REVIEW ARTICLE

Laser: Tissue Interaction and Its Application in Clinical Dentistry

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ABSTRACT

The word "Laser" is a generic for the many examples of instruments that deliver specific electromagnetic (photonic) energy. The clinician may choose one of many laser wavelengths to achieve adjunctive therapy; the success of a given laser treatment will depend upon the predictability of the interaction of photonic energy with target tissue. This paper serves to present theoretical and practical aspects of laser-tissue interaction, drawing upon evidence-based published investigation.

Keywords: Laser, Tissue, Interaction, Dentistry, Absorption.

INTRODUCTION

In 1960, Theodore Maiman exposed a human tooth to his prototype Ruby laser. The emission wavelength of the laser at 633 nm (deep red visible light) offered no beneficial interaction with the tooth, with much of the energy transmitting the enamel and dentine with presumable attenuation by the pigmented pulpal tissue.

The inconsistencies of laser-tissue interaction continue to pose some difficulty for the dental clinician; however, the development of many laser machines, amounting to a facility to produce laser photonic energy at several wavelengths between the visible and far infrared areas of the electromagnetic spectrum, addresses many of the inconsistencies. The oral cavity is a complex environment, where hard and soft tissues exist in close proximity and all within bacteria laden saliva. All oral tissues are receptive to laser treatment, but the biophysics governing laser-tissue interaction demands a knowledge of all factors involved in delivery of this modality. Through this knowledge, correct and appropriate treatment can be delivered in a predictable manner.

PHOTONIC ENERGY

The fundamental theories on light of the latter 19th and early 20th centuries—notably work of Maxwell, Planck, Hertz, Einstein and Bohr—provided a coalescence of the prevailing opinions of light being composed of either particles or waves. Newton, through his 'Corpuscular' theorem,[1] in which light travelled as discrete packets (corpuscles), was at variance with earlier work of Huygens. Popular acceptance of a predominant belief in light propagation by waves re-emerged in early 18th century in England, with the slit-experiments of Thomas Young.[2] With the confirmation that light energy is a form of electromagnetic (EM) radiation, capable of causing a photo-electric effect with certain metals, proposed a duality of existence for 'packets' of light energy. Einstein was attributed[3] with providing the annotation "photon" (origin Greek, meaning "light") and with others listed before, provided an understanding that photonic energy is a form of energised EM radiation with each photon travelling at the speed of light (approximately 300×10^6 m/sec) in a sinusoidal wave pattern.

The emission of a single photon from an atom is the result of a shift in the energy status of that origin. Plank proposed all matter existed in a state of energy relative to extreme of a lower (ground) state and a higher (energised) state, commensurate with entropic physical form.[4] Bolzmann through his theories on thermodynamics,[5] readily accounted a direct relationship between matter, energy and temperature. Put simply, an electric light filament at room temperature is a dull, inert wire, but rapidly heats when energised by an electric circuit. At this higher energy state, the volatility of constituent electrons gives rise to higher thermal energy and the emission of such energy as light.

Laser photonic energy assumes the production of high-energy photons from an energized source, whereby each photon scribes an identical wave-form and each photon has identical energy value. Plank and Einstein had established an inverse relation between wavelength and photonic energy, a direct proportional relationship between photonic energy and frequency and Neils Bohr paved a way for the "Quantum" (amount) nature of emitted photons to be calculated and thus, provide a predictable base for the development of the Maser and optical-Maser, or Laser.

The energy of emitted photons is expressed in Joules or more conveniently, eV (energy derived by acceleration through a PD of 1 Volt). Since photonic energy is related to wavelength, photons emitted from different sources will have differing energy values. However, $1\text{eV} = 1.602 \times 10^{-19}$ J and it is possible to evaluate energy-equivalent values for the many laser wavelengths.

