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Human Laser Skin Dose-Response Model

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14. ABSTRACT The increased use of lasers in outdoor, uncontrolled environments requires a generalized human dose-response model for skin injuries to achieve improved fidelity for risk assessment. Such a general model was developed, covering the spectral range from 400 nm to 2000 nm and the temporal range from 1 µs to 10 s. It is based on experimental data and simulation results and includes effects from minimal visible lesions to 3 rd - and 4 th -degree burns and onset of ablation. The model was constructed to capture the essential bio-physical features contributing to human susceptibility to laser injury of the skin, including variability between humans and the effect of the angle of incidence.					
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1.0 INTRODUCTION

The increased use of lasers in outdoor, uncontrolled environments is deriving the need for a risk-based approach for laser hazard analyses. For controlled environments, safety with no possibility of injury is the criterion for the analysis; however, for less controlled environments, risk is the more appropriate criterion. While there is a finite probability of injury, this probability needs to be estimated and within an acceptable range. The transition to a risk-based approach to laser hazard analyses requires improved fidelity in models used to assess the risk.

An important model in such a risk-based approach is the probability of skin injury resulting from a laser exposure, quantified by a dose-response model. This model uses a cumulative log-normal distribution to calculate the probability of injury for a given dose. A log-normal distribution has two parameters – the mean and the standard deviation. The mean is the dose that results in a 50 % probability of injury, while the standard deviation quantifies the width of the distribution. The mean effective dose spans effects from threshold (minimum visible lesion) to supra-threshold (3rd- and 4th-degree burns, and ablation onset) and the standard deviation accounts for variability between humans and uncertainties in the model. For laser hazards, these parameters are functions of irradiance, wavelength, exposure duration, and beam diameter.

The following begins with an overview of the dose-response model, including the components of the model. Subsequent sections derive and discuss the three components of the model: 1) a new ED_{50} model for the skin developed from porcine experimental data, 2) a model for the slope resulting from human variability and uncertainties, and 3) a model for effect from the angle of incidence. The first two components address the mean and standard deviation, respectively, required for a log-normal dose-response model. The third component addresses the reduced dose resulting from the angle of incidence. The next two sections detail calculation of the effective dose and a probability of injury, followed by a section applying the model to an example. The final section provides a summary of the human skin dose-response model.

2.0 DOSE-RESPONSE MODEL OVERVIEW

The dose in a dose-response model is typically termed the effective dose with symbol ED . For skin, ED is a radiant exposure with units J/cm^2 . The effective dose for which there is a 50 % probability of injury is termed ED_{50} . Similarly, the effective doses for 16 % and 84 % probabilities of injury are termed ED_{16} and ED_{84} , respectively. The Slope S is defined as

$$S = \frac{ED_{84}}{ED_{50}} \quad \text{or} \quad S = \frac{ED_{50}}{ED_{16}} \quad (1)$$

The output of the dose-response model is the probability of injury P , given by the cumulative log-normal distribution

$$P(q) = \frac{1}{\sqrt{2\pi}\sigma^2} \int_{-\infty}^q \exp\left[-\frac{(x - \mu)^2}{2\sigma^2}\right] dx = \frac{1}{2} \operatorname{erfc}\left[\frac{-(q - \mu)}{\sqrt{2}\sigma}\right] \quad (2)$$

where

$$q = \log_{10}(ED), \quad (3)$$

$$\mu = \log_{10}(ED_{50}), \quad (4)$$

$$\sigma = \log_{10}(S). \quad (5)$$

The logic flow of the human laser skin dose-response model is summarized in Fig. 1, which illustrates the components, inputs, and data flow to arrive at a probability of injury using the quantities in Eqs. (3) to (5). The model is a function of inputs of wavelength λ , exposure duration T , $1/e^2$ beam diameter D_2 , irradiance E , and degree of burn. There are two aspects to the complete model, the mean effective dose ED_{50} and the slope S . Both have models that are functions of wavelength, and functions of additional parameters in the case of the mean effective dose. This human laser skin dose-response model covers the wavelength range from 400 nm to 2000 nm.

The ED_{50} Model determines the mean effective dose for a minimum visible lesion (MVL) as a function of the exposure conditions, and the ED_{50} Calculation combines this with the burn degree selected to determine the ED_{50} . Likewise, the Slope Model determines the Slope for a MVL as a function of wavelength, and the Slope Calculation combines this with the burn degree selected to determine the final Slope. The effective dose ED is a function of the exposure duration T and the incident irradiance E . The probability of injury calculation includes a component due to variability in the angle of incidence, which modifies Eq. (2). The output of the model is a probability of injury for a laser exposure to the human skin.

All the modules shown in Fig. 1 are detailed in the following sections. The ED_{50} , Slope, and Angle models were constructed to capture the essential physical features involved in each, but can be refined in the future as more empirical and modeling results are available and included.

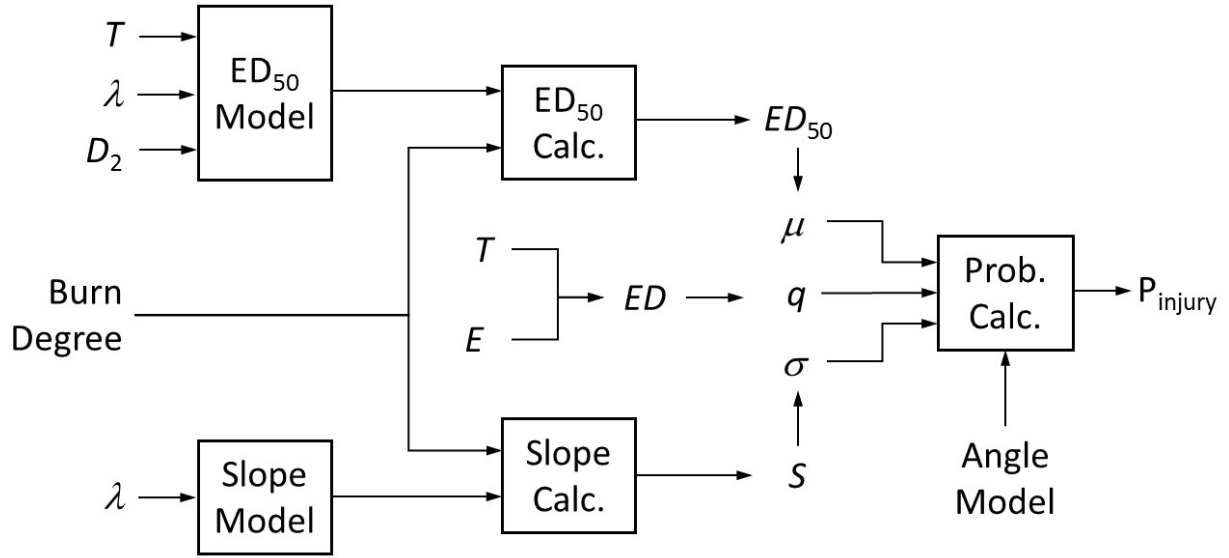


Figure 1. The components of the dose-response model, inputs, and data flow. The components are the ED_{50} and Slope Models, the ED_{50} and Slope Calculations, and the Probability Calculation. The inputs are the wavelength λ , exposure duration T , $1/e^2$ beam diameter D_2 , irradiance E , and degree of burn.

3.0 ED_{50} MODEL

3.1 Introduction

The ED_{50} Model is a generalized form for the ED_{50} , also known as the damage threshold, across all applicable wavelengths, exposure durations, and beam diameters. A mathematical formulation empirically describes the spectral-temporal-spatial domain (400 nm to 2000 nm, 1 μ s to 10 s, and 0.5 cm to 10 cm) in a functional form. As will be shown, the ED_{50} Model scales the maximum permissible exposure (MPE) in the ANSI Z136.1 American National standard for safe use of laser [1] across all applicable wavelengths and exposure durations, with an additional factor accounting for beam diameter.

Unlike the case with retina ED_{50} data, the skin ED_{50} data is sparse. For consistency, the sources of data used to model the ED_{50} were further limited to those generated by Air Force Research Laboratory (AFRL) personnel or collaborators [2-6] using Yucatan mini-pigs at near-infrared (NIR) wavelengths (1000 nm to 2000 nm) with a MVL requirement 24 hours after exposure. The ED_{50} for skin is expressed in terms of peak radiant exposure H_0 , with units of J/cm². The sources of data typically report ED_{50} in terms of power Φ or energy Q , and all report spot sizes as $1/e^2$ diameters D_2 . For an exposure duration T , the relationships between quantities are

$$Q = \Phi \cdot T \quad (6)$$

and

$$H_0 = \frac{8 Q}{\pi D_2^2} \quad (7)$$

3.2 Exposure Duration Dependence

The ANSI Z136.1 standard MPE has a $T^{1/4}$ exposure duration dependence [1]. The experimental data have a similar trend with exposure duration, as shown in Fig. 2. Therefore, a $T^{1/4}$ exposure duration dependence for the ED_{50} , based on the MPE trend, is reasonable.

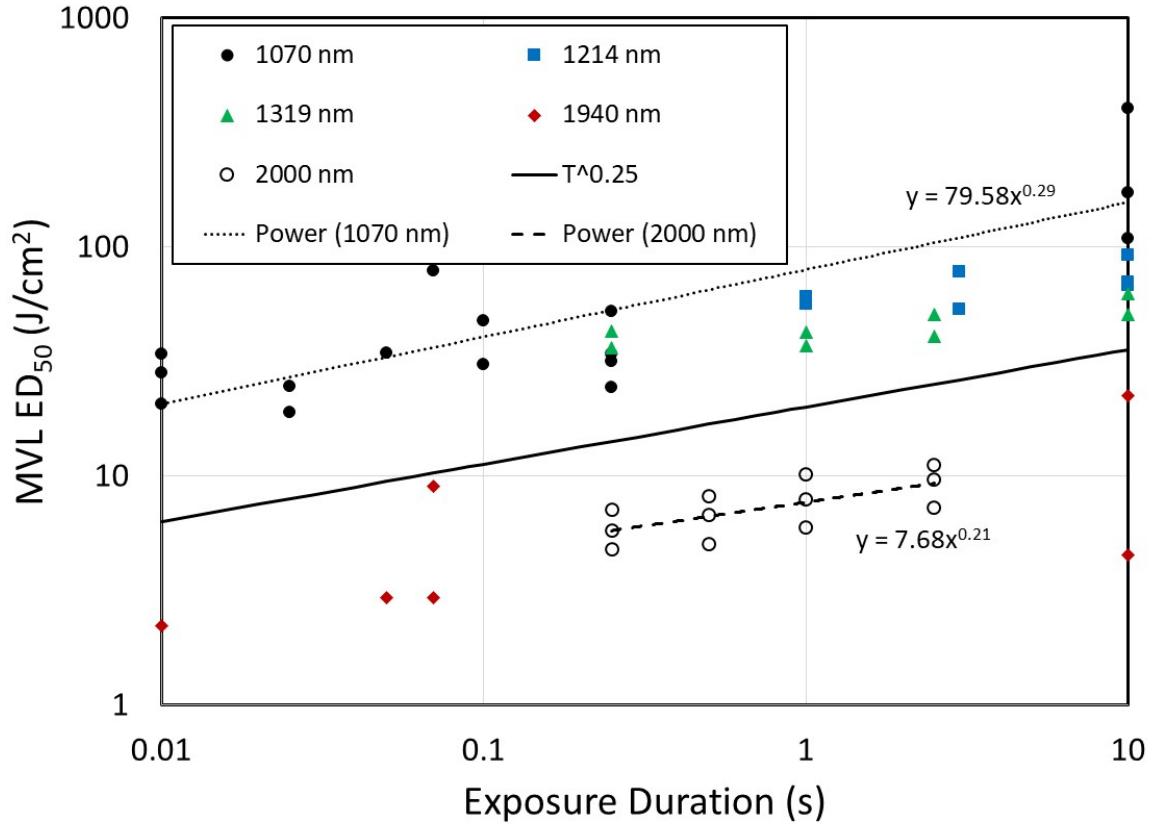


Figure 2. Exposure duration dependence of the ED_{50} from experimental data. Fits to a power law are shown for selected wavelengths and for the $T^{1/4}$ dependence.

3.3 Beam Diameter Dependence

Determining the dependence of ED_{50} on beam diameter used a combination of experimental data and simulation results. The Scalable Effects Simulation Environment (SESE) computer program models the thermal response of tissue to incident laser radiation by performing time-dependent simulations in a three-dimensional spatial domain [7]. The relevant physical, optical, and thermal properties of the skin tissue layers required as inputs to SESE are listed in Table 1. Experimental

and simulation results for ED_{50} as a function of beam diameter are shown in Figs. 3 and 4, respectively. The ED_{50} always decreases with increasing beam diameter due to effects of thermal diffusion. From the experimental data, the dependence on beam diameter D varies with wavelength, with an average dependence of $D^{-1/3}$. While the experimental data suggests a simple power-law dependence on beam diameter, the SESE results shown in Fig. 4 do not support this conclusion. The beam diameters simulated with SESE extend to both smaller and larger diameters than the experimental data, and show a non-power-law dependence on beam diameter.

