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Importance of Cutaneous Cooling During Photothermal Epilation: Theoretical and Practical Considerations

Kurt G. Klavuhn, PhD[1]* and David Green, MD[2]
[1]*Lumenis Inc., Pleasanton, California 94566*
[2]*Howard University Hospital, Washington, DC 20060*

Background and Objectives: Sapphire contact cooling is widely used to prevent non-specific epidermal injury from occurring during selective laser treatment of unwanted hair and vascular lesions. This small study was performed to examine the clinical response of the skin to 800-nm laser irradiation with varying extent of cutaneous sapphire contact cooling. Observed clinical responses are compared to those predicted by theoretical analysis in an attempt to construct a more complete picture of sapphire contact cooling and its role in preventing non-targeted tissue devitalization during laser treatment of the skin using a wavelength, pulse duration, and radiant exposure commonly used for laser hair removal.

Study Design/Materials and Methods: Three subjects each received a total of three pulses of laser light (800 nm) of equal radiant exposure (60 J/cm^2), pulse duration (30 msec), and spot size (9 mm $\times$ 9 mm), but with varying extent of cutaneous cooling. One site was pre-cooled and heat-sinked with a chilled (5°C) sapphire window in contact with the skin; another site was heat-sinked only with a room-temperature (20°C) sapphire window in contact with the skin; and a third site received no pre-cooling or heat-sinking. Each site was examined immediately after treatment and at intervals throughout a 3-month period. The thermal response of the tissue was calculated in each case using a Monte Carlo model for light transport in multi-layered tissues coupled with an axisymmetric finite-difference heat diffusion model. Thermal injury was modeled as a first-order kinetic rate process using an Arrhenius expression.

Results: In all three subjects, the sites that were pre-cooled and heat-sinked showed no evidence of epidermal or dermal devitalization. The three sites that were heat-sinked only had a few patches of perifollicular epidermal devitalization and subsequent desquamation without any permanent epidermal or dermal injury, as would be evidenced by pigmentary alteration or textural change. In each subject, the site that received no pre-cooling or heat-sinking sustained epidermal and dermal devitalization, appearing as ulceration and resulting in sustained erythema and textural alteration. Clinical responses predicted by theoretical analysis agree with the clinical observations and show that the dominant effect of sapphire contact cooling for pulse durations of 30 msec or less is the reduction of fluence within the epidermis resulting from index matching at the skin surface.

Conclusions: The results of this small study suggest that by judiciously selecting the laser pulse duration and pre-cooling and heat-sinking the epidermis in a manner that provides index matching and compression of the skin, epidermal damage can be avoided while administering the highest, most effective radiant exposures. Lasers Surg. Med. 31:97–105, 2002. © 2002 Wiley-Liss, Inc.

Key words: hair removal; heat-sinking; laser–tissue interaction; pre-cooling; sapphire contact cooling; selective thermal injury; 800-nm diode laser

INTRODUCTION

Hair removal using lasers is achieved by selectively depositing light energy into the hair shaft and pigmented follicular epithelium, such that the rapid rise in temperature and subsequent heat transfer to adjacent tissue causes local thermal necrosis of the follicle's regenerative structures. The selective deposition of energy is accomplished by illuminating the treatment area with sufficient radiant exposure (delivered energy per unit area) at a wavelength that is preferentially absorbed by the endogenous melanin of the target hair shaft and pigmented follicular epithelium, but not by the surrounding tissue. In order to localize the thermal effects, the energy is typically delivered within a time less than or comparable to the thermal relaxation time of the target structure.

There is a direct correlation between the effectiveness of the treatment (i.e., the percentage of follicles permanently damaged) and the radiant exposure used. In independent studies comprising a total of 85 patients (39 males and 46 females of Fitzpatrick's skin phototype II–VI) treated with an 800-nm pulsed diode laser (10–40 J/cm^2, 5–30 msec, 9 mm $\times$ 9 mm) with a chilled (5°C) sapphire tip (Lumenis Inc., Pleasanton, CA), 32% hair reduction was

Kurt G. Klavuhn is a Staff Development Engineer.
David Green is a Clinical Assistant Professor of Dermatology.
*Correspondence to: Kurt G. Klavuhn, Lumenis Inc., 1249 Quarry Lane, Suite 100, Pleasanton, CA 94566.
E-mail: kklavuhn@lumenis.com
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observed at 20 months, following a single treatment using a radiant exposure of 40 J/cm^2 and a pulse duration of 20 msec, while 25% was observed for settings of 20 J/cm^2 and 10 msec [1,2]. Interestingly, multiple pulses ($3\times$) using the same radiant exposure did not produce measurably better results. These results indicate that the higher the peak temperature reached by the target structures, the more effective the treatment.

Unfortunately, because of the unavoidable absorption of some of the energy by the melanin in the epidermis, the maximum radiant exposure (for a given pulse duration) that can be safely used is limited by the onset of collateral tissue damage caused by the heating of the epidermis. Thermal damage to the epidermis can result in its devitalization with subsequent alteration in pigmentation and texture [3]. Although usually temporary, such side effects are nonetheless undesirable. Therefore, in order to achieve effective heating of the target hair shafts and follicles while avoiding thermal damage to the epidermis, it is critical to optimize the device design and the treatment procedure to minimize the heating of the epidermis.

