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Er:YAG Laser Skin Resurfacing Using Repetitive Long-Pulse Exposure and Cryogen Spray Cooling: II. Theoretical Analysis

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Background and Objective: To analyze the effects of laser pulse duration and cryogen spray cooling (CSC) on epidermal damage and depth of collagen coagulation in skin resurfacing with repetitive Er:YAG laser irradiation.
Study Design/Materials and Methods: Evolution of temperature field in skin is calculated using a simple one-dimensional model of sub-ablative pulsed laser exposure and CSC. The model is solved numerically for laser pulse durations of 150 and 600 μsec, and 6 msec cryogen spurts delivered just prior to ("pre-cooling"), or during and after ("post-cooling") the 600 μsec laser pulse.
Results: The model indicates a minimal influence of pulse duration on the extent of thermal effect in dermis, but less epidermal damage with 600 μsec pulses as compared to 150 μsec at the same pulse fluence. Application of pre- or post-cooling reduces the peak surface temperature after laser exposure and accelerates its relaxation toward the base temperature to a different degree. However, the temperature profile in skin after 50 msec is in either example very similar to that after a lower-energy laser pulse without CSC.
Conclusion: When applied in combination with repetitive Er:YAG laser exposure, CSC strongly affects the amount of heat available for dermal coagulation. As a result, CSC may not provide spatially selective epidermal protection in Er:YAG laser skin resurfacing. Lasers Surg. Med. 28:131–137, 2001. © 2001 Wiley-Liss, Inc.

Key words: dynamic cooling; laser pulse duration; repetitive laser exposure; thermal damage

INTRODUCTION

In laser therapy of several dermatological conditions (port wine stain birthmarks, telangiectasias, spider veins) as well as some cosmetic procedures (tattoo removal, hair removal), dynamic cooling of the skin surface using cryogenic sprays or cooled windows can reduce nonspecific thermal injury to the epidermis [1–3]. As a result, higher laser dosages can be used to induce selective thermal damage to the subsurface targets, which enhances the therapeutic outcome, while cryogen spray cooling (CSC) prevents adverse effects due to epidermal injury (such as blistering, dyspigmentation, and scarring) and reduces patient discomfort [4–6].

The same concept of selective cooling has been recently applied to laser skin resurfacing (LSR) with the aim to minimize epidermal disruption, prevent patient cosmetic morbidity due to the open wound, reduce the risk of infection and shorten the healing time after the procedure [7]. At the same time, the extent of dermal thermal injury should be sufficient to cause neo-collagen formation, leading to cosmetic improvement of rhytids.

The few reported attempts at such non-ablative LSR have been variably successful. The irradiation sources included a 1.32 μm Nd:YAG laser [8,9], Er:glass laser (1.54 μm) [10], or non-coherent pulsed light source [11], applied in combination with either CSC or a contact cooling device. All these modalities utilize relatively weakly absorbed radiation, which enables heat deposition deep into the dermis, and active cooling of the skin surface. However, none of these modalities has thus far demonstrated the degree of collagen coagulation, neo-collagen formation, nor rhytid improvement similar to that observed after CO_2 or Er:YAG LSR. Mordon et al. applied a sequence of Er:glass laser pulses (at 3 Hz) to allow for relaxation of the epidermal temperature rise between the individual pulses. With the help of a contact cooling device, they achieved a subsurface zone of thermal injury at a depth of 200–500 μm and a completely intact epidermis [12,13].

In a recently published study, Majaron et al. explored the same principle of repetitive exposure with strongly absorbed Er:YAG laser (2.94 μm, repetition rate 10 or 33 Hz), and demonstrated coagulation of in vivo animal (rat) dermis up to 250 μm below the epidermal–dermal junction [14]. Although the epidermis was very thin (13 μm), it was not completely ablated at several irradiation conditions, despite the fact that no active cooling of the skin surface was used. The results matched reasonably well the predictions of an earlier numerical model of thermo-mechanical laser ablation of skin [15,16].