Fig. 1: Light Pioneers: Eminent scientists, who defined the understanding of electromagnetic radiation and laser photonics

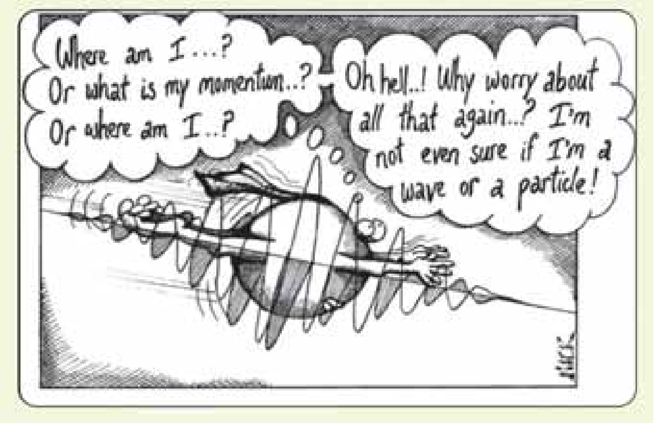


Fig. 2: Photon self-identity problems: Conflicting evidence has existed as to the nature of propagation of light through a medium. Einstein finally defined a duality of photon motion as both waveform and particulate

Photonic Energy and Target Molecular Structures

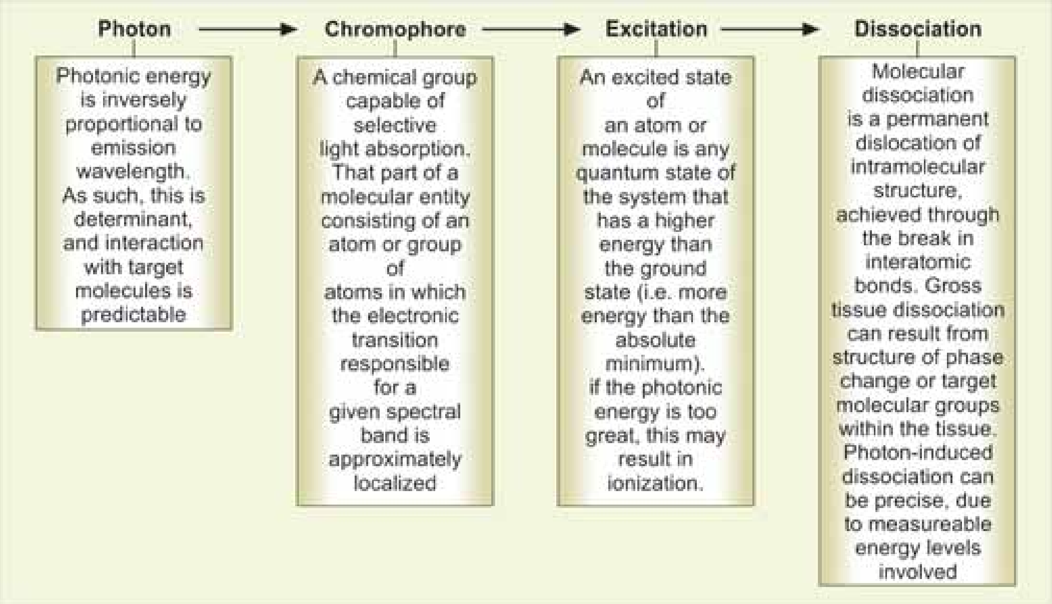
A simplistic look at one of the many graphic representations of the relationship of target tissue elements, incident laser wavelengths and relative absorption potential, would suggest that laser photonic energy is capable of ablative interaction with target tissue elements (chromophores).

As is evident, almost none of the popular laser photonic energies is capable of direct intramolecular bond cleavage and one may be forgiven for concluding that dental lasers cannot ablate target oral tissue through the use of empirical-state photonic energy. Certainly, when the binding (ionic) lattice energies of crystalline carbonated hydroxyapatite are exposed to the mid IR laser wavelengths (Er, Cr:YSGG, Er:YAG), the photonic energy value is pitiful compared to the dissociation energy of hard dental tissue.[7]

Something else must be happening …

Target tissue is composed of gross structure (glandular, muscle, tissue layers), microscopic structure (cells) and sub-microscopic structure (molecules, e.g. chromophores, water, hemoglobin, melanin). Molecules exist as stable groups of atoms, where covalent and ionic bonds serve to bind one atom to another.

Additionally, a state of energy exists which, through Bolzman's definition, defines a level of temperature. A ground state exists for such molecules, whereby there is a minimum level of vibration and rotation. As the molecule is excited, the level of rotation and vibration follows pathways specific to each molecule, raising the internal energy to an upper excited state. After this, the temperature rise or electromagnetic energy may deform or dislocate the molecular structure, leading to possible physical phase change.