Table 1. Skin tissue layer optical and thermal properties at the indicated wavelengths.

Layer	Thickness (cm)	Density (kg/m ³)	Absorption Coeff. (1/m)		Reduced Scattering Coeff. (1/m)		Specific Heat (J/(kg K))	Thermal Conductivity (W/(m K))
			1070 nm	2000 nm	1070 nm	2000 nm		
Epidermis	6.8×10^{-3}	1190	36	2176	6020	0	3600	0.21
Dermis	0.35	1116	17	5802	1540	0	3660	0.49
Fat	1.5	971	74	N/A	1120	N/A	2070	0.16

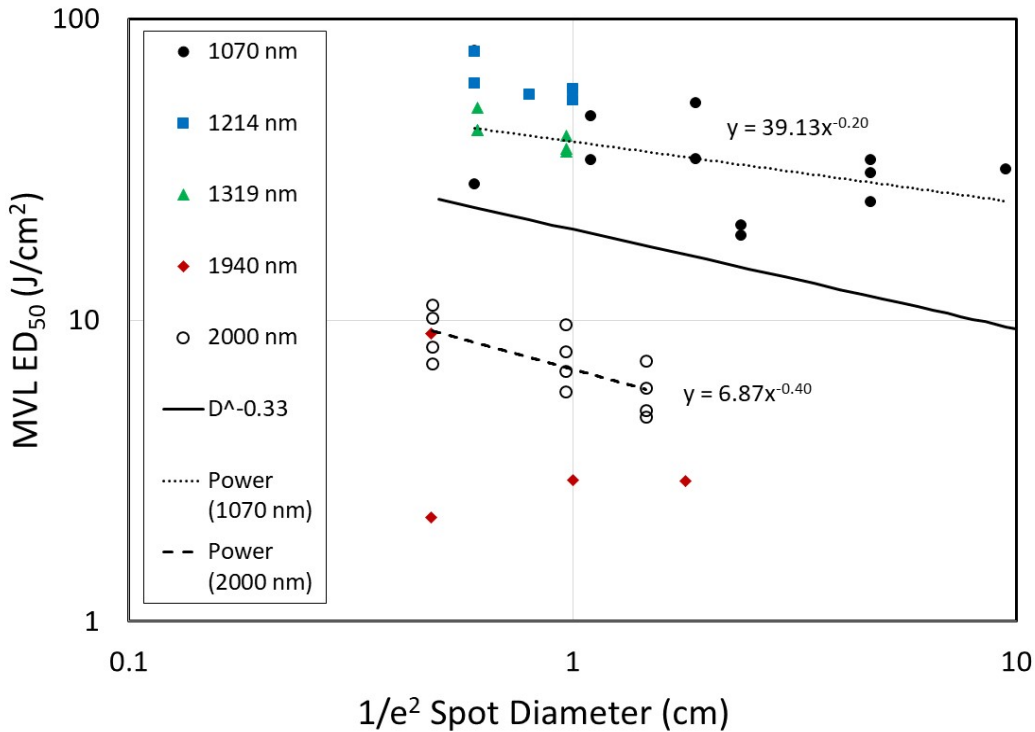


Figure 3. Beam diameter dependence of the ED_{50} from experimental data. Fits to a power law are shown for selected wavelengths and for a $D^{-1/3}$ dependence.

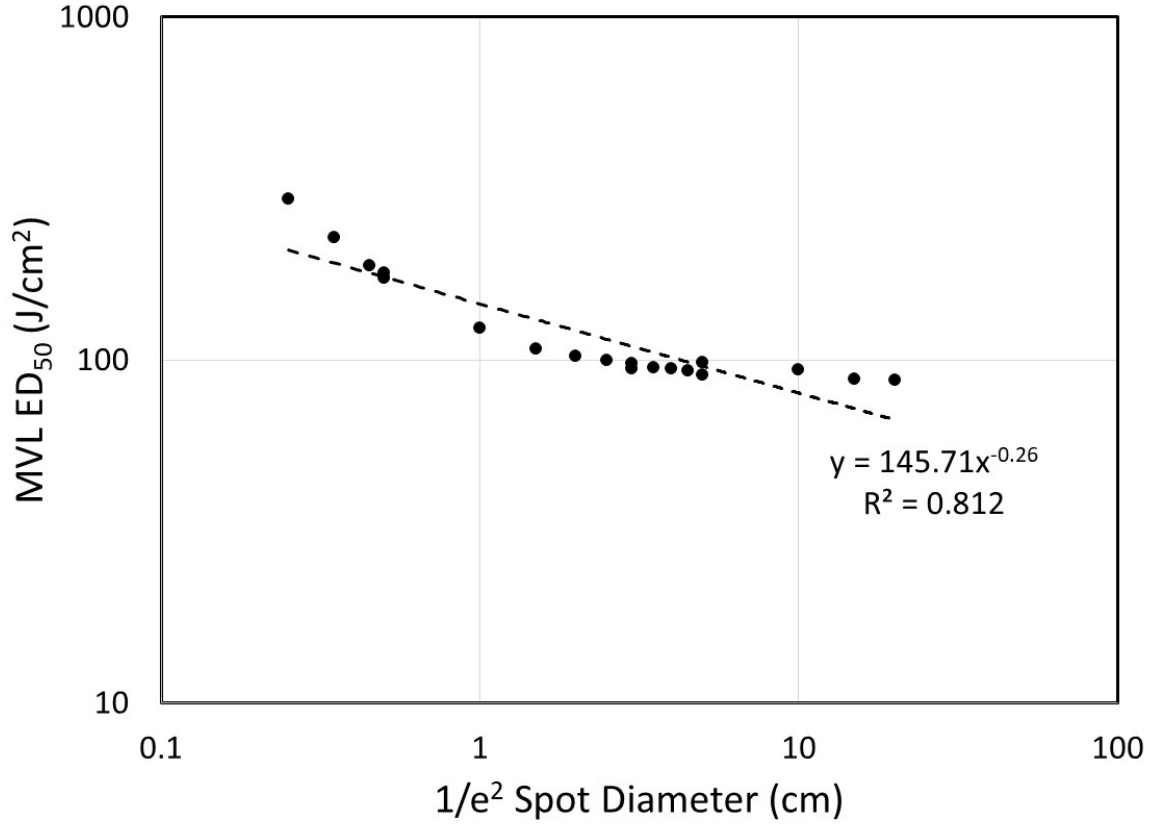


Figure 4. Beam diameter dependence of the ED_{50} from SESE simulations at a wavelength of 1070 nm and 1 s exposure duration. Points are model output and the dashed line is a power law fit to the modeled outputs.

The SESE results shown in Fig. 4 prompted additional SESE simulations at different exposure durations, but at a wavelength of 2000 nm to facilitate comparison with the best experimental data as a function of beam diameter [6]. The results of these simulations are shown in Fig. 5 over a range of exposure durations. Dependence on beam diameter increases as the exposure duration increases, with essentially no dependence for the larger beam diameters. A fit of the SESE results with the expression

$$ED_{50} = aD^{-2} + b. \quad (8)$$

yields excellent agreement over a range of exposure durations, as shown in Fig. 6.

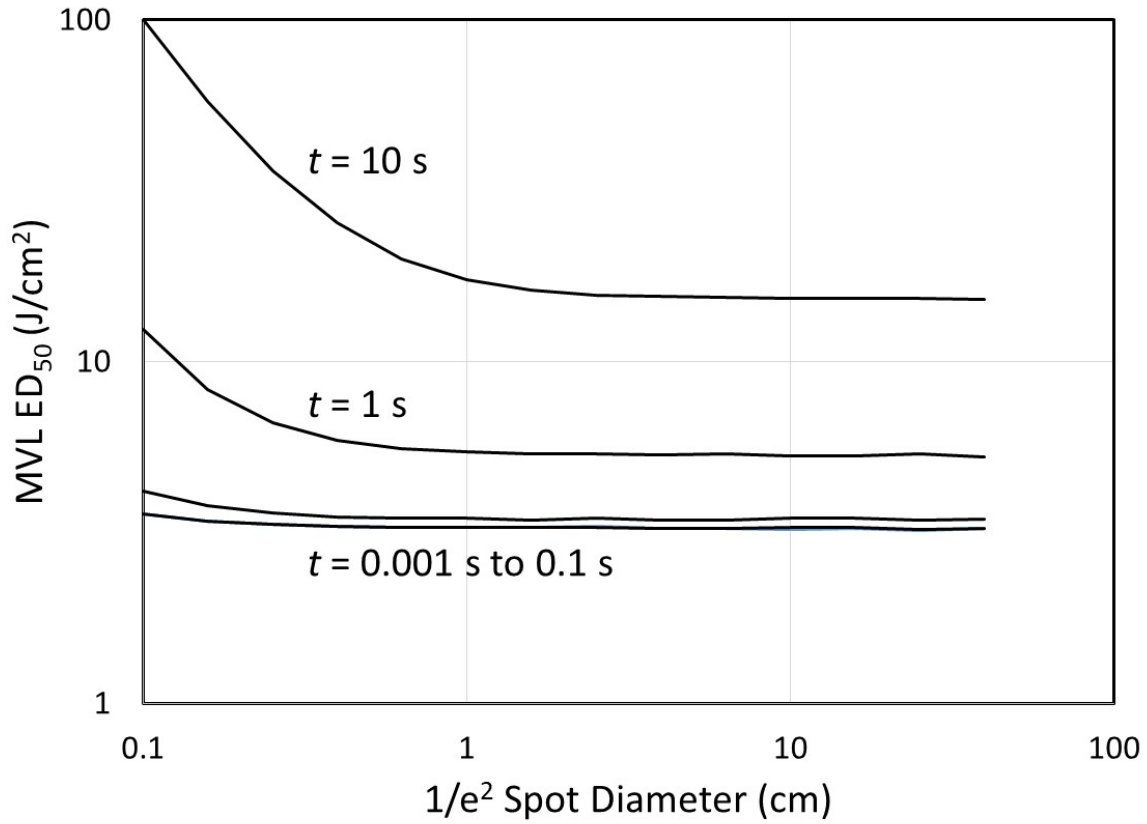


Figure 5. SESE simulation results at a wavelength of 2000 nm as a function of beam diameter with indicated exposure durations.

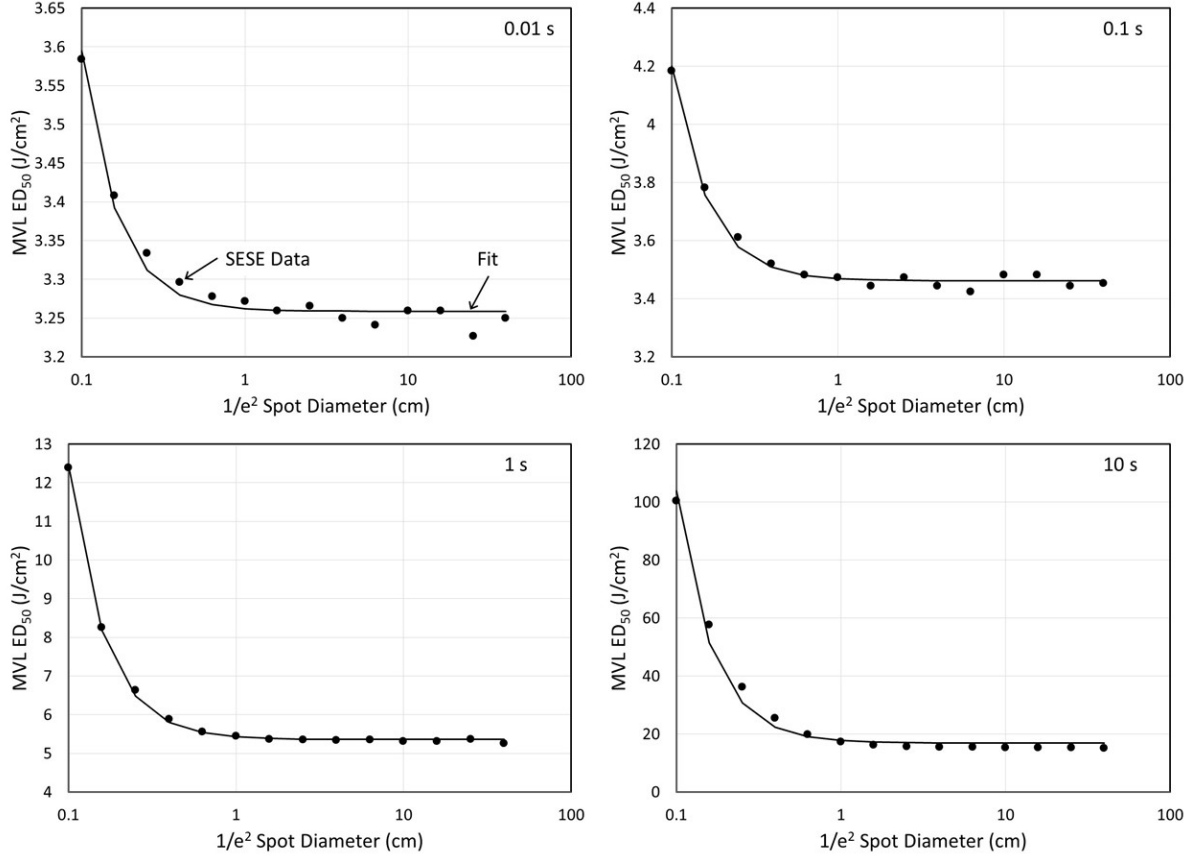


Figure 6. Model fits of SESE simulation data at a wavelength of 2000 nm for the indicated exposure durations.