Various methods have been used to provide cutaneous cooling in an attempt to preserve the epidermis during laser- or lamp-based photothermal epilation procedures. The most common methods are (1) spraying the skin surface with a short cryogen spurt, or (2) pressing a chilled sapphire window onto the skin surface. To date, most studies examining the chilled sapphire window method have focused predominantly on the pre-cooling aspect and/or have not related theoretical predictions of clinical response to corresponding clinical observations [4–6]. This small study was performed to examine the clinical response of the skin to 800-nm laser irradiation (1) with chilled (5°C) sapphire contact pre-cooling and heat-sinking, (2) with room-temperature (20°C) sapphire contact heat-sinking only, and (3) without cutaneous cooling (i.e., no pre-cooling or heat-sinking). Observed clinical responses are compared to those predicted by theoretical analysis in an attempt to construct a more complete picture of sapphire contact cooling and its role in preventing non-targeted tissue devitalization during laser treatment of the skin using a wavelength, pulse duration, and radiant exposure commonly used for laser hair removal.

MATERIALS AND METHODS

Clinical Study

Three subjects were each treated with a LightSheer™ EP Diode Laser System (Lumenis Inc.). The LightSheer EP Diode Laser System is FDA approved for permanent hair reduction, as well as the treatment of pseudofolliculitis barbae, benign pigmented lesions, and leg veins. The laser emits 800-nm light of a fixed 9×9-mm spot size, radiant exposures up to 60 J/cm^2, and pulse durations up to 30 msec. The light source consists of a series of compact and efficient semiconductor diode laser arrays in the handpiece. The laser emission emanates from the handpiece through a 9×9-mm sapphire ChillTip™ that is cooled to a temperature of 5°C (Fig. 1). All three subjects were treated on hair-bearing skin of the thigh with and without cutaneous cooling but, otherwise, under conditions comparable to that of actual clinical use when targeting hair follicles. Prior to treatment, the sites were shaved to eliminate absorption of light by hair above the skin surface. Each subject had Fitzpatrick Type II complexion, were not tan, and had no sun exposure at the treatment sites during the preceding 6 months.

Each subject received a total of three pulses of light of radiant exposure 60 J/cm^2 and pulse duration 30 msec at three adjacent sites. One site received a single pulse of light with the ChillTip maintained at 5°C and in direct contact with the skin for approximately 250 msec prior to and for approximately 1 second after the delivery of the pulse of light (pre-cooling and heat-sinking). The second site received a single pulse of light with the ChillTip at room temperature (~20°C) and in direct contact with the skin for approximately 250 msec prior to and for approximately 1 second after the delivery of the pulse of light (heat-sinking only). A third site received a single pulse of light with the ChillTip maintained at least 1 mm above the skin surface (no pre-cooling or heat-sinking). The subjects were instructed not to provide any skin care to any of the three treatment sites. They were permitted to maintain all normal activities including bathing. All three volunteers were examined 1 minute, 1 hour, 24 hours, 5 days, 10 days, 21 days, and 90 days post treatment.

Modeling

Light propagation. A Monte Carlo model [7,8] for light transport in multi-layered tissues was used to calculate the distribution of fluence rate ϕ (W/cm^2) for a 10-mm diameter (approximately equal to 9 mm $\times$ 9 mm) laser beam of uniform irradiance, incident normal to the tissue surface. A three-layer model was used representing an 80-μm-thick epidermis, 20-μm-thick basal layer, and underlying dermis (Fig. 2). Two different skin boundary conditions were examined, representing the beam being applied through external mediums of air ($n_e = 1.0$) and sapphire ($n_e = 1.76$). The skin surface was assumed to be smooth, and any back reflections from within the sapphire were considered negligible. The absorption coefficients μ_a (cm^{-1}), scattering coefficients μ_s (cm^{-1}), anisotropy coefficients g, and indices of refraction n used in the model are summarized in Table 1.

Heat transfer. Given the relatively short treatment times, heat generated by metabolism or transferred via perfusion was assumed negligible. Thus, the thermal response of the laser-irradiated tissue was modeled using a simplified axisymmetric heat diffusion equation [9],

$$\frac{1}{r}\frac{\partial}{\partial r}\left[k(r,z)r\,\frac{\partial T(r,z,t)}{\partial r}\right] + \frac{\partial}{\partial z}\left[k(r,z)\frac{\partial T(r,z,t)}{\partial z}\right] + S(r,z,t) = \rho(r,z)c(r,z)\,\frac{\partial T(r,z,t)}{\partial t}, \quad (1)$$

