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Authors
Ramirez-San-Juan, Julio C
Aguilar, Guillermo
Tuqan, Alia T
et al.

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Skin Model Surface Temperatures During Single and Multiple Cryogen Spurts Used in Laser Dermatologic Surgery

Julio C. Ramirez-San-Juan, PhD,1,2 Guillermo Aguilar, PhD,1,3* Alia T. Tuqan,1 Kristen M. Kelly, MD,1,4 and J. Stuart Nelson, MD, PhD1,4

INTRODUCTION

The importance of cryogen spray cooling (CSC) in conjunction with laser therapy of various dermatoses such as port wine stain (PWS) [1, 2], telangiectasias, hemangiomas [3], hair-removal, and rhytides [4] has been widely documented [5]. CSC prevents excessive heating of the superficial skin layers, thus allowing the safe use of higher light doses while avoiding complications such as hypertrophic scarring or dyspigmentation [6].

When compared to other epidermal cooling methods, CSC is particularly useful for treatment of superficial targeted lesions, since it permits [7]: (1) accurate control of the cryogen application time (typically 5–100 milliseconds) and, consequently, cooling time; and (2) high heat transfer rates as cryogen is deposited onto the skin and evaporates very quickly therefrom. These two characteristics are instrumental in achieving efficient and spatially selective epidermal cooling.

Despite these advantages, concern has been expressed that CSC may induce cryo-injury [8]. In order to address this concern, computational models [9], epoxy phantoms [7, 10] and, more recently, human skin tissue culture models (RAFT) [11] have been used to evaluate the effects of prolonged exposure of human skin to CSC.

BACKGROUND: Although cryogen spray cooling (CSC) is used to minimize the risk of epidermal damage during laser dermatologic surgery, concern has been expressed that CSC may induce cryo-injury. In order to address this concern, it is necessary to evaluate the effects of prolonged exposure of human skin phantoms (HSP) to CSC.

OBJECTIVE: To measure the minimum surface temperature ($T_{min}$) and the time at which it occurs ($t_{min}$) as well as determine the time the sprayed HSP surface remains below $0^\circ$C (sub-zero time, $\Delta t_s$) and $-26^\circ$C (residence time, $\Delta t_r$) during the application of single (SCS) and multiple (MCS) cryogen spurts. Two initial HSP substrate temperatures were studied, $T_s$: 23 and 70°C.

STUDY DESIGN/MATERIALS AND METHODS: An epoxy-based HSP was constructed to measure $T_{min}$, $t_{min}$, $\Delta t_s$, and $\Delta t_r$, for 17 spray patterns: 1 SCS with a total cryo-delivery time ($\Delta t_c$) of 40 milliseconds; 8 MCS patterns with identical $\Delta t_c$, but with a total cooling time ($\Delta t_{total}$) varying from 50 to 280 milliseconds; and 8 SCS patterns that matched the $\Delta t_{total}$ of the MCS patterns.

RESULTS: For both $T_s$, our results show that it is possible to distinguish between two different cooling regimes. For $\Delta t_{total} \leq 110$ milliseconds, the differences between SCS and MCS patterns with the same $\Delta t_{total}$ for all variables ($T_{min}$, $t_{min}$, $\Delta t_s$, $\Delta t_r$) are negligible. Most importantly, all these variables show a remarkable linear dependence with $\Delta t_{total}$. In the interval 110 milliseconds $< \Delta t_{total} < 280$ milliseconds, $T_{min}$ and $t_{min}$ are similar for SCS and MCS, while $\Delta t_s$ and $\Delta t_r$ show more pronounced differences between the two spray patterns. In this interval, the values of $T_{min}$ and $\Delta t_s$ for MCS remain invariant and similar to the corresponding values for $\Delta t_{total} = 110$ milliseconds.

CONCLUSIONS: These results suggest that: (1) similar epidermal protection may be attained with SCS and MCS for $\Delta t_{total} \leq 110$ milliseconds; and (2) for 110 milliseconds $< \Delta t_{total} \leq 280$ milliseconds, MCS help to maintain $\Delta t_s$ similar to that of SCS at $\Delta t_{total} = 100$ milliseconds, which may be beneficial to prevent cryo-injury. Lasers Surg. Med. 36:141–146, 2005. © 2005 Wiley-Liss, Inc.

Key words: dynamic cooling; cooling selectivity; cryo-injury; port wine stain

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In this work, we investigate systematically the thermal response of human skin phantoms (HSP) by measuring the minimum surface temperature ($T_{\text{min}}$) and the time ($t_{T_{\text{min}}}$) at which it occurs, as well as determine the time the sprayed surface remains below $0^\circ$C (sub-zero time, $D_{t_{\text{s}}}$) and $-26^\circ$C (residence time, $\Delta t_r$) during the application of single (SCS) and multiple (MCS) cryogen spurts for two initial HSP substrate temperatures $T_i$: 23 and $70^\circ$C.