Photonic energy is inversely proportional to emission wavelength. As such, this is determinant, and interaction with target molecules is predictable

A chemical group capable of selective light absorption. That part of a molecular entity consisting of an atom or group of atoms in which the electronic transition responsible for a given spectral band is approximately localized

An excited state of an atom or molecule is any quantum state of the system that has a higher energy than the ground state (i.e. more energy than the absolute minimum). if the photonic energy is too great, this may result in ionization.

Molecular dissociation is a permanent dislocation of intramolecular structure, achieved through the break in interatomic bonds. Gross tissue dissociation can result from structure of phase change or target molecular groups within the tissue. Photon-induced dissociation can be precise, due to measureable energy levels involved

Fig. 3: Offers a summary of the interaction between a photon and target chromophore molecule, through successive stages of absorption, excitation and dissociation. Such predictive events might account for why certain laser wavelengths interact (are absorbed) with certain oral tissues

Table 1: The list of the photonic energy values of some common dental laser wavelengths, along with the calculation of energies required to break some intramolecular atomic arrangements (dissociation energy).[6] In this table, it may be seen that the inherent photonic energy of a given laser wavelength is mostly insufficient to break target interatomic bonds. Consequently, laser-tissue ablation is due to other associated activity, such as (but not exclusively) thermal rise

Dissociation energy of selected chemical bonds

Type of bond	*Dissociation energy (eV)*
C—O	7.1
C—C	6.4
O—H	4.8
N—H	4.1
C—C	3.6
C—N	3.0
C—S	2.7
Fe—OH	0.35

(eV)	*Laser*	*λ (nm)*
2.4	KTP	532
2.0	He-Ne	633
1.6	Diode	810
1.2	Nd:YaG	1064
0.4	Er:YaG	2940
0.1	CO_2	10600

Adapted from: Mó O, Yáñez M, et al. Periodic trends in bond dissociation energies: A theoretical study. J Phys Chem A. May 2005 19;109(19):4359-65.

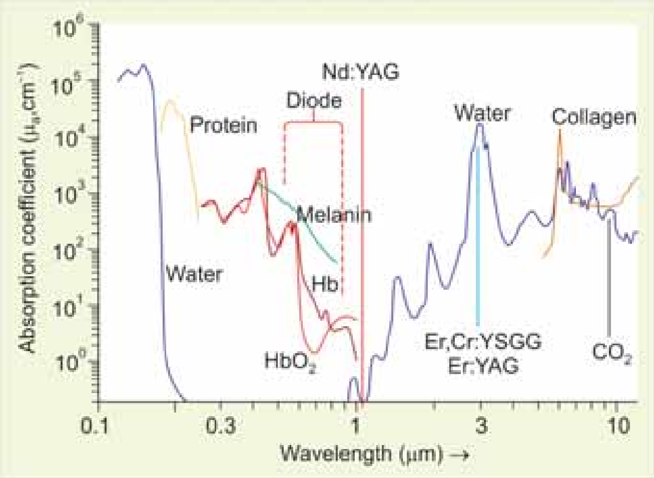


Fig. 4: Representation of the differing absorption characteristics of common oral tissue chromophores, relative to laser wavelengths used in clinical dentistry

Given such a possibly simplistic and generalized explanation, it serves to establish for a given chromophore the energy difference between a ground and excited state. Incident photonic energy will be inversely proportional to wavelength and where there is compatibility between the incident photonic energy and the difference in energy levels in the recipient molecule, absorption will occur. According to the first law of thermodynamics, the energy delivered to the tissue must be conserved, and three possible pathways exist to account for what happens to the delivered light energy when laser photonic energy is delivered into tissue:

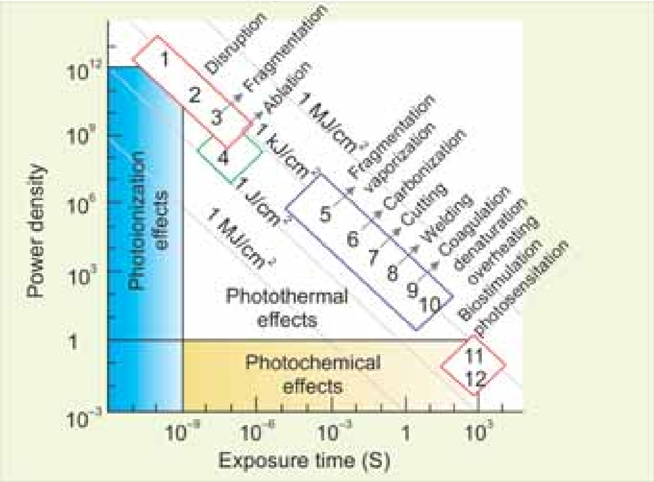


Fig. 5: Laser photoablation phenomena: The relationship between ascending power density of an incident laser beam and exposure time. Higher power density/shorter exposure time results in tissue fragmentation (*Source:* Boulnosis J-L, Laser Med. Sci. 1986;(1): 47-66)

1. The commonest pathway that occurs when light is absorbed by living tissue is called internal conversion. The energy of the electronically excited state gives rise to an increase in the vibrational modes of the molecule; in other words, the excitation energy is transformed into heat.[8] In many instances, the thermal rise is near-instantaneous and substantial and quickly leads to conductive thermal energy into surrounding tissue. In the case of oral soft tissue and visible/near IR laser wavelengths, the absorption by tissue chromophores gives rise to protein denaturation and secondary vaporization of interstitial water. The result is a visible ablation and vaporization of target tissue.[9]

   With longer laser wavelengths, mid IR and far IRZ the prime chromophores in both soft and hard oral tissue is water. Ablation of tissue in achieved through the near-instantaneous vaporisation of interstitial water, leading to an explosive fragmentation of tissue structure. With hard oral/dental tissue, this interaction can be quite dramatic.[9]
2. With incident laser photonic energy values that fall below target tissue ablation, a second pathway can occur as fluorescence. Fluorescence is a luminescence or re-emission of light in which the molecular absorption of a photon triggers the emission of another photon with a longer wavelength. Such action provides the basis for optical scanning techniques used in caries detection in enamel and dentine and tomographic techniques in the scanning of soft tissue for neoplastic change.
3. The third pathway is broadly termed as photochemistry.[10] Because of the energy of the photons involved, covalent bonds cannot be broken. However, the energy is sufficient for the first excited singlet state to be formed and this can undergo intersystem crossing to the long-lived triplet state of the chromophore. The long life of this species allows reactions to occur, such as energy transfer to ground state molecular oxygen to form the reactive species and singlet

oxygen. Singlet or nascent oxygen is an ultrashort lived form of the parent molecule that can cause cell apoptosis through oxidative stress. Such action can be commonly seen in photodynamic therapies where an intermediary chemical —photosensitizer—is employed to direct energy transfer to target tissue sites.[11,12]

Electron transfer reactions are highly important in the host cell mitochondrial respiratory chain,[13] where the principal chromophores involved in laser therapy are thought to be situated. An additional photochemistry pathway that can occur after the absorption of a red or NIR photon within a host cell is the dissociation of a non-covalent bond ligand from a binding site on a metal containing cofactor in an enzyme. The most likely candidate for this pathway is the binding of nitric oxide to the iron-containing and copper-containing redox centers in unit IV of the mitochondrial respiratory chain, known as cytochrome c oxidase. Such action may induce an increase in cell pH and production of ATP and has been cited as basic cellular theory in photobiomodulation with low-level lasers.

The ability of a chromophore to absorb electromagnetic radiation depends on a number of factors, mainly:

- Harmonizing $E_{\text{photon (h}\nu)}$ with $E_{\text{molecule}} = E_{\text{upper state}} - E_{\text{lower state}}$
- The electronic constitution of its atoms and molecules
- The wavelength of radiation
- The thickness of the absorbing layer
- Internal parameters, such as the temperature or concentration of absorbing agents.