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In a follow-up histological study, using the same animal model, we investigated more systematically the influence of pulse fluence and duration on dermal coagulation depth, epidermal damage, and neo-collagen formation [17]. CSC was applied to selected test sites as 6 msec cryogen spurts delivered just prior to ("pre-cooling"), or during and after ("post-cooling") each of the 10 sequential laser pulses. At pulse fluences near the ablation threshold, where the coagulation depths were maximal, no significant difference in dermal coagulation depth and neo-collagen formation was observed between the pulse durations of 150 and 550 μsec. Application of CSC reduced epidermal damage, but at the same time reduced also the coagulation depth. Dermal coagulation up to a depth of ~140 μm was achieved with a partially preserved (albeit injured) epidermis, but the results indicated that CSC did not offer observable epidermal protection at a given dermal coagulation depth.

In the present paper, we analyze the relationship between improved epidermal preservation and reduced dermal coagulation of repetitive low-fluence Er:YAG laser irradiation in combination with CSC using a simple theoretical model of laser heating, CSC, and heat propagation in skin. Using the same model, influence of the laser pulse duration and differences between pre- and post-cooling are addressed as well.

METHODS

Temperature dynamics in human skin (density, $\rho = 1100$ kg/m^3, specific heat, $c = 3500$ J/kg K; conductivity, $\kappa = 0.42$ W/m K) are calculated in one-dimensional approximation. This approach is sufficient to analyze experimental situations where diameters of both cryogen spray and laser beam are much larger than the relevant skin depths (< 0.3 mm). Temperature evolution $T(z,t)$ is thus given by the one-dimensional heat diffusion equation

$$\frac{\partial T(z,t)}{\partial t} = \frac{\kappa}{\rho c}\frac{\partial^2 T(z,t)}{\partial z^2} + \frac{q(z,t)}{\rho c}, \qquad (1)$$

where $q(z,t)$ represents local heating due to absorption of the laser beam. For the strongly absorbed mid-infrared radiation from the Er:YAG laser, the spatial dependence of this term is governed by Beer's law ($\mu = 300$ mm^{-1}). As a function of time, it is prescribed to be constant for duration of the laser pulse, and zero at other times.

Heat exchange at the skin surface during CSC is modeled by a boundary condition of the third kind (Robin):

$$\kappa \frac{\partial T(z,t)}{\partial z}\bigg|_{z=0} = h_c[T(z=0,t) - T_c], \qquad (2)$$

which is customary to describe convective heat transfer at a liquid/solid or gas/solid interface [18]. Inasmuch as the cryogen temperature T_c and heat transfer coefficient h_c may not be constant during the cryogen spurt, this approach is only a first approximation, which has been shown to describe the cooling dynamics of epoxy phantoms reasonably well [19,20].

Parameters T_c and h_c may vary with a number of factors, including the cryogen delivery device, atomizer nozzle geometry, substrate composition and texture, etc. Based on earlier studies using tetrafluoroethane ($C_2H_2F_4$, used also in commercial medical laser systems) and similar cryogen nozzles [20–22], we use here the value of $T_c = -45$°C. The heat transfer coefficient of $h_c = 2500$ W/m^2 K was chosen to be somewhat lower than the recently determined values [20,23], to reflect the fact that the cryogen spray, as used in this study and related experiments [17], does not fully develop during a 6 msec spurt [22]. For times before and after the CSC spurt, the same boundary condition (Eq. 2) is applied to represent convective and radiative heat exchange with ambient air, by replacing T_c with $T_a = 20$°C, and h_c with $h_a = 25$ W/m^2 K [24]. The initial skin temperature is set at 35°C for all depths.

