Bull. Mater. Sci., Vol. 11, Nos 2 & 3, November 1988, pp. 239–244. © Printed in India.

Laser–tissue interaction studies for medicine

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Abstract. A brief review of laser–tissue interactions is given in this article. The choice of a laser system for therapeutic use is based on laser–tissue interaction reports. Knowledge of specific molecular events that follow laser irradiation of biological materials is very important.

Keywords. Photocoagulation; photodisruption; photoablation.

1. Introduction

When two different fields like laser physics and biology begin to interact, extremely valuable and exciting new directions in research are created. McKenzie and Carruth (1984) and Telle (1986) have given extensive accounts of lasers in medicine. The biophysical modalities used in laser treatment are separated into thermal and non-thermal ones. Thermal mechanisms include vaporization and photocoagulation, while non-thermal mechanisms account for photoablation and photo-dry-etching of tissues. The details of these mechanisms are considered below.

2. Photocoagulation

Photon absorption is the first event in initiation of all photobiologic effects. Photon absorption may result in ionization, bond breaking and electron excitation or vibrational excitation. The radiant energy is absorbed by the tissue and converted into heat. The divergence angle θ of a laser beam can be written as $\theta = 4\lambda/\pi d$, where λ is the wavelength of the laser light and d is the diameter of the laser beam. Typically θ is of the order of milliradians for tissues (McKenzie and Carruth 1984). By passive thermal diffusion heat is transferred beyond the target site on the tissue. The temperature rise produced by laser irradiation is a function of time, laser energy and wavelength. It also depends upon the optical and thermal properties of the absorbing tissue. At a temperature around 60–70°C coagulation effect is dominant, and at 100°C cell water boils, resulting in cell rupture. At a temperature in the range 70–100°C the structural integrity of the cell is lost. This process of thermal denaturation leads to coagulation. Laser-induced vaporization of tissue is followed by formation of pressure waves that can cause mechanical damage in adjacent tissue. Consider the CO_2 laser whose wavelength is 10·6 μm. The absorption coefficient for radiation around 10 μm in tissue is approximately 200 cm^{-1}. From this it follows that 90% of the radiation is absorbed in a layer of less than 100 μm and the layer is heated quickly to temperatures greater than 100°C. While the cells at the surface are vaporized and removed the bulk temperature stays generally below 100°C causing coagulation, as shown in figure 1.

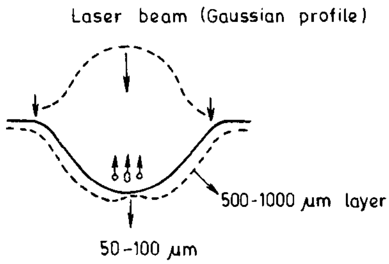


Figure 1. Photocoagulation. (Reproduced from Telle 1986.)

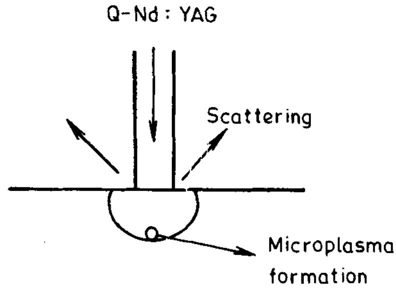


Figure 2. Photodisruption. (Reproduced from Telle 1986.)

2.1 *Retinal photocoagulation*

Retinal photocoagulation is commonly used in the treatment of retinopathy. In retinopathy abnormalities are developed in blood vessels on the surface of the retina. These new abnormal vessels are fragile and break resulting in vision loss. In the technique of pan-retinal photocoagulation (PRP), laser burns are made with 500 μm argon lasers on the retina leaving the macula untouched. PRP reduces the chances of hemorrhage and retinal detachment. However, the mechanism by which PRP produces regression of the abnormal blood vessels is not yet known.

