Epidermal Protection: A Comparative Analysis of Sapphire Contact and Cryogen Spray Cooling

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BACKGROUND. Laser hair removal is becoming an increasingly popular alternative to traditional methods such as shaving, waxing, depilatory creams, or electrolysis. Numerous laser systems are currently available offering different methods for protecting the epidermis from thermal injury during treatment.
OBJECTIVE. To analyze the effectiveness of sapphire contact and cryogen spray cooling in the context of laser hair removal.
METHODS. A detailed analysis of each technique including calculations of the skin's thermal response to each cooling method before, during, and after the treatment pulse was performed.
CONCLUSION. Sapphire contact cooling is significantly more effective than cryogen spray cooling in protecting the epidermis from unwanted thermal damage during laser hair removal treatment. Calculations show that a system using sapphire contact cooling with a 30 ms pulse duration is approximately two times more effective in protecting the epidermis than cryogen cooling with 3 ms pulses given equal target heating. Efficient precooling of the epidermis, compression of the skin, and concurrent heat-sinking of the epidermis with a chilled sapphire window in conjunction with a longer treatment pulse duration result in superior epidermal protection. The concurrent heat-sinking of the epidermis in conjunction with a longer treatment pulse duration is the largest contributing factor reducing the temperature rise of the epidermis by over 40%. In addition to being more effective, sapphire contact cooling provides protection of the epidermis at significantly lower cost, with no risk of freezing and maximum comfort for the patient by cooling before, during, and after the treatment pulse.

LASER HAIR REMOVAL is becoming an increasingly popular alternative to traditional methods such as shaving, waxing, depilatory creams, or electrolysis. With a global device market estimated at approximately $200 million per year, laser hair removal is currently by far the largest opportunity in aesthetic lasers. Consequently, numerous manufacturers are now producing laser and non-laser based systems aimed specifically at serving this market.

In order to compare the relative merits of each of these systems, it is important to consider the underlying principles governing the treatment. This technical note, the first of a series discussing the important aspects of laser hair removal, focuses on methods of protecting the epidermis from thermal damage during treatment with high fluence levels. In particular, the effectiveness of sapphire contact and cryogen spray cooling are examined in detail.

A comparison of sapphire contact and cryogen spray cooling in the more general context of thermally mediated therapeutic procedures has appeared previously in the literature [1]. However, in that article, the two methods were evaluated based on precooling efficiency alone and not on the basis of their ability to protect the epidermis during laser illumination. Other more dominant factors, such as the effects on light propagation or the benefits of concurrent heat-sinking (i.e. simultaneous epidermal heat-sinking and target heating), were not considered. To more realistically compare these two methods, a more complete analysis in the context of laser hair removal is presented in this technical note.

Photothermal Epilation

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 follicles' regenerative structures. For time periods characteristic of photothermal epilation, the thresh-

old temperature for thermal necrosis is on the order of 70°C [2]. The selective deposition of energy is accomplished by illuminating the treatment area with sufficient fluence (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 fluence is typically delivered within a time less than or comparable to the thermal relaxation time of the target structure. The process of selective absorption leading to local thermal necrosis is known as selective photothermolysis [3].

Epidermal Preservation

As one might expect, the effectiveness of the treatment (i.e. the percentage of follicles permanently damaged) scales with the amount of fluence used. In a study of 92 patients (45 males and 47 females of varying hair color and skin type) treated with a Lumenis LightSheer™ Diode Laser System at the Massachusetts General Hospital in Boston and the Laser and Skin Surgery Center of New York in New York City, 32.5% hair reduction was observed at 12 months following a single treatment using a fluence of 40 J/cm^2 and a pulsewidth of 20 ms, while 25.9% was observed for settings of 20 J/cm^2 and 10 ms [4]. Interestingly, multiple pulses (3×) using the same fluence levels 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 amount of fluence (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 blistering or irregularities in pigmentation. Although almost invariably (but not necessarily) 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.