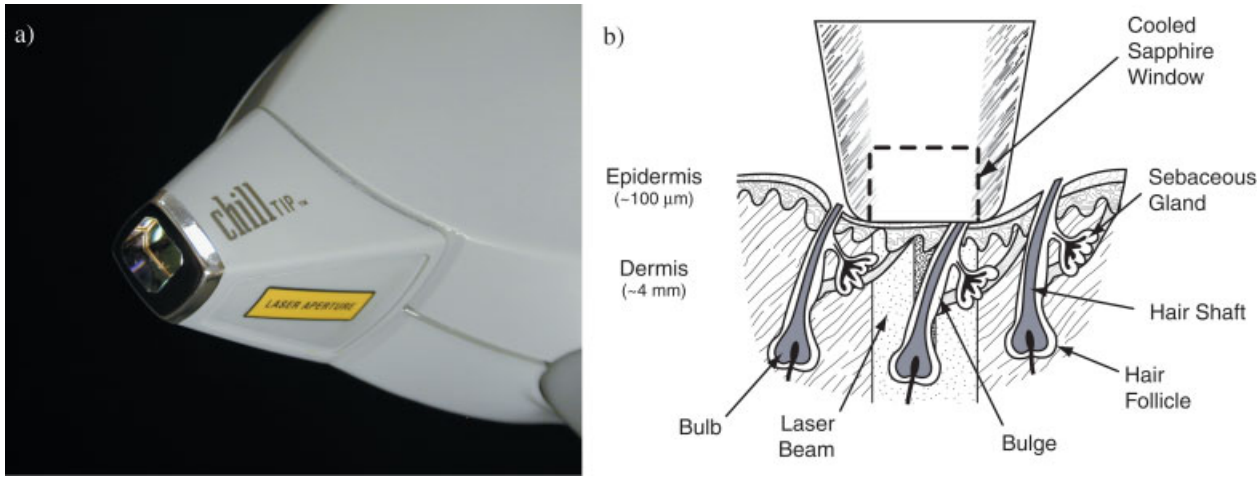

Fig. 1. (**a**) Laser emission emanates from the LightSheer handpiece through the 9×9-mm sapphire ChillTip that is cooled to a temperature of 5°C. (**b**) During normal use, the ChillTip is pressed directly onto the skin overlying the targeted structures for approximately 250–500 msec prior to the administration of the pulse of light and remains in direct contact with the skin for a brief duration (≤ 1 second) after the pulse is delivered.

where r is the radial dimension (cm), k is the thermal conductivity (W/cm · °C), T is the temperature (°C), z is the axial dimension (cm), ρ is the density (g/cm^3), and c is the specific heat (J/g · °C). The rate of internal heat generation S (W/cm^3) is given by

$$S(r,z,t) = \phi(r,z,t)\mu_a(r,z), \tag{2}$$

where ϕ is the local fluence rate (W/cm^2). The incident

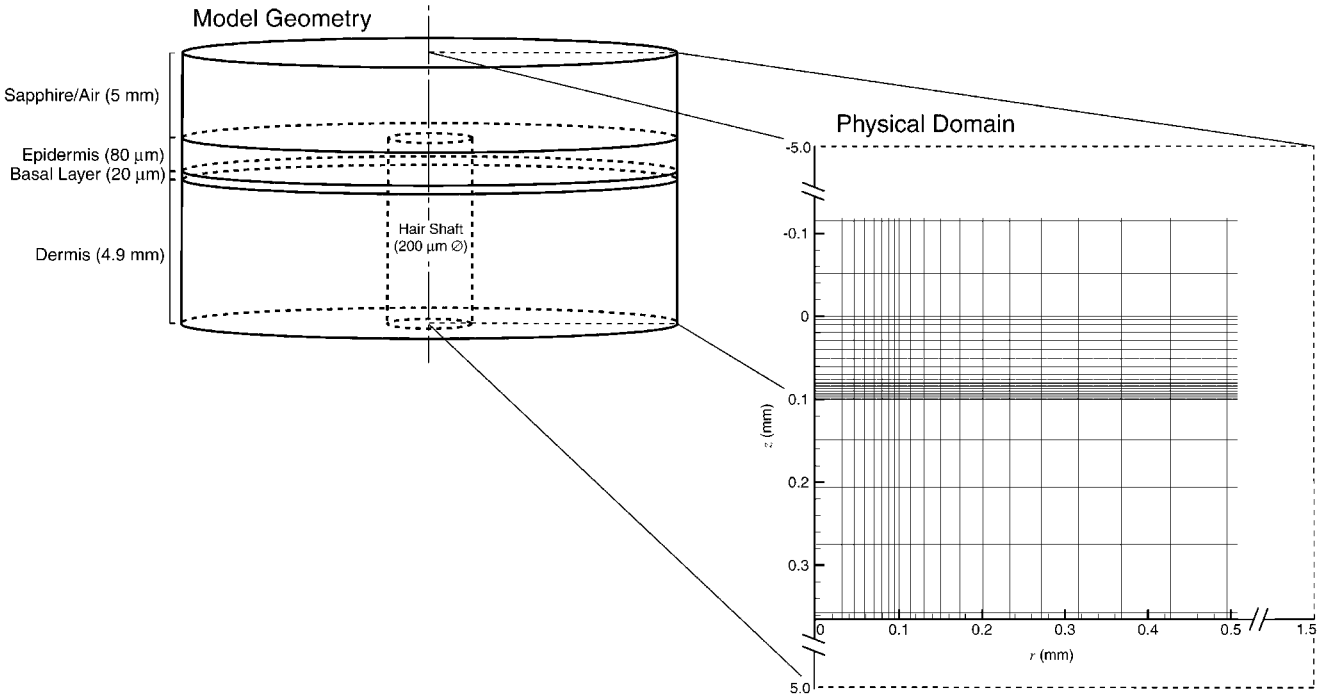

Fig. 2. Model geometry used for the Monte Carlo light transport and axisymmetric finite-difference heat diffusion calculations. The skin was modeled as three parallel horizontal layers (80-μm-thick epidermis, 20-μm-thick basal layer, and underlying dermis) with a central 200-μm diameter vertical hair shaft. A non-uniform 30×60 grid representing the physical domain was used in order to efficiently resolve large temperature gradients.