The next step is to make a connection to experimental data. The data at a wavelength of 2000 nm [6] has a power-law dependence on beam diameter,

$$ED_{50} = cD^n. \quad (9)$$

Matching ED_{50} slopes and large-diameter values between Eqs. (8) and (9) yields expressions for the parameters a and b in terms of c and n ,

$$a = \frac{-c}{2} D^{n+2}, \quad (10)$$

$$b = \frac{n+2}{2} cD^n. \quad (11)$$

The values of c and n from experimental results, and the corresponding values of a and b , are listed in Table 2 for a range of exposure durations. The resulting fits to the experimental data are shown in Fig. 7 for three exposure durations. The best agreement is achieved at larger beam diameters,

which are typically of greater interest for dose-response models applicable for outdoor, uncontrolled environments.

Table 2. Experiment and model fitting parameters for ED as a function of beam diameter.

	Experiment		Model	
$T(s)$	c	n	a	b
0.25	5.5627	-0.358	0.9957	4.567
0.5	6.1712	-0.418	1.2898	4.8814
1	7.3568	-0.469	1.7252	5.6316
2.5	8.8103	-0.368	1.6211	7.1892

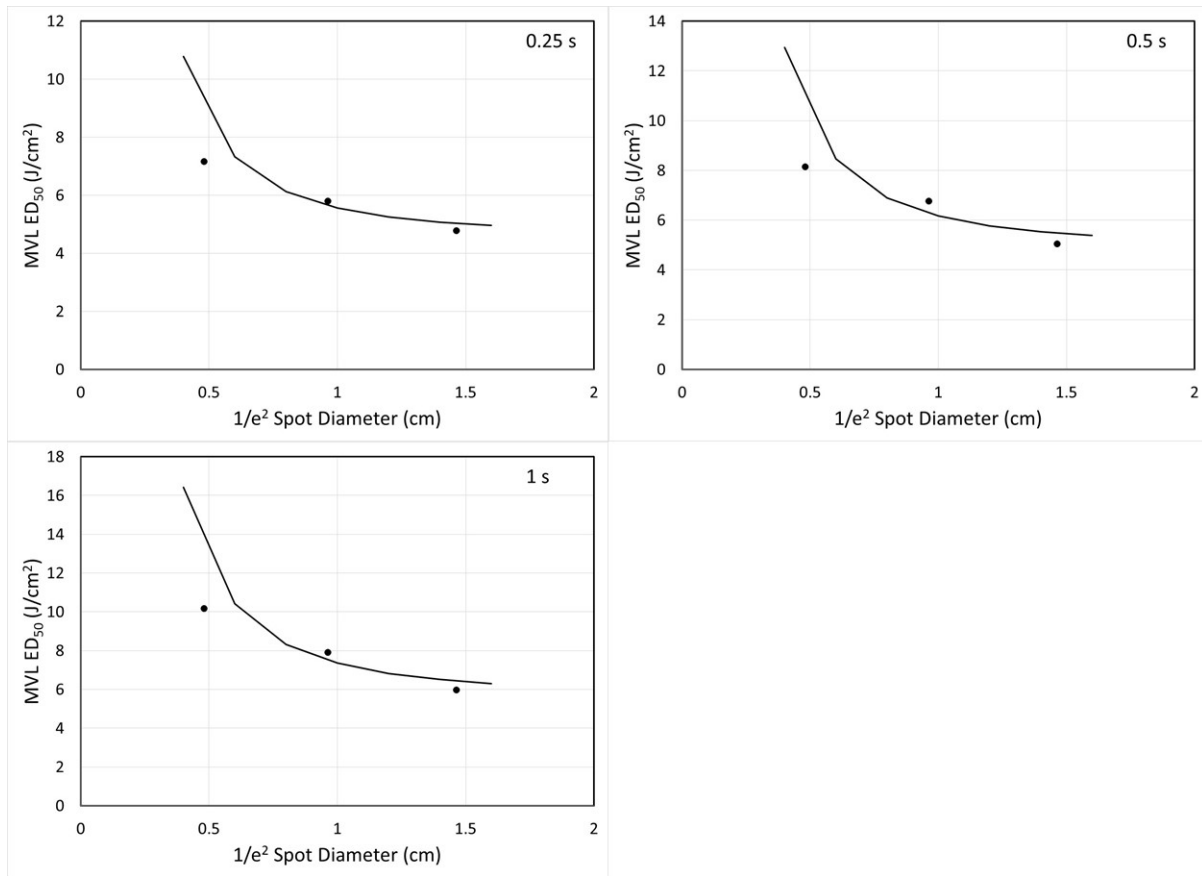


Figure 7. Empirical model fits to experimental data for beam diameter dependence at a wavelength of 2000 nm for the indicated exposure durations.

Normalizing to large beam diameters yields

$$ED_{50}(T, D) \propto A(T)D^{-2} + 1, \quad (12)$$

where the normalization factor $A(T) = a/b$ is given by

$$A(T) = 0.3 \cdot T^{1/4}. \quad (13)$$

based on the exposure duration dependence shown in Fig. 8.

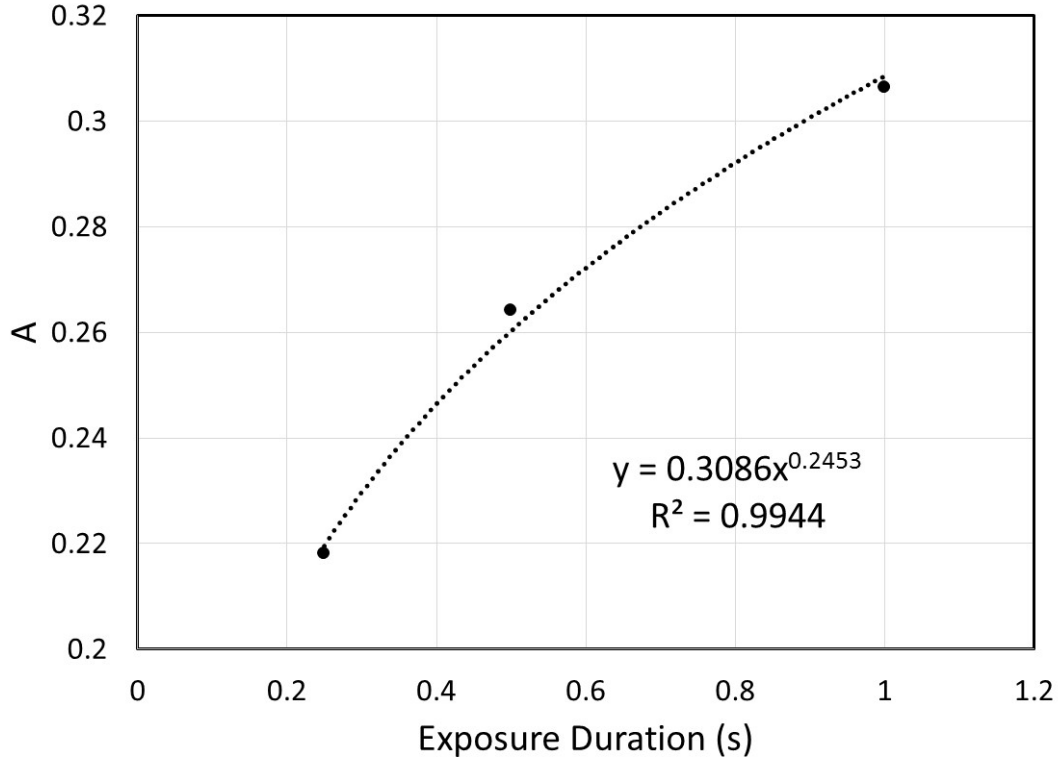


Figure 8. Exposure duration dependence of the normalization factor A in the ED_{50} model dependence on beam diameter.

The diameter of the limiting aperture D_L in the ANSI Z136.1 standard is 3.5 mm [1] which is associated with a $1/e$ diameter for the exposing beam. This corresponds to a $1/e^2$ diameter of 0.5 cm. The conversion of an ED_{50} determined with a beam diameter D_2 to its value with a beam diameter D_L is

$$ED_{50}(T, D_L) = ED_{50}(T, D_2) \cdot \left[\frac{A(T)D_L^{-2} + 1}{A(T)D_2^{-2} + 1} \right]. \quad (14)$$

The ratio of the modeled ED_{50} at this beam diameter to the experimental ED_{50} , for various exposure durations and beam diameters, provides an estimate of the uncertainty of the beam diameter model. The ratio of ED_{50} at experimental beam diameters to that at the limiting beam diameter D_L of 0.5 cm is given in Table 3. Based on these results, a 20 % uncertainty in the ED_{50} resulting from the beam diameter model is assigned.

Table 3. Uncertainty in the beam diameter model.

T (s)	D (cm)	$ED_{50}(T, D) / ED_{50}(T, D_L)$		Difference (%)
		Calculated	Experiment	
0.25	1	0.656	0.809	19
0.25	1.5	0.592	0.668	11
0.5	1	0.623	0.831	25
0.5	1.5	0.553	0.617	10
1	1	0.591	0.776	24
1	1.5	0.515	0.587	12

3.4 MVL ED_{50}

The MVL ED_{50} for skin scales as $T^{1/4}$ and D_2^{-2} for exposure duration and $1/e^2$ beam diameter, respectively, as detailed in the previous two sections. The remaining step is to assign a value to the MVL ED_{50} based on the ratio of experimental values to the MPE. The most extensive experimental data was collected at a wavelength of 1070 nm [2]. Applying the beam diameter model to obtain ED_{50} values at a common diameter of 0.5 cm, the ratio of ED_{50} to MPE over a range of exposure durations is 21.5 with a standard deviation of 7.5. The specific data used for the ratio is given in Table 4. Here, D_2 , T , and Q are the experimental $1/e^2$ beam diameter, exposure duration, and threshold energy, respectively. The ED_{50} at a beam diameter of D_2 is calculated using Eq. (9), while the ED_{50} at the limiting beam diameter D_L is calculated using Eq. (14). The largest and smallest ratios, 52.15 and 11.21, were excluded from the average ratio.

The ratio at a wavelength of 1070 nm, and other wavelengths [3-6], along with another experiment at 1070 nm [8], are shown in Fig. 9. The ratios at wavelengths of 1214 nm and 1319 nm are significantly less than 21.5, while those at the longer wavelengths of 1940 nm and 2000 nm are in agreement with the ratio at 1070 nm, as is the most-recent data by DeLisi at a wavelength of 1070 nm [8]. Investigations of the origin of the discrepancy at wavelengths in the 1200 nm to 1300 nm range yielded no conclusions, although possibilities are incorrect MPEs or the influence of water content and absorption. The agreement of ratios at wavelengths near 1000 nm and 2000 nm provides confidence in using a value of 21.5 to scale the MPE to the MVL ED_{50} . Since porcine experimental subjects have skin properties comparable to those of humans, there is no adjustment from a non-human to a human ED_{50} , in contrast to the adjustment in the retinal human dose-response model [9].

Table 4. Experimental data at a wavelength of 1070 nm used to scale the MPE to the ED_{50} .