Fig. 6: Predictable laser tissue interaction may be represented as the close matching of incident photonic energy values to the "energy gap" that may exist in a target molecule, between a "ground" state and upper (entropic) excited state. Such absorption of additional energy may lead to the disintegration of target tissue molecules and consequent ablation

Manipulation of Laser Photonic Energy Delivery

The use of a magnifying glass to concentrate the sun's rays is a simple example of power density. Power (energy per second) is an expression of a laser's ability to do work and when measured over the area exposed to the beam, it will be readily acknowledged that the greater concentration of photons, the greater level of potential interaction. Consequently, for any given laser delivery system—reduce the spot size of the beam and one can expect to speed up the interaction—assuming all other parameters are constant.[14]

The output of any laser over time is expressed as average power and equates to the total number of Watts delivered per second. For a continuous wave emission laser, the average power will equal of the maximum output; for a micropulsed free-running emission, the average power output may be of the order of a few watts, but due to the active photonic emission only lasting possible 20% of each second, there will be peaks of energy. A typical free-running emission laser, such as Nd:YAG or Er:YAG, may deliver an average power value of 3.0 watt, but due to the pulse width of 150 microseconds there will be peak power bursts of 1,000 + watt.[15]

For any given laser-tissue interaction, assuming absorption can occur the equation of power density with exposure time may enable the clinician to influence the type of interaction that occurs. It has already been established that at everyday levels of power delivery in dentistry, the predominant effect is tissue ablation through thermal rise—photothermolysis. By reducing the exposure time to milliseconds and microseconds, successively higher peak power density above 10^8 watt/cm^2 can be obtained. At such powerful levels, the intensity of energy is so great that electromagnetic fields developed around the interaction are sufficient to tear target molecules apart—photo plasmolysis.[16] Reference to the work of Boulnois and the graphic representation of laser-tissue interaction can be seen as an ascending phenomenon and product of ultrashort exposure time and megawatt peak power.[17]

Of practical interest to the clinician, the following factors will each and collectively affect the absorption of laser light by a chosen target tissue:[18]

- Laser wavelength
- Laser emission mode
- Tissue (composition)
- Tissue thickness
- Surface wetness due to water or saliva
- Incident angle of the laser beam
- Exposure time.

Contact *vs* noncontact modes employed between laser delivery tip and tissue.

Thermal relaxation factors : Exogenous (water spray, tissue precooling, high-speed suction, pulsing/gating laser emission) and endogenous (tissue type and density, blood supply).

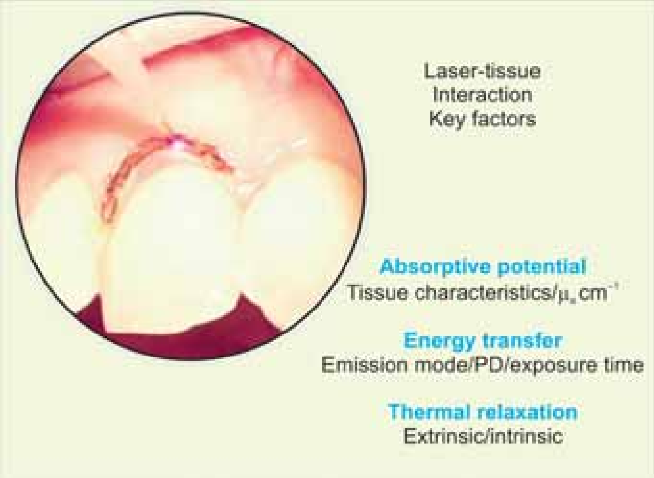


Fig. 7: Laser-tissue interaction key factors

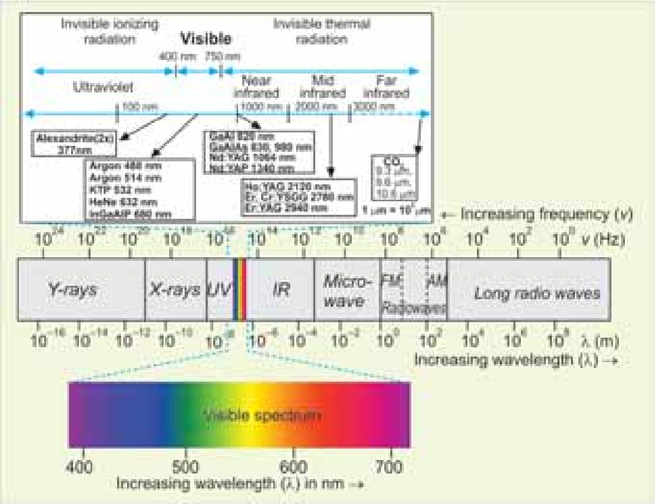


Fig. 8: Electromagnetic spectrum: The spectrum represents the extremes of X-ray and long radio radiation. Of particular note is the narrow band of visible to far infra-red, within which all current dental laser wavelengths may be found