TABLE 1. Optical Properties of Skin Used in the Monte Carlo Model for Light Transport in Multi-Layered Tissues (λ = 800 nm) [11,12]

	μ_a (cm^{-1})	μ_s (cm^{-1})	g	n
Epidermis	0.3	40	0.8	1.37
Basal layer	3.0	40	0.8	1.37
Dermis	0.3	40	0.8	1.37

laser beam was modeled temporally as a square pulse of constant irradiance ($E_0 = 2{,}000$ W/cm^2) over the duration of the pulse ($\tau_p = 30$ msec) resulting in a total radiant exposure of 60 J/cm^2. An explicit axisymmetric finite-difference computer model based on Equation 1 was used to calculate the temperature distribution in the skin at discrete time steps before, during, and after irradiation. As shown in Figure 2, a non-uniform 30×60 grid representing the physical domain was used in order to efficiently resolve large temperature gradients. The thermal properties for the skin components were calculated using the following empirical relations based on tissue water content [10]:

$$\rho = (1.3 - 0.3w) \quad \text{g/cm}^3, \tag{3}$$

$$c = 4.18\left(0.37 + 0.67\frac{w}{\rho}\right) \quad \text{J/g} \cdot {}^\circ\text{C}, \tag{4}$$

$$k = \rho c\left(0.1333 + 1.36\frac{w}{\rho}\right) \times 10^{-3} \quad \text{W/cm} \cdot {}^\circ\text{C}, \tag{5}$$

where w (g/cm^3) is the water content of the tissue. A value of $w = 0.5$ g/cm^3 was used for the epidermis, basal layer, and hair, and $w = 0.75$ g/cm^3 was used for the dermis. The thermal properties used in the heat transfer model, including those for the skin components calculated using Equations 3–5, are summarized in Table 2.

Thermal damage. Thermal damage was modeled as a first-order kinetic rate process using an Arrhenius expression [13],

$$\Omega(r,z,\tau) = \int_0^\tau \omega(r,z,t)\,\mathrm{d}t, \tag{6}$$

where $f_d = 1 - \exp[-\Omega(\tau)]$ represents the fraction of damaged tissue at time τ (s). The temperature-dependent damage rate ω (s^{-1}) is given by,

$$\omega(r,z,t) = \frac{k_b T(r,z,t)}{h}\exp\left[\frac{\Delta S}{R} - \frac{\Delta H}{RT(r,z,t)}\right], \tag{7}$$

TABLE 2. Thermal Properties Used in the Heat Transfer Model [9,10]

Component	k (W/cm · °C)	ρ (g/cm^3)	c (J/g · °C)
Sapphire	4.60×10^{-1}	3.97	7.65×10^{-1}
Epidermis	2.30×10^{-3}	1.15	2.76
Basal layer	2.30×10^{-3}	1.15	2.76
Dermis	4.10×10^{-3}	1.08	3.50
Hair	2.30×10^{-3}	1.15	2.76

where k_b is Boltzmann's constant (J/K), T is the absolute temperature (K), h is Planck's constant (J · s), R is the universal gas constant (J/mol · K), ΔS is the entropy of reaction (J/mol), and ΔH is the enthalpy of reaction (J/K · mol). The coefficients used were $\Delta S = 2.85 \times 10^2$ J/mol and $\Delta H = 1.92 \times 10^5$ J/K · mol [14]. The tissue is considered irreversibly damaged when $\Omega \geq 1$.

Initial and boundary conditions. The initial conditions for the thermal model are given by

$$T(r,z,0) = \begin{cases} T_s, T_a & \delta_s \leq z < 0 \\ T_i + \left(\dfrac{T_\delta - T_i}{\delta}\right)z & 0 \leq z \leq \delta, \end{cases} \tag{8}$$

where $T_s = 5$°C (T_s, $T_a = 20$°C for room-temperature sapphire or air), $\delta_s = -5$ mm is the coordinate of the upper surface of the sapphire, $T_i = 30$°C is the initial temperature of the skin surface at $z = 0$, and $T_\delta = 37$°C is the constant temperature of the dermis at depth $\delta = 5$ mm. In the case of sapphire contact cooling, circulating water continuously cools the upper surface of the sapphire. The boundary condition at the sapphire-water interface is

$$h_w\,[T_w - T\,(r,\delta_s,t)] = -k\left.\frac{\partial T}{\partial z}\right|_{z=\delta_s}, \tag{9}$$

where h_w (W/cm^2 · °C) is the cooling water convection coefficient, $T_w = 5$°C ($T_w = 20$°C without active cooling) is the temperature of the cooling water, and $T(r,\delta_s,t)$ is the temperature of the upper surface of the sapphire (°C). A cooling water convection coefficient of $h_w = 0.30$ W/cm^2 · °C was used. Heat transfer at the sapphire–skin boundary, given some contact resistance R (cm^2 · °C/W), is subject to the condition of continuous heat flow resulting in the following boundary condition,

$$k\left.\frac{\partial T}{\partial z}\right|_{0^-} = \frac{T|_{0^-} - T|_{0^+}}{R} = k\left.\frac{\partial T}{\partial z}\right|_{0^+}, \tag{10}$$

evaluated at the sapphire–skin interface where $z = 0$. For this analysis, a relatively low contact resistance $R = 1.0 \times 10^{-6}$ cm^2 · °C/W was used, representing near ideal contact between the sapphire and the skin. In the case of no contact cooling, the boundary condition at the air–skin interface is

$$h_a\,[T_a - T(r,0,t)] = -k\left.\frac{\partial T}{\partial z}\right|_{z=0}, \tag{11}$$

where h_a (W/m^2 · K) is the free convection coefficient, $T_a = 20$°C is the temperature of the air, and $T(r,0,t)$ is the temperature of the skin surface. A constant free convection coefficient of $h_a = 2.5 \times 10^{-3}$ W/cm^2 · °C was used. At the bottom of the computation grid, the temperature is held constant, or

$$T(r,\delta,t) = T_\delta, \tag{12}$$

and given the axisymmetric nature of the computation, the temperature gradient in the r-direction was set equal to

zero along the line of symmetry and at the outer boundary of the computation region, or

$$\left.\frac{\partial T}{\partial r}\right|_{r=0,\, r_{\max}} = 0, \tag{13}$$

where $r_{\max} = 1.5$ mm.

