Hemostasis and Coagulation with Ablative Soft-Tissue Dental Lasers and Hot-Tip Devices

Keys to effective soft-tissue cutting

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ABSTRACT

Erbium laser wavelengths circa 3,000 nm are highly energy efficient and spatially accurate for photothermal ablation; their photothermal coagulation depths are significantly shorter than gingival blood vessel diameters. Carbon dioxide (CO₂) laser wavelengths circa 10,000 nm are extremely effective and spatially accurate photothermal ablation tools with exemplary coagulation ability as a result of a close match between their photothermal coagulation depths and the diameters of oral soft-tissue blood capillaries. In nonablative applications, coagulation depth can be increased for long pulses with extended heat propagation-driven coagulation depth in excess of the photothermal coagulation depth. Unlike CO₂ and erbium lasers, soft-tissue ablative dental diodes are contact thermomechanical cutting devices. Their coagulation depth depends on the degree of the diode’s glass tip charring and can range from sub-millimeter (heat propagation-driven coagulation for significantly charred tips) to multi-millimeter (photothermal radiant coagulation for poorly charred tips).

The key to the success of soft-tissue ablative dental lasers is their ability to simultaneously cut and coagulate the tissue. Although the optical, structural, and thermodynamic properties of soft tissue (including optical absorption and scattering and photothermal ablation and coagulation) have been studied extensively,1-5 a discrepancy remains between: (a) the industry-propagated notion about efficient near-infrared (IR) 800-nm to 1,100-nm laser ablation of the oral soft tissue6-9; and (b) studies reporting inefficient near-IR absorption/ablation of the oral soft tissue.2,5,7,10-18

Photothermal Laser Ablation

The process of photothermal vaporization of intra- and extracellular water heated by the laser light within the irradiated soft tissue is the most efficient soft-tissue laser ablation (as well as incision and excision).2-5 Water vapors quickly steam out of the strongly laser-heated soft tissue, carrying cellular ashes and other various by-products of this swift boiling and vaporization process with them. To understand how the laser light cuts the soft tissue, clinicians should examine how its absorption coefficient spectrum1-5 applies to the three absorption and scattering and photothermal ablation and coagulation processes.

LEARNING OBJECTIVES

• Determine the most efficient soft-tissue laser ablation
• Describe the most efficient heating of irradiated tissue and cooling of tissue adjacent to the ablated zone
• Discuss the process of photothermal laser ablation
• Discuss the coagulation process and how it is affected by other factors, such as temperature and blood vessel diameter

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wavelength groups of practical dental lasers presented in Figure 1: circa 1,000 nm (diodes and Nd:YAG laser); circa 3,000 nm (erbium lasers); and circa 10,000 nm (CO₂ lasers). The near-IR diode and Nd:YAG laser wavelengths circa 1,000 nm are highly inefficient and spatially inaccurate photothermal laser ablation devices because of their weak absorption and strong scattering by the soft tissue. Conversely, as a result of their high absorption by the soft tissue, mid-IR erbium (circa 3,000 nm) and IR CO₂ (circa 10,000 nm) laser wavelengths are very efficient and spatially accurate laser ablation tools with a low ablation fluence threshold (Figure 1).

Laser pulsing is as important for soft-tissue surgery as the laser wavelength. Highly efficient heating of the irradiated tissue occurs when the energy of a laser pulse is high and the duration of the pulse is much shorter than the thermal relaxation time (TRT), which is also presented in Figure 1. If time duration between laser pulses is much greater than the TRT, it yields the most efficient cooling of the tissue adjacent to the ablated zone. Such laser pulsing is referred to as superpulse. Because of its ability to minimize the depth of coagulation, superpulse is an essential feature of any soft-tissue surgical CO₂ laser.

Photothermal Laser Coagulation
Coagulation transpires in the 60°C to 100°C temperature range, which significantly reduces bleeding (and oozing of lymphatic liquids) on the ablated tissue margins during laser ablation (including incision and excision) procedures. Because blood is contained within and is transported through blood vessels, blood vessel diameter, B, (ranging from 21 μm to 40 μm) is a crucial spatial parameter that impacts the efficiency of the photocoagulation process. Photothermal coagulation is also joined by hemostasis because of the contraction of the walls of blood and lymphatic vessels through the shrinking of collagen at increased temperatures. Relative to the blood vessel diameter, B, the photothermal coagulation depth, H, is a key criterion of coagulation and hemostasis efficiency. The coagulation depth, H, (for the 60°C to 100°C temperature range below the ablation margins) was shown to be proportional to the absorption depth, A, (an inverse of the absorption coefficient presented in Figure 1), and is also presented in Figure 1 for short pulse conditions.

For ablative photothermal settings, the depth of coagulation is determined by the photothermal coagulation depth H (Figure 1) only if H is significantly shorter than the depth of ablation, which is often the case for practical cutting lasers in surgery and dentistry such as erbium and CO₂ lasers (and not for diode lasers):

- As illustrated in Figure 2 (a and b), just like a sharp scalpel, a laser beam with short photothermal coagulation depth (H << B, such as erbium lasers)
is not capable of stopping bleeding from a severed blood vessel, because photothermal coagulation takes place on a relatively short spatial scale. Such wavelengths are excellent scalpels but poor coagulators.