Laser Photonic Energy and Target Soft Tissue

Various laser wavelengths exist for clinical use with target oral soft tissue and span the visible (green) EM spectrum through to the far infrared. Examples of laser wavelength currently available to the clinician are shown in Figure 8.

Currently, all soft tissue ablation is due to photothermolysis[19] and in general, chromophore absorption is by pigmented molecules (haem, melanin) with short wavelengths (532 to 1064 nm), whereas longer wavelengths experience greater interaction with tissue water components (H_2O and –OH radicals), with peak absorption occurring at approximately 3,000 nm and 10,600 nm.

Shorter wavelengths tend to penetrate soft tissue to depths of 2 to 6 mm[20] and scatter is a significant event, both back-scatter of photons as well as forward scatter into the tissue. Longer wavelengths are attenuated at or near the tissue surface, due to water content of cellular tissue. As tissue ablation proceeds, short wavelength photonic energy causes protein denaturation and conductive effects as the tissue is heated. A typical soft tissue zone of near IR laser ablation is surrounded by a zone of reversible edema and little evidence of acute inflammatory response. Classically, the progression of near IR laser ablation of soft tissue is through a crater-shaped zone where depth and volume removed appear proportional.[21]

Certainly, even incisions will have a U-shaped cross-sectional appearance and this is due in part to progression of photonic energy through scatter as well as some direct conductive thermal spread.[16]

With longer laser wavelengths, a more V-shaped cross-sectional appearance prevails. The bulk of laser-tissue interaction occurs at or within the confines of the tissue surface and as an incision is developed the majority of excess energy (thermal) is released through the escape of vaporized tissue water.[16] A risk exists with soft tissue in that desiccation of target tissue can predispose to the formation of carbonized tissue elements and very high temperatures that might cause collateral tissue damage and postoperative pain. Various techniques have been developed to address this risk, including short-pulse laser emission modes or coaxial water spray that may enhance tissue thermal relaxation.

Fig. 9: Lateral border of tongue. Image of immediate postoperative laser-assisted removal of fibroma, using Nd:YAG laser. A central zone of ablation is surrounded by a thin zone of reversible edema. Of particular note is the lack of bleeding, due to a protective layer of laser-induced preteinaceous coagulum

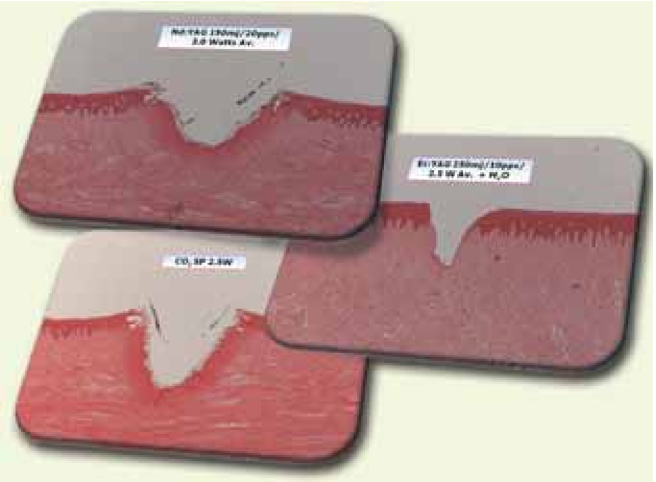


Fig. 10: Histological examination of porcine epithelium exposed to different laser wavelengths—Nd:YAG, Er:YAG, carbon dioxide. Shorter laser wavelengths produce wider, more spherical incision, compared to longer wavelength "V" shape profile

