Laser Applications in Medicine

Interaction between Laser Radiation and Biological Tissue

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The use of lasers for therapy depends on the interaction of laser beams with tissue. And the interaction between electromagnetic radiation and biological tissue depends on:

1. The wavelength of light, which determines the energy of each photon of light.
2. The intensity of radiation (energy delivered).
3. The shape of irradiation (continuous or pulsed).
4. Spatial nature of the beam (focused or unfocused).

Mechanisms of Laser-Tissue Interactions

There are many different mechanisms by which laser light can interact with tissue, and these have been classified in a number of different ways by different authors. For the purposes of these section, the most common interaction mechanisms for therapeutic and surgical applications will be divided into five broad
classes:

1. **Photochemical Interaction**
2. **Photothermal Interactions**
3. **Photoablation Interaction**
4. **Plasma-induced Photoablation**
5. **Photodisruption**

The characteristic energy density ranges from approximately 1 J/cm2 to 1000 J/cm2. This is surprising, since the power density itself varies over 15 orders of magnitude! Thus, a single parameter distinguishes and primarily controls these processes: the duration of laser exposure which is mainly identical with the interaction time itself.

continuous wave or exposure times > 1s for photochemical interactions, 1s down to 1μs for thermal interactions, 1μs down to 1ns for photoablation, and < 1ns for plasma-induced ablation and photodisruption. The difference between the latter two is attributed to different energy densities.

1. Photochemical Interaction:

When a molecule absorbs a photon, the energy in the photon is transferred to the molecule’s electrons. More energetic electrons can more easily escape the nuclear forces keeping them close to the nuclei, and so excited molecules are more likely to undergo chemical reactions (exchanging or sharing of electrons) with other molecules. Photochemical interactions take place at very low power densities (typically 1W/cm2) and long exposure times ranging from seconds to continuous wave. Careful selection of laser parameters yields a radiation distribution inside the tissue that is determined by scattering. In most cases, wavelengths in the visible range (e.g. Rhodamine dye lasers at 630 nm) are used because of their efficiency and their high optical penetration depths.

Summary of Photochemical Interaction

- Main idea: using a photosensitizer acting as catalyst (only in photodynamic therapy)
- Observations: no macroscopic observations
- Typical lasers: red dye lasers, diode lasers
- Typical pulse durations: 1 s . . . CW
- Typical power densities: 0.01 . . . 50W/cm2
- Special applications: photodynamic therapy, biostimulation

2 Photothermal Interactions

The energy of the photons absorbed by chromophores (a name given to any light-absorbing molecules) is converted into heat energy, which can cause a range of thermal effects from tissue coagulation to vaporization. Applications include tissue cutting and welding in laser surgery.

Summary of Thermal Interaction

- Main idea: achieving a certain temperature which leads to the desired thermal effect.

- **Observations: either coagulation, vaporization, carbonization or melting**
- **Typical lasers: CO2, Nd:YAG, Er:YAG, Ho:YAG, argon ion and diode lasers**
- **Typical pulse durations: 1 µs . . . 1s**
- **Typical power densities: 10 . . . 106 W/cm2**
- **Special applications: coagulation, vaporization, melting, thermal decomposition, treatment of retinal detachment, laser-induced interstitial thermotherapy.**

3. Photoablation Interactions

High-energy, ultraviolet (UV) photons are absorbed and, because they are more energetic than the chemical bonds holding the molecules together, cause the dissociation of the molecules. This is followed by rapid expansion of the irradiated volume and ejection of the tissue from the surface. This is used in eye (corneal) surgery, among other applications. Photoablation, or ablative photodecomposition, refers to a mechanism of laser ablation whereby the atoms bound together as molecules are dissociated through the direct breaking of the chemical bonds holding them together. If very short (ps) pulse durations are used, then there are no thermal effects associated with this process and it is therefore sometimes known as cold ablation. The fact that photoablation causes no thermal damage, and the very accurate etching that can be achieved, are the main advantages of this technique. High energy UV photons from an excimer laser, eg. ArF laser, raise the bonding electrons into non-bonding orbital.

They can then either fluoresce (and fluorescence is often seen during laser ablation) or, at the very next molecular vibration following the electronic excitation, the two atoms previously bonded can separate, i.e. dissociate. When the rate at which bonds are being broken, the rate of bond dissociation, is greater than the rate at which they reform, then photoablation can occur, the photon energy must be somewhat greater than the bond energy before dissociation will occur.

Summary of Photoablation

- Main idea: direct breaking of molecular bonds by high energy UV photons
- Observations: very clean ablation, associated with audible report and visible fluorescence
- Typical lasers: excimer lasers, e.g. ArF, KrF, XeCl, XeF
- Typical pulse durations: 10 . . . 100 ns
- Typical power densities: 107 . . . 1010 W/cm2
- Special applications: refractive corneal surgery