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Physics of Laser Interactions with ToothEnamel and Dentine

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Abstract

Laser has been found to be an exciting and rewarding technology in dental surgery (e.g., dental ablation , cosmetic tasks, dental caries prevention and hypersensitivity treatment) due to advantages such as directivity, monochromaticity and pulsed mode ability. However, there is a major concern with the overheating of enamel and dentine during tooth-laser interaction, which causes carbonization, melting and cracking of the enamel and dentine, as well as inflammation and necrosis of the pulp.Laser interactions with tissue are complicated and no single parameter alone will determine how the laser affects the tissue. Dental hard tissue application include ablation of caries lesions, cavity preparation for restoration, caries detection, endodontic surgery and the potential for caries preventive therapy. The parameters of prime concern in understanding desirable or undesirable tissue effects are wavelength, whether continuous or pulsed, absorption properties, scattering, energy, fluence (energy/surface area), power density, repetition rate, number of pulses, pulse duration, and pulse shape.In this study it is found that treatment of enamel and dentine by specific pulsed laser(CO_2, Nd:YAG, Er:YAG and Er:YSGG) irradiation can markedly inhibit subsequent caries progression. During irradiation, heat causes carbonate loss from the carbonated hydroxyapatite mineral, converting it into a low solubility hydroxyapatite like calcium phosphate. It is possible to produce a laser that can selectively remove carious tissue, leading to a conservative cavity preparation, and also providing protection against later caries challenges.

Key words– Lasers, enamel, dentine, dental caries, caries inhibition

Introduction

Laser has been found to be an exciting and rewarding technology in dental surgery (e.g., dental ablation, cosmetic tasks, dental caries prevention and hypersensitivity treatment) due to advantages such as directivity, monochromaticity and pulsed mode ability. Lasers interactions with tissue are complicated and no single parameter alone will determine how the laser affects the tissue. In recent years the clinical use of lasers for hard tissue modification in dentistry has become a reality. Dental enamel and dentine consist of mineral, protein, lipid and water. The two tissues are very different in their structure, but having similar components. Figure-1 shows

Approximate composition of enamel and dentine as volume percent of each of the components involved (1).

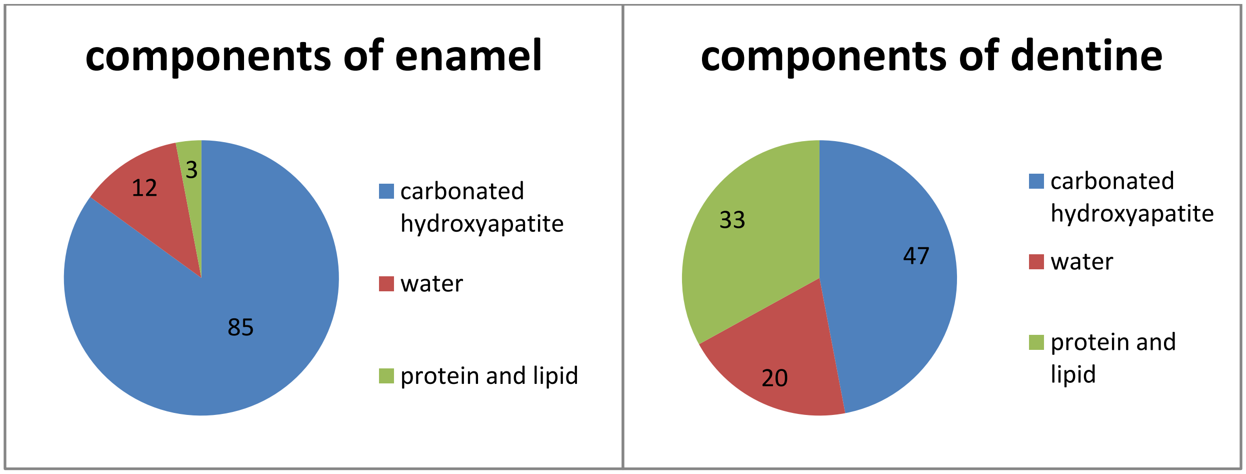

Figure -1. Composition of enamel and dentine as volume percent of each of the components