Laser Photonic Energy and Target Hard Oral Tissue

Both Erbium (Erbium YAG, Erbium Chromium YSGG) laser wavelengths have free-running pulsed emission modes (pulse width 50-150 μsec), which give rise to high peak power levels (>1,000 watt). Such power levels result in an instantaneous, explosive vaporization of the water content of enamel and dentine which leads to dissociation of the tissue and ejection of microfragments.[22] In addition, commercial models of both lasers use co-axial water spray to aid dispersal of ablated tissue and to cool the target.[23] In comparison with rotary

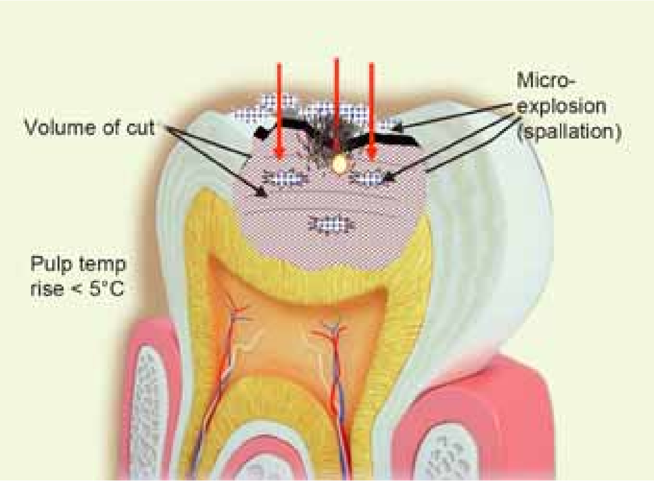


Fig. 11: Schematic of laser-assisted ablation of tooth tissue, observed with mid-IR wavelengths (Er:YAG and Er,Cr:YSGG lasers). Laser photonic energy, delivered in microsecond pulses is absorbed by interstitial water. Vaporization results in microexplosions. Expansive energy release and co-axial water spray results in minimal temperature rise within the tooth structure

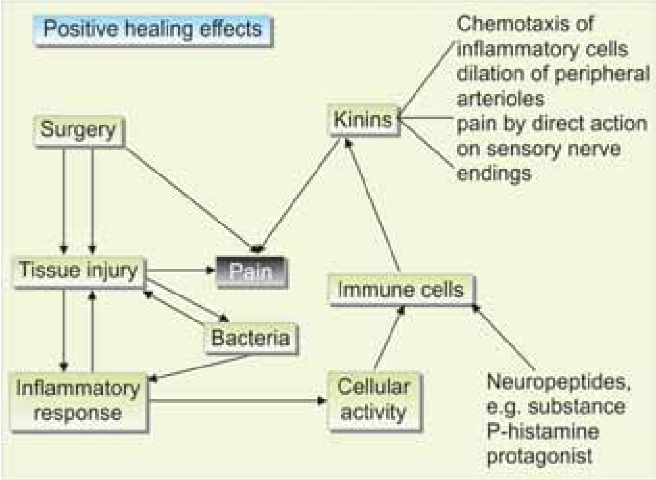


Fig. 12: Soft tissue healing: Not quicker but less eventful. Intraoral soft tissue injury, such as a surgical incision will quickly become contaminated with bacteria and a classic acute inflammatory reaction will result in pain through the release of kinins and other mediators. Laser-assisted pathogen reduction, incisional hemostasis and photobiomodulation effects may interfere with inflammatory reactions. Consequently, tissue healing may be more comfortable for the patient

instrumentation, pulpal temperature rise is minimal when Erbium laser wavelengths are employed in cavity preparation.[24]

The increased water content of caries results in rapid and preferential ablation of such material compared to normal enamel and dentine; to some extent, this may allow cavity preparation to be accomplished with a more conservative preservation of intact dental tissue.