Optimization for epidermal preservation without compromising hair reduction results requires close examination of the principles governing laser-tissue interaction. Given a uniform incident beam, the peak temperature T_f(°C), experienced by absorptive tissue at depth z (cm), irradiated with incident fluence rate ψ_0 (W/cm^2), is approximated by,

$$T_f \cong \frac{\mu_a \tau_p \psi_0 f(z)}{\rho C}\left(\frac{1-e^{-\tau_p/\tau_r}}{\tau_p/\tau_r}\right) + T_i \quad , \qquad (1)$$

where μ_a (cm^{-1}) is the absorption coefficient of the tissue, τ_p (s) is the laser pulse duration, $f(z)$ represents the dependence of the fluence rate on depth, ρ (g/cm^3) is the tissue density, C (J/g•°C) is the specific heat of the tissue, τ_r (s) is the thermal relaxation time of the tissue, and T_i (°C) is the initial temperature of the tissue.

Examination of Eq. (1) reveals that for a given skin type, determined by μ_a, and incident fluence $\tau_p\psi_0$ (J/cm^2), epidermal preservation can best be effected by:

precooling the epidermis to lower its initial temperature,

heat-sinking the epidermis during the laser pulse to effectively shorten its thermal relaxation time, and

using longer pulse durations to allow the heat generated within the epidermis to dissipate.

Although it is not obvious from Eq. (1), by

compressing the skin to enable the target structures to be heated more efficiently,

less incident fluence would be required and the thermal load on the epidermis would be reduced accordingly. Each of these aspects and their influence on system design are discussed briefly below.

Precooling the Epidermis. Precooling the epidermis lowers its initial temperature, and according to Eq. (1), reduces its peak temperature by a corresponding amount. Thus, precooling of the epidermis from 30°C to 5°C, for example, would reduce the peak temperature of the epidermis by 25°C, given equal incident fluence and target heating.

Heat-Sinking the Epidermis. If the skin is in contact with an effective heat sink during the treatment pulse, the increased rate of heat extraction from the epidermis, in effect, lowers its thermal time constant. Low-

ering the thermal time constant of the epidermis increases the ratio τ_p/τ_r, and the term in parenthesis in Eq. (1), which represents the effect of heat transfer during the treatment pulse, will reduce accordingly resulting in less thermal load on the epidermis.

Using Longer Pulse Durations. In a similar manner, the ratio τ_p/τ_r can be increased by simply administering the treatment fluence over a longer pulse duration. Because the larger target follicle structures retain heat longer than the smaller (or thinner) epidermis, and because the exposed epidermis can lose heat faster than an insulated hair follicle, the target follicle structures will retain more of the energy deposited by a longer pulse than the epidermis. Thus by using longer pulses, the target follicle structures can be brought to the damage threshold temperature while the overlying epidermis remains minimally affected.

However, in order to most efficiently heat the target structures while limiting the thermal impact to the adjacent tissue, it is necessary to deposit the energy into the target structures within a period of time less than or comparable to the amount of time it takes for the heat generated to diffuse out of the target structures and into the surrounding tissue. The time it takes for the heat to diffuse is characterized by the thermal relaxation time, τ_f(s), of the target structure, which is approximated by [5],

$$\tau_f \cong d^2/k\alpha \quad , \qquad (2)$$

where α is the thermal diffusivity of the target structure and its surroundings (approximately 1.1×10^{-3} cm^2/s for tissue [6]), and k is a geometrical factor (equal to 16 for a long cylinder of diameter d). The target structures for photothermal epilation are believed to include the hair shaft, the stem cells of the bulb and the more superficially located inner and outer root sheaths surrounding the follicle. The cross-sectional diameter of the bulb, for example, ranges from 200–300 μm [7]. Assuming that the target includes the tissue within a cylinder of diameter 1.5 times that of the bulb, the laser pulse duration τ_p can safely have a maximum value of 50–100 ms in length, depending on the size of the hair. Note, however, that as the pulse duration increases, more of the heat dissipates into the surrounding tissue requiring proportionally greater fluence to achieve the same peak target temperature.