The results are calculated numerically using a finite difference scheme (central forward), implemented in Microsoft Excel spreadsheet and run on a personal computer (Pentium II, 350 MHz). The computational grid and step were chosen to be $\Delta z = 4$ μm and $\Delta t = 10$ μsec, respectively, except for a few milliseconds during and following the laser irradiation, where a finer discretization ($\Delta z = 1$ μm, $\Delta t = 0.7$ μsec) was necessary due to the very high temperature gradients. In both cases, a low Fourier number ($D \cdot \Delta t/\Delta z^2 \sim 0.07$) ensures good computational stability [25].

RESULTS

Figure 1a presents calculated temperature profiles in skin during (lines a–c), and up to 1.5 msec after irradiation (d–h) with a 150 μsec Er:YAG laser pulse. The dotted line indicates the base temperature of 35°C. The amplitude of the heating term $q(z,t)$ in Equation (1) is adjusted so that the surface temperature peaks around 210°C, which is believed to be close to ablation temperature of skin with the Er:YAG laser [16,26,27]. The influence of heat diffusion during the laser pulse is evidenced by the increasing depth of thermally affected zone, and less than proportional increase of surface temperature during the pulse. Due to extremely high temperature gradients induced in the superficial layer of skin, the surface temperature rise relaxes very rapidly, and drops to half its peak value approximately 300 μsec after the end of laser exposure.

At a pulse duration of 600 μsec (Fig. 1b), the influence of heat diffusion during the laser pulse is much more pronounced, and reduces the peak surface temperature to ~150°C at the same pulse energy. As a result, the temperature gradients are diminished compared with the previous example, and the temperature rise relaxes somewhat more slowly, so that the temperature profiles a few milliseconds after irradiation are hardly discernible between the two pulse durations.

Figure 2 presents temperature profiles induced in skin during (lines a–c) and after (d,e) a 6-msec cryogen spurt. The dotted line indicates the base temperature (35°C). As can be seen, the maximal temperature drop obtained with such a short cryogenic spurt is 12°C, relatively small