D_2 (cm)	T (s)	Q (J)	$ED_{50}(D_2)$ (J/cm ²)	$ED_{50}(D_L)$ (J/cm ²)	MPE (J/cm ²)	ED_{50}/MPE
0.6	0.01	4	28.29	30.89	1.74	17.76
0.6	0.07	11.1	78.52	88.88	2.83	31.42
0.6	10	57.1	403.90	510.01	9.78	52.15
1.1	0.01	16.1	33.88	43.34	1.74	24.92
1.1	0.1	22.6	47.56	69.91	3.09	22.60
1.1	10	82	172.57	375.34	9.78	38.38
1.9	0.05	48.6	34.28	51.70	2.60	19.88
1.9	0.25	74.2	52.34	91.38	3.89	23.50
1.9	10	154	108.63	296.61	9.78	30.33
2.4	0.01	46.6	20.60	27.96	1.74	16.08
2.4	0.025	43	19.01	27.51	2.19	12.58
2.4	0.25	55.3	24.45	43.59	3.89	11.21
4.7	0.025	213.3	24.59	36.13	2.19	16.52
4.7	0.1	267	30.78	51.16	3.09	16.54
4.7	0.25	295	34.01	62.26	3.89	16.01
9.5	0.25	1125	31.74	58.54	3.89	15.05

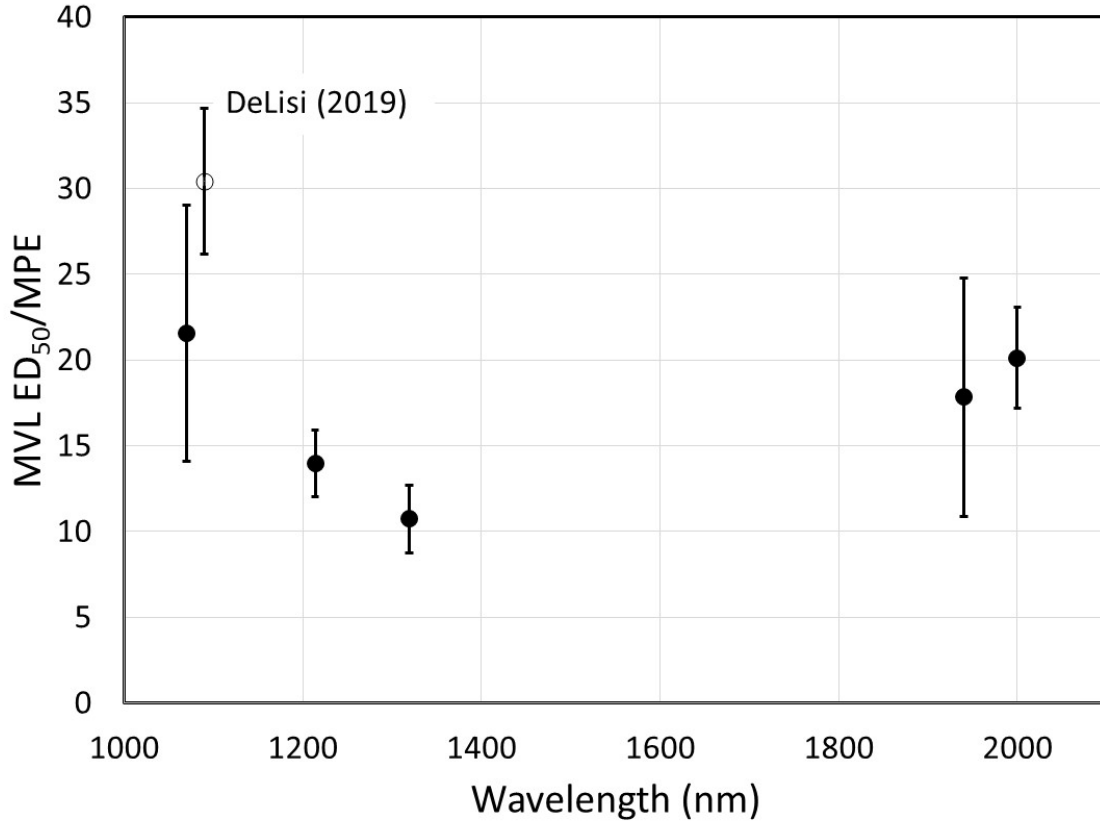


Figure 9. Ratio of experimental ED_{50} to MPE over ranges of exposure duration at each wavelength, with experimental results scaled to a common beam diameter of 0.5 cm.

The ED_{50} model for skin MVL is therefore

$$MVL ED_{50}(\lambda, T, D_2) = 21.5 \times MPE(\lambda, T) \times \left[\frac{A(T)D_2^{-2} + 1}{A(T)(0.5 \text{ cm})^{-2} + 1} \right], \quad (15)$$

with

$$A(T) = 0.3 \cdot T^{0.25}, \quad (16)$$

where λ is the wavelength, T is the exposure duration, and D_2 is the $1/e^2$ beam diameter. The agreement between model and experiment is illustrated in Fig. 10 at a wavelength of 1070 nm as a function of exposure duration. While the Vincelette data [2] was used to determine the ratio of ED_{50} to MPE, the excellent agreement between model and experiment for other sources of data [8, 10, 11] provides high confidence in the model.

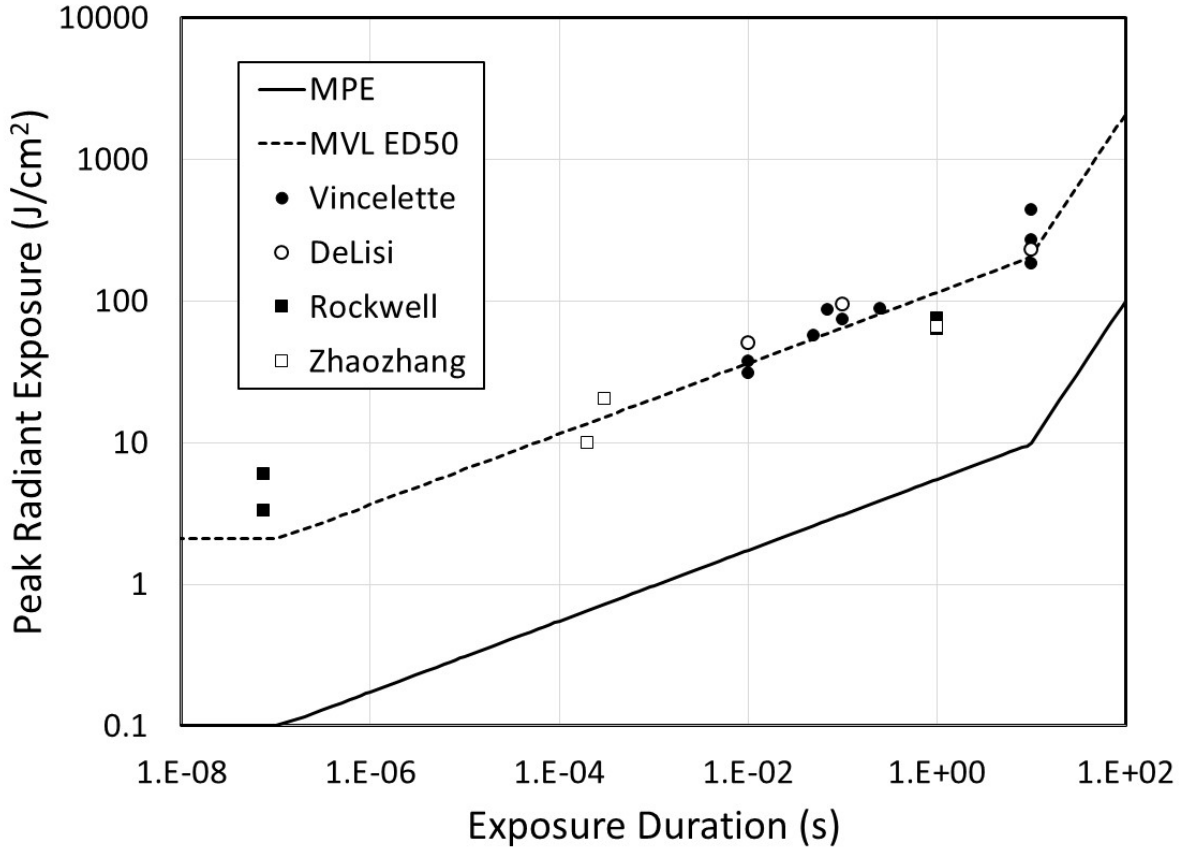


Figure 10. Time dependence of ED_{50} at 1070 nm for experimental data, the MVL ED_{50} model, and the MPE.

3.5 Supra-Threshold ED_{50}

An MVL is equivalent to a first-degree burn. Laser illumination can also cause more severe burns, termed supra-threshold effects [12]. The thresholds for these effects were determined using SESE simulations at a wavelength of 1070 nm. The Arrhenius damage integral Ω quantifies the damage, for which $\Omega = 0.1$ and 10,000 correspond to 1st- and 3rd-degree burns, respectively, and a temperature of 131 °C at the base of the epidermis layer is a 4th-degree burn [12]. At higher energies, ablation occurs at the onset of tissue removal. SESE calculated the threshold radiant exposures required for the different burn severities over ranges of exposure durations and beam diameters. The ratios of supra-threshold radiant exposures to those for 1st-degree burns are shown in Fig. 11 for all simulation conditions. The sections of data correspond to fixed beam diameters, with increasing exposure duration within each section. The average ratios and standard deviations for supra-threshold effects are given in Table 5.

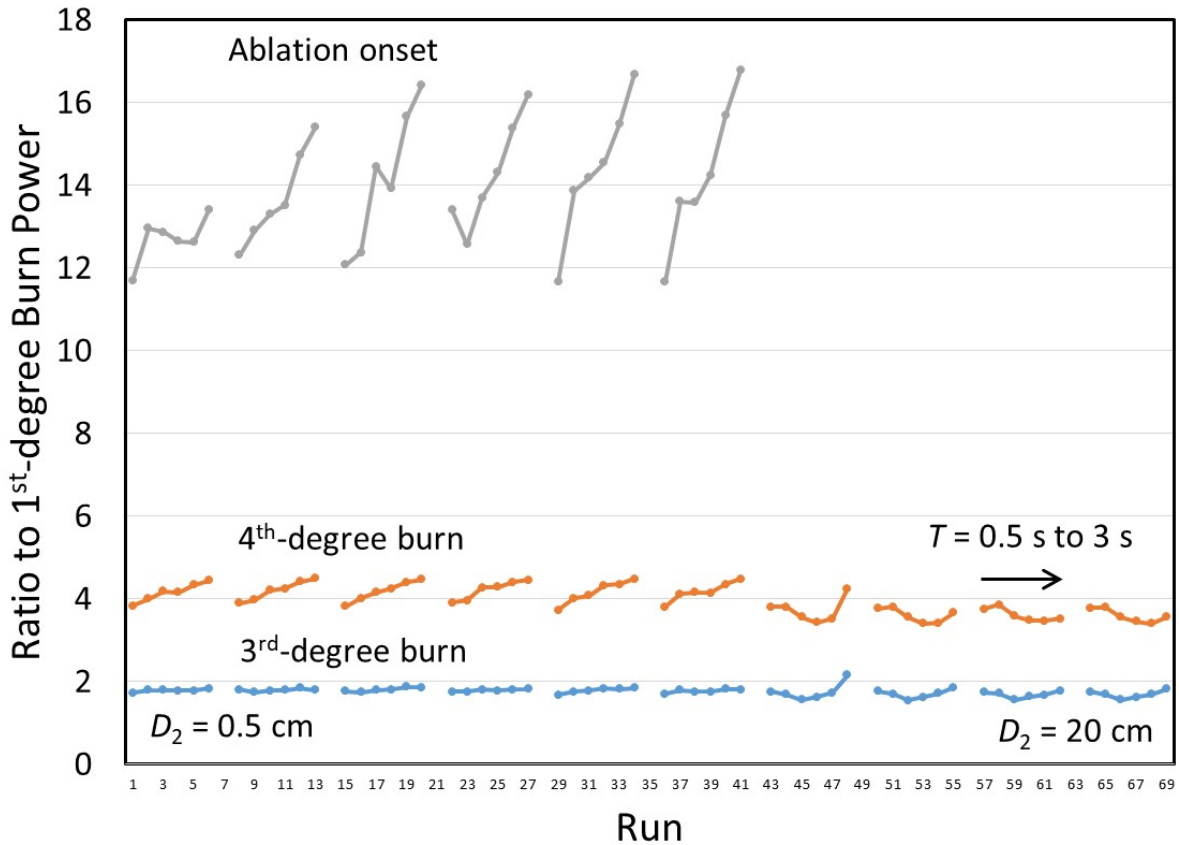


Figure 11. Ratio to 1st-degree burn power for 3rd-degree burn, 4th-degree burn, and ablation onset.

Table 5. Supra-threshold ratios for burn severities.

	Supra-threshold Radiant Exposure Ratio to MVL Radiant Exposure	
Burn Severity	Average	Standard Deviation
1 st	1	----
3 rd	2	0.1
4 th	4	0.3
Ablation	14	2

The supra-threshold ED_{50} is given by

$$\text{Supra}_{\text{threshold}} ED_{50} = \alpha \cdot \text{MVL } ED_{50}, \quad (17)$$

where α corresponds to the average for the supra-threshold burn severity in Table 5.

4.0 SLOPE MODEL

Skin susceptibility to laser damage is a bio-physical process, so variability among humans contributes to the Slope model. The human population has a range of skin pigmentation density, but the amount of pigment is not always directly related to susceptibility. Skin contains multiple chromophores such as melanin, hemoglobin, water, and fat. The concentration of melanin determines skin color, with very low concentrations for light complexioned Caucasian skin (Type I) to high concentrations for black African skin (Type IV) [13]. The other chromophores also contribute to susceptibility, and attempts to model human variability based on absorption by these chromophores were unsuccessful. The approach by Jacques [14] resulted in excessive variability at short wavelengths due to melanin content, and also suffered from complexity and insufficient data, so was not pursued further.