Compressing the Skin. Compressing the skin squeezes the blood out of the treatment area and forces the hair follicles to lie down bringing the roots closer to the surface. 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 at the target structures at a depth of 1–3 mm. And, in 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 levels. Because the fluence level within the skin drops rapidly with depth, even a small decrease in depth can result in a relatively large increase (depending on the initial depth) in fluence. Thus, skin compression enables the target structures to be heated more efficiently, so that less fluence is required resulting in less thermal load on the epidermis.

In summary, by judiciously selecting the laser pulse duration and actively cooling the epidermis prior to and heat-sinking the epidermis during the treatment pulse in a manner that provides compression of the skin, epidermal damage can be avoided while administering the highest, most effective fluence levels.

Analysis of Sapphire Contact and Cryogen Spray Cooling

As protecting the epidermis is critical to safe and effective hair removal, commercially available laser hair removal systems attempt to cool the epidermis without significantly reducing the temperature of the target hair shafts and surrounding follicle structures, which lie at least 1 mm below the skin surface. A number of different strategies are employed including the application of a refrigerated gel to the skin surface prior to treatment, the precooling of the skin surface through contact with a chilled metal plate, the precooling of the skin through rapid evaporation of a

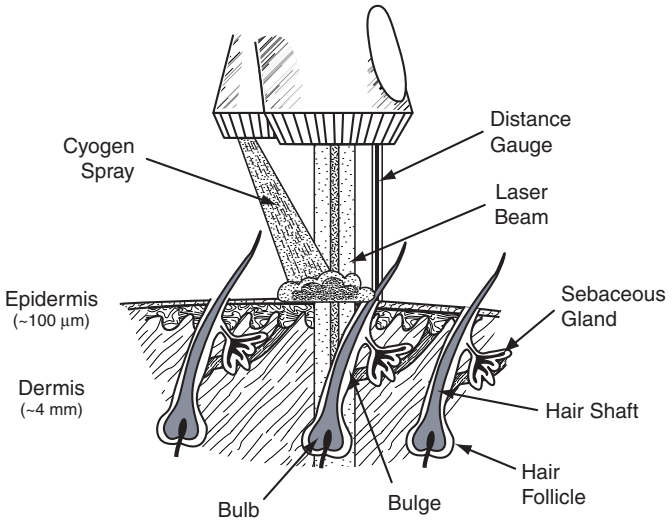

Figure 1. A typical cryogen spray cooling device emits a focused spray of cryogen on the treatment area milliseconds before each laser pulse.

cryogen spray applied to the skin just prior to the treatment pulse, the cooling of the skin before, during, and after the treatment pulse with chilled air or through contact with a chilled sapphire window. The following is a detailed comparison of two of these strategies, cryogen spray cooling (e.g. the Dynamic Cooling Device™ used on the Candela® GentleLASE®), and contact cooling via a chilled sapphire window (e.g. the ChillTip™ handpiece used on the Lumenis LightSheer Diode Laser System).

Cryogen Spray Cooling

A typical cryogen spray cooling device is illustrated in Fig. 1. Such devices typically use HFC-134a (1,1,1,2-tetrafluoroethane), an odorless, colorless, liquefied chlorofluorocarbon substitute. It should be noted that although relatively nontoxic, HFC-134a can cause central nervous system depression after prolonged inhalation exposure and, thus, should only be used in well-ventilated areas [8]. The cryogen spray cooling device delivers a spurt of HFC-134a to the treatment area just prior to the treatment pulse. The duration of the spurt is typically adjustable from 20–100 ms, and the distance from the treatment area is set by a distance gauge.

Evaporation of the cool liquid cryogen droplets (Boiling Point = -26.5 °C at 1 atm) as they impinge the relatively warm skin surface, rapidly cools the epidermis. As the skin surface temperature decreases toward the boiling point of the cryogen, the rate of heat extraction from the skin is no longer sufficient to completely evaporate the cryogen droplets and a film of cryogen droplets and ice (a result of the condensation of water vapor present in the air) begins to accumulate on the skin surface. A thin vapor layer between the cryogen-ice film and the 'hot' skin surface [9,10] protects the epidermis from the severely low <-44 °C temperature of the cryogen-ice film, but reduces the heat transfer rate at the skin surface limiting the overall cooling efficiency [10]. It should also be noted that because cryogen spray devices rely on atomization of the cryogen for uniform dispersal of the droplets, irregularities in droplet size may lead to variable localized cooling resulting in insufficient epidermal protection, especially when the skin is exposed to a fluence level exceeding the damage threshold for uncooled skin.

