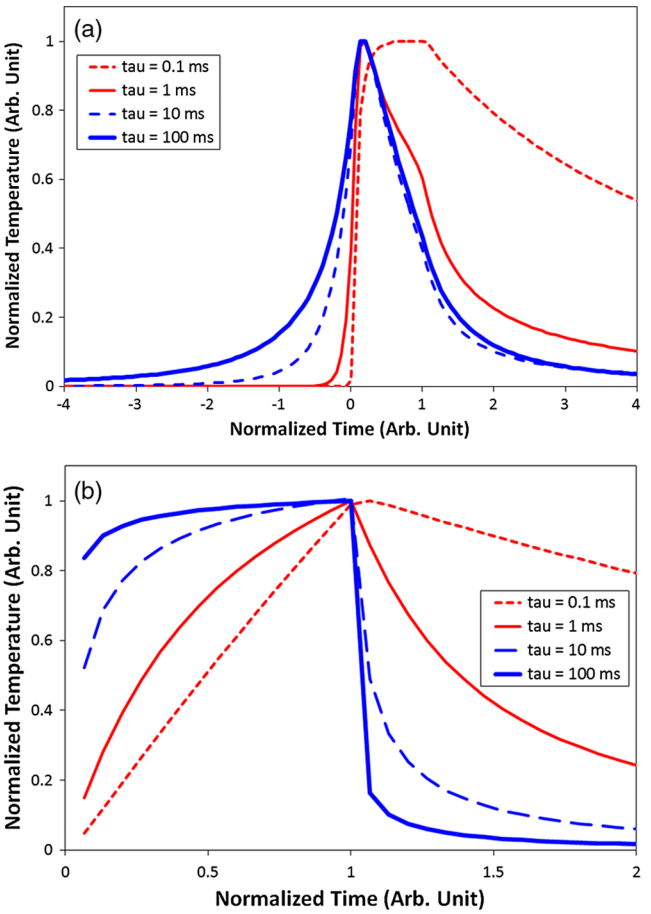

Fig. 4 Normalized temperature rise as a function of normalized time for 30-μm square source spot for (a) scanning and (b) pulsed sources. Temperature is normalized to the peak temperature, and time is normalized to the pulse duration.

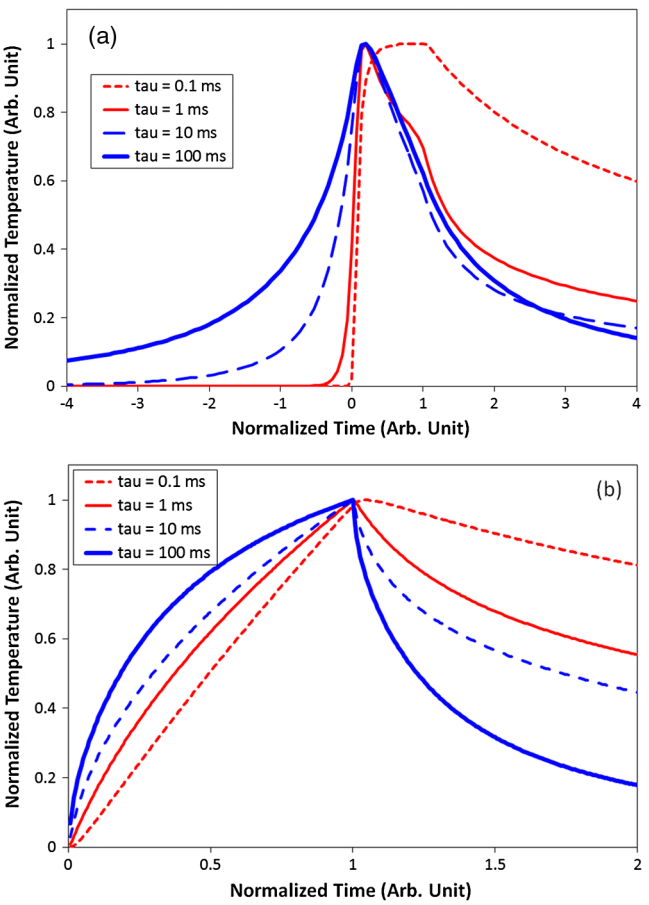

Fig. 5 Normalized temperature rise as a function of normalized time for 300-μm square source spot for (a) scanning and (b) pulsed sources. Temperature is normalized to the peak temperature, and time is normalized to the pulse duration.