RESULTS

Clinical Study

A series of photographs from one subject documenting the results of a 60-J/cm^2, 30-msec, 800-nm pulse with pre-cooling and heat-sinking, heat-sinking only, and no pre-cooling or heat-sinking are shown in Figure 3.

Pre-cooling and heat-sinking. All three of these sites displayed minimal, if any, erythema, which lasted for up to 3 minutes (Fig. 3a). There was no epidermal or dermal devitalization after treatment and no development of pigmentary alteration or textural change. Each subject experienced a slight stinging sensation with the delivery of the pulse of light, lasting for a few seconds.

Heat-sinking only. Each of these three sites displayed slight erythema which persisted for up to 10 days (Fig. 3b). A few follicles sustained perifollicular epidermal devitalization, which desquamated within one week after treatment. No sustained pigmentary alteration or textural change developed. There was slightly more stinging experienced by all three subjects compared to those sites that were exposed to pre-cooling and heat-sinking. However, it also lasted for only a few seconds.

No pre-cooling or heat-sinking. In all three of these sites, there was immediate erythema, and the epidermis appeared translucent and gray, indicative of epidermal devitalization (Fig. 3c). The extent of epidermal and dermal necrosis became more obvious with time post-treatment, peaking at day 10. Wound healing began subsequently with reconstitution of the dermis and epidermis. However, erythema and textural change persisted at 90 days. All three subjects reported a burning pain at the time of treatment, which gradually diminished over the subsequent 5–7 days.

Modeling

The results from the Monte Carlo simulation of the penetration of 800-nm radiation along the centerline of a 10-mm diameter beam applied through external mediums of air ($n_e = 1.0$) and sapphire ($n_e = 1.76$) for the skin parameters in Table 1 are shown in Figure 4. In the case of no sapphire contact, the scattered photons reflected internally by the air-skin interface enhance the fluence rate up to 444% at the skin surface and 441% at a depth of 90 μm compared to only 253% and 290%, respectively, for the same beam applied through sapphire in contact with the skin surface. Thus, given equal irradiance, sapphire contact cooling inherently reduces the fluence rate enhancement at the basal layer by 34%. Beyond approximately 1 mm in depth, the reduction in fluence rate enhancement by sapphire contact cooling is a relatively uniform 21%.

The calculated thermal history of the pigmented basal layer [$r = 1.17$ mm (i.e., independent of the presence of the hair), $z = 90$ μm depth] with pre-cooling and heat-sinking, heat-sinking only, and no pre-cooling or heat-sinking using the corresponding fluence rate distributions of

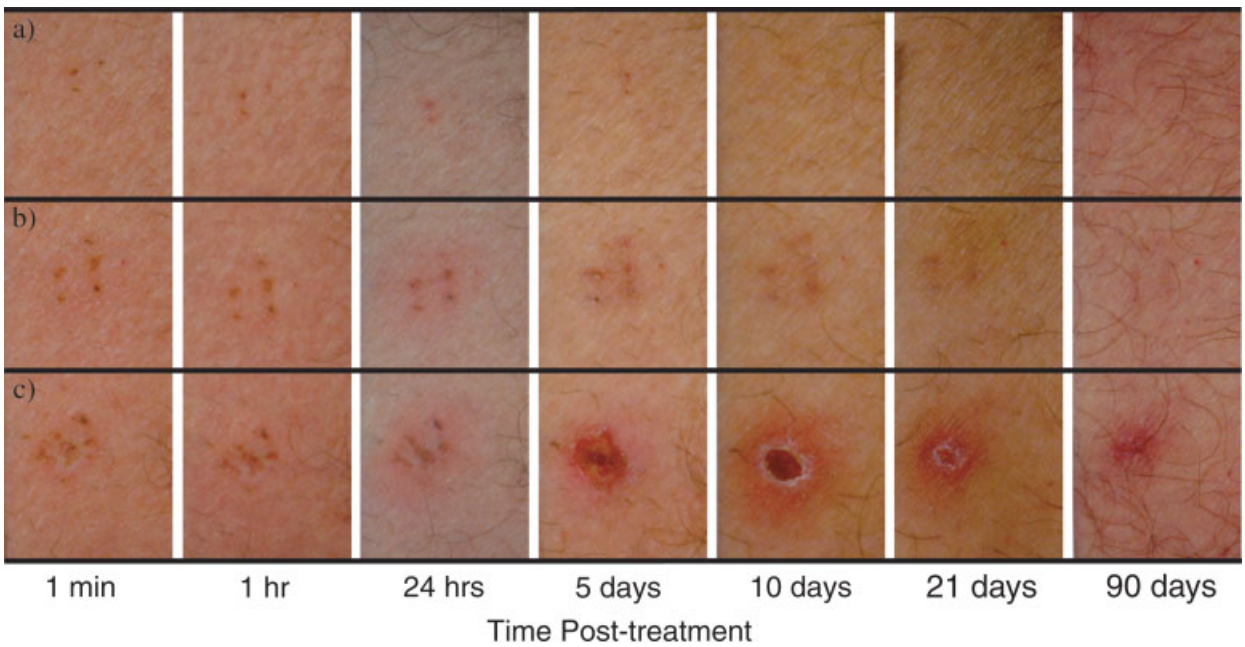

Fig. 3. Series of clinical photographs from one subject showing the results of a 60-J/cm^2, 30-msec, 800-nm pulse with (**a**) pre-cooling and heat-sinking, (**b**) heat-sinking only, and (**c**) no pre-cooling or heat-sinking.

Figure 4 are shown in Figure 5. Calculated contours of maximum temperatures and predicted thermal damage are shown in Figure 6.