Neglecting potential nonuniformities, a simple one-dimensional heat transfer analysis of cryogen cooling, shown in Fig. 2, reveals that a spurt duration of 50 ms is sufficient to cool the surface of the epidermis to 6 °C, but the more vulnerable basal layer (which contains approximately 2/3 of the epidermal melanin) at a depth of approximately 60–80 μm (depending on the thickness of the epidermis) is cooled to only 18–22 °C. Longer spurt durations provide somewhat better cooling but risk damaging the epidermis from freezing. As can be seen, for spurt durations up to 100 ms, layers below 500 μm in depth remain relatively unaffected.

Because the thermal time constant of the relatively thin epidermis is on the order of milliseconds, cooling of the skin with cryogen spray must be effected immediately prior to the laser pulse. Otherwise, the relatively shallow layer of cooled tissue will rapidly recover in temperature partially negating the cooling achieved with the cryogen spray.

Cryogen-Ice Film. As mentioned previously, humidity in the surrounding air may cause a cryogen-ice layer to form on the surface of the skin during cryo-

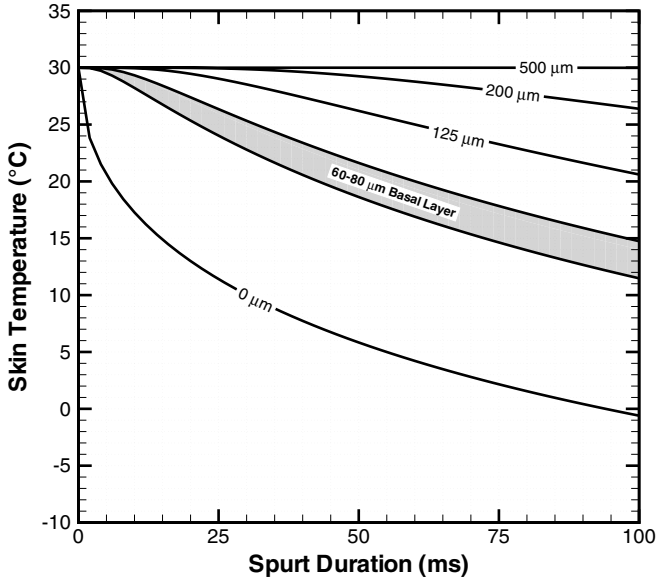

Figure 2. Skin temperature at various depths in response to cryogenic spray cooling of durations up to 100ms [11]. The 60–80μm basal layer is indicated by the shaded band.

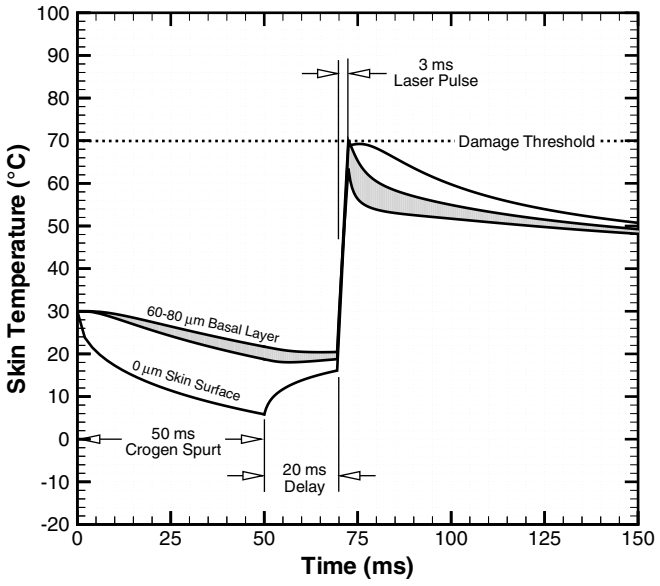

Figure 3. Skin temperature response to a 20J/cm^2, 755nm treatment pulse with a pulse duration of 3ms after a 50ms cryogen spurt and 20ms delay [15]. The 60–80μm basal layer is indicated by the shaded band.

