Def Sci J, Vol 35, No 1, January 1985, pp 25–32

Thermal Effect of Pulsed Laser on Human Skin

N. C. MAJUMDAR
Defence Institute of Physiology & Allied Sciences, Delhi Cantt-110010

V. K. KOCHHAR
Defence Science Centre, Delhi-110054

Received 12 May 1982; revised 12 March 1984

Abstract. An attempt has been made to derive from theoretical considerations, some idea about safety limits of exposure with regard to radiant energy skin burns. This may be regarded as a preliminary enquiry in respect of thermal tissue damage by pulsed laser radiation, since the effects of isolated single pulses from ruby laser only have been considered. The study needs to be extended to other wavelengths as well as to trains of pulses.

1. Introduction

The technology of lasers has developed to a stage where they emit pulsed radiations of hundreds of joules with durations of the order of nanoseconds and even pico seconds, and also continuous radiation with power output of several kilowatts. It is important to have an idea of the tolerance of the human body to such intense radiations.

The subject of tolerance of the human body to microwaves has been intensively studied in the past and norms[1] have been laid down with a fair margin of safety. In the case of laser beams, the tolerance limits are still being discussed. In this paper, we shall try to derive from theoretical considerations some idea of the tolerance levels.

The skin of the human body responds differently to different wavelengths of electromagnetic radiation and, therefore, the spectral characteristics of the laser emission would determine the tolerance. In the ultraviolet, for example, photochemical reactions convert certain sterols into vitamin D and, therefore, such radiations are, up to a certain energy level, most beneficial.

Recent studies have also shown that artificial lights may be harmful to human glands. Prof Wirtman of MIT has shown that the mechanism of action is through the eye, brain and pineal gland, controlling the hormone melatonin, which in turn controls other hormones of the body. However, these involve prolonged exposures, with which the present paper is not concerned.

It has been observed that of all parts of the human body, the eye is the most sensitive to laser beams and most of the damage is caused to the retina. Injury to the eye occurs in two distinct ways. Firstly, visible light is focussed and damages the retina, and secondly, ultraviolet and infra-red may be absorbed by the cornea, lens and vitreous humour heating them beyond the danger point. For Ruby Laser (6943° A), the safe limits are given in the safety manual[2].

The specified maximum intensity permitted on the skin (excluding the eye) for all laser beams, visible, near infra-red or infra-red, is as follows :

(a) 0.1 J/cm²/pulse for pulsed lasers, and

(b) 1.0 Watt/cm² for CW lasers.

For carbon dioxide laser 0.1 Watt/cm² on the cornea and 0.3 Watt/cm² on the skin cause lesions.

For electromagnetic waves, the human body behaves very much like water and the response is dependent on the wavelength. In the past the subject of temperature distribution inside the layered tissues was studied by Chan[3], *et al.* The tissues were radiated by external energy sources such as microwave, ultrasound and numerical results were obtained by solving thermal diffusion equation by method of finite difference. In this paper, we consider lasers emitting radiation in the visible part of the spectrum only. In this band of wavelengths, it is the colour of the skin which determines the fraction of the radiation which would penetrate. A black skin, therefore, absorbs a greater fraction of light than white skin. The reflectance of human skin as a function of wavelength is shown for the two complexions[2] in Fig. 1. We shall, therefore, discuss the

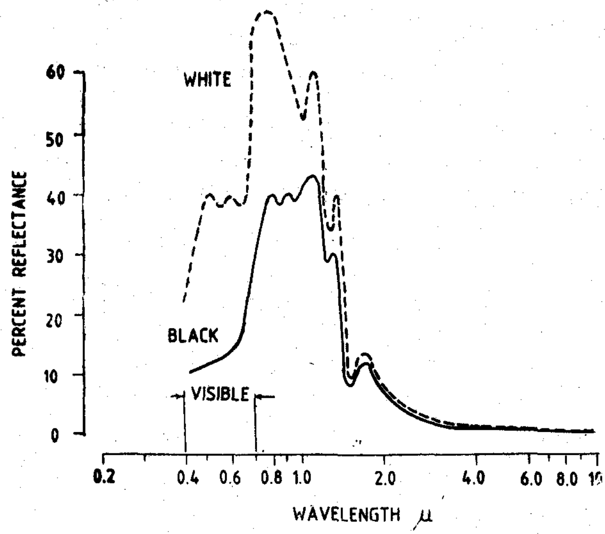

Figure 1. Spectral reflectance of black and white skin

effect on the skin for the two cases, the white skin and the black skin, and also try to estimate the effect on average Indian skins.