The mineral in our teeth is composed of a highly substituted hydroxyapatite. The substitutions in the mineral crystal lattice disturb the structure and make it much more acid soluble than the pure hydroxyapatite (23). The proteins in enamel are primarily a very thin covering of the individual crystals and comprise approximately half of the organic material. The other half of the organic material in the enamel is lipid (30). The water content of enamel is sufficient for diffusion of acids and other components into the tooth and of mineral, namely calcium and phosphate, out of the tooth during the decay process (2). Dentine has a similar mineral composition, although the carbonate content is much higher (5% vs 3%), the mineral is much more soluble, and a large component of the tissue is collagen type I with about 10% of the protein comprised of a range of non-collagenous proteins (24). There is also about 1% by weight of lipid in dentine (30). As can be seen from Figure-(1), the water content of dentine is substantial.

Laser interactions with the tissues fall into three major categories, namely,

1) Interaction with the mineral
2) Interaction with the protein
3) Interaction with the water

If detection of early decay is of interest, then the laser wavelength must be chosen where the transmission is at the highest level and where that wavelength of light will scatter in the carious region or have altered fluorescence properties. If caries removal, or enamel or dentine removal, is desired, the wavelength must be such that there is a major interaction with either the mineral or the water or both, unless there is plasma mediated ablation by ultra-short pulses. In the case of caries prevention, the laser interaction will most likely need to change the mineral from its acid soluble form to a much less soluble form. Light that is not specifically absorbed in these tissues will be extremely inefficient and energy densities at very high unsafe levels will be required to have any effect at all.

Characteristics of dental hard tissue for laser interaction

Absorption coefficients

The absorption coefficient is a measure of the level of absorption that occurs in a specific tissue by a specific wavelength of laser light. A low number indicates little absorption and a high number indicates high absorption. The low numbers for visible light in the green and red region indicate that enamel and dentine readily transmit visible light, especially towards the red end of the spectrum where there is less scattering. Further, the near infrared wavelength shows similar high transparency in the region of 1053 nm, which is very close to the Nd:YAG laser (1064 nm). In contrast, at wavelengths in the mid IR where water and mineral are highly absorbing, the absorption coefficients are very high. Measurement of these high absorption coefficients is technically difficult and accurate measurements have only been reported by Zuerlein and coworkers (36). The Er:YAG and Er:YSGG laser irradiation is strongly absorbed by the water and additionally the Er:YSGG is absorbed by the OH^- group in the carbonated hydroxyapatite mineral of the tooth. The carbon dioxide wavelengths, especially at 9.3 and 9.6 µm are highly absorbed by the apatite mineral and wavelengths of 10.3 and 10.6 µm to an order of magnitude smaller level (Fig. 2).