METHODS AND PROCEDURES

Numerical Simulation

We computed the radiant energy distribution resulting from a single laser pulse (beam radius = $5 \text{ mm}$; fluence = $4 \text{ J/cm}^2$) using the well-known Monte Carlo code (MCML/CONV) developed by Wang et al. [12,13]. In order to estimate the total heat extracted from the HSP surface throughout a specific cryogen-laser pattern, we developed a numerical simulation using commercial finite element software (FEMLAB™, COMSOL, Burlington, MA). The output of the Monte Carlo code is entered as the heat source required by the FEMLAB code [14] to simulate heat diffusion. For simplicity, each cryogen spurt was simulated by imposing a convective boundary condition on the HSP surface with constant $h$ (heat transfer coefficient) and $T_c$ (cryogen temperature) values of $7,000 \text{ W/m}^2 \text{ K}$ and $-40^\circ$C, respectively.

We simulated a cryogen-laser pattern similar to those employed in commercially available devices, as represented in Figure 1. The thickness, thermal [9] and optical [15] properties of human skin layers used for calculations of the radiant energy distribution and total heat extracted, respectively, are shown in Table 1.

HSP

The HSP consisted of a thin (90 $\mu$m) rectangular ($3.42 \times 3.50 \text{ mm}$) silver foil placed on top of an epoxy resin and a type-K thermocouple of $\sim 50 \mu$m bead diameter with a response time of 3 milliseconds (Omega, Stamford CN), positioned in between. Thermal paste was applied around the bead to ensure good thermal contact. The foil was sufficiently thin to ensure fast response and a spatially averaged measurement. The purpose of the HSP was to provide thermal properties on the same order of magnitude as those of human skin [9,10]. In general, the CSC procedures are used clinically at room temperature, which is the reason for selecting $T_i = 23^\circ$C; however, it is believed that $70^\circ$C is the threshold temperature for instantaneous skin-thermal injury [16]. Therefore, and in order to simulate heat generated by the laser pulses, in another series of experiments a copper plate heated (by a pair of thermo-electric coolers: TEC) the HSP to $T_i$ of $70^\circ$C prior to cryogen application.

Cryogen Delivery

The only FDA-approved cryogen compound currently used in laser dermatologic surgery is 1,1,1,2 tetrafluoroethane, also known as R134a, with boiling temperature $T_b \approx -26.2^\circ$C at atmospheric pressure. R-134a is contained at saturation pressure (6.7 bar at $25^\circ$C) and delivered through a standard high-pressure hose to a control valve. A commercial cryogen spray nozzle (with approximate inner diameter of 0.5 mm) used for laser treatment of vascular lesions and hair removal was employed to spray the cryogen on to the HSP.

The nozzle-to-sprayed surface distance, $z$, was 31 mm, (similar to that currently used in several commercially available CSC devices) for all experiments. The relative humidity was 39% and the room temperature $\approx 23^\circ$C. A schematic of the experimental setup is shown in Figure 2.

In this study, we employed electronically controlled SCS and MCS spray patterns. $T_{\text{min}}$, $t_{T_{\text{min}}}$, $\Delta t_{t_{\text{s}}}$, and $\Delta t_r$ were systematically measured for 17 spray patterns: (a) 1 SCS of...

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**TABLE 1. Thickness, Thermal and Optical Properties of Human Skin Layers Used With the Finite Element and MCML/CONV Models for $\lambda = 1,450 \text{ nm}$**

| Layer | Epidermis | Dermis |
|-------|-----------|--------|
| Thickness (mm) | 0.05 | 1 |
| $k$ (W/(m K)) | 0.21 | 0.53 |
| $\rho$ (kg/m$^3$) | 1,200 | 1,200 |
| $c$ (J/(kg K)) | 3,600 | 3,800 |
| $\mu_a$ (1/cm) | 20 | 2 |
| $\mu_a$ (1/cm) | 120 | 120 |
| $g$ | 0.9 | 0.9 |
| $n$ | 1.37 | 1.37 |

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**Fig. 1.** Schematic showing alternate cryogen spray, delay time, and laser pulses employed in our numerical simulation.