Fortunately, the spectrophotometry group at the National Institute of Standards and Technology (NIST) recently measured and reported the spectral reflectance $\rho(\lambda)$ of human skin for 100 participants in the study [15]. The range of skin spectral reflectance is shown in Fig. 12, where there is obviously greater variability at wavelengths less than 1000 nm than at longer wavelengths. Also note the decrease in variability at the shortest wavelengths, in contrast to expectations based on only melanin concentration, which should have greatest variability at these wavelengths. Since thermal damage is proportional to the energy absorbed by the skin, the important quantity is the spectral absorbance $\alpha(\lambda)$,

$$\alpha(\lambda) = 1 - \rho(\lambda). \quad (18)$$

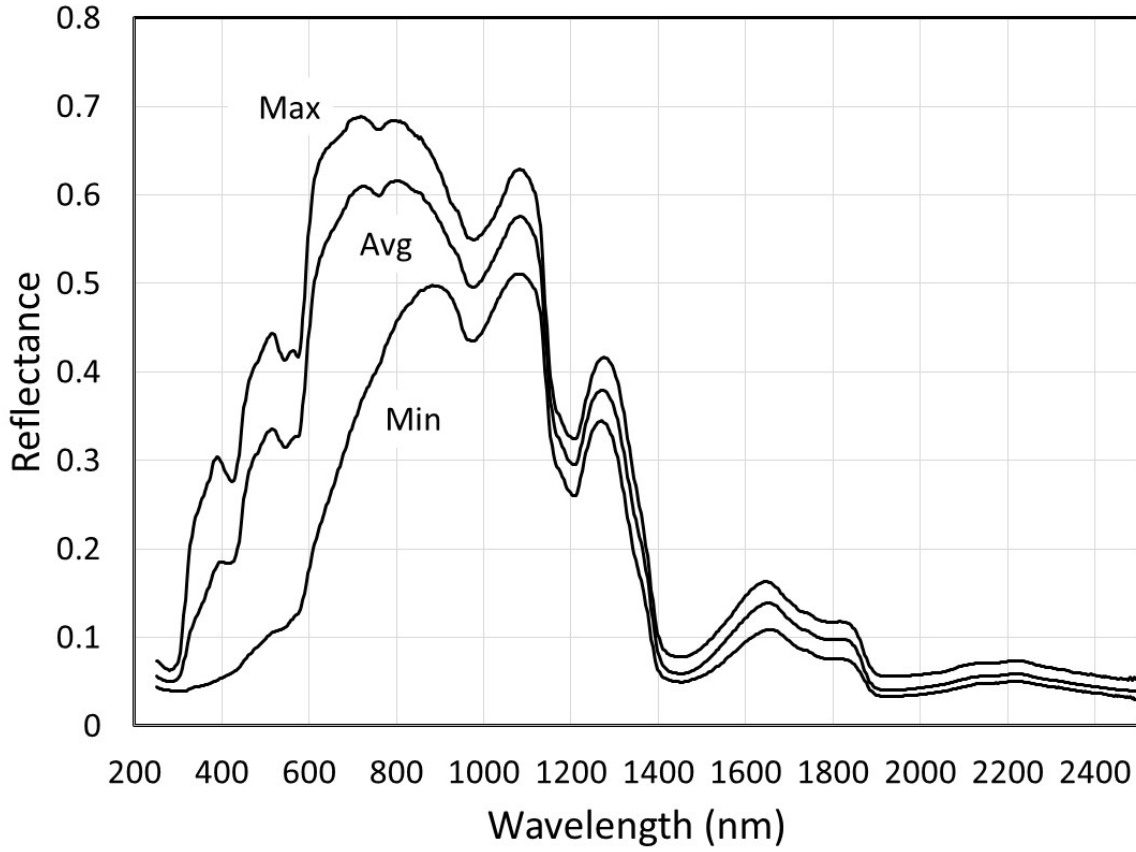


Figure 12. Spectral reflectance of human skin from NIST data.

The human skin reflectance data [15] did not include information on skin color or demographics. Therefore, the maximum and minimum values of absorptance at each wavelength are assumed to be one-standard deviation values of a Gaussian distribution. Using Eq. (1), the Slope S is therefore

$$S = \frac{\alpha_{max}}{\alpha_{mean}} \text{ or } S = \frac{\alpha_{mean}}{\alpha_{min}}. \quad (19)$$

Taking the geometrical mean yields the Slope S_A due to variability in human skin absorptance,

$$S_A(\lambda) = \sqrt{\frac{\alpha_{max}(\lambda)}{\alpha_{min}(\lambda)}}. \quad (20)$$

The maximum and minimum spectral absorptance of human skin using the NIST data is listed in Appendix A, and the resulting standard deviation σ_A is shown in Fig. 13. Variability is greatest at visible wavelengths.

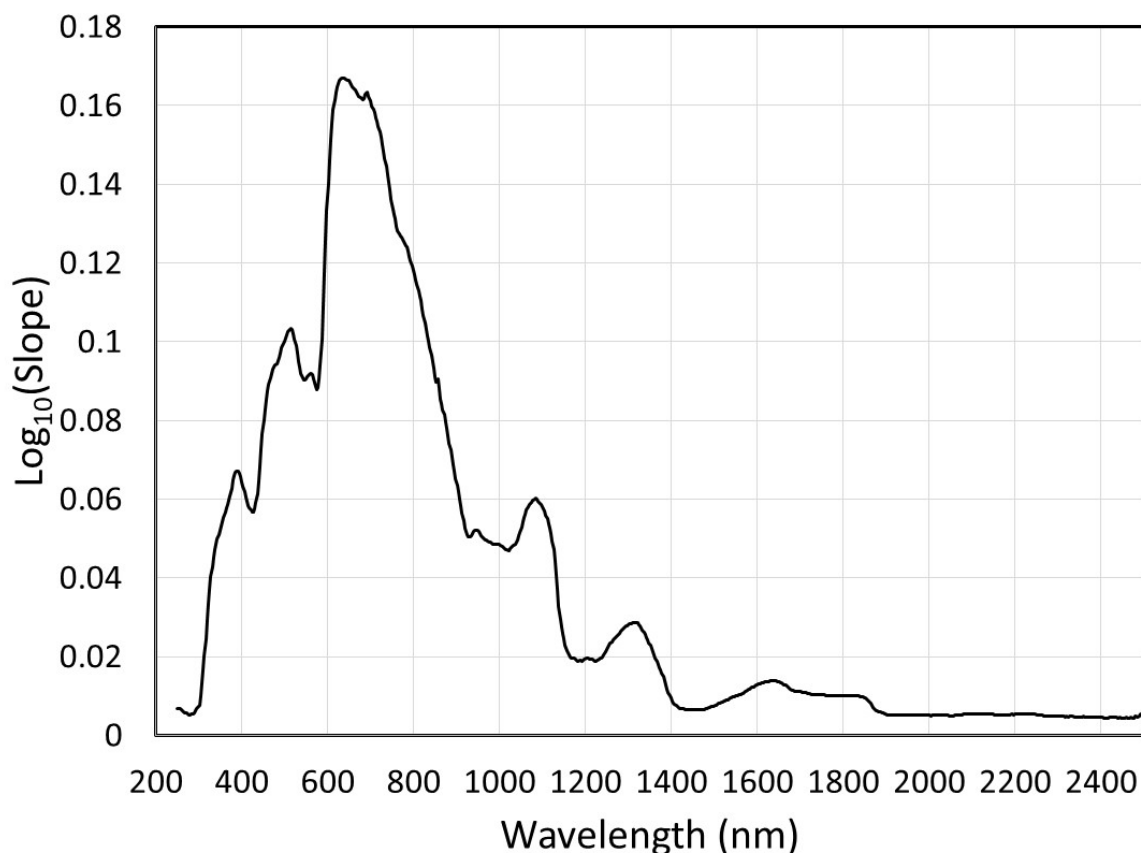


Figure 13. Spectral absorbance of human skin from NIST data.

Variability in scaling and the beam diameter dependence also contribute to the Slope, and the values v and standard uncertainties u for these sources of variability are listed in Table 6.

Table 6. Sources of variability with values and standard uncertainties, and corresponding standard deviations.

Source of Variability	Value v	Standard Uncertainty u	Standard Deviation	
			Symbol	Value
MPE Scaling	21.5	7.5	σ_M	0.130
D_2 Dependence	1	0.2	σ_D	0.079
3 rd -Degree Burn Scaling	2	0.1	σ_3	0.021
4 th -Degree Burn Scaling	4	0.3	σ_4	0.031
Ablation Scaling	14	2	σ_{Abl}	0.058

The Slope S for each source of variability is

$$S = 1 + \frac{u}{v}. \quad (21)$$

The standard deviation σ for each source of variability used in the dose-response model is given by Eq. (5), and is also listed in Table 6 with its corresponding symbol. These standard deviations add in quadrature for the final standard deviation. Therefore, for an MVL ED_{50} , the standard deviation is

$$\sigma^2 = \sigma_A^2 + \sigma_M^2 + \sigma_D^2, \quad (22)$$

while for a supra-threshold ED_{50} , the standard deviation is

$$\sigma^2 = \sigma_A^2 + \sigma_M^2 + \sigma_D^2 + \sigma_S^2, \quad (23)$$

where σ_S corresponds to either σ_3 , σ_4 , or σ_{AbI} in Table 6.

5.0 ANGLE OF INCIDENCE MODEL

The angle of incidence reduces the effective dose. For an angle of incidence θ_i , the effective dose ED in Eq. (3) is multiplied by $\cos\theta_i$ and

$$q = \log_{10}(ED \cdot \cos\theta_i) = \log_{10}(ED) + \log_{10}(\cos\theta_i). \quad (24)$$

Since the angle of incidence reduces the effective dose, the probability of injury decreases for a fixed effective dose, as illustrated in Fig. 14. Alternatively, the effective dose for a given probability of injury increases with increasing angle of incidence.

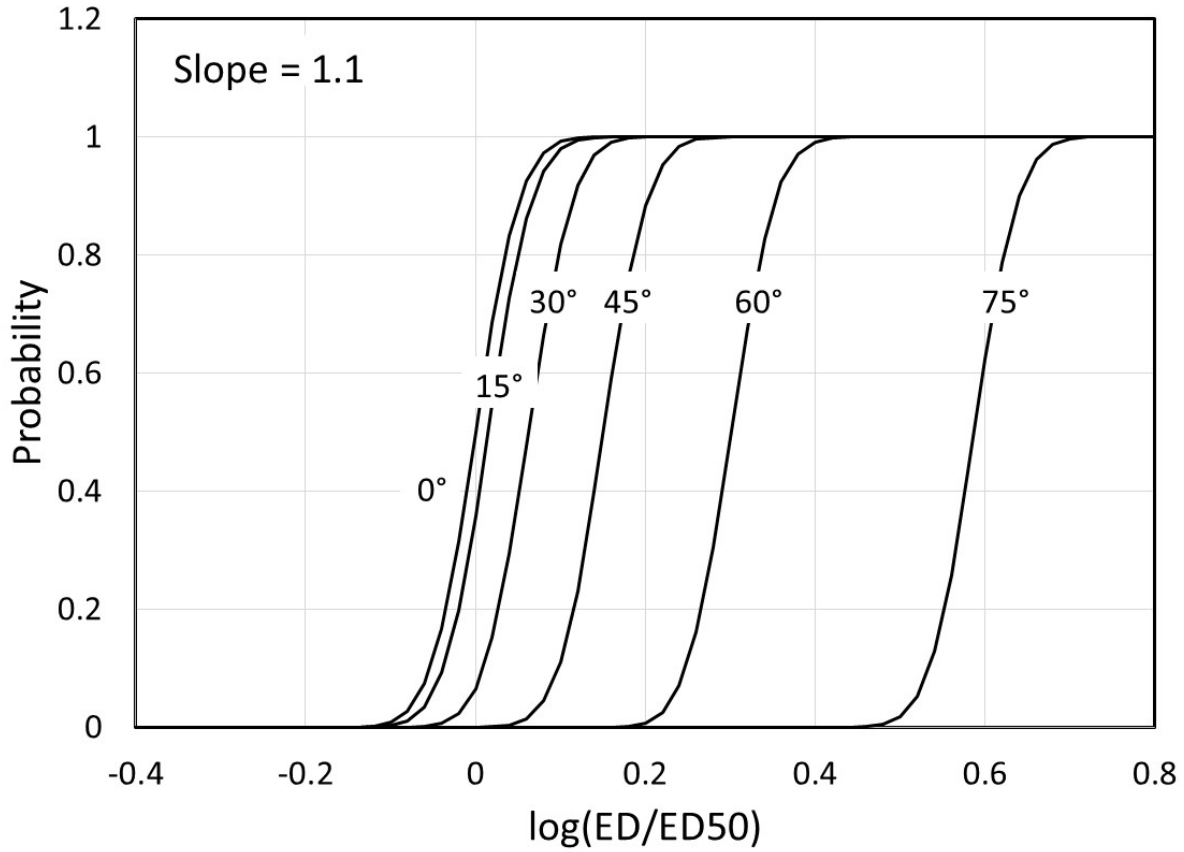


Figure 14. Probability of injury as a function of normalized effective dose for the indicated angles of incidence.