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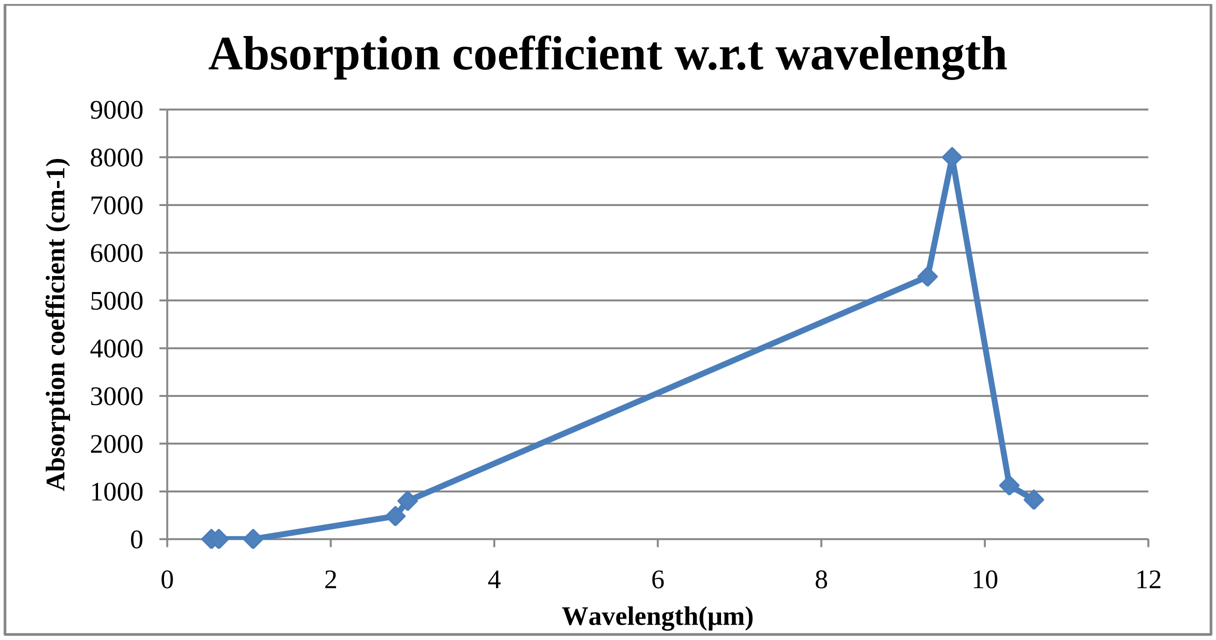

Figure – 2. Wavelength dependent absorption coefficient(37)