Laser ablation of bone with Erbium laser wavelengths proceeds in a similar fashion. The higher water content and lower density of bone compared to enamel allows faster cutting through dislocation of hydroxyapatite and cleavage of the collagen matrix. This ease of cutting places the use of Er:YAG and Er, Cr:YSGG laser wavelengths as the preferred choice for laser bone ablation when compared to other wavelengths.[25]

Additional Aspects of Laser Tissue Interaction

It is considered appropriate to conclude this article with a brief discussion of two possibly contentious aspects of laser-assisted dental surgery. Much of the sensational aspects of claims of superior benefits of laser use have been placed in proper context through evidence-based and peer-reviewed investigations:

Positive healing effects following laser surgery: One of the often cited side-effects of laser-assisted surgery is the lack of postoperative inflammation and uneventful healing. Inasmuch as many claims are anecdotal, often if not always, the need for dressings or sutures can be avoided and irrespective of the laser wavelength employed, all soft tissue healing will be by secondary intention in that it will be impossible to oppose the cut tissue edges to their original alignment. Of note, however, is the phenomenon of lack of postincisional contamination by bacteria, due to a possible sterility of the cut surface[26] but certainly through the protective layer of coagulum of plasma and blood products—a tenacious film that allows early healing to take place underneath.[27] Additionally, studies with longer wavelengths show that there is a lack of fibroblast alignment associated with the incision line and consequently reduced tissue shrinkage through scarring.[28] Such findings are often borne out in the clinical setting.

Fisher[29] defines a comprehensive understanding of photon scattering into deeper soft tissue areas that is seen with the use of visible and near IR lasers. With successive interaction and as photons are absorbed, the possibility exists for a scenario whereby the ablation threshold of the host tissue at deeper sites is greater than the photonic energy. This “energy gradient” phenomenon might provide explanation as to how distant effects of (surgical) laser use may mimic essentially low-level (photobiomodulation) stimulation of cells and host tissue. Standard textbooks[30] provide authoritative and evidence-based explanations of how the host tissue may respond positively to low-level photonic energy and the reader is directed to such references for further information. Suffice that a summary of how this complex interaction may influence tissue healing—the lack of inflammatory response and reduced complications.

Reduced pain response associated with laser use: Investigation into pain response during surgical laser use has revealed findings that are inconsistent with many anecdotal reports and may provide an opportunity for the essential subjective aspects of patient receptiveness to be accepted. Pain is a defence mechanism and pain perception is innate and subjective. Equally, all stimuli applied to excess will result in pain.

Pain perception is multifactorial and may be influenced through the following, either singularly or in combination:

- Emotion: Fear, anxiety, stress syndrome, excitement
- Awareness: Trust, previous experience, conditioning e.g., hypnosis, activity subordination
- Threshold potential: Age, infirmity, drugs, alcohol, social factors.

The avoidance of pain during restorative and dental surgical procedures remains a strong factor in promoting patient acceptance of treatment and many studies have been carried out to evaluate this.[31-33] The use of the Nd:YAG (1064 nm) laser in developing pulpal analgesia, possibly through interference with the 'gate theory' of neural stimulus propagation, was an early mainstay benefit of this laser following its launch into dental practice in 1990. However, investigation into the subjectivity or placebo effect has rendered its application inconsistent.[34-36] Chaiyavej et al found that Er:YAG laser use, similar to rotary bur cutting of tooth tissue, caused neural response in both A and C intradental fibers.[37]

Perhaps of greater significance in exploring this area may be the lack of tactile and thermal stimulation compared to rotary instrumentation during laser-assisted restorative dentistry. In seeking to understand the essentially-anecdotal reports of soft tissue surgery using laser photonic energy in what is a thermally-based interchange, there is the patient-centerd factor of trust in the operator, together with a possible harmonization of micropulsed free-running emissions with regeneration potential of acetylcholine at synaptic junctions within the sensory neuron.

It is without question that when used correctly and with recommended operating parameters, laser-assisted surgical procedures on soft and hard tissue are less physically injurious when compared to both scalpel and rotary bur. Patient acceptance, peer-pressure and a general acceptance of "hi-tech" approach to treatment may all propose an enhancement of tolerance of sensory stimulation.

CONCLUSION

An overview has been presented to explore the physical and biological aspects of interaction of laser photonic energy with target oral hard and soft tissue. Any inconsistency may be viewed in terms of the precise mechanisms governing molecular energy dynamics but also the great diversity in tissue types and their close approximation within the oral cavity. The clinician is faced with technical challenges in manipulating any given laser wavelength to employ it as broadly as possible during clinical procedures; the additional facility of power density phenomena in helping to initiate an essentially photothermal event may help to deliver predictable and precise surgical outcomes.

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