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A Comparative Study of Human Skin Thermal Response to Sapphire Contact and Cryogen Spray Cooling

Bahman Anvari,* Thomas E. Milner, B. Samuel Tanenbaum, *Senior Member, IEEE*, and J. Stuart Nelson

Abstract—Surface cooling, in conjunction with various thermally mediated therapeutic procedures, can provide a means to protect superficial tissues from injury while achieving destruction of deeper targeted structures. We have investigated the thermal response of *in-vivo* human skin to: 1) contact cooling with a sapphire window (6–12 °C); and 2) spray cooling with a freon substitute cryogen [tetrafluoroethane; boiling point ≈ -26 °C at 1 atmospheric pressure (atm)]. Measurements utilizing infrared radiometry show surface temperature reductions from 30 °C to 14–19 °C are obtained within approximately 1 s in response to sapphire contact cooling. Surface temperature reductions to values between 5 °C and -9 °C are obtained in response to 20–100-ms cryogen spurts. Computational results, based on fitting the measured radiometric surface temperature to estimate heat transfer parameters, show: 1) temperature reductions remain localized to approximately 200 μm of superficial tissue; and 2) values of heat flux and total energy removed per unit skin surface area at least doubled when using cryogen spray cooling.

Index Terms—Dermatology, lasers, port wine stains, selective injury, tetrafluoroethane.

I. INTRODUCTION

THERMALLY-MEDIATED therapeutic procedures utilizing microwave, infrared, or visible electromagnetic radiation are of considerable interest to many investigators and clinicians. In many of these procedures, the objective is to induce thermal injury to subsurface targeted structures while preserving superficial tissue. For example, successful laser

treatment of selected hypervascular cutaneous malformations such as port wine stain (PWS) birthmarks, hemangiomas (benign vascular tumors of infancy), and telangiectasias requires photocoagulation of subsurface targeted blood vessels while protecting the overlying epidermis from thermal injury.

Surface cooling can provide a means to protect superficial skin structures from undesired thermal injury [1]–[5]. Heat may be removed from skin by generating a thermal gradient at the surface. We analyze cases where a thermal gradient is generated by: 1) placing a cold sapphire window in contact with skin; and 2) spraying a short (ms) cryogen spurt onto the skin surface; both sapphire contact and cryogen spray cooling (CSC) are currently utilized by clinicians to induce selective photocoagulation of PWS blood vessels without damaging the overlying epidermis [6], [7]. Theories incorporating thermal and radiometric considerations to compute skin temperature distributions, and experiments that use infrared radiometry to measure the *in-vivo* response of human skin to these cooling modalities are presented.

II. THEORY

A. Heat Transfer

We assume skin is a semi-infinite medium cooled by sudden contact with a: 1) semi-infinite sapphire window; or 2) thin film ($\approx 10\text{--}40$ μm) consisting of liquid cryogen and ice (formed as a result of water vapor condensation) at the surface (Fig. 1). We assume the lateral dimensions of the cooled surface are much larger than skin thickness (≈ 1 mm) so the temperature distribution may be computed by solving the one-dimensional heat conduction equation

$$\frac{\partial^2 T(z > 0, t > 0)}{\partial z^2} = \frac{1}{\alpha_{\text{skin}}} \frac{\partial T(z, t > 0)}{\partial t} \quad (1)$$

where $T(z > 0, t > 0)$ (°C) is skin temperature in response to cooling (beginning at time zero), z (m) is distance into the skin (with origin at the skin surface), t (s) is time, and α_{skin} is skin thermal diffusivity ($1.1 \times 10^{-7} \text{ m}^2 \times \text{s}^{-1}$) [8]. Inasmuch as skin is a multilayered structure, an accurate analysis of heat conduction should take into account the thermal properties of various components (i.e., epidermis and dermis). However for simplicity, we assume a homogeneous medium with spatially uniform thermal properties.

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Fig. 1. Model geometry consisting of skin in contact at $z = 0$ with *a*): semi-infinite sapphire window or *b*) cold and infrared-attenuating cryogen-ice film of varying thickness $l(t)$. Various thermal and infrared properties are represented by the quantities within the parentheses. Thermal resistance between sapphire-skin interface is assumed.

A Robin boundary condition at the skin surface is implemented

$$-k \frac{\partial T(z, t > 0)}{\partial z} \Big|_{z=0} = h[T_{\infty} - T(0, t > 0)] \quad (2)$$

where k is thermal conductivity ($0.45 \text{ W} \times \text{m}^{-1} \times \text{K}^{-1}$ for skin [8]), $T_{\infty} (^{\circ}\text{C})$ is temperature of the sapphire window or cryogen-ice film, and h ($\text{W} \times \text{m}^{-2} \times \text{K}^{-1}$) is the average heat transfer coefficient over the surface due to either: 1) thermal resistance at the sapphire-skin interface or 2) convective/evaporative effects when cryogen is sprayed onto the skin surface.