**Fig. 2.** Experimental system employed to measure the sprayed HSP surface temperatures during the application of SCS and MCS, for two different $T_i$ HSP temperatures (23 and $70^\circ$C).
**RESULTS AND DISCUSSION**

Although the dynamics of a MCS spray pattern of CSC and laser-induced heating is different from that of a SCS of same Δt_total followed by one laser pulse, both spray patterns can be compared in terms of the total heat extracted. According to the numerical simulation described above with the optical and thermal parameters described therein, the total heat extracted through the pattern shown in Figure 1 is \( \sim 10.9 \text{ kJ/m}^2 \), which is similar to that \( \sim 9.2 \text{ kJ/m}^2 \) from the pre-heated HSP (at 70°C) exposed to a SCS of 40 milliseconds. For this reason, the Δt for all MCS patterns was selected to be 40 milliseconds.

Figure 4 shows a typical HSP surface temperature measurement in response to a MCS pattern as well as the definitions employed to describe the temperature profile as a function of time. As spray droplets impinge on the surface, very fast heat extraction occurs at the cryogen–HSP interface. A rapid decrease in surface temperature (quantitatively similar to that expected to occur on human skin) is noted and continues for some time after spurt termination. A \( T_{\text{min}} \) is reached at a certain time \( t_{\text{min}} \), which depends on the Δt_total employed in each cryogen spray pattern. Often, the interface can reach and maintain a local constant temperature near \( T_b \) for several milliseconds which may be attributed to the presence of a thin residual cryogen layer, which evaporates during and after spurt termination. Aguilar et al. [7] defined the Δt as the period that the surface temperature remains below (the cryogen boiling point) \( T_b \approx -26.2 \text{ °C} \). The increase in temperature from \( T_b \) up to the freezing temperature of water \( T_m \) is gradual and relatively linear. Often, a plateau is noted at \( T_m \), which may be attributed to condensation, freezing, and subsequent melting of ambient water on the surface. The period the surface temperature remains below 0°C is defined as the Δt_c. Water condensation and freezing on the sprayed surface do not occur during the spurt, despite the sub-zero temperature that may have been reached [17,18]. This is because tetrafluorethane is a hydrophobic compound, which impedes the mixing of cryogen with water and, therefore, does not allow frost to form on the sprayed surface until the cryogen has evaporated completely [7].

Figures 5 and 6 show, respectively, \( T_{\text{min}} \) and \( t_{\text{min}} \) as a function of Δt_total for all spray patterns described in Figure 3 and for the two initial HSP temperatures, \( T_i \) (23 and 70°C). For \( T_{\text{min}} \), the differences between SCS and MCS with the same Δt_total are small. Note, however, that \( T_{\text{min}} \) has a strong dependence on \( T_i \) (between 12 and 18°C). For \( T_i = 23^\circ \text{C} \), \( T_{\text{min}} \) varies between \(-40\) and \(-46^\circ \text{C} \) (~15%) and, for \( T_i = 70^\circ \text{C} \), \( T_{\text{min}} \) varies between \(-20\) and \(-32^\circ \text{C} \) (~60%) for the range of Δt_total under study. From Figure 5, it is possible to distinguish between two different cooling regimes. For \( \Delta t_{\text{total}} \leq 110 \text{ milliseconds} \), \( T_{\text{min}} \) shows a linear dependence with \( \Delta t_{\text{total}} \). In the interval 110 milliseconds < \( \Delta t_{\text{total}} \leq 280 \text{ milliseconds} \), \( T_{\text{min}} \) reaches an asymptotic value (~46°C for \( T_i = 23^\circ \text{C} \) and ~32°C for \( T_i = 70^\circ \text{C} \)), for both SCS and MCS. Figure 6 also shows the linear dependence of \( t_{\text{min}} \) with \( \Delta t_{\text{total}} \), although the same dependence holds throughout the entire range of Δt_total. The slope of this linear behavior is ~1, which means that for both SCS and MCS, \( T_{\text{min}} \) is always reached at spurt termination for all parameters under study and there is no dependence on \( T_i \).
Figure 5. Minimum surface temperature ($T_{\text{min}}$) versus total cooling time ($\Delta t_{\text{total}}$) for SCS and MCS at two different $T_1$, HSP temperatures. Two different cooling regimes are distinguished: For $\Delta t_{\text{total}} \leq 110$, $T_{\text{min}}$ shows a linear decrease with the $\Delta t_{\text{total}}$, and for 110 milliseconds < $\Delta t_{\text{total}}$ < 280 milliseconds, $T_{\text{min}}$ is similar for SCS and MCS.

Figure 7. $\Delta t_s$ as a function of the $\Delta t_{\text{total}}$. $\Delta t_s$ shows two different cooling regimes, in the interval $\Delta t_{\text{total}} \leq 110$ milliseconds, the differences between SCS and MCS for $\Delta t_s$ are negligible. In the interval 110 milliseconds < $\Delta t_{\text{total}}$ < 280 milliseconds, $\Delta t_s$ becomes greater for SCS than for MCS by a factor of almost 2.