If the angle of incidence is known, Eq. (24) applies. If the angle of incidence is unknown, assumptions are required. For a flat surface, the incidence direction Ω is assumed to be uniform over the hemisphere above the surface. If the probability on the incidence direction is $P(\Omega)$, then $P(\Omega) = P(\theta, \phi) = P$. The total probability is

$$\int_0^{2\pi} \int_0^{\pi/2} P \sin\theta d\theta d\phi = 2\pi P, \quad (25)$$

so $= \frac{1}{2\pi}$. The cumulative probability function of incident angle $F(\theta)$ is

$$F(\theta) = \frac{1}{2\pi} \int_0^{2\pi} \int_0^\theta \sin\theta d\theta d\phi = 1 - \cos\theta. \quad (26)$$

Therefore, $\cos\theta \propto F(\theta)$ and if $F(\theta)$ is uniform over the interval $[0, 1]$, then $\cos\theta$ is also uniform over that interval.

For a spherical surface, illumination is assumed uniform over the cross-section of the sphere. The angle of incidence a distance r from the center of a spherical surface with unit radius is

$$\cos\theta_i = \sqrt{1 - r^2} . \quad (27)$$

For a unit sphere, the total probability is

$$\int_0^{2\pi} \int_0^1 P r dr d\varphi = \pi P , \quad (28)$$

so $P = \frac{1}{\pi}$. The cumulative probability function with radius $F(r)$ is

$$F(r) = \frac{1}{\pi} \int_0^{2\pi} \int_0^r r dr d\varphi = r^2 = 1 - \cos^2\theta_i . \quad (29)$$

Therefore, $\cos^2\theta \propto F(r)$ or $\cos\theta \propto F^{1/2}(r)$, where $F(r)$ is uniform over the interval $[0, 1]$.

Simulations of the distribution of incidence angle for a variety of surface shapes yielded the curves shown in Fig. 15. The curves for a flat plate and a sphere provide bounds for all curves. As the surfaces become more rounded, the associated curves approach that for a sphere. Since most body surfaces are rounded, a sphere provides the most reasonable and tractable assumption for the surface shape.

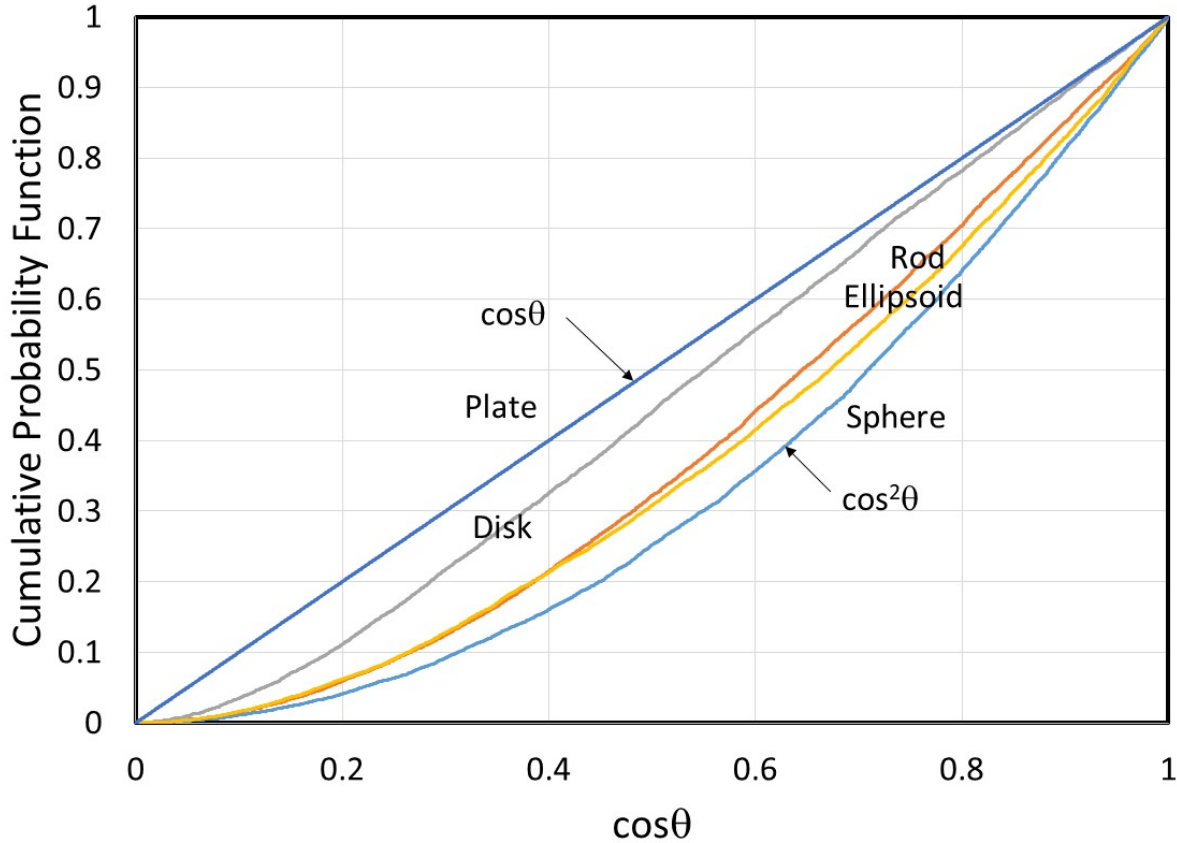


Figure 15. Cumulative probability function of incidence angle for the indicated surface shapes.

6.0 ED CALCULATION FOR SWEEP SOURCE

The effective dose ED is expressed as a peak radiant exposure with units of J/cm^2 , to correspond to the units of MPE for skin. The exposing laser beam is typically characterized by its peak irradiance E_0 and exposure duration T . For a stationary exposure, such as with experiments used to determine an ED_{50} , the exposure duration is the time interval over which the laser was illuminating the skin. An equivalent exposure duration is required if the laser sweeps over the skin. Effects from lasers depend on the energy deposited over a time interval. In general, the radiant exposure H for a time-varying irradiance is

$$H = \int E(t)dt . \quad (30)$$

If the time dependence of the irradiance is Gaussian, with time interval T_1 between the times when the irradiance is $1/e$ of its peak value E_0 ,

$$E(t) = E_0 \exp \left[- \left(\frac{2t}{T_1} \right)^2 \right] . \quad (31)$$

With this time-dependence of the irradiance, and assigning a maximum exposure duration $T_{\max}$, Eq. (30) becomes

$$H = \int_{-T_{\max}/2}^{T_{\max}/2} E_0 \exp \left[- \left(\frac{2t}{T_1} \right)^2 \right] dt . \quad (32)$$

Now,

$$\int_0^x \exp[-u^2] du = \frac{\sqrt{\pi}}{2} \operatorname{erf}(x) . \quad (33)$$

Using a change of variables $u = 2t/T_1$ and the symmetry of a Gaussian function, Eq. (32) becomes

$$H = 2E_0 \frac{T_1}{2} \int_0^{T_{\max}/T_1} \exp[-u^2] du = E_0 \frac{\sqrt{\pi}}{2} T_1 \operatorname{erf} \left(\frac{T_{\max}}{T_1} \right) . \quad (34)$$

Therefore, the exposure duration T for which the energy deposited during the exposure is given by $H = E_0 \cdot T$ is

$$T = \frac{\sqrt{\pi}}{2} T_1 \operatorname{erf} \left(\frac{T_{\max}}{T_1} \right) . \quad (35)$$

If $T_{\max} \gg T_1$ then $= \frac{\sqrt{\pi}}{2} T_1$, while if $T_{\max} \ll T_1$ then $T = T_{\max}$.

In all cases, the effective dose is

$$ED = E_0 \cdot T . \quad (36)$$

7.0 PROBABILITY CALCULATION

Calculating the probability of injury P uses an extension of Eq. (2) to account for a variable angle of incidence,

$$P(q) = \frac{1}{2} \int_0^1 \operatorname{erfc} \left[\frac{-(q + \operatorname{Log}(x^n) - \mu)}{\sqrt{2} \sigma} \right] dx , \quad (37)$$

where the shape of the surface determines the value of n . For a flat surface, $n = 1$, while for a spherical surface, $n = 1/2$. If the angle of incidence is known, then $n = 0$ and the effective dose is given by Eq. (22). Probabilities of injury for different surface shapes are shown in Fig. 16.

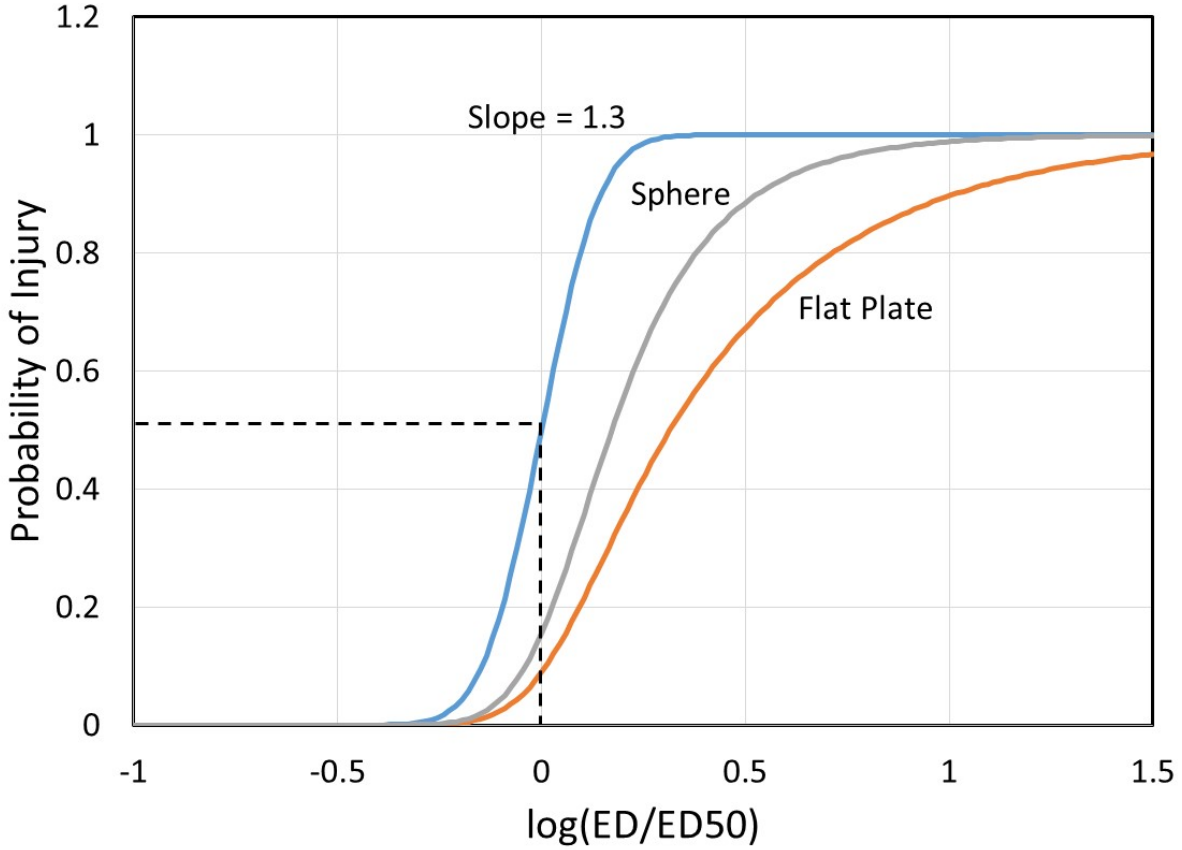


Figure 16. Probability of injury as a function of normalized effective dose for indicated surface shapes.

8.0 EXAMPLE

As an example to illustrate calculating a probability of injury, consider a laser exposure at a wavelength $\lambda = 532$ nm. The laser has a peak irradiance $E_0 = 500$ W/cm² and a $1/e^2$ beam diameter $D_2 = 5$ cm, and sweeps over the skin with an interval between times of $1/e$ of the peak irradiance of $T_1 = 100$ ms. What is the probability of a 4th-degree burn?

Since the beam is sweeping, the exposure duration T , using Eq. (32) with $T_{max} \gg T_1$, is $T = 88.6$ ms. The MPE for a wavelength $\lambda = 532$ nm and exposure duration $T = 88.6$ ms, from the ANSI Z136.1 standard, is $MPE = 0.6$ J/cm². The factor A for the beam diameter, using Eq. (16), is $A = 0.164$. The MVL ED_{50} , using Eq. (15), is

$$MVL\ ED_{50}(532, 0.0866, 5) = 21.5 \times 0.6 \times \left[\frac{0.164 \cdot 5^{-2} + 1}{0.164 \cdot 0.5^{-2} + 1} \right] = 7.84\ \text{J/cm}^2$$

The ED_{50} for a 4th-degree burn, using the ratio from Table 5, is $4^{\text{th}}\text{-}ED_{50} = 31.36$ J/cm². From Appendix A, the minimum and maximum human skin absorptance at $\lambda = 532$ nm are 0.5757 and

0.8918, respectively, so using Eq. (20) the slope $S = 1.245$ and, using Eq. (5), $\sigma_A = 0.095$. From Table 6, $\sigma_M = 0.130$, $\sigma_D = 0.079$, and $\sigma_4 = 0.031$, so $\sigma = 0.182$ using Eq. (23). The effective dose $ED = 44.3 \text{ J/cm}^2$ using Eq. (31), so $q = 1.646$. Likewise, using the 4th-degree ED_{50} , $\mu = 1.496$. Substituting these values for q , μ , and σ into Eq. (37) and using $n = 0.5$ for a spherical surface yields a probability of injury for a 4th-degree burn of 0.44. For comparison, the probability of injury for an MVL is 0.96.