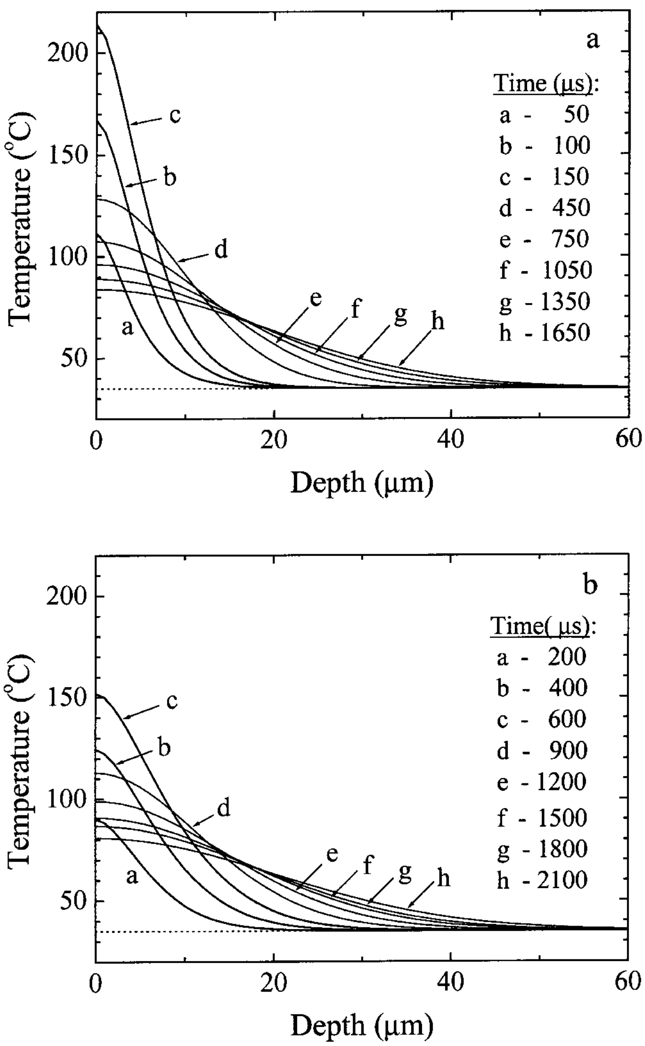

Fig. 1. **a**: Temperature profiles in skin during (lines a–c), and up to 1.5 msec after irradiation (d–h) with a 150-μsec Er:YAG laser pulse. The dotted line indicates the base temperature (35°C). **b**: The same, for 600 μsec pulse duration and same pulse fluence.

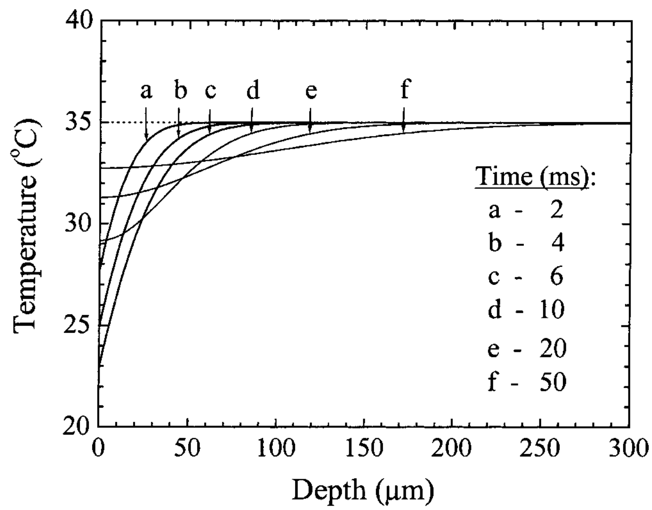

Fig. 2. Temperature profiles in skin during (bold lines, **a–c**), and after (thin lines, **d–e**) a 6-msec CSC spurt. The dotted line indicates the base temperature (35°C).

compared with the peak temperature increase due to the laser pulse alone.

Figure 3 presents the temporal evolution of skin temperature at various skin depths (see the legend) for the case of pre-cooling – 6-msec cryogen spurt applied just prior to a 600-μsec laser pulse. The surface temperature evolution obtained without CSC is also plotted for comparison (dashed line).

Temperature profiles calculated for the same pre-cooling conditions as in Figure 3 are presented in Figure 4a. The times chosen correspond to the end of the 6 msec cryogen spurt (line a), the end of the laser pulse (b), and three subsequent times (c–e). Dashed line represents the temperature profile at the end of the laser pulse ($t = 6.6$ msec) with no cooling applied, and the dotted line marks the base temperature (35°C). Figure 4b presents temperature profiles at time $t = 50$ msec, when the next cryogen spurt would begin in a 20 Hz sequence of CSC and laser pulse heating. These results are of special importance, since the temperature profile induced by repetitive cooling–heating is known to be a superposition of profiles induced by individual cycles. Plotted are the profiles obtained using pre-cooling (line a) and no cooling (dashed b). Line c presents a profile obtained with no cooling and the laser pulse energy reduced to 79%, so that surface temperature at time $t = 50$ msec matches that obtained with pre-cooling.

Figure 5 shows the temporal evolution of skin temperatures at various skin depths (see the legend) for the case of post-cooling — a 6-msec cryogen spurt starts synchronously with the 600-μsec laser pulse. For comparison, the surface temperature evolution obtained without CSC is also presented (dashed line), and the dotted line indicates the base temperature of 35°C. It is interesting to note that post-cooling reduces the peak surface temperature by a smaller amount than pre-cooling, but makes it relax faster after the laser irradiation ends.