the temperature reaches steady state within single pulse.[7] Lack of steady state temperature for scanning irradiation means that thermal additivity is negligible, thus thermal damage threshold may not be lower than that of repetitive-pulsed irradiation. The limits of such noninteracting source and the CW source coincide at the pulse duration of TOT.[7]

3.4 *Additivity of Thermal Effect*

Evaluation of photochemical effects for pulsed sources mainly rely on total energy (dose) delivered to the tissue. Careful measurement or calculation of radiant exposure of scanning source with consideration of overlap and dwell time variation will suffice for evaluating photochemical effect. Photothermal effect from repetitive-pulsed irradiation cannot be evaluated by only measuring (or calculating) total radiant exposure because deposited heat will not dissipate into another tissue volume immediately. In addition to the temporal temperature characteristics considered in the previous section, additivity of thermal effect needs to be considered for photothermal effect. For pulsed sources, additivity of thermal effect, thus additivity of Arrhenius integral, has already been discussed in great detail in others' work.[7] For scanning sources, spatial dependence must also be considered because scanning sources are basically moving heat sources.

Shown in Fig. 6(a) is an illustration of a linear scanning source with scan length L and spot size d. Location 1 and Location 2 indicate the mid-point and turning-point of scanning. One period (T) of scanning is the time duration for the source to leave Location 2 and to return back to Location 2. Dwell time (t) is the time duration for the source to irradiate the local tissue area, which can be obtained by dividing spot size (d) by scanning speed (v). Assuming that the scanning speed (v) is

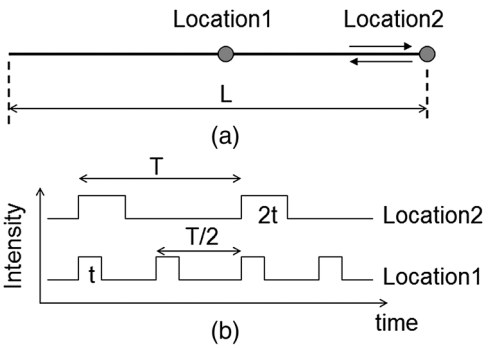

Fig. 6 (a) Illustration of linear scanning source of scanning length L and spot size d. Location 1 and Location 2 indicate the mid-point and turning-point of scanning, respectively. Solid line represents the laser scanning path (for the eye); (b) time-lapsed intensity measured at Location 1 and Location 2.

constant, there are two extreme schemes for scanning exposure, both of which are illustrated in Fig. 6(b):

1. At Location 1, scanning exposure is delivered every $T/2$ with each dwell time of t. Duty cycle of this repetitive exposure is $t/(T/2) = 2t/T$.
2. At Location 2, scanning exposure is delivered every T with each dwell time of $2t$. Duty cycle of this repetitive exposure is $2t/T$.

The main differences are: the period of (1) is half that of (2), and the dwell time of (2) is twice as long as (1). Case (1) imposes a higher probability that the next exposure is delivered before the temperature returns to original, whereas case (2) imposes a higher probability to reach damage threshold due to the longer dwell time.

Practical scanning devices of recent design, especially imaging devices, typically have at least 500 pixels × 500 pixels of scanning dimension. This implies that one scan length (L) is at least 500 times larger than that of one spot size (d). At constant scanning speed, this also implies that T is 1000 times larger than t because $T = 2L/v = 2(500d)/v = 1000t$. For both (1) and (2), the duty cycle is small enough so that each exposure can be treated independently. It is more probable that the longer exposure time of (2) will produce a larger Arrhenius integral value than the shorter exposure interval of (1) will give additivity in the Arrhenius integral. Sinusoidal scanning generates a dwell time at Location 2 much longer than $2t$, thus evaluating the photothermal effect at turning points seems to be a reasonable worst case scenario analysis.