9.0 SUMMARY

A general model for human laser skin dose-response was developed and presented, with the objective of improving the fidelity of models used to assess the risk of skin injury from exposure to laser radiation. The model covers the spectral range from 400 nm to 2000 nm and the temporal range from 1 μs to 10 s. It is based on experimental data and simulation results, and includes effects from minimal visible lesions to 3rd- and 4th-degree burns and onset of ablation. The model was constructed to capture the essential bio-physical features contributing to human susceptibility to laser injury of the skin, including variability between humans.

The human laser skin dose-response consists of three component models – those for the ED_{50} , the slope, and the angle of incidence. The ED_{50} model includes dependencies on wavelength, exposure duration, and beam diameter. It scales the ANSI Z136.1 safety standard MPE to an MVL ED_{50} to achieve both wavelength and exposure duration dependence. Beam diameter dependence uses an empirical fit to simulation results and experimental data. The MVL ED_{50} is further scaled to a supra-threshold ED_{50} for 3rd- or 4th-degree burns or the onset of ablation. The slope model includes variability in skin optical absorptance between humans and uncertainties in the ED_{50} model due to scaling and beam diameter dependence. The effective dose depends on the angle of incidence, and the angle of incidence model accounts for this. It assumes a uniform probability of direction and calculates an average resulting probability of injury specific to a surface shape.

While the model for human laser skin dose-response presented here captures the essential bio-physical features, the process of quantifying these features indicated many possible future improvements. Scaling the MPE to an MVL ED_{50} based on sparse experimental data is just one example. Categorizing the bio-physical features as relating to human variability or to scaling helps to organize future improvements. The simple model for human variability, based on skin reflectance, should be significantly expanded by the use of first-principles laser-tissue interaction simulations. With the proper optical and thermal properties of skin tissue layers, the simulation should approximate the human skin reflectance data shown in Fig. 12 and then provide insight on various parts of the body with different tissue layer thicknesses. This high-fidelity simulation would also improve the scaling factors for supra-threshold effects, as would additional experiments evaluating these effects. Carefully chosen and executed experiments could also refine the scaling of MPE to MVL ED_{50} , and the dependence on beam diameter. While there was sufficient experimental data to derive scaling values, additional high-quality experiments would refine and provide more confidence in these values.

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APPENDIX A – Human Skin Spectral Absorptance Range

Table A.1. Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
250	0.9263	0.9563		385	0.6984	0.9496
253	0.9269	0.9569		388	0.6967	0.9488
256	0.9281	0.9574		391	0.6963	0.9480
259	0.9295	0.9581		394	0.6971	0.9474
262	0.9312	0.9587		397	0.6993	0.9466
265	0.9328	0.9593		400	0.7028	0.9459
268	0.9341	0.9593		403	0.7066	0.9452
271	0.9351	0.9597		406	0.7102	0.9446
274	0.9357	0.9598		409	0.7137	0.9437
277	0.9367	0.9599		412	0.7171	0.9430
280	0.937	0.9600		415	0.7197	0.9422
283	0.9368	0.9602		418	0.7217	0.9415
286	0.9365	0.9603		421	0.723	0.9408
289	0.9351	0.9604		424	0.7238	0.9400
292	0.9331	0.9605		427	0.7229	0.9391
295	0.9314	0.9606		430	0.7194	0.9381
298	0.9299	0.9609		433	0.7136	0.9370
301	0.9275	0.9611		436	0.7051	0.9358
304	0.9169	0.9611		439	0.6939	0.9343
307	0.9039	0.9610		442	0.68	0.9326
310	0.8905	0.9609		445	0.6656	0.9307
313	0.875	0.9607		448	0.652	0.9286
316	0.8574	0.9605		451	0.6407	0.9266
319	0.8388	0.9601		454	0.6312	0.9248
322	0.8224	0.9594		457	0.6229	0.9228
325	0.8083	0.9586		460	0.6155	0.9212
328	0.7958	0.9579		463	0.6094	0.9195
331	0.7856	0.9573		466	0.6043	0.9178
334	0.777	0.9568		469	0.5999	0.9164
337	0.7699	0.9564		472	0.5965	0.9150
340	0.7645	0.9562		475	0.5939	0.9135
343	0.7596	0.9559		478	0.5913	0.9122
346	0.7555	0.9556		481	0.5895	0.9110
349	0.7515	0.9552		484	0.5866	0.9097
352	0.7475	0.9550		487	0.5833	0.9082
355	0.7434	0.9546		490	0.5795	0.9067
358	0.7393	0.9541		493	0.5752	0.9053
361	0.7348	0.9538		496	0.5716	0.9036
364	0.7309	0.9534		499	0.569	0.9021
367	0.727	0.9528		502	0.5657	0.9006
370	0.7232	0.9522		505	0.5626	0.8992
373	0.7192	0.9516		508	0.56	0.8978
376	0.7128	0.9515		511	0.5578	0.8965
379	0.7053	0.9508		514	0.5565	0.8954

382	0.7011	0.9502		517	0.5566	0.8944
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Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
520	0.5582	0.8935		664	0.3365	0.7158
523	0.5614	0.8929		667	0.3352	0.7112
526	0.5657	0.8926		670	0.3337	0.7065
529	0.5707	0.8923		673	0.3323	0.7020
532	0.5757	0.8918		676	0.3306	0.6973
535	0.5796	0.8913		679	0.329	0.6926
538	0.5829	0.8907		682	0.327	0.6879
541	0.5855	0.8900		685	0.3244	0.6834
544	0.5865	0.8891		688	0.3205	0.6786
547	0.5859	0.8879		691	0.3174	0.6735
550	0.5838	0.8864		694	0.3168	0.6687
553	0.5813	0.8847		697	0.3152	0.6643
556	0.5789	0.8830		700	0.3144	0.6602
559	0.5769	0.8811		703	0.314	0.6558
562	0.5759	0.8791		706	0.3133	0.6520
565	0.5756	0.8774		709	0.3128	0.6483
568	0.5771	0.8758		712	0.3125	0.6439
571	0.5812	0.8746		715	0.3121	0.6399
574	0.5827	0.8732		718	0.312	0.6358
577	0.5798	0.8712		721	0.3119	0.6322
580	0.5724	0.8681		724	0.3121	0.6285
583	0.5599	0.8636		727	0.3132	0.6248
586	0.5397	0.8577		730	0.3139	0.6217
589	0.515	0.8507		733	0.3151	0.6186
592	0.4908	0.8431		736	0.3167	0.6160
595	0.468	0.8354		739	0.318	0.6127
598	0.4476	0.8276		742	0.3193	0.6097
601	0.4297	0.8200		745	0.3204	0.6065
604	0.4142	0.8126		748	0.3226	0.6038
607	0.4015	0.8058		751	0.3246	0.6010
610	0.3909	0.7996		754	0.3254	0.5984
613	0.3818	0.7939		757	0.3256	0.5956
616	0.3747	0.7885		760	0.3265	0.5924
619	0.3691	0.7833		763	0.3263	0.5890
622	0.3646	0.7782		766	0.3253	0.5850
625	0.3608	0.7735		769	0.3238	0.5808
628	0.3573	0.7691		772	0.3218	0.5763
631	0.3543	0.7646		775	0.3199	0.5717
634	0.3521	0.7600		778	0.3188	0.5680
637	0.3501	0.7556		781	0.318	0.5642
640	0.348	0.7512		784	0.317	0.5611
643	0.3464	0.7468		787	0.3166	0.5580
646	0.3449	0.7425		790	0.3166	0.5547
649	0.3432	0.7381		793	0.3167	0.5515
652	0.3417	0.7336		796	0.3167	0.5484
655	0.3405	0.7292		799	0.3164	0.5450

658	0.3394	0.7249		802	0.3163	0.5420
661	0.338	0.7204		805	0.3169	0.5396

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
808	0.3167	0.5370		952	0.4344	0.5515
811	0.3178	0.5349		955	0.4392	0.5564
814	0.3185	0.5326		958	0.4436	0.5603
817	0.3189	0.5304		961	0.4466	0.5626
820	0.3205	0.5280		964	0.4481	0.5636
823	0.3217	0.5260		967	0.4489	0.5643
826	0.3237	0.5245		970	0.4495	0.5650
829	0.3256	0.5235		973	0.4502	0.5654
832	0.3275	0.5226		976	0.4507	0.5653
835	0.3287	0.5212		979	0.4506	0.5646
838	0.3298	0.5193		982	0.4501	0.5635
841	0.3313	0.5171		985	0.4492	0.5620
844	0.3327	0.5153		988	0.4479	0.5604
847	0.3334	0.5126		991	0.4465	0.5586
850	0.3355	0.5105		994	0.4449	0.5564
853	0.3366	0.5087		997	0.4431	0.5540
856	0.3350	0.5081		1000	0.4412	0.5517
859	0.3385	0.5081		1003	0.4396	0.5492
862	0.3423	0.5075		1006	0.4377	0.5463
865	0.3435	0.5062		1009	0.4357	0.5431
868	0.3451	0.5052		1012	0.4337	0.5399
871	0.3467	0.5045		1015	0.4317	0.5367
874	0.3490	0.5038		1018	0.4296	0.5336
877	0.3514	0.5033		1021	0.4271	0.5304
880	0.3540	0.5028		1024	0.4239	0.5272
883	0.3569	0.5025		1027	0.4207	0.5241
886	0.3599	0.5027		1030	0.4177	0.5210
889	0.3633	0.5027		1033	0.4148	0.5181
892	0.3664	0.5028		1036	0.4118	0.5152
895	0.3693	0.5030		1039	0.4085	0.5121
898	0.3726	0.5033		1042	0.4049	0.5092
901	0.3760	0.5040		1045	0.4011	0.5065
904	0.3795	0.5046		1048	0.3974	0.5039
907	0.3832	0.5054		1051	0.3934	0.5018
910	0.3873	0.5066		1054	0.3894	0.4997
913	0.3916	0.5080		1057	0.3857	0.4977
916	0.3963	0.5093		1060	0.3824	0.4955
919	0.4008	0.5110		1063	0.3793	0.4939
922	0.4046	0.5134		1066	0.3769	0.4926
925	0.4080	0.5158		1069	0.3749	0.4912
928	0.4110	0.5183		1072	0.3736	0.4903
931	0.4131	0.5210		1075	0.3725	0.4895
934	0.4148	0.5240		1078	0.3716	0.4893
937	0.4165	0.5276		1081	0.3710	0.4894
940	0.4187	0.5318		1084	0.3709	0.4893

943	0.4221	0.5363		1087	0.3716	0.4897
946	0.4256	0.5411		1090	0.3727	0.4903
949	0.4297	0.5464		1093	0.3741	0.4913

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
1096	0.3759	0.4927		1240	0.6206	0.6799
1099	0.3778	0.4940		1243	0.6144	0.6749
1102	0.3803	0.4959		1246	0.6085	0.6708
1105	0.3830	0.4979		1249	0.6034	0.6670
1108	0.3862	0.4995		1252	0.5988	0.6637
1111	0.3894	0.5017		1255	0.5949	0.6610
1114	0.3934	0.5040		1258	0.5917	0.6591
1117	0.3980	0.5071		1261	0.5892	0.6575
1120	0.4036	0.5110		1264	0.5869	0.6563
1123	0.4114	0.5167		1267	0.5854	0.6555
1126	0.4216	0.5240		1270	0.5844	0.6554
1129	0.4351	0.5336		1273	0.5840	0.6558
1132	0.4528	0.5463		1276	0.5838	0.6569
1135	0.4740	0.5620		1279	0.5840	0.6584
1138	0.4980	0.5791		1282	0.5848	0.6603
1141	0.5230	0.5987		1285	0.5860	0.6628
1144	0.5476	0.6216		1288	0.5877	0.6658
1147	0.5695	0.6416		1291	0.5897	0.6694
1150	0.5888	0.6589		1294	0.5926	0.6735
1153	0.6052	0.6725		1297	0.5961	0.6779
1156	0.6189	0.6834		1300	0.6002	0.6834
1159	0.6284	0.6919		1303	0.6051	0.6898
1162	0.6360	0.6986		1306	0.6106	0.6962
1165	0.6416	0.7035		1309	0.6165	0.7035
1168	0.6453	0.7068		1312	0.6232	0.7113
1171	0.6478	0.7091		1315	0.6303	0.7196
1174	0.6503	0.7117		1318	0.6382	0.7283
1177	0.6534	0.7145		1321	0.6467	0.7375
1180	0.6571	0.7179		1324	0.6558	0.7468
1183	0.6617	0.7220		1327	0.6655	0.7562
1186	0.6652	0.7260		1330	0.6752	0.7655
1189	0.6683	0.7295		1333	0.6848	0.7743
1192	0.6710	0.7322		1336	0.6943	0.7828
1195	0.6724	0.7343		1339	0.7034	0.7911
1198	0.6736	0.7360		1342	0.7122	0.7988
1201	0.6746	0.7380		1345	0.7207	0.8059
1204	0.6755	0.7392		1348	0.7287	0.8121
1207	0.6759	0.7398		1351	0.7367	0.8182
1210	0.6758	0.7393		1354	0.7446	0.8239
1213	0.6742	0.7369		1357	0.7525	0.8296
1216	0.6708	0.7330		1360	0.7605	0.8353
1219	0.6664	0.7273		1363	0.7686	0.8416
1222	0.6604	0.7200		1366	0.7774	0.8481
1225	0.6529	0.7123		1369	0.7870	0.8554