Specifics of the post-cooling approach are further illustrated by temperature profiles at the end of the laser pulse (Fig. 6a, line a), and three subsequent times (lines b–d). The dashed line represents the temperature profile at the end of the laser pulse ($t = 0.6$ msec) with no CSC applied, and the dotted line marks the base temperature (35°C). A subsurface temperature peak is evident at times $t = 3$ msec and 6 msec. In Figure 6b, temperature profile obtained with post-cooling at time $t = 50$ msec (line a) is compared to those obtained with no cooling and the same laser pulse energy (line b, dashed), and the laser pulse energy reduced to 61% (line c), so that surface temperature matches that obtained with post-cooling. The lines a and c

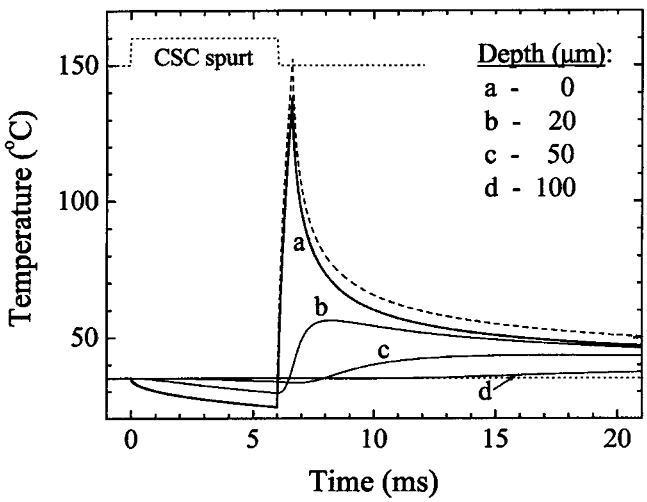

Fig. 3. Temporal evolutions of skin temperature at the surface (line a) and three different depths (b–d) for a 600-μsec laser pulse in combination with 6-msec cryogen spurt delivered just prior to laser exposure ("pre-cooling"). The dashed line represents the surface temperature evolution without CSC, and the dotted line indicates the base temperature of 35°C.