2. Theoretical Analysis

Safety limits of exposure with regard to radiant energy skin burns can be based only on the knowledge of temperature response of skin. The problem is rather complicated in the case of normal living skin which is remarkably translucent and far from homogeneous in depth, while reliable data on thermal and optical constants of deeper tissues are scarce. A recent computer analysis[4] of experimental observations on blackened human skin has shown marked temperature dependence of tissue conductivity.

The simplest physical model closely resembling normal unblackened skin and amenable to mathematical analysis, is a translucent, and semi-infinite composite solid. Fortunately in the case of pulsed laser radiation, certain simplifications are made possible by the fact that the pulse is monochromatic and of short duration. It follows from the principle of conservation of energy that, for a given energy input, shorter the pulse duration, the smallar the depth of penetration by the radiation and higher the rise in surface temperature. These facts are of great significance in connection with the present problem. Further, it will be reasonable to assume that the thermal inertia of the tissue will prevent any significant change in its thermal and optical constants during the short exposure period.

For mathematical formulation of the problem, we imagine the skin as a semi-infinite, homogeneous solid with distributed source along depth x from the surface, which accounts for energy absorption. The thermal conductivity, k, density, ρ, and specific heat, c, do not change during exposure period. Initially, temperature is uniform throughout the depth. The differential equation of heat conduction in one dimension is then given by

$$\frac{\partial T}{\partial t} = h \frac{\partial^2 T}{\partial x^2} + q/\rho c, \; x \geqslant 0, \; t \geqslant 0 \tag{1}$$

where, h the thermal diffusivity, equals $(k/\rho c)$, and q the rate of energy absorption per unit volume is a function of x and t. T is temperature rise above initial value.

The two boundary conditions may be expressed, as usual by

$$T = 0 \text{ for all values of } x \text{ at } t = 0 \tag{2}$$

and

$$T = 0 \text{ for all values of } t \text{ at } x = \infty. \tag{3}$$

The effect of penetrating radiation leads to the third boundary condition, viz.

$$(1 - r)\, H = - \; k\frac{\partial T}{\partial x}, \quad \text{at } x = 0 \tag{4}$$

where H is the constant intensity of the incident radiation, and r the spectral reflectance of the skin for the particular wavelength, λ. In other words, $(1-r) H$ is the rate at which energy is absorbed per unit area of the surface. If α be the absorption coefficient (cm^{-1}) of the tissue for the given λ, then it follows from Beer's Law, that

$$q = \alpha H \cdot e^{-\alpha x} \tag{5}$$

This satisfies the principle of conservation of energy, since

$$\int_0^{\infty} q \, dx = H$$

Details of the solution of Eqn. (1) with the help of Eqns. (2) through (5) have been omitted. The final solution may be put in the form

$$\begin{aligned} \Delta T_x = \frac{(1-r) H}{\alpha k} \Bigg[& 2 \alpha \sqrt{\frac{ht}{\lambda}} \left\{ e^{-x^2/4ht} - \frac{x}{2} \sqrt{\frac{\lambda}{ht}} \, erfc \left(\frac{x}{2\sqrt{ht}} \right) \right\} \\ & + \frac{1}{2} e^{\alpha^2 ht} \left\{ e^{\alpha x} \, erfc \left(\alpha \sqrt{ht} + \frac{x}{2\sqrt{ht}} \right) \right. \\ & \left. + e^{-\alpha x} \, erfc \left(\alpha \sqrt{ht} - \frac{x}{2\sqrt{ht}} \right) \right\} - e^{-\alpha x} \Bigg] \end{aligned} \tag{6}$$

where; ΔT_x is temperature rise at depth x.

In the limit $x \to 0$, the rise in surface temperature T_s, will be given by

$$\Delta T_s = \frac{(1-r) H}{\alpha k} \left[2 \alpha \sqrt{\frac{ht}{\lambda}} + e^{\alpha^2 ht} \, erfc (\alpha \sqrt{ht}) - 1 \right] \tag{7}$$

Here $erfc\ (z)$ is the complimentary error function given by

$$erfc\ (z) = \frac{2}{\sqrt{\pi}} \int_0^{\infty} e^{-u^2} \, du.$$

From Eqns. (6) and (7) it is readily seen that temperature rise at any depth is always less than that at surface during the exposure period. From the stand point of tissue damage, we should, therefore confine ourselves to a study of ΔT_s, since damage will start at the surface.