Pre-cooling and heat-sinking. During the 250-msec pre-cooling period, the 5°C sapphire cools the basal layer of the skin from 30 to 16°C (Fig. 5). As can be seen (Fig. 6a), the relatively long pulse duration enables approximately 56% of the heat deposited in the pigmented basal layer to dissipate into the sapphire and pre-cooled neighboring tissue, thereby significantly reducing the maximum temperature experienced by the epidermis. Given the relatively low thermal conductivity of the epidermal tissue, only ~4% of the heat actually reaches the sapphire during the pulse. Thus, for pulse durations ≤ 30 msec, concurrent heat-sinking plays a relatively minor role. However, because sapphire is an efficient heat sink as a result of its relatively high thermal conductivity, it continues to cool the skin during the relatively long post-pulse contact period increasing the rate at which the basal layer returns to its normal temperature. This rapid thermal relaxation limits the amount of time the tissue is at an elevated temperature, resulting in less tissue necrosis and increased comfort for the patient (Fig. 5).

Heat-sinking only. Even without actively cooling the ChillTip, the room-temperature (20°C) sapphire reduces the basal layer temperature from 30 to 25°C during the 250-msec pre-pulse contact period (Fig. 5). Because there is still efficient heat-sinking during and after the laser pulse, the 9°C higher initial temperature of the basal layer simply shifts the temperature history curve up by ~9°C. As expected, the higher temperature history curve translates into a slightly greater predicted fraction of tissue necrosis in the basal layer region (Fig. 6b). Such damage would not be expected to be extensive or irreversible in nature, but reflective of the persistent erythema experienced by each subject in these test sites. In addition, the higher post-pulse temperature correlates with the slightly greater and longer-lasting discomfort experienced by each subject.

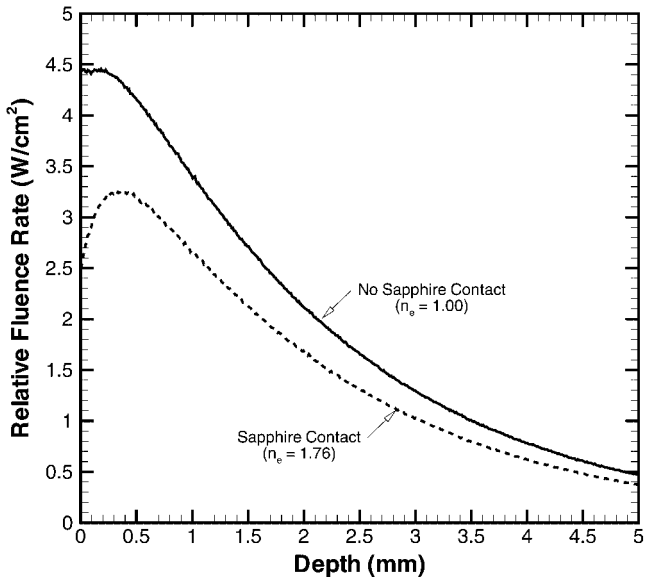

Fig. 4. Calculated penetration of 800-nm radiation along the centerline of a 10-mm diameter beam in tissue with ($n_e = 1.76$) and without ($n_e = 1.0$) sapphire contact using the tissue properties of Table 1.

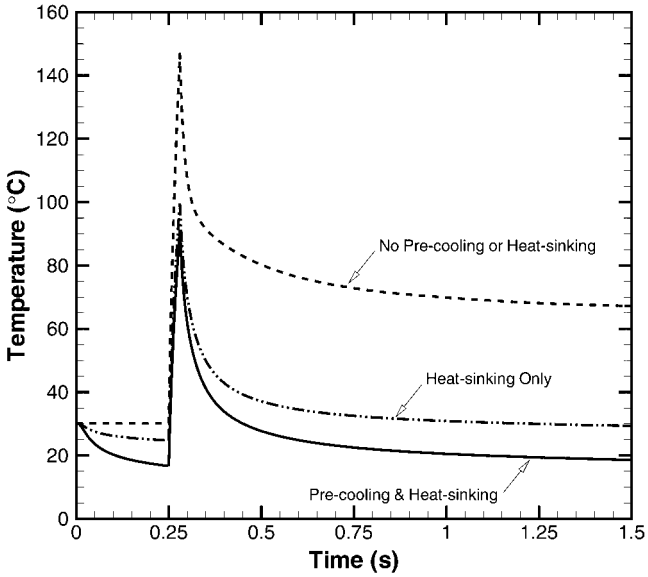

Fig. 5. Calculated thermal history of the pigmented basal layer [$r = 1.17$ mm (i.e., independent of the presence of the hair), $z = 90$ μm depth] resulting from a 60-J/cm^2, 30-msec, 800-nm pulse with pre-cooling and heat-sinking, heat-sinking only, and no pre-cooling or heat-sinking.

No pre-cooling or heat-sinking. Without any pre-cooling or concurrent heat-sinking (i.e., no sapphire in contact with the skin), the epidermis is subjected to 52% more fluence in the region of the basal layer (see Fig. 4), resulting in a proportionally higher temperature rise (Fig. 5). In addition, the relatively low heat transfer rate at the air-skin interface causes the heat to remain and diffuse within the tissue (Fig. 6). The higher temperature and longer period at which the tissue remains at elevated temperature results in the prediction of complete damage to the entire epidermis and a wider extent of irreversible damage surrounding the target area. The prediction agrees well with the epidermal and dermal necrosis that became quite evident in the test sites by day 10. The relatively long-lasting burning pain reported by each subject is in agreement with the extent of predicted tissue damage and high post-pulse temperatures.