gen spray cooling. This layer has been measured to be up to 20μm thick for a spurt duration of 80ms [12] and is capable of attenuating the incident fluence by as much as 30–35% (λ=755nm)[13]. The attenuation is largely a result of the backward scattering of the incident beam from the exposed treatment area. The beam scattering and accompanying beam attenuation can be avoided by either eliminating the ice formation through reduction of the local relative humidity to 5% or below [14], or by delaying the laser pulse until the film evaporates.

Measurements have shown that the evaporation time for the ice layer can be as much as 100–300ms for typical relative humidity levels of 30–60% [14]. Although the ice film acts as a heat sink maintaining the skin surface at 0°C or below until it evaporates, the amount of delay required for evaporation of the film is uncertain. Minor miscalculations in the delay can lead to significant temperature recovery in the epidermis prior to the treatment pulse.

Computed Thermal Response. Fig. 3 shows the calculated response of the skin temperature to a 755nm treatment pulse (3ms pulse duration, fluence of 20J/cm^2) following cryogen spray cooling (50ms spurt duration, 20ms delay). The effects of cryogen-ice film formation have been neglected, and for simplicity, the epidermal melanin has been assumed to be uniformly distributed throughout the epidermis. As can be seen, the 50ms cryogen spurt cools the skin surface to 6°C and the 60μm deep basal layer to 18°C. However, during the subsequent 20ms delay, the skin surface temperature recovers to 16°C in 20°C air. As the laser irradiates the treatment area, the relatively low 20J/cm^2 fluence heats both the surface of the skin and the 60μm deep basal layer to approximately 70°C.

This relatively high epidermal temperature results from a number of factors, including the short (essentially adiabatic) pulse duration, lack of heat-sinking during the pulse, and the delay required to allow clearance of the cryogen. Because cryogen spray cooling does not provide significant heat-sinking and the heat transfer into the adjacent air is relatively poor, the heat generated in the epidermis by the relatively short 3ms pulse does not have a chance to dissipate into the surrounding tissue or air. And although relatively short, the 20ms delay enables the skin surface temperature to recover by approximately 42%. In

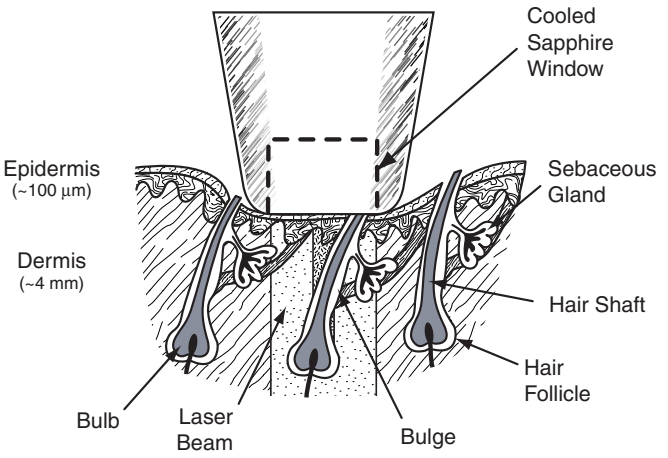

Figure 4. A typical sapphire contact cooling device lowers the epidermal temperature through contact with its actively cooled sapphire window. Pressing the window onto the skin creates good thermal contact while squeezing out the blood and bringing the hair follicles closer to the skin surface and into areas of higher fluence.

addition, the lack of active cooling during and after the laser pulse prolongs the time for the skin to return to its normal temperature, thereby increasing patient discomfort.

Cost. The cryogen spray and disposable distance gauges are consumables and contribute significantly to the operating cost of a system using cryogen spray cooling. For example, assuming an average cost per spurt of $0.01–0.03, a high-volume practice using 500,000–1,500,000 pulses per year would incur annual operating costs of approximately $5,000–$45,000 for cryogen spray alone.