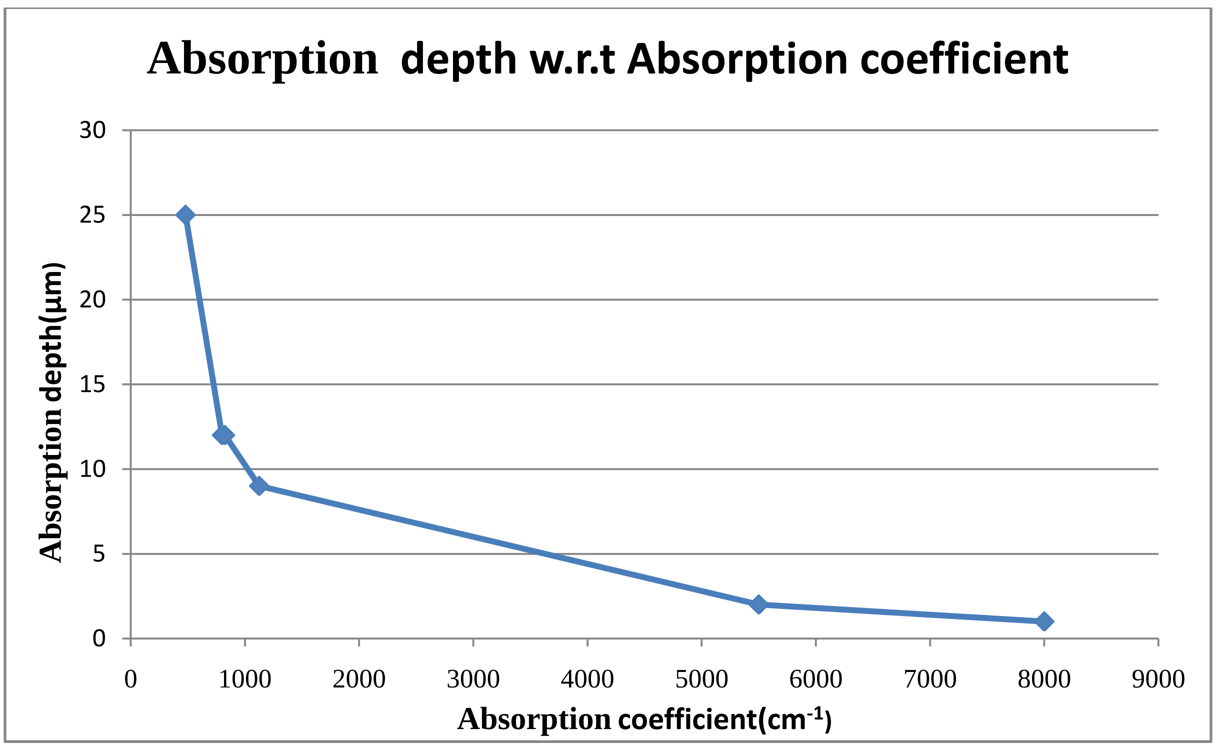

Figure- 3. Absorption coefficient versus absorption depth (37)

Consequently, for caries detection it is desirable to choose wavelengths in the red or near infrared region to optimize transmission through sound tissue. For ablation, the choice is from lasers such as Er:YAG, Er:YSGG or CO_2, for which strong absorption by the tissue is found. For caries prevention purposes, the choice should be to have a wavelength that will alter the mineral to make it less soluble and therefore the primary choice will be the carbon dioxide lasers (9.3–10.6 μm) with the possibility also that the lasers which are strongly absorbed by the water around 3 μm may be useful.

The higher the absorption coefficient, the smaller is the absorption depth. The absorption depth is the depth within which the majority of the energy is absorbed during a laser pulse. This absorbed energy is converted to heat and then the heat flows as a thermal radiation phenomenon into or out of the tissue. The calculated absorption depths are given in Figure-3 for the appropriate lasers.

Thermophysical properties

The thermophysical properties of teeth vary between different layers (e.g., enamel and dentine)(40) and depend on their microstructures. For instance, the thermal conductivity of human dentine decreases with increasing volume fraction of dentine tubules (41). The flow of dentinal fluid in the dentine tubules upon heating (or cooling) can also enhance heat transfer within the pulp. In addition, pulpal blood flow rate increases when the intrapupal temperature rises above 42^o C (38) and decreases during cooling (39). The perfused blood plays an important role in the thermoregula- tion of pulpal soft tissue(38,42), working as a heat sink under heating and as a heating source when subjected to cooling.

Temperature studies and caries prevention

Surface temperatures of 800 °C and above, up to 1200 °C caused the mineral of tooth to melt and transform when cooled (9, 25). Other studies have shown that temperatures of 400 °C and above are needed to decompose the carbonate inclusions in enamel mineral and transform the carbonated hydroxyapatite to the much less soluble hydroxyapatite (6, 23). For better understanding of the effect of fluence, the incident