It will be more convenient to generalise Eqn. (7) by introducing dimensionless parameters θ and ϕ for time and temperature rise respectively. We thus write,

$$\left. \begin{array}{l} \text{generalised time,} \quad \theta = \alpha^2 \, ht \\ \text{generalised surface temperature rise} \\ \text{per unit radiant intensity} \quad \phi = \dfrac{\alpha k}{(1-r)} \cdot \dfrac{\Delta T_s}{H} \end{array} \right\} \tag{8}$$

Substitution in Eqn. (7) yields

$$\phi = \frac{2}{\sqrt{\pi}} \sqrt{\theta} + e^{\theta} \cdot erfc \sqrt{\theta} - 1 \tag{9}$$

In the case of pulsed radiation, we are more concerned with the energy density (cals/sq cm) and not intensity of the pulse (cals/cm² sec). We, therefore, define generalised surface temperature rise per unit energy density as

$$\psi = \frac{\phi}{\theta} = \frac{\rho c}{\alpha (1-r)} \cdot \frac{\Delta T_s}{Q} \tag{10}$$

where energy, density, Q, equals H.t. The relationship between ψ and θ is shown in Fig. 2 wherefrom it will be seen that the rise in surface temperature approaches its maximum value within one per cent for a generalised pulse duration of 10^{-4}. The fall in the value is progressively steeper (on a log scale) with increasing pulse duration.

3. Practical Application

Interpretation of the above result in terms of practical parameters demands reliable knowledge of the values of the constants involved. Assuming an initial comfortable skin temperature (about 33°C), one can take $\rho c = 1$ and $k = 10^{-3}$ c. g. s. units, energy being expressed in calories. Values of optical constants depend on the nature of radiation employed, while spectral reflectance of skin surface also depends on its complexion. We shall consider the case of a ruby laser of wavelength 6943°A. From

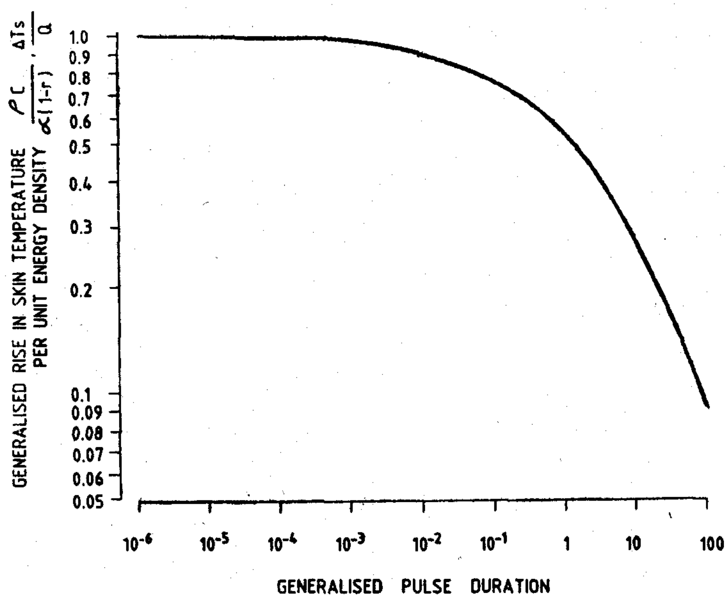

Figure 2. Generalised response of bare-skin temperature to pulsed laser radiation

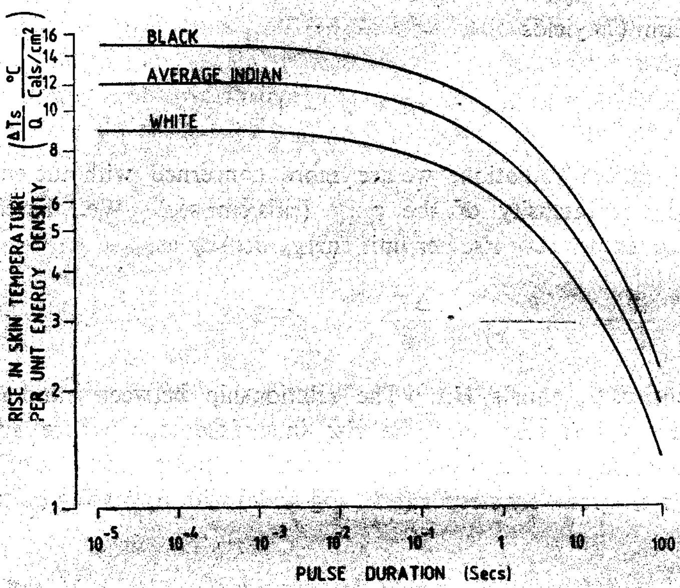

Figure 3. Temperature rise of bare human skin per unit energy density related to duration of ruby laser pulse.