Figure 8. $\Delta t_r$ versus total cooling time ($\Delta t_{\text{total}}$). Note the obvious similarity between SCS and MCS, and the pronounced linear increase of $\Delta t_r$ at $T_1 = 23^\circ C$. Different between SCS and MCS for both $T_1$, and $\Delta t_r$ becomes greater for SCS than for MCS by a factor of almost 2.
different spray patterns suggest that the increase in $\Delta_s$ depends on the time the surface temperature remains almost constant near $T_b$, as well as on the surface temperature rise from $T_b$ to $T_m$ (both of which may be attributed to the presence and linear evaporation of a residual cryogen layer and to the temperature gradient generated within the HSP during cryogen deposition). Longer spurts induce greater heat extraction, leading to lower HSP surface temperatures but, also, deeper cooling. The latter situation leads to lower temperature gradients close to the surface upon spurt termination and, therefore, the rate of heat transfer from the HSP to the cryogen layer is lower for longer spurts, prolonging the evaporation time, that is, $\Delta_s$, which is clearly shown in Figure 9. Note that longer spurts lead to lower average slopes of the temperature curves in the region from $T_b$ to $T_m$, as illustrated by the dotted lines. It should be noted that the temperature in this range increases $\sim$100% faster for the shortest $\Delta_{total}$ (40 milliseconds) than for the longest (110 milliseconds). The superposition of these two linear processes leads to the linear dependency of $\Delta_s$ on $\Delta_{total}$.

Tuquan et al. [11] recently performed histologic evaluations of in vitro model human skin exposed to four (marked with “+” in Fig. 3) of our five MCS spray patterns. Their work demonstrated that for spurts with a $\Delta_{total}$ of 110 milliseconds or less, delivering the cryogen in MCS patterns increases the risk of cryo-injury as compared to one SCS with the same $\Delta_c$. As such, when the $\Delta_{total}$ is less than 110 milliseconds, the risk of injury appears to depend on $\Delta_{total}$ and not $\Delta_c$. In this study, we have shown that $\Delta_s$ continues to increase for SCS patterns while it remains essentially constant for MCS patterns within the interval 110 milliseconds $< \Delta_{total} \leq 280$ milliseconds, implying that for $110 \text{ milliseconds} < \Delta_{total}$ it may be beneficial to use MCS to minimize the risk of cryo-injury to human skin during laser dermatologic surgery.

It is important to recognize that this HSP do not fully represent the thermal and mechanical behavior of human skin (e.g., skin indentation during CSC [19]), which might influence the magnitude of all the parameters measured in this study and, also, that our experimental procedures did not consider the combined application of cryogen and laser irradiation. Evidently, the heat generated by laser light absorption and scattering within the superficial layers of human skin would reduce both $\Delta_s$ and $\Delta_t$. However, the present results describe the relative variation in the dynamics of the surface temperature of HSP between SCS and MCS, which is valuable information that will aid in the design of more appropriate procedures for optimal CSC on human skin.

**CONCLUSIONS**

An HSP was constructed and used to measure the dynamic temperature produced by MCS with the same total cryogen delivery time ($\Delta_{total} = 40$ milliseconds) as SCS but with different $\Delta_{total}$. The temporal distribution of temperature for either SCS or MCS is strongly dependent on $T_i$. Our results show that it is possible to distinguish between two different cooling regimes. For $\Delta_{total} \leq 110$ milliseconds, the differences between SCS and MCS with the same $\Delta_{total}$ are negligible for all variables under study ($T_{min}, t_{r}, \Delta_s, \Delta_t$), which show a linear dependence on $\Delta_{total}$. The longer $\Delta_{total}$, the longer $t_{r}$, $\Delta_s$, $\Delta_t$, and the lower $T_{min}$. This response occurs for the two $T_i$ studied herein. In the interval 110 milliseconds $< \Delta_{total} \leq 280$ milliseconds, however, only $\Delta_s$ shows notable differences between SCS and MCS. For the same $\Delta_{total}$, $T_{min}$ is similar for SCS and MCS and $\Delta_t$ become larger for SCS than MCS by a factor of almost 2.

These results suggest that similar epidermal protection may be attained with SCS and MCS in the interval $\Delta_{total} \leq 110$ milliseconds. For 110 milliseconds $< \Delta_{total} = 280$ milliseconds, MCS help to maintain $\Delta_s$ similar to that of SCS at $\Delta_{total} = 100$ milliseconds, which may be beneficial to prevent cryo-injury.

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![Fig. 9. Dynamic surface temperature versus time for three of the SCS studied herein with different $\Delta_{total}$.](image-url)
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