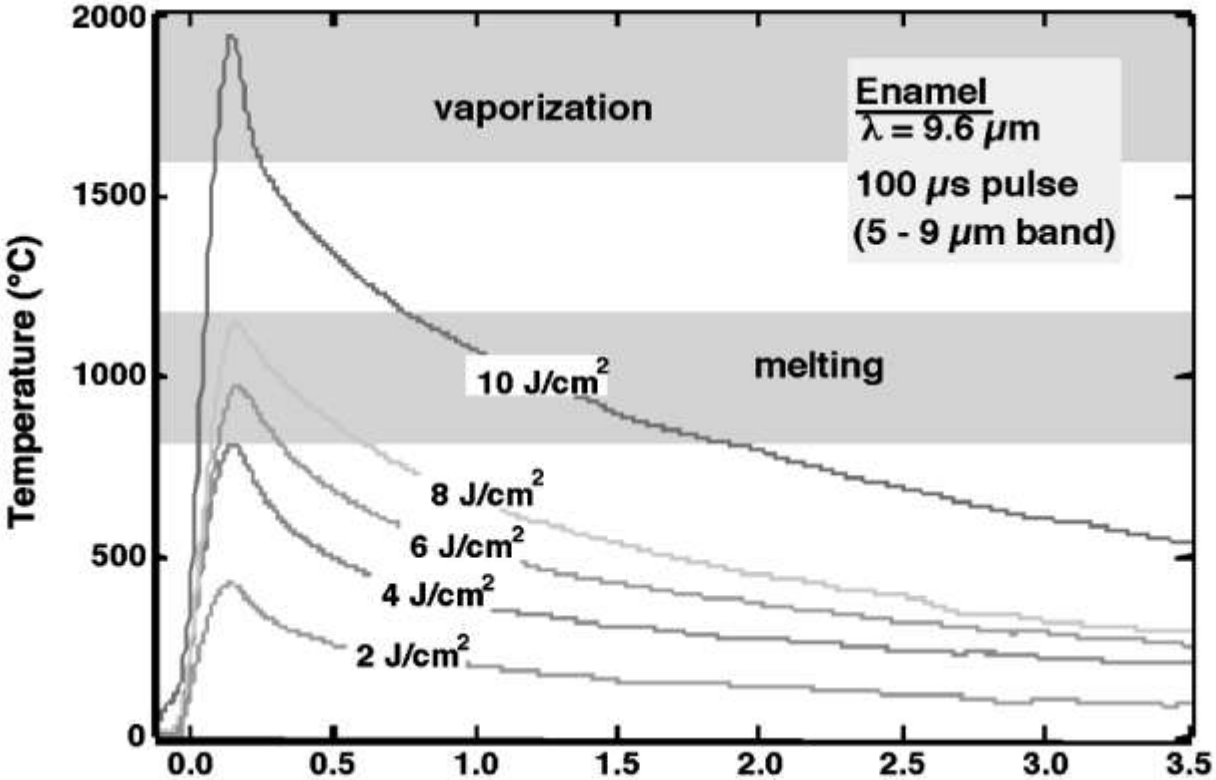

Figure- 4. Plot of temperature at the surface of dental enamel versus time following irradiation by a carbon dioxide layer at 9.6 µm , over a range of fluences and with pulse duration 100 µs (11).

fluence can be converted to absorbed fluence as was done for subsequent modeling of thermal effects in the tissue by Zuerlein and coworkers (35). Similar experiments using Er:YAG and Er:YSGG wavelengths(12) showed that considerably higher incident fluences (approximately 8 J/cm^2) were needed to produce temperatures of 400 °C at 2.76 and 2.94 µm, whereas even at 20 J/cm^2 the Ho:YAG (2.10 µm) produced surface temperatures of less than 50 °C.

Scattering

Scattering of light by the tissue ismarkedly dependent on wavelength. It can be seen that at the green end of the visible spectrum, the scattering coefficient in enamel is relatively high and this falls towards the red end and falls even further in the near infrared. These properties are clearly important in caries detection where minimal absorption and minimal scattering in the sound enamel is desired. Fluorescence of the tissue or of the carious tissue by way of pigmented bacterial by products in that tissue can also be used to advantage for caries detection as reviewed elsewhere (20, 34). Dentin, on the other hand, scatters visible and near infrared light in a similar fashion. It can be expected that carious lesions will scatter similarly because of the loss of mineral and the relatively high porosity. At the highly absorbed wavelengths in the 3 μm and 9 through 11μm region, the scattering is negligible and unmeasurable because the absorption is so high. It is obvious that a wavelength of around 1053 or 1064 nm is unlikely to have much effect on enamel or dentine because the absorption coefficients are so low. Therefore, the Nd:YAG laser is extremely inefficient for ablation of hard tissue and high fluences are needed to have an effect. However, it is possible to utilize it for ablation of pigmented carious lesions because of the absorption at this wavelength by the pigment in the tissue (17, 22).

Reflectance

Reflection is minimalat visible and near infrared wavelengths because the tissue is largely transparent to the laser light at these wavelengths.However, this is not the case in the mid-infrared region where these wavelengths are markedly reflected by the tissue. Fried and coworkers (9, 12) measured the reflectance at the four primary wavelengths of the carbon dioxide laser as well as Er:YAG, Er:YSGG lasers and reported values of 5%, 5%, 13%, 16%, 49% and38% for the wavelengths of 2.79, 2.94, 10.6, 10.3, 9.6and 9.3 μm respectively. Reflectance must be taken into account when determining incident energy or fluence values for clinical use of lasers particularly in the 9 through 11 μmregion.