- A laser beam with an excessively long photothermal coagulation depth \( H \gg B \), such as diode and Nd:YAG laser wavelengths (Figure 1), is capable of coagulating multiple blood vessels over extended volumes of the soft tissue. Such wavelengths are excellent coagulators but poor scalpels.\(^{2,5,7}\)

- When \( H \approx B \) (CO\(_2\) laser wavelengths (Figure 1)), coagulation reaches just deep enough into a severed blood vessel to stop the bleeding. In other words, the high coagulation efficiency of the CO\(_2\) laser is because of the close match between the photothermal coagulation depth of approximately 50 \( \mu \text{m} \) and the diameters of the oral soft-tissue blood capillaries of approximately 20 \( \mu \text{m} \).\(^{8}\)

For nonablative long-pulse settings, the heat propagation-driven coagulation depth, \( HT \), can be derived from the temperature profile inside the tissue, approximated as

\[
T = 37 + 63 \left[ 1 - 1.5 \left( \frac{x}{\delta} \right) + 0.5 \left( \frac{x}{\delta} \right)^3 \right]
\]

where

\[
\delta = \frac{45}{K} \left( \frac{\text{mm}}{\text{sec}} \right)
\]

is the heat propagation distance.\(^{9-12}\) \( K = 0.155 \text{ mm}^2/\text{sec} \) is soft-tissue thermal diffusivity,\(^{9}\) and \( t \) is the pulse duration or the “ON” time of the heat source at the surface of the tissue) for \( HT \gg H \) conditions. The heat propagation-driven coagulation depth \( HT = 0.45 (8 \text K t)^{0.5} \) contains the 60\(^\circ\)C to 100\(^\circ\)C tissue temperatures as indicated in Figure 3. For long-pulse erbium lasers (short depth of photothermal coagulation \( H \approx 3 \mu \text{m} \) to 10 \( \mu \text{m} \) (Figure 1), the heat propagation-driven coagulation depth \( HT \) can exceed 20 \( \mu \text{m} \) (ie, \( HT \gg H \)) for pulse durations of \( 2 \) msec and longer. For long-pulse CO\(_2\) lasers (depth of photothermal coagulation \( H \approx 50 \mu \text{m} \) (Figure 1), the heat propagation-driven coagulation depth \( HT \) can exceed 200 \( \mu \text{m} \) (ie, \( HT \gg H \)) for pulse durations of \( 200 \) msec and longer.

**Dental Diode Hot Glass Tip**

Dental diode near-IR laser wavelengths are not suitable for oral soft-tissue cutting.\(^{2,5,7}\) Instead, the tissue is cut thermomechanically on contact with a charred glass “hot tip.” First, an optically dark carbonized material\(^{17,18}\) or “char” (eg, organic matter, burnt ink, or burnt corkwood), is deposited on the very end of the glass tip. The optical energy of the diode laser heats the charred tip of the glass fiber up to 900\(^\circ\)C to 1,500\(^\circ\)C.\(^{17,18}\) As a result, the soft tissues are heated up through the heat conduction/diffusion from the hot glass tip to and through the soft tissue, as illustrated in Figure 2. The cutting speed of such a charred hot glass tip is limited by its disintegration\(^9\) at elevated temperatures (up to 1,500\(^\circ\)C), thus raising concerns about biocompatibility\(^{20,21}\) of the burnt tip’s cladding chemicals and thermally fractured glass (not sapphire tips,\(^2\) which are more rugged).

The ideal 100%-optically black hot tip acts as a nonlaser, wavelength-independent ablation thermal device (similar to electrocautery) with an approximate temperature profile in the soft tissue shown in Figure 3.\(^2\) Figure 4 presents

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**FIG. 2**

**热扩散深度**

**FIG. 3**

**热扩散驱动凝固深度**

\[
HT = 0.45 \delta = 0.45 \left( 8 \text{ K t} \right)^{1/2},
\]

where \( \delta = \left( \frac{8 \text{ K t}}{1/2} \right) \) is heat propagation distance, \( K = 0.155 \text{ mm}^2/\text{sec} \) is soft tissue’s thermal diffusivity, and \( t \) is ON time of the heat source at the surface of the soft tissue.

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**FIG. 3**

(3.) Approximate temperature distribution in soft tissue,\(^{9,12}\) assuming heat propagation distance \( \delta \gg A \), where \( A \) is an absorption depth (an inverse of the absorption coefficient presented in Figure 1). Ablation temperature is 100\(^\circ\)C, coagulation temperature is 60-100\(^\circ\)C, and body temperature is 37\(^\circ\)C.

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Summary
Erbium laser wavelengths circa 3,000 nm are extremely energy efficient and spatially accurate for photothermal ablation; their photothermal coagulation depths are much shorter than gingival blood vessel diameters. CO₂ laser wavelengths circa 10,000 nm are highly effective and spatially accurate photothermal ablation tools with exceptional coagulation ability as a result of the close match between photothermal coagulation depth and the diameters of oral soft-tissue blood capillaries. In nonablative applications, coagulation depth can be increased for long pulses with extended heat-propagation-driven coagulation depth in excess of the photothermal coagulation depth.

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Disclosures
Dr. Peter Vitruk is the owner of LuxaCare, Aesculight, and Light Scalpel, LLC. Dr. Levine has no financial relationships to disclose.

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References