When cooling is induced by a sapphire window in contact with skin, solution to (1) with boundary condition (2) is [9]

$$T(z > 0, t > 0) = T_1 \left\{ 1 + \eta \left[\text{erf}(\tilde{z}) + \exp(-\tilde{z}^2) \text{erfcx}(\tilde{z} + \tilde{h}_{\text{SCC}}) \right] \right\} + T_{\infty} \quad (3)$$

where

$$T_1 = \frac{\gamma_{\text{skin}}(T_i - T_{\infty})}{\gamma_{\text{sapph}} + \gamma_{\text{skin}}} \quad (4a)$$

$$\eta = \frac{\gamma_{\text{sapph}}}{\gamma_{\text{skin}}} \quad (4b)$$

$$\text{erfcx}(x) = \exp(x^2) \text{erfc}(x) \quad (4c)$$

$$\tilde{h}_{\text{SCC}} = \frac{h_{\text{SCC}}(\gamma_{\text{sapph}} + \gamma_{\text{skin}})\sqrt{t}}{\gamma_{\text{sapph}}\gamma_{\text{skin}}} \quad (4d)$$

$$\tilde{z} = \frac{z}{2\sqrt{\alpha_{\text{skin}}t}} \quad (4e)$$

In the above expressions, T_i is skin initial temperature prior to cooling (assumed 30°C), $\text{erfc}(x)$ is the complementary error function ($1 - \text{erf}(x)$), γ_j is defined as $k_j/\sqrt{\alpha_j}$ the thermal effusivity with j corresponding to the sapphire window ($k_{\text{sapph}} = 46 \text{ W} \times \text{m}^{-1} \times \text{K}^{-1}$, $\alpha_{\text{sapph}} = 15.1 \times 10^{-6} \text{ m}^2 \times \text{s}^{-1}$ [10]) or skin, and h_{SCC} is the average heat transfer coefficient that accounts for thermal resistance associated with sapphire contact cooling (SCC) at the sapphire-skin interface. As $h_{\text{SCC}} \rightarrow \infty$, thermal resistance at sapphire-skin interface diminishes and approaches a perfect contact between the two media; conversely, as $h_{\text{SCC}} \rightarrow 0$, resistance becomes infinite.

When cooling is induced by spraying cryogen onto the skin surface, a solution that has a similar form to (3) is obtained [9]

$$T(z, t > 0) = (T_i - T_{\infty}) \times \left[\text{erf}(\tilde{z}) + \exp(-\tilde{z}^2) \text{erfcx}(\tilde{z} + \tilde{h}_{\text{CSC}}) \right] + T_{\infty} \quad (5)$$

here, $\tilde{h}_{\text{CSC}} = \frac{h_{\text{CSC}}\sqrt{\alpha t}}{k}$ where h_{CSC} is the average heat transfer coefficient that accounts for convective/evaporative effects due to CSC.

The instantaneous heat flux, $q(t)$ ($\text{W} \times \text{m}^{-2}$), and total energy removed per unit area of skin surface, $Q(t)$ ($\text{J} \times \text{m}^{-2}$) are, respectively

$$q(z = 0, t > 0) = h_j[T_{\infty} - T(0, t > 0)] = h_j(T_{\infty} - T_i) \text{erfcx}(\tilde{h}_j) \quad (6a)$$

and

$$Q(z = 0, t > 0) = - \int_0^t q(z = 0, t' > 0) dt' = F(T_i - T_{\infty}) \left[\text{erfcx}(\tilde{h}_j) + \frac{2\tilde{h}_j}{\sqrt{\pi}} - 1 \right] \quad (6b)$$

where

$$F = \begin{cases} \frac{\gamma_{\text{sapph}}^2 \gamma_{\text{skin}}^2}{h_{\text{SCC}}(\gamma_{\text{sapph}} + \gamma_{\text{skin}})^2} & \text{for SCC} \\ \frac{k^2}{h_{\text{CSC}}\alpha} & \text{for CSC} \end{cases} \quad (7)$$

and $\tilde{h}_j = \tilde{h}_{\text{SCC}}$ or $\tilde{h}_{\text{CSC}}$.

B. Infrared Radiometry

Radiometric measurements are dependent on the temperature distribution below the surface and the infrared properties of skin in the detected spectral bandwidth ($3\text{--}