Sapphire Contact Cooling

A typical sapphire contact cooling arrangement is illustrated in Fig. 4. A 5°C liquid-cooled sapphire window at the tip of the handpiece is pressed against the patient's skin for approximately 250 ms prior to initiating the treatment pulse. Because the sapphire window is above freezing, there is no risk of skin damage as a result of overcooling. Moreover, there is no ice formation on the skin surface and the treatment fluence is most effectively coupled into the skin.

Results from a simple one-dimensional heat transfer analysis of sapphire contact cooling are shown in Fig. 5. The results indicate that the surface of the epidermis is cooled to approximately 9°C during the initial 250 ms of contact with the chilled sapphire, while the more vulnerable basal layer at a depth of approximately 60–80 μm (depending on the thickness of the epidermis) is cooled to 13–15°C, a temperature comparable to that achieved with a 50 ms cryogen spurt. As with the cryogen spray cooling, the temperatures of the important targets at depths of greater than 1 mm remain essentially unchanged even for contact times of up to 1 second. And although in practice it is difficult to precisely judge a contact time of 250 ms, Fig. 5 shows that for the depths of interest, $0 \le z \le 80$ μm, little variation in the skin temperature results for contact periods as short as 100 ms or as long as 1 second.

Skin Compression. The pressure of the sapphire window against the skin not only provides excellent thermal contact and optical coupling of the laser pulse into the tissue, but also squeezes out the blood and forces the hair follicles to lie down bringing the roots closer to the surface. As discussed earlier, compression of the skin results in approximately 3–7% greater fluence at the target structures at a depth of 1–3 mm as a

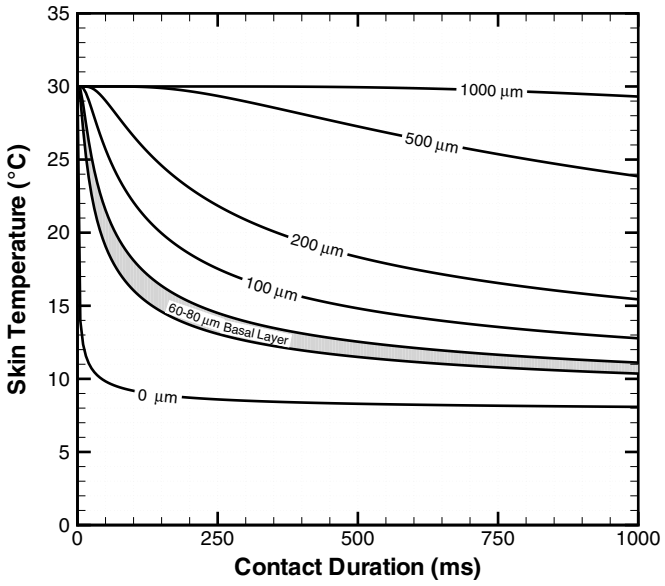

Figure 5. Isothermal contours in response to contact cooling with a sapphire window with constant temperature of 5°C [16]. The 60–80 μm basal layer is indicated by the shaded band.