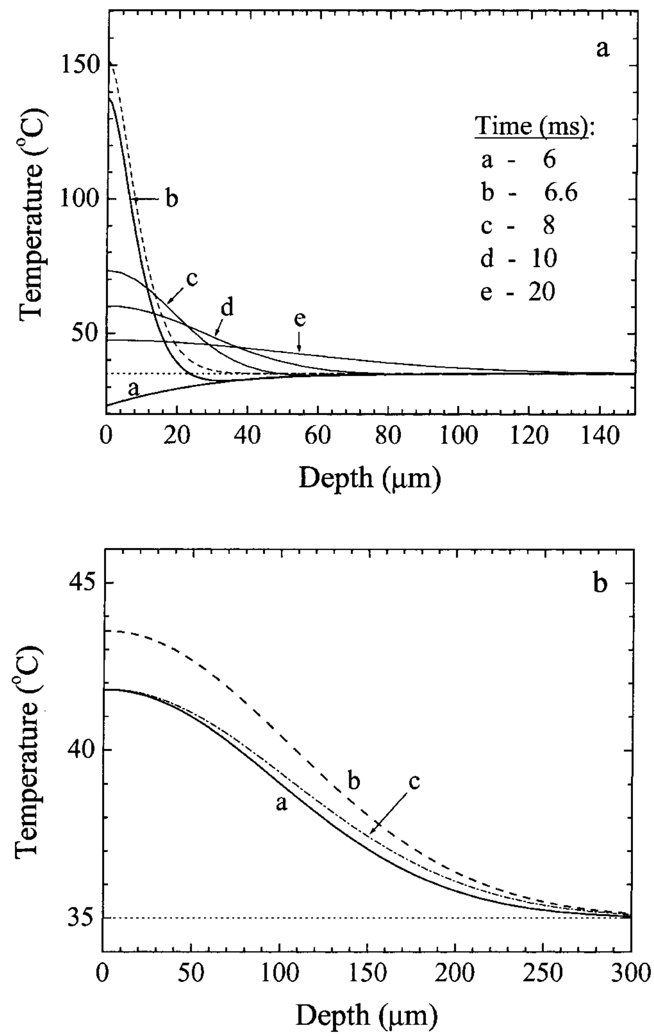

Fig. 4. **a**: Temperature profiles in skin for the 600-μsec laser pulse with pre-cooling (same conditions as in Fig. 3). The times chosen correspond to the end of the cryogen spurt (line a), end of the laser pulse (b), and three subsequent times (c–e). Dashed line represents the case with no CSC, and the dotted line indicates the base temperature (35°C). **b**: Temperature profiles in skin at time $t = 50$ msec with the same pre-cooling conditions as above (line a), the same laser pulse with no CSC (b), and laser pulse with energy reduced to 79% (c).

are very similar, even more so than in the case of pre-cooling (see Fig. 6b).

DISCUSSION

Figures 1a and 1b illustrate the influence of heat diffusion during sub-ablative irradiation of skin with 150 and 600 μsec Er:YAG laser pulses with the same energy. The thermally affected zone increases in depth during the laser pulse (lines a–c), and the surface temperature rise is less than proportional with time. This effect is much more pronounced with 600 μsec pulse duration and reduces the peak surface temperature to ~ 150°C, compared with ~ 210°C at 150 μsec. In fact, the latter example is not far from meeting the condition of thermal confinement, as $\mu^2/D \sim 110$ μsec. Even during the relatively long (600 μsec) laser pulse, however, the thickness of the thermally affected zone is only ~ 20 μm (Fig. 1b). All thermal effects induced in the deeper skin layers are therefore exclusively due to heat transport after laser irradiation has ended (lines d–h).

Since the temperature profile induced by the 600 μsec pulse duration is less steep, the surface temperature rise relaxes somewhat slower as compared to 150 μsec. As a result, the temperature profiles a few milliseconds after the irradiation are hardly discernible between the two pulse durations. We can therefore expect only a marginal influence of the pulse duration on dermal coagulation at depths of 100–300 μm. The same has been earlier predicted by a more detailed model of Er:YAG laser irradiation of human skin [15,16], and corresponds well to the histologic observation in our most recent in vivo study [17]. The model prediction would be different, however, if the pulse energy were sufficient to cause skin ablation. Under such conditions, shorter laser pulses would feature higher ablation efficiency, resulting in thinner layer of residual thermal damage underneath the ablation crater. Evidently, the largest influence of the pulse duration can be observed at fluences where peak surface temperature reaches the ablation value with shorter, but not with longer pulses.

Most features of the temperature profiles induced in skin by CSC alone (Fig. 2) are very similar to the ones discussed above for the case of laser irradiation without CSC. This is actually surprising, considering that the laser irradiation effects are described by a heating term in

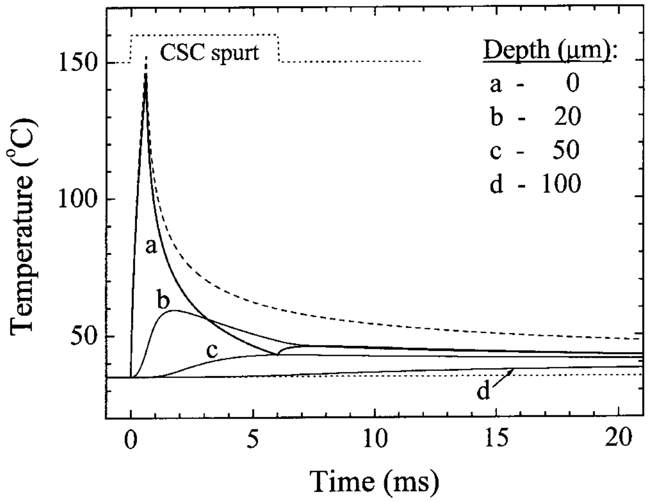

Fig. 5. Temporal evolutions of skin temperature at various depths (see the legend) for the post-cooling conditions — 6-msec cryogen spurt starts synchronously with the laser exposure (at time $t = 0$). The dashed line indicates the surface temperature without CSC, and the dotted line indicates the base temperature of 35°C.