3. Photodisruption

Photodisruption is defined as the use of high-power ionizing laser pulses to disrupt tissues (Steinert and Puliafito 1985). Light energy creates optical breakdown ionization of the target tissue with the formation of plasma seen as a spark. The discovery of the laser spark was the focus in plasma physics for more than ten years after 1963. In the early 1980s the potential of laser-induced photodisruption in ophthalmology was realized. High local temperatures occur briefly in the region of microplasma formation but the total heat energy is low during photodisruption. The clinical effects of photodisruption are related to the propagation of acoustic transients and cavitation (Puliafito and Steinert 1985). The first effect is the rapid plasma expansion that begins as a hypersonic wave. A second, weaker source of sonic waves is stimulated Brillouin scattering in which the laser light generates pressure waves and scatters them. The local heating can lead to a phase change and thermal expansion.

Q-switched and mode-locked Nd:YAG lasers are used as photodisrupters. Once formed, the plasma absorbs and scatters the incident light (figure 2). This property shields the underlying structures in the pathway of the laser beam. Membranes in physiological saline solution have been used as targets to demonstrate plasma shielding (Puliafito *et al* 1983; Steinert *et al* 1983).

Photodisruption is used for cutting the membrane inside the eye. In extracapsular cataract surgery, the lens nucleus and cortex are removed but the posterior capsule of the lens is retained. Creation of microplasma clears the optical pathway of the cloudy posterior capsule in cataract.

4. Photoablation

The photophysical mechanisms in tissue ablation are currently under research. Srinivasan and co-workers at IBM Waston Research Centre have demonstrated (Srinivasan 1986) that when pulsed UV radiation falls on the surface of a biological tissue the material at the surface is spontaneously etched away to a depth of 0·1 μm. The depth of etching is controlled by the pulse-width and energy. There is no detectable thermal damage to the substrate tissue. The material removed by etching consists of products ranging from atoms to small fragments of tissue. Photoablation characteristics of an organic polymer, and corneal and cardiovascular tissues were studied using an excimer laser of wavelength 193 nm.

The schematic representation of the impact of laser pulse on tissue surface is shown in figure 3. The expression

$$l_f = \frac{1}{\alpha} \log F/F_0,$$

which relates the etch depth per pulse (l_f) to the fluence (F), the fluence threshold (F_0) and the absorptivity (α) at that wavelength, has been derived by a number of workers (Andrew *et al* 1983; Jellinek and Srinivasan 1984). The three aspects of the problem are (1) the reaction path in which the bonds are actually broken, (2) model of etch behaviour as a function of pulse-width energy and wavelength, and (3) time profile of ablation.

The pulsed source is able to deliver energy to the target area in an interval that is much shorter than the time required for radial diffusion of the deposited energy. The excess energy, beyond that which is required to vaporize the irradiated tissue, is expressed in the vibrational, rotational and translational modes of the ejected tissue. The dynamics of the ejection of the material during etching can be studied in a number of ways such as mass spectral analysis.

The excimer wavelength (193 nm) has been found particularly suitable to correct lens disorders of the eye. Angioplasty, i.e. opening of the blocked coronary artery, has been done successfully by excimer laser (Linsker *et al* 1984). Schematic drawings are shown in figure 4. However, several other considerations of photoablation are critical in tissue application. Fibre-optic probes, area definition and course of tissue heating are critical points for clinical use. It is well known that DNA has a strong absorption peak in the UV region near 250 nm which coincides with KrF excimer wavelength. This radiation has a mutagenic effect on DNA molecules.

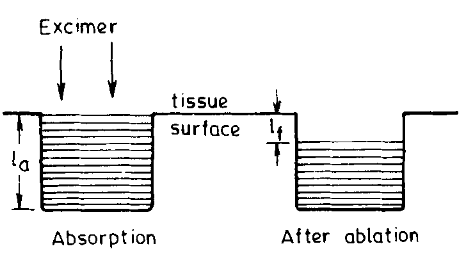
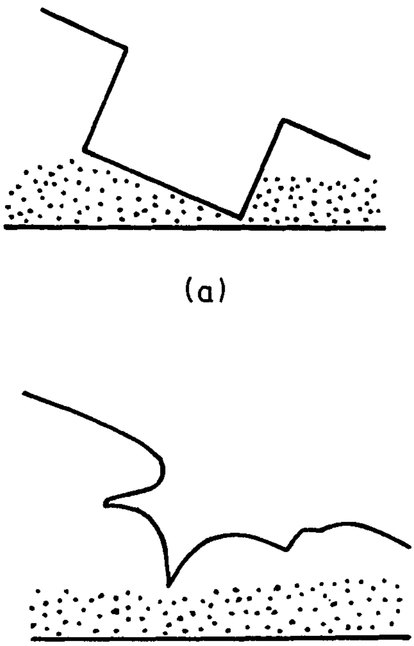