Laser parameters

Wavelength

The laser wavelength is the primary determinant of the extent to which the light will be absorbed by a particular tissue.

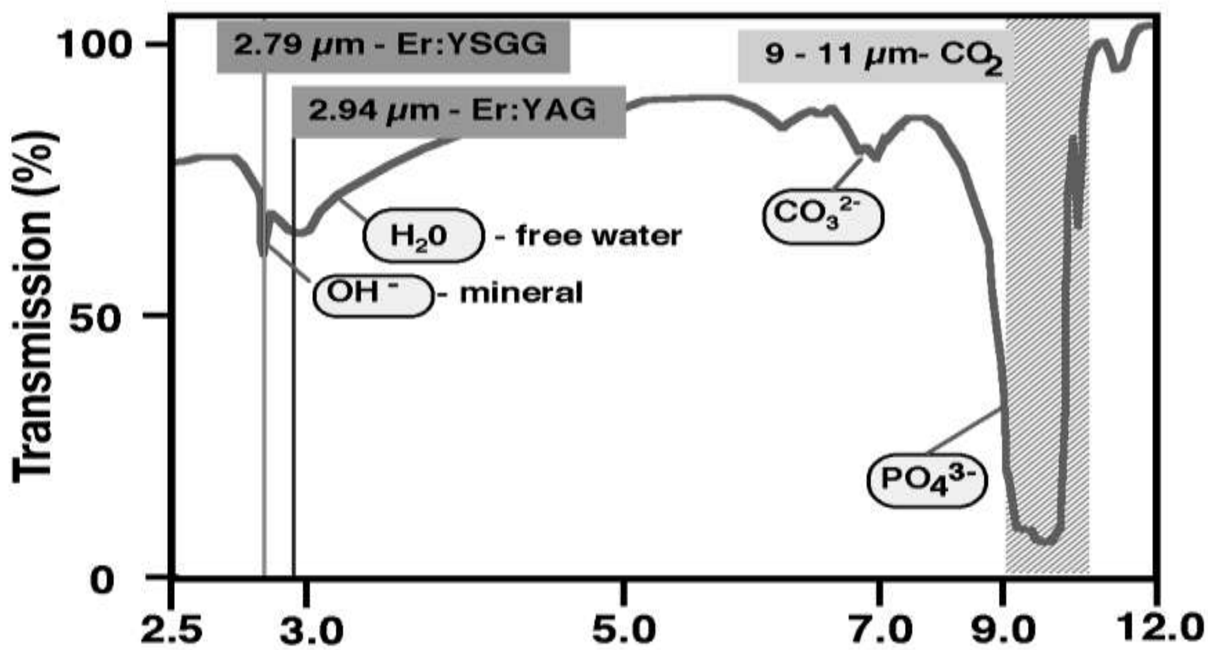

Figure-5. Infrared transmission spectrum of dental enamel showing the position of the primary absorbers, namely phosphate (PO_4^{3-}), carbonate (CO_3^{2-}), hydroxyl (OH^-) and water (H_2O), together with the overlapping positions of the Er:YSGG, Er:YAG and carbon dioxide (9.3, 9.6, 10.3 and 10.6 µm) lasers [37].

Figure-5 shows an infrared transmission spectrum of dental enamel. It can be seen that the primary absorbing bands are at around 3 µm, around 7 µm and between 9 to 11 µm. The absorption at 3 µm is related primarily to water in the tissue, but there is also a spike at about 2.8 µm related to the OH^- ion in the hydroxyapatite mineral. The band at around 7 µm is where the carbonate ion that substitutes in dental mineral for phosphate absorbs light (26). In the region of 9 through 11 µm, the primary absorber is the phosphateion. The carbonate ion also absorbs in the same region (26). Therefore, laser light coincident with 9–11 µm wavelengths is likely to have a rapid and major effect on the mineral. Laser light around 3 µm will have a major effect on the water, heating it, and rapidly expanding it leading to ablation (31). At wavelengths in the 9 through 11 µm region, there is also significant water absorption, so that laser light in this wavelength region will not only be absorbed in the mineral, but also in the water of the tissue. The absorption spectrum for protein is due to the amide groups of the proteins also around 7 µm. The wavelengths in the near infrared are poorly absorbed by dental mineral as are those in the red region of the visible spectrum. At the blue end of the spectrum and into the ultraviolet region, absorption increases, especially in the protein components.