The above statement may not be valid when the scanning length is very small compared with the spot size, although such scanning devices are not practical. Additivity of thermal effect for such special scanning devices can be analyzed using the Arrhenius integral. For a pulsed (or scanning) irradiation of total duration τ_{tot}, the Arrhenius integral is

$$\Omega(\tau) = \int_0^{\tau_{\text{tot}}} A e^{\left[\frac{-E_a}{RT(\tau)}\right]} d\tau, \tag{1}$$

where A is a material parameter (frequency factor), E_a is the activation energy, $T(\tau)$ is the temperature at time τ, and R is the universal gas constant. If this integral reaches unity during or shortly after irradiation, then thermal damage to the skin has occurred. When there is repetitive independent pulse irradiation with each Arrhenius integral less than unity, then this type of repetitive pulse irradiation will never exceed the damage threshold. However, if repetitive pulse irradiation is not independent, Eq. (1) can be expanded into multiple individual integrals:

$$\begin{aligned}\Omega(\tau) &= \int_0^{\tau_{\text{tot}}} A e^{\left[\frac{-E_a}{RT(\tau)}\right]} \mathrm{d}\tau \\ &= \int_0^{\tau_1+\tau_2+\cdots+\tau_n} A e^{\left[\frac{-E_a}{RT(\tau)}\right]} \mathrm{d}\tau \\ &= \int_0^{\tau_1} A e^{\left[\frac{-E_a}{RT_1(\tau)}\right]} \mathrm{d}\tau + \int_0^{\tau_2} A e^{\left[\frac{-E_a}{RT_2(\tau)}\right]} \mathrm{d}\tau + \cdots + \int_0^{\tau_n} A e^{\left[\frac{-E_a}{RT_n(\tau)}\right]} \mathrm{d}\tau.\end{aligned} \tag{2}$$

Adaptation of different temperature functions $T_1(\tau), \ldots, T_n(\tau)$ in the integral reflects the fact that the starting temperatures for individual pulses are different due to insufficient cooling between pulses. Arrhenius integrals for cases (1) and (2) can be expressed using Eq. (2):

$$\Omega_{(1)}(\tau) = \sum_1^n \int_0^t A e^{\left[\frac{-E_a}{RT_i(\tau)}\right]} \mathrm{d}\tau, \tag{3}$$

$$\Omega_{(2)}(\tau) = \sum_1^{n/2} \int_0^{2t} A e^{\left[\frac{-E_a}{RT_i(\tau)}\right]} \mathrm{d}\tau. \tag{4}$$

For such special case of scanning irradiations, measurement (or calculation) of worst-case-scenario radiant exposure is to be performed at Location 1 of Fig. 6(a) if Eq. (3) is larger than Eq. (4), or at Location 2 if Eq. (4) is larger than Eq. (3).

3.5 *Local Heat Buildup*

In 2-D scanning, heat is not only dissipated in x-direction dominantly, but also is dissipated in y-direction. Also, overlap of EPs greatly differs depending on the scanning scheme. Local hotspot may exist due to local heat buildup in y-directional moving heat source, and it requires rigorous computational power to calculate such 2-D heat distribution and dissipation from 2-D scanning device. This is an area for future investigation.

4 Conclusion

Using a numerical method, MGLM, the photothermal effect from scanning and pulsed sources was calculated and compared. The results confirmed previous investigations, which produced similar thermal damage thresholds for both scanning and pulsed sources restricted in measurement aperture. These results also showed that the thresholds for both types of sources are not significantly different when the source is scanned without any restricting aperture. Various spot-sizes were also considered, and the calculated thermal damage thresholds demonstrated inverse dependence on spot size, which is similar to the pulsed source case. Temporal temperature characteristics showed that scanning sources do not reach steady state in temperature, thus each exposure can be treated independently. Such noninteracting pulses can be regarded as single long pulses using TOT pulse duration for thermal damage. Analysis of additivity of thermal effect at the mid-point and turning-point of scanning suggests that the worst case scenario (higher photothermal damage) is observed at the turning-point, unless the scanning length is impractically small compared with the spot size. Further study is needed to calculate the heat buildup from a 2-D scanning source and to address effect of overlap of EPs.

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