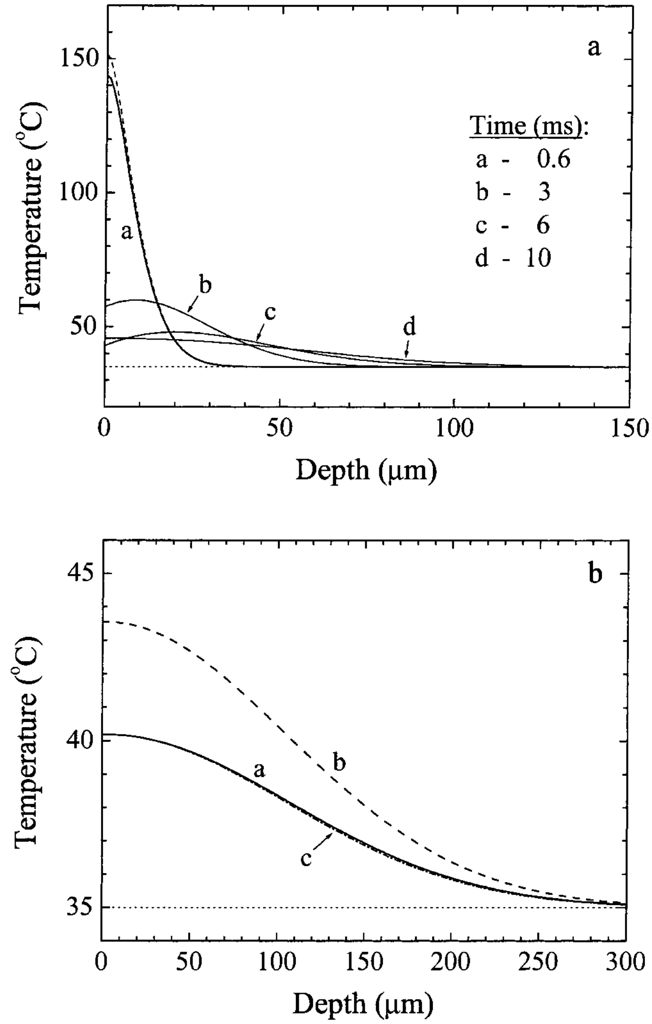

Fig. 6. **a**: Temperature profiles in skin for the 600-μsec laser pulse with post-cooling (same as in Fig. 5). The times chosen correspond to the end of the laser pulse (line a), mid-point and the end of the cryogen spurt (lines b and c, respectively), and one subsequent time (d). Dashed line represents the case with no CSC, and the dotted line indicates the base temperature (35°C). **b**: Temperature profiles in skin at time $t = 50$ ms using the same post-cooling conditions (a), the same laser pulse with no CSC (b), and a laser pulse with energy reduced to 61%.

the heat diffusion equation (1), whereas the cooling is accounted for exclusively by the boundary condition (2). The fundamental difference between the two processes is, thus, that cooling intrinsically affects only the skin surface. As a result, the depth of cooling profiles is governed primarily by the rate of heat diffusion inside the skin, and varies only marginally with CSC parameters (such as T_c and h_c). The depth of laser heating, in contrast, is defined primarily by skin's absorption (and scattering) coefficient, which can vary by several orders of magnitude. For most pulsed lasers, the influence of heat diffusion on the heating profile is negligible or presents only a small correction to the absorption profile of the laser beam.