Choice of wavelength for caries prevention

In the studies on caries prevention by lasers we therefore chose laser wavelengths that would be most strongly absorbed by the mineral of dental enamel. The carbon dioxide laser wavelengths of 9.3, 9.6, 10.3 and 10.6 μm were therefore chosen since they overlap the strong phosphate absorption bands of the mineral as described above. As illustrated by the absorption coefficients 9.3 and 9.6 μm light is very strongly absorbed and therefore likely to have the best effect at the lowest fluence. We also chose to use pulsed lasers since this would allow for short high intensity delivery of energy with periods of relaxation in between to ensure safety of the pulp and the surrounding tissue.

Pulse Duration

Many early studies on laser interactions with teeth were carried out with continuous wave lasers because these were the lasers that were initially available for the investigators to utilize (15, 16, 32, 33). However, continuous wave lasers add unnecessary amounts of energy to the tissue without necessarily having the beneficial effects desired. Pulsed lasers have the advantage that high energy densities can be delivered for short periods of time leaving non-irradiation periods in between the pulses for heat to be dissipated (3, 8, 11, 12, 14, 35, 36). For ablation or for caries prevention purposes, pulsed lasers are therefore most desirable as the tissue interactions can be optimized for short periods of time (10). Safe periods can be allowed in between pulses and the total irradiation energy delivered can be held well below thresholds for peripheral damage or most importantly for pulpal damage.

Pulse duration and ablation

Fried and coworkers has clearly shown that the pulse duration and shape has a dramatic effect on the ablation characteristics of the laser (10). Ablation studies were performed at 9.6 and 10.6 μm with a TEA laser with a gain switched spike of 100–200 ns. The ablation rates were restricted to 2–3 μm/pulse for enamel and 6–8 μm/pulse for dentineby the onset of plasma formation. When the pulse duration was stretched to around 8 μs, with an order of magnitude reduction in the gain switched spike, the threshold for plasma formation was raised, leading to ablation rates of around 25 μm/pulse for enamel and 50 μm/pulse for dentin.

Therefore, for the ablation of enamel or dentine one must choose the right wavelength, so that absorption is high enough to contain the energy deposition near the surface, the right wavelength to avoid unnecessary scattering, the correct energy to be above the ablation threshold, but also the correct pulse duration so that sufficient energy can be delivered in an optimum period of time to ablate without stalling.

A further parameter that can be calculated is the thermal relaxation time that is the time within which the bulk of the laser energy from a pulse would be absorbed by the tissue. For optimum ablation or caries prevention, the pulse duration of the appropriate wavelength laser should be matched approximately with the thermal relaxation time. Times dramatically shorter than the thermal relaxation time will provide excessive energy densities and pulse durations markedly in excess of the thermal relaxation time will distribute unnecessary energy deeper into the tissue (10, 13, 35, 36)

Pulse duration and caries prevention

With respect to conditions for caries preventive therapy earlier work by McCormack et al. (25) showed clear differences in the surface melting characteristics of dental enamel, not only at different wavelengths, but with different pulse durations of 50, 100, 200 and 500 µs. For example, at 9.3 µm with a fluence of 5 J/cm^2 using a multimode carbon dioxide laser, the surface showed minor melting with the 500 µs pulse duration ranging up to complete fusion and formation of large octahedral crystals at the 50 µs pulse duration with the same fluence. This phenomenon can be readily explained in that the thermal relaxation time at this wavelength is on the order of 2 µs (36). Therefore, each of these relatively long pulse durations deposit some energy at the surface and the remainder in the subsurface. This phenomenon has been further illustrated by Zuerlein and coworkers by mathematical modeling of the heat transfer and by experimental determination of the loss of carbonate at various depths (35, 36). With shorter pulse durations closer to the thermal relaxation time of the tissue, one would expect to be able to use much lower fluences to produce similar effects. This is discussed further below under the section that describes modeling of caries inhibition.