1228	0.6450	0.7046		1372	0.7974	0.8636
1231	0.6376	0.6974		1375	0.8080	0.8723
1234	0.6312	0.6908		1378	0.8194	0.8815
1237	0.6255	0.6850		1381	0.8321	0.8918

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
1384	0.8460	0.9021		1528	0.8978	0.9354
1387	0.8592	0.9115		1531	0.8961	0.9344
1390	0.8708	0.9194		1534	0.8944	0.9333
1393	0.8804	0.9262		1537	0.8926	0.9322
1396	0.8889	0.9317		1540	0.8908	0.9310
1399	0.8960	0.9360		1543	0.8891	0.9298
1402	0.9018	0.9392		1546	0.8874	0.9286
1405	0.9064	0.9416		1549	0.8857	0.9273
1408	0.9100	0.9435		1552	0.8840	0.9260
1411	0.9128	0.9449		1555	0.8823	0.9247
1414	0.9148	0.9459		1558	0.8808	0.9235
1417	0.9163	0.9467		1561	0.8793	0.9223
1420	0.9176	0.9474		1564	0.8773	0.9210
1423	0.9186	0.9479		1567	0.8752	0.9197
1426	0.9194	0.9484		1570	0.8730	0.9183
1429	0.9201	0.9489		1573	0.8708	0.9169
1432	0.9206	0.9493		1576	0.8686	0.9156
1435	0.9209	0.9496		1579	0.8665	0.9143
1438	0.9213	0.9499		1582	0.8646	0.9130
1441	0.9215	0.9501		1585	0.8626	0.9116
1444	0.9217	0.9502		1588	0.8606	0.9103
1447	0.9218	0.9502		1591	0.8587	0.9090
1450	0.9220	0.9504		1594	0.8569	0.9077
1453	0.9220	0.9504		1597	0.8550	0.9065
1456	0.9220	0.9504		1600	0.8532	0.9053
1459	0.9219	0.9503		1603	0.8515	0.9041
1462	0.9217	0.9501		1606	0.8498	0.9029
1465	0.9213	0.9499		1609	0.8484	0.9018
1468	0.9209	0.9494		1612	0.8470	0.9007
1471	0.9204	0.9489		1615	0.8456	0.8996
1474	0.9198	0.9484		1618	0.8444	0.8986
1477	0.9191	0.9478		1621	0.8433	0.8976
1480	0.9183	0.9473		1624	0.8421	0.8967
1483	0.9174	0.9468		1627	0.8410	0.8960
1486	0.9164	0.9463		1630	0.8399	0.8951
1489	0.9154	0.9458		1633	0.8390	0.8943
1492	0.9143	0.9453		1636	0.8382	0.8937
1495	0.9132	0.9447		1639	0.8376	0.8930
1498	0.9120	0.9440		1642	0.8370	0.8924
1501	0.9107	0.9433		1645	0.8368	0.8919
1504	0.9095	0.9426		1648	0.8368	0.8914
1507	0.9082	0.9419		1651	0.8370	0.8912
1510	0.9068	0.9411		1654	0.8375	0.8911

1513	0.9054	0.9402		1657	0.8383	0.8911
1516	0.9039	0.9393		1660	0.8394	0.8912
1519	0.9024	0.9384		1663	0.8402	0.8915
1522	0.9009	0.9375		1666	0.8413	0.8920
1525	0.8994	0.9365		1669	0.8426	0.8925

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
1672	0.8441	0.8932		1816	0.8823	0.9241
1675	0.8459	0.8940		1819	0.8823	0.9242
1678	0.8481	0.8951		1822	0.8824	0.9245
1681	0.8501	0.8964		1825	0.8826	0.9247
1684	0.8518	0.8977		1828	0.8829	0.9249
1687	0.8535	0.8990		1831	0.8834	0.9253
1690	0.8549	0.9003		1834	0.8839	0.9258
1693	0.8563	0.9017		1837	0.8847	0.9264
1696	0.8577	0.9029		1840	0.8857	0.9272
1699	0.8589	0.9041		1843	0.8871	0.9283
1702	0.8601	0.9052		1846	0.8886	0.9294
1705	0.8614	0.9063		1849	0.8906	0.9308
1708	0.8627	0.9075		1852	0.8928	0.9324
1711	0.8640	0.9086		1855	0.8953	0.9342
1714	0.8653	0.9097		1858	0.8985	0.9362
1717	0.8668	0.9107		1861	0.9021	0.9385
1720	0.8682	0.9117		1864	0.9060	0.9410
1723	0.8694	0.9127		1867	0.9104	0.9435
1726	0.8703	0.9133		1870	0.9150	0.9459
1729	0.8710	0.9138		1873	0.9196	0.9484
1732	0.8714	0.9141		1876	0.9236	0.9510
1735	0.8717	0.9144		1879	0.9272	0.9541
1738	0.8720	0.9147		1882	0.9303	0.9567
1741	0.8724	0.9151		1885	0.9328	0.9590
1744	0.8731	0.9159		1888	0.9351	0.9607
1747	0.8738	0.9166		1891	0.9372	0.9621
1750	0.8748	0.9175		1894	0.9388	0.9633
1753	0.8760	0.9185		1897	0.9403	0.9643
1756	0.8771	0.9195		1900	0.9414	0.9650
1759	0.8781	0.9204		1903	0.9424	0.9655
1762	0.8790	0.9211		1906	0.9428	0.9659
1765	0.8797	0.9219		1909	0.9431	0.9662
1768	0.8803	0.9224		1912	0.9434	0.9663
1771	0.8808	0.9227		1915	0.9437	0.9664
1774	0.8812	0.9231		1918	0.9438	0.9665
1777	0.8817	0.9234		1921	0.9439	0.9668
1780	0.8820	0.9238		1924	0.9440	0.9667
1783	0.8822	0.9240		1927	0.9439	0.9666
1786	0.8825	0.9242		1930	0.9438	0.9667
1789	0.8827	0.9244		1933	0.9437	0.9668
1792	0.8828	0.9245		1936	0.9438	0.9668
1795	0.8827	0.9245		1939	0.9439	0.9669

1798	0.8827	0.9245		1942	0.9440	0.9667
1801	0.8826	0.9244		1945	0.9441	0.9667
1804	0.8825	0.9244		1948	0.9442	0.9665
1807	0.8824	0.9243		1951	0.9440	0.9664
1810	0.8824	0.9243		1954	0.9438	0.9663
1813	0.8823	0.9242		1957	0.9439	0.9663

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
1960	0.9439	0.9662		2104	0.9313	0.9552
1963	0.9439	0.9661		2107	0.9310	0.9548
1966	0.9439	0.9661		2110	0.9308	0.9544
1969	0.9438	0.9661		2113	0.9305	0.9541
1972	0.9436	0.9661		2116	0.9301	0.9540
1975	0.9434	0.9659		2119	0.9299	0.9536
1978	0.9433	0.9658		2122	0.9298	0.9532
1981	0.9429	0.9656		2125	0.9296	0.9530
1984	0.9426	0.9654		2128	0.9293	0.9527
1987	0.9425	0.9654		2131	0.9293	0.9525
1990	0.9426	0.9653		2134	0.9291	0.9524
1993	0.9427	0.9651		2137	0.9288	0.9523
1996	0.9426	0.9649		2140	0.9288	0.9523
1999	0.9424	0.9646		2143	0.9288	0.9520
2002	0.9422	0.9644		2146	0.9288	0.9520
2005	0.9421	0.9642		2149	0.9287	0.9520
2008	0.9418	0.9642		2152	0.9288	0.9517
2011	0.9416	0.9640		2155	0.9290	0.9518
2014	0.9414	0.9638		2158	0.9289	0.9519
2017	0.9411	0.9636		2161	0.9289	0.9517
2020	0.9408	0.9634		2164	0.9288	0.9516
2023	0.9407	0.9632		2167	0.9289	0.9517
2026	0.9405	0.9630		2170	0.9290	0.9518
2029	0.9403	0.9627		2173	0.9289	0.9515
2032	0.9403	0.9625		2176	0.9289	0.9516
2035	0.9401	0.9624		2179	0.9287	0.9516
2038	0.9399	0.9621		2182	0.9285	0.9514
2041	0.9398	0.9620		2185	0.9284	0.9513
2044	0.9397	0.9618		2188	0.9282	0.9512
2047	0.9395	0.9615		2191	0.9279	0.9509
2050	0.9394	0.9612		2194	0.9276	0.9506
2053	0.9392	0.9610		2197	0.9275	0.9504
2056	0.9388	0.9607		2200	0.9271	0.9503
2059	0.9383	0.9604		2203	0.9268	0.9501
2062	0.9380	0.9602		2206	0.9267	0.9502
2065	0.9374	0.9598		2209	0.9265	0.9501
2068	0.9369	0.9595		2212	0.9265	0.9501
2071	0.9364	0.9591		2215	0.9264	0.9501
2074	0.9359	0.9588		2218	0.9262	0.9499
2077	0.9353	0.9584		2221	0.9261	0.9498
2080	0.9348	0.9581		2224	0.9261	0.9499

2083	0.9343	0.9577		2227	0.9262	0.9499
2086	0.9339	0.9572		2230	0.9262	0.9500
2089	0.9333	0.9568		2233	0.9265	0.9501
2092	0.9330	0.9565		2236	0.9268	0.9502
2095	0.9326	0.9563		2239	0.9272	0.9506
2098	0.9320	0.9559		2242	0.9275	0.9507
2101	0.9316	0.9556		2245	0.9278	0.9509

Table A.1 (cont.) Minimum and maximum spectral absorptance of human skin.

Wavelength (nm)	Absorptance			Wavelength (nm)	Absorptance	
	Minimum	Maximum			Minimum	Maximum
2248	0.9281	0.9512		2377	0.9412	0.9612
2251	0.9288	0.9515		2380	0.9414	0.9614
2254	0.9294	0.9518		2383	0.9420	0.9621
2257	0.9297	0.9519		2386	0.9422	0.9621
2260	0.9300	0.9523		2389	0.9415	0.9623
2263	0.9306	0.9525		2392	0.9418	0.9625
2266	0.9311	0.9529		2395	0.9421	0.9627
2269	0.9316	0.9532		2398	0.9424	0.9627
2272	0.9319	0.9535		2401	0.9430	0.9633
2275	0.9321	0.9537		2404	0.9433	0.9636
2278	0.9329	0.9538		2407	0.9432	0.9627
2281	0.9329	0.9543		2410	0.9434	0.9627
2284	0.9330	0.9546		2413	0.9440	0.9634
2287	0.9334	0.9547		2416	0.9444	0.9636
2290	0.9337	0.9550		2419	0.9437	0.9640
2293	0.9341	0.9553		2422	0.9444	0.9646
2296	0.9344	0.9553		2425	0.9438	0.9638
2299	0.9342	0.9554		2428	0.9450	0.9648
2302	0.9344	0.9555		2431	0.9453	0.9654
2305	0.9349	0.9558		2434	0.9452	0.9653
2308	0.9349	0.9563		2437	0.9455	0.9661
2311	0.9354	0.9566		2440	0.9462	0.9657
2314	0.9358	0.9567		2443	0.9465	0.9664
2317	0.9360	0.9564		2446	0.9463	0.9654
2320	0.9359	0.9568		2449	0.9467	0.9656
2323	0.9363	0.9569		2452	0.9472	0.9668
2326	0.9362	0.9574		2455	0.9468	0.9661
2329	0.9367	0.9581		2458	0.9465	0.9665
2332	0.9368	0.9581		2461	0.9466	0.9664
2335	0.9372	0.9581		2464	0.9471	0.9668
2338	0.9376	0.9583		2467	0.9470	0.9668
2341	0.9380	0.9585		2470	0.9475	0.9674
2344	0.9387	0.9589		2473	0.9474	0.9667
2347	0.9390	0.9594		2476	0.9483	0.9678
2350	0.9396	0.9595		2479	0.9464	0.9676
2353	0.9399	0.9597		2482	0.9450	0.9668
2356	0.9396	0.9596		2485	0.9487	0.9690
2359	0.9395	0.9604		2488	0.9465	0.9677
2362	0.9403	0.9605		2491	0.9452	0.9698
2365	0.9405	0.9612		2494	0.9470	0.9701

2368	0.9403	0.9605		2497	0.9457	0.9708
2371	0.9408	0.9611		2500	0.9480	0.9771
2374	0.9411	0.9613				