Calculations were performed for a 60-J/cm^2, 30-msec, 800-nm treatment pulse administered with various combinations of index matching, pre-cooling, heat-sinking, and post-cooling in order to assess the relative importance of each individual aspect of contact cooling (and combinations thereof) in preventing tissue necrosis. The calculated maximum temperature and predicted tissue necrosis of the pigmented basal layer for each case are listed in Table 3. Index matching alone (Case VIII) is the strongest

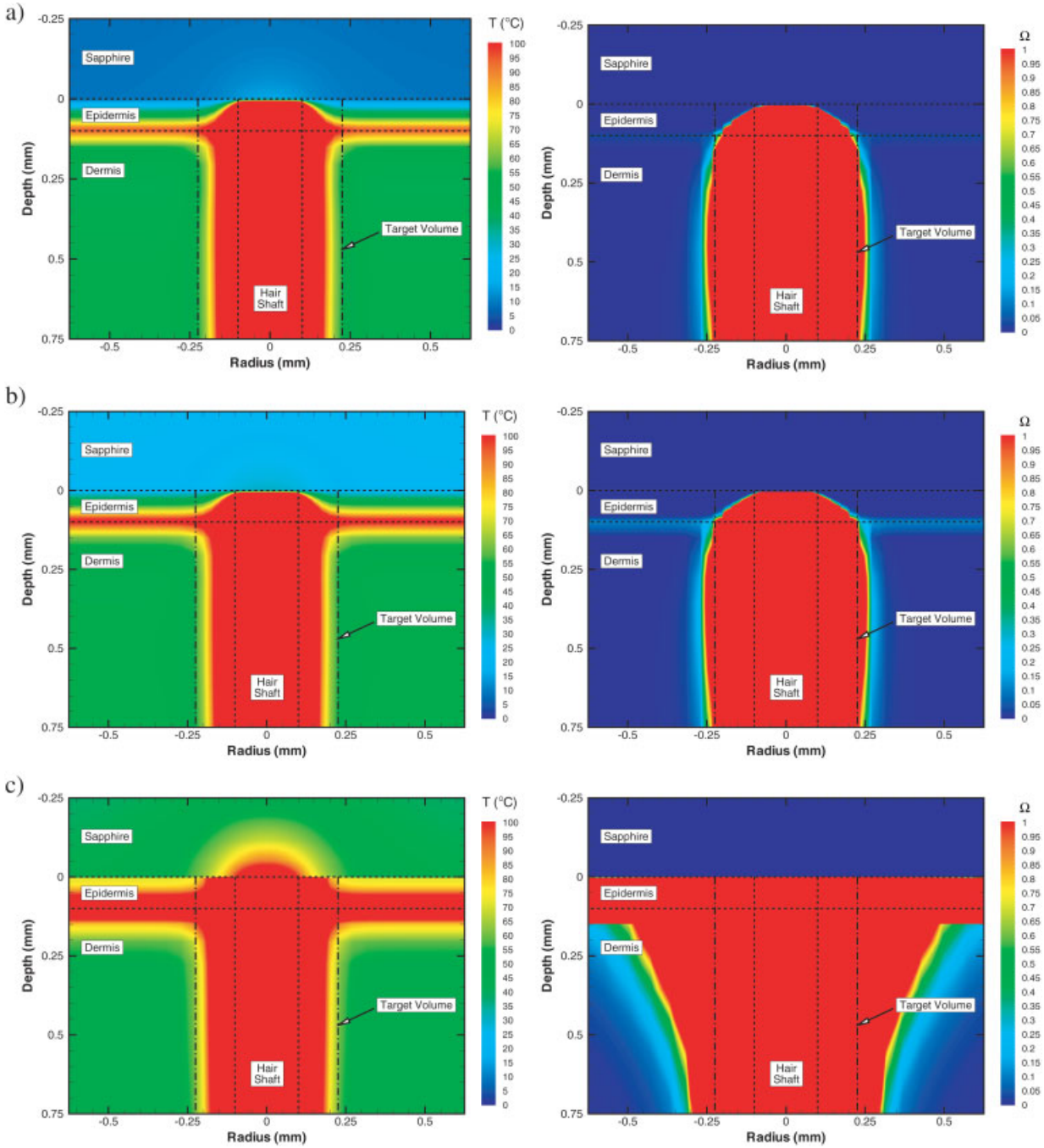

Fig. 6. Calculated contours of maximum temperatures (i.e., at the end of the treatment pulse) and predicted thermal necrosis (tissue is considered irreversibly damaged when $\Omega \geq 1$) resulting from a 60-J/cm^2, 30-msec, 800-nm pulse. (**a**) With pre-cooling and heat-sinking, the epidermis remains cool and the basal layer experiences only a brief period of elevated temperature. Thermal necrosis is confined to the target volume. (**b**) With heat-sinking only, the temperature of the epidermis and basal layer are approximately 15°C higher, resulting in a slight increase in predicted fraction of tissue necrosis in the basal layer. (**c**) With no pre-cooling or heat-sinking, complete damage to the entire epidermis and a wide volume surrounding the target is predicted.

contributor preserving 83.4% of the tissue compared to 0% without cooling or index matching (Case XV). When combined with pre-cooling, heat-sinking, and post-cooling (Case I), index matching spares an additional 98.3% of the tissue compared to pre-cooling, heat-sinking, and post-cooling alone (Case IX). The second largest contributor is pre-cooling. Although, pre-cooling the basal layer and surrounding tissue to 16°C alone (Case XII) does not

protect the tissue appreciably, pre-cooling in combination with index matching (Case IV) preserves an additional 14.8% of the tissue compared to index matching alone (Case VIII). Heat-sinking and post-cooling are relatively minor contributors. Heat-sinking in combination with index matching and pre-cooling (Case II) preserves only an additional 0.5% of the tissue compared to index matching and pre-cooling alone (Case IV) while post-cooling contributes an additional 0.1–1.0%. Post-cooling, however, contributes significantly to the reduction of pain experienced by the patient during treatment.