Energy and fluence

The amount of energy delivered to a tissue must be sufficient to have the desired effect, but no more than necessary as extraneous energy can be absorbed by surrounding tissue causing thermal stress, or pulpal damage and death of the tissue. For caries detection purposes, power (energy over time) can be in the mW region delivering low levels of energy to the tissue while at the same time having the desired effect of differentiating tissue. On the other hand, for ablation, Thefluence must be above the ablation threshold. This ablation threshold is the point above which sufficient energy has been added to the surface in a short enough period of time to cause expansion and/or vaporization of the tissue. For the Er:YAG and Er:YSGG lasers, the primary mechanism of action for ablation is to heat the water at the surface and the subsurface, thereby expanding it and causing tissue to be exploded out from the surface (18, 19, 31). In the case of the carbon dioxide laser, both absorption in the mineral and water will occur with some melting and vaporization of the mineral at around 1000 ºC and above, as well as heating and expansion of subsurface water (10).

In the case of caries preventive therapy, the lowest fluence possible needs to be chosen so that there will be surface modification and transformation of the mineral to a less soluble form, while at the same time keeping ablation to a minimum. Therefore, the fluence chosen should be below the ablation threshold, but sufficient to cause the thermal effects that are desired.

Repetition rate

For pulsed lasers, the repetition rate in most cases should be such that there is time between the pulses for any excess heat to be dissipated. On the other hand, higher repetition rates will be desirable so as to cut the clinical time to a manageable level. For example, early studies on caries prevention by Nelson and coworkers (5, 27–29) showed a measurable level (15–50%) inhibition of artificial caries-like progression in enamel utilizing a TEA carbon dioxide laser at 9.6 µm. However, the fluence per pulse was low (approximately 0.12 J/cm^2) and the repetition rate was 0.6 Hz (pulses/second), requiring 200–400 pulses over a period of several minutes for a measurable effect. Subsequent experiments, with a laser designed specifically for the purpose, showed much higher inhibition of demineralization with repetition rates of 10 Hz and fluences as low as 2.5 J/cm^2. The latter studies utilized a 2.5 second irradiation time, thereby approaching clinical reality and applicability (4).

Effect of number of pulses and repetition rate

Pulsed lasers can accumulate heat in the tissue if the pulses are close enough together. Studies by Fried and coworkers using surface radiometry indicated that at least 10 pulses at 10 Hz with wavelengths9.3–10.6 µm would provide ideal temperature rise at the enamel surface for caries inhibition (12). Kantorowitz et al. (21), subsequently confirmed this by further pH-cycling studies. The results indicated a minimum of 10 pulses per spot with a 10 Hz repetition rate. Pilot studies (unpublished) using 30 Hz produced similar results, suggesting the possibility that a total elapsed irradiation time of approximately one third of a second could be sufficient at each spot of 1 mm diameter.

Conclusions

The application of laser on dental hard tissue is based upon a thorough knowledge of the tissue optics and the consequent laser /tissue interactions.To make enamel resistantto dissolution by acids in the dental caries process arange of specific laser conditions can be used to treat the enamel.There are specific set of irradiation conditions for laser light that most efficiently and effectively interact with dental hard tissues. The efficient conversion of light to heat as the laser light is absorbed results in increased resistance of tooth minerals to dissolution by acid in dental caries process.

It will be possible to remove enamel carieswith a careful selection of laser parameters, that is based upon fundamental knowledge of laser/hard tissue interactions,while at the same time the remaining enamel surface resistant to future caries attack.

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