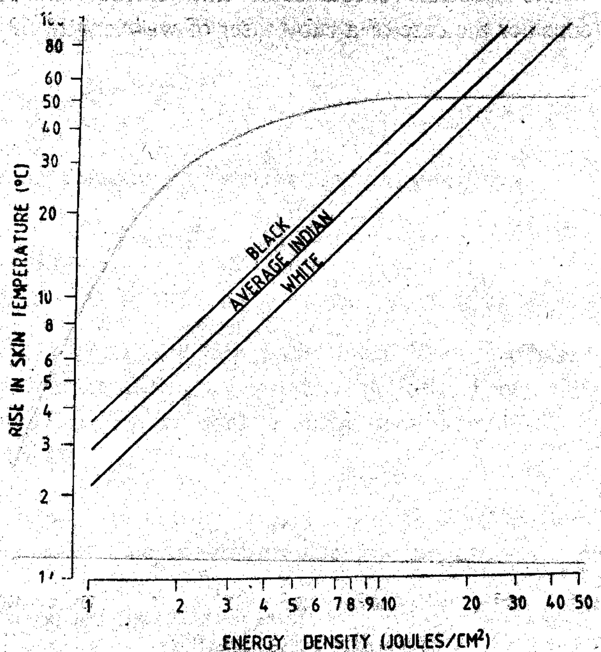

Figure 4 Temperature response of bare human skin to pulsed ruby laser of any duration below 1 milli second

the measurements reported by Hendler *et al*[1], r for this wavelength may be taken to be about 55 per cent for white skin and 25 per cent for Negro skin. For the average Indian skin, a value of about 40 per cent seems reasonable. The absorption coefficient α of subcutaneous tissue does not depend on surface complexion. Its value for $\lambda = 6943°$ A has been taken as 20 cm^{-1} as obtained from the diagram of Davis[5]. Results of computation have been shown in Fig. 3 which gives rise in skin temperature per unit energy density, as a function of 'duration of ruby laser pulse for bare human skin.

It will be seen that the temperature rise increases with decreasing pulse duration, the curve getting progressively less steep, and approaches its maximum level for a millisecond pulse. Further decrease in pulse duration has no effect on temperature rise. It is also seen that rise in temperature for average Indian skin and white skin are, respectively, 80 per cent and 60 per cent of the rise for Negro skin.

In the case of pulsed ruby laser the pulse duration can be safely assumed to be below 1 millisecond . Fig. 4 gives the temperature response as a function of energy density of the pulse for the three complexions of skin. Hardy[6] has established that the threshold temperature for tissue damage is about 45°C. If initial skin temperature as stated earlier, be 33°C, this means, all exposures up to a 12°C temperature rise may be regarded as safe. It follows that tolerance levels for white skin, average Indian skin and Negro skin are respectively 5.5, 4.2 and 3.3 joules/cm^2/pulse.

4. Conclusion

This paper may be regarded as a preliminary enquiry in respect of thermal tissue damage by pulsed laser radiation, since the effects of isolated single pulses from ruby laser only have been considered. These studies have to be extended to other wavelengths and to trains of pulses. Further studies should incorporate the total time-temperature history, so that the cumulative damage can be evaluated on the basis of reaction rate theory.

Acknowledgement

The authors are grateful to Gp. Capt. K. C. Sinha, Director, DIPAS, for his keen interest in the study and his kind permission to publish this paper.

References

1. Hendler, H., Hardy, J. D. & Dorothy Murgatroyd, 'Temperature : Its Measurement and Control in Science & Industry' (Reinhold Publishing Corporation), Vol. 3, Pt. 3, 1963, p. 211.
2. *Journal of Chemical Education*, July (1969), 492.

3. Andrew K. Chan, Rubens A. Sigelmann, Arthur W. Guy & Justus F. Lehmann, *IEEE Transactions on Bio-medical Engg*, **BME-20** (1973), 86.

4. Weaver, John, A., & Stoll, Alice, M., *Aerospace Medicine*, Jan (1969), 24.

5. Davis, Thomas, P., 'Temperature : Its Measurement and Control in Science and Industry' (Reinhold Publishing Corporation), Vol. 3, Pt. 3, 1963, p. 149.

6. Hardy, J. D., 'Proc. First National Biophysics Conference' (New Haven, Yale University Press), 1959, p. 557.