DISCUSSION

The buildup of fluence rate at the skin surface has important implications when attempting to protect the pigmented epidermis at a depth of 0–100 μm during treatment. The results of this small study suggest that by providing favorable index matching at the skin surface, epidermal heating during treatment can be significantly reduced. Irradiation of the treatment area through sapphire in contact with the skin, for example, limits the accumulation of fluence rate at the skin surface by enabling a broader range of low-angle photons to couple back out of the skin instead of reflecting internally. As a consequence, given equal irradiance, somewhat lower fluence rates at target depths of 1–3 mm result (see Fig. 3). However, even when using 26% more radiant exposure to equal the fluence rates that occur at depths of 1–3 mm without sapphire contact cooling, treatment through sapphire in contact with the skin can reduce epidermal heating up to 17%, regardless of any additional pre-cooling or heat-sinking benefits.

For pulse durations on the order of 30 msec, relatively little of the heat has a chance to diffuse through the 80-μm-thick epidermis and into the sapphire heat sink. By using longer pulse durations, proportionately more heat would diffuse out of the epidermis and into the sapphire and surrounding tissue, thereby enhancing the heat-sinking effect significantly. Because the target structures are relatively large, pulse durations on the order of 100 msec can be used without significantly compromising the spatial specificity of the technique. Likewise, because the target structures are relatively deep within the skin, a significantly longer pre-cooling time of up to one second, resulting in a somewhat lower pre-pulse basal layer temperature of ~11°C, can be used without sacrificing efficacy.

Additional benefits of sapphire contact cooling, which were not included in the theoretical analysis presented herein, result from the compression of the tissue as the sapphire is pressed against the skin. Firm contact of the sapphire not only ensures good thermal contact and efficient optical coupling, but also squeezes the blood out of the treatment area. Blood contains hemoglobin, a competing chromophore that has an absorption coefficient of approximately 5 cm^{-1} at 800 nm. Assuming a uniformly distributed 1.0% volume fraction of blood, squeezing out the blood results in approximately 3–7% greater fluence rate at the target structures at a depth of 1–3 mm. In

TABLE 3. Predicted Maximum Temperature and Tissue Necrosis of the Pigmented Basal Layer [$r = 1.17$ mm (i.e., Independent of the Presence of the Hair), $z = 90$ μm depth] Resulting From a 60-J/cm^2, 30-msec, 800-nm Treatment Pulse Administered With Various Combinations of Index Matching, Pre-Cooling, Heat-Sinking, and Post-Cooling

Case	Index match[a]	Pre-cool[b]	Heat-sink[b]	Post-cool[b]	Maximum temperature (°C)[c]	Ω[d]	f_d (%)[e]
I	◆	◆	◆	◆	90.7	0.01235	1.23
II	◆	◆	◆		90.7	0.01324	1.32
III	◆	◆		◆	92.5	0.01687	1.67
IV	◆	◆			92.5	0.01866	1.85
V	◆		◆	◆	104	0.1284	12.0
VI	◆		◆		104	0.1339	12.5
VII	◆			◆	106	0.1698	15.6
VIII	◆				106	0.1817	16.6
IX		◆	◆	◆	130	5.311	99.5
X		◆	◆		130	5.340	99.5
XI		◆		◆	132	7.580	100
XII		◆			132	7.687	100
XIII			◆	◆	144	36.64	100
XIV			◆		144	36.85	100
XV				◆	146	50.83	100
XVI					146	51.57	100

[a]Fluence profile for (◆) sapphire contact or ( ) no sapphire contact (see Fig. 3).
[b]With (◆) 5°C sapphire or ( ) 20°C air in contact with the skin.
[c]Maximum temperature at the end of the treatment pulse for $r = 1.17$ mm, $z = 90$ μm.
[d]$\Omega(\tau)$ at $\tau = 1.5$ seconds [see Equation 6].
[e]Fraction of damaged tissue $f_d = 1 - \exp[-\Omega(\tau)]$ at $\tau = 1.5$ seconds for $r = 1.17$ mm, $z = 90$ μm.

addition to squeezing out the blood, the compression of the skin brings the target structures somewhat closer to the surface where they are exposed to proportionally higher fluence rates. Because the fluence rate within the skin drops rapidly with depth (see Fig. 4), even a small decrease in depth can result in a relatively large increase (depending on the initial depth) in fluence rate. Thus, skin compression enables the target structures to be heated more efficiently, so that less radiant exposure is required resulting in less thermal load on the epidermis.

For the theoretical analysis presented herein, the skin surface was assumed to be smooth, and any back reflections from within the sapphire were neglected. In practice, however, some of the photons scattered out of the skin and into the sapphire would be reflected back into the skin (i.e., recycled) as a result of scattering from the sapphire surfaces, and the actual coupling of photons into and out of the skin would depend somewhat on the roughness of the skin surface. As a consequence, the curves in Figure 4 representing the external mediums of air and sapphire may actually lie somewhere between the two shown. Moreover, for laser irradiation at 800 nm, the fluence distribution within the skin and the consequent heating of absorptive tissue are highly dependent on the scattering and absorption coefficients. Published values for skin scattering and absorption coefficients vary by almost an order of magnitude [15,16]. In addition, these coefficients have been shown to vary somewhat with temperature and degree of tissue thermal necrosis [17,18]. Nonetheless, the calculated results presented herein using constant coefficients at the lower end of the range appear to agree well with the clinical observations.

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