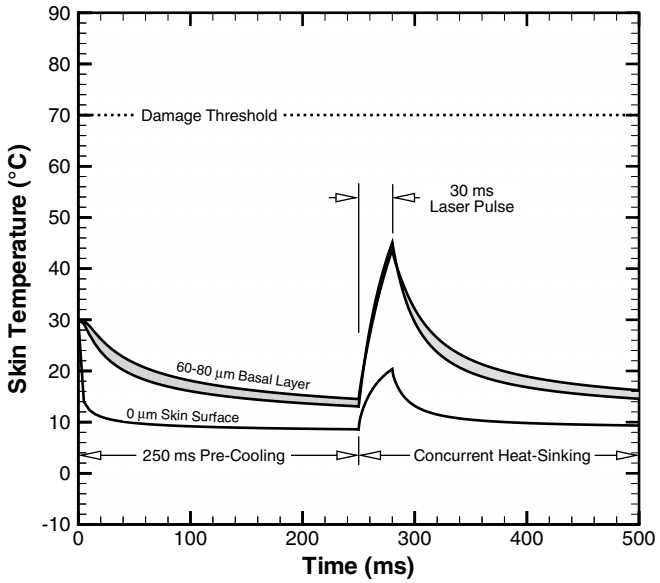

Figure 6. Skin temperature response to a 800 nm treatment pulse (30 ms pulse duration, fluence of 24 J/cm^2) with concurrent sapphire contact heat-sinking following 250 ms of precooling [17]. With this fluence, the target hair shaft and follicle are heated to the same peak temperature as the treatment pulse (20 J/cm^2, 3 ms, 755 nm) of the cryogen cooled system of Fig. 3. Note the much lower epidermal heating. The 60–80 μm basal layer is indicated by the shaded band.

result of blood dispersal and brings the target structures somewhat closer to the surface where they are exposed to proportionally higher fluence levels. These gains in efficiency enable less fluence to be used for the same level of efficacy, thereby decreasing the thermal load on the epidermis.

Computed Thermal Response. Fig. 6 shows the calculated response of the skin temperature to a 800 nm treatment pulse (30 ms pulse duration, fluence of 24 J/cm^2) with concurrent sapphire contact heat-sinking following 250 ms of precooling. As in the previous calculation for cryogen spray cooling, the epidermal melanin has been assumed to be uniformly distributed throughout the epidermis. With this fluence, the target hair shaft and follicle are heated to the same peak temperature as the 20 J/cm^2, 3 ms, 755 nm treatment pulse of the cryogen-cooled system. The extra energy accounts for the lower melanin absorption coefficient at 800 nm and the greater fluence required by the longer pulse duration which is offset, in part, by an improvement in efficiency attributable to skin compression.

During the precooling period, the 5 °C sapphire cools the surface of the skin from 30 °C to 9 °C. Unlike cryogen spray cooling, the sapphire continues to cool the surface of the skin and, as a result of its relatively high thermal conductivity, acts as an efficient heat sink during the laser pulse. As can be seen, the relatively long pulse duration enables the dissipation of a significant amount of heat into the sapphire and neighboring tissue keeping the entire epidermis well below the damage threshold. Moreover, continued cooling after the laser pulse increases the rate at which the skin returns to its normal temperature, resulting in increased comfort for the patient.

Cost. Because the sapphire window is an integral part of the light delivery system and does not use any consumables, there are no additional operating costs associated with this cooling method.

Conclusions

Sapphire contact cooling is significantly more effective than cryogen spray cooling in protecting the epidermis from unwanted thermal damage during laser hair removal treatment. Calculations show that a system using sapphire contact cooling with a 30 ms pulse duration is approximately twice as effective in protecting the epidermis than cryogen cooling with 3 ms pulses given equal target heating.

Efficient precooling of the epidermis, compression of the skin, and concurrent heat-sinking of the epidermis with a chilled sapphire window in conjunction with a longer treatment pulse duration result in superior epidermal protection. The concurrent heat-sinking of the epidermis in conjunction with a longer treatment pulse duration is the largest contributing factor reducing the temperature rise of the epidermis by over 40%. In addition to being more effective, sapphire contact cooling provides protection of the epidermis at significantly lower cost, with no risk of freezing and maximum comfort for the patient by cooling before, during, and after the treatment pulse.

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16. Calculation assumed T_∞=5°C, T_i=30°C, h=30kW/m^2•K, k_s=0.45W/m•K, $\alpha_s=1.1\times10^{-7}$ m^2/s, k_{Sa}=46W/m•K, $\alpha_{Sa}=1.51\times10^{-5}$ m^2/s.
17. Calculation assumed T_∞=5°C, T_i=30°C, h=30kW/m^2•K, k_s=0.45 W/m•K, $\alpha_s=1.1\times10^{-7}$ m^2/s, k_{Sa}=46W/m•K, $\alpha_{Sa}=1.51\times10^{-5}$ m^2/s, μ_a=3cm^{-1}, μ_s=40cm^{-1}, g=0.8 ($0\leq z\leq$80μm), μ_a=0.3cm^{-1}, μ_s=40cm^{-1}, g=0.8 ($z>$80μm).

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