Figure 3. Schematic of impact of excimer on tissue surface (Reproduced from Srinivasan 1986.)



(a)

(b)

Figure 4. Angioplasty. (**a**) Cross-section of aortic wall (schematic) showing 0·35 mm trench produced by excimer at 193 nm, pulse width 14 nsec, fluence 0·25 J/cm^2; (**b**) cross-section of aortic wall (schematic) 0·4 mm trench produced by laser at 53 nm, pulse width 5 nsec, fluence 1·0 J/cm^2. (Reproduced from Srinivasan 1986).

5. Choice of laser

Th^ above three photo-processes help in making an effective choice of a laser sys.em for medical applications. Typical properties of some standard lasers used in medical practice are given below.

5.1 *Lasers in far-IR*

CO_2 laser of 10·6 μm wavelength is most commonly used for cutting action. Typically, 0·25 J is required to vaporize 1 mm^2 of tissue at a depth of 100 μm. As each layer of the cell is vaporized and removed exposing the next layer, the depth of the incision increases at a steady rate. Various workers have considered the problem of heat diffusion from the source of laser incision. The problem is one of moving phase transitions (Stefans 1980).

5.2 *Lasers in near-IR*

Nd:YAG laser of wavelength 1·06 μm penetrates pure water far deeper than CO_2 laser. But the scattering coefficient of cells is much larger at this wavelength. This disqualifies the Nd:YAG as a precise "scalpel". On the other hand, haemostasis at this wavelength is superior and small vessels can be sealed. After sealing, the nature of the collagen bonds and the form of the tissue are normal.

5.3 *Lasers in visible range*

At shorter wavelengths the scattering effects in the cells become prominent. At the same time absorption coefficients change significantly owing to the presence of "chromophores". Therefore visible laser radiation is used to study the differential absorption qualities of different tissues such as skin and blood. Krypton laser (647 nm) is used for treating the choroid layer of the eye beyond the pigment epithelium. The ocular medium transmits light between 380 nm and 1400 nm. At wavelengths shorter than 380 nm the UV absorbing properties of lens and cornea limit retinal exposure. Water absorption limits transmission of wavelengths above 1400 nm. The ocular chromophores (coloured pigments) are melanin, haemoglobin in blood vessels and xanthophyll in macula. Each chromophore has a characteristic absorption peak.

Tunability of dye lasers to a desired absorption band of the tissue has significant applications in skin and retinal treatment.

5.4 *Lasers in UV*

The interaction of excimer lasers with tissues is described as photoablation. Cutting rates of 8–80 μm/sec and non-thermal effects of excimer lasers are very important in dealing with cardiovascular and neural tissues and a class of polymers called as polymides. It is possible to make geometric alterations of polymide films and neural tissues. Patterns of neural tissues obtained by this technique can be very useful for studies of neuronal architecture. A number of investigations have been reported (Haller *et al* 1985; Nornes *et al* 1985) that deal with the potential use of UV lasers in corneal and neurosurgery and in angioplasty. The high absorption cross-section of excimer (193 nm) limits the depth of damage. The possibility of reshaping the entire lens surface to make a controlled refractive path in the cornea is a very interesting application.

6. Conclusions

Photocoagulation, photodisruption and photoablation studies of biological materials with lasers promise to be of continuing interest. On the basis of these processes desirable biochemical, cellular and tissue effects can be achieved.

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