In fact, the described difference between the (volumetric) laser heating and (surface) cooling forms the basis for spatial selectivity in most approaches to subsurface skin remodeling (as well as in other applications of dynamic cooling in laser dermatology). The Er:YAG laser, in contrast, acts almost like a surface heater due to extremely shallow penetration depth of its mid-infrared radiation, and relies on heat diffusion to affect deeper layers of the dermis. When using CSC in combination with the Er:YAG laser, heating and cooling diffusion waves are launched into the skin essentially from the surface and, thus, largely cancel each other long before reaching the depths of 100–300 μm, which are of interest for LSR. As a result, the main influence of cooling on dermal coagulation is to effectively reduce the amount of delivered heat, while the spatial selectivity of cooling is minimal, at best.

This effect can be seen nicely in Figure 3, where the influence of pre-cooling on the temperature evolution is minimal already at depth of 50 μm (line c), and essentially nonexistent at 100 μm (d). Similarly, the temperature profiles for the same example display no temperatures below the base value a couple of milliseconds after the laser exposure (Fig. 4a, line d), and resemble profiles after laser irradiation without CSC. In fact, the temperature profile 50 msec after the beginning of pre-cooling cycle (Fig. 4b, line a) is very similar to the one obtained with no cooling and laser pulse energy reduced to 79%, so that the two surface temperatures match (line c). The time $t = 50$ msec is of special importance, since such profiles accumulate (superimpose) during sequential irradiation at repetition rate of 20 Hz, as used in our recent experiments [17]. The discussed similarity between the two profiles, therefore, suggests that in repetitive Er:YAG laser exposure, the thermal damage to the dermis with pre-cooling is likely to be similar to the effect of correspondingly weaker laser pulses.

Temperature evolutions for post-cooling conditions (Fig. 5) demonstrate that the effect of CSC during the 600 μsec laser pulse decreases the peak surface temperature by no more than 8°C. Since the CSC is applied synchronously with the laser irradiation, it affects the temperature profile only in a very superficial layer (Fig. 6a, line a). This is different from pre-cooling, where the temperature profile at the end of the laser pulse is affected by CSC to a depth of ~70 μm (Fig. 4a, line b).

On the other hand, post-cooling induces much faster relaxation of the superficial temperature rise as compared with pre-cooling and, in particular, no CSC (Fig. 5). As a result, a subsurface temperature peak develops during the latter part of the cryogen spurt (lines b, c). The temperature profile obtained at time $t = 50$ msec (Fig. 6b, line a) is essentially the same as with the laser pulse energy reduced to 61% and no CSC (line c). This indicates that, with regard to thermal pile-up in repetitive laser exposure, post-cooling displays a higher overall cooling efficacy, and a more favorable ratio between the dermal and epidermal temperatures as compared with pre-cooling. In view of the above differences, optimal timing of CSC clearly depends on a number of factors, such as single-pulse fluence and duration, number of pulses and repetition rate of the sequence, as well as dynamics of thermal modification in both epidermis and dermis.

With either pre- or post-cooling, however, the temperature profiles obtained at $t = 50$ msec (Figs. 4b, 6b) are comparable to profiles resulting from strongly attenuated laser pulses applied without CSC, which would induce significantly lower surface temperature peaks. As a result, we can conclude that in LSR with repetitive Er:YAG exposure, CSC does not offer epidermal protection at the same dermal coagulation effect, as is the case when used in combination with deeper penetrating radiation. This is in good agreement with our recent histological observations [17].

CONCLUSION

At sub-ablative pulse fluences, the model indicates less epidermal damage with 600-μsec Er:YAG laser pulses as compared to 150-μsec, but a minimal influence of pulse-length on the extent of thermal damage deeper in the dermis. Temperature profiles in skin 50 msec after laser exposure with either pre- or post-cooling are predicted to be very similar to those after a lower-fluence laser pulse without cooling. This suggests that application of CSC with repetitive Er:YAG laser exposure of skin will not improve epidermal preservation with the same dermal coagulation effect, as it does when used in combination with deeper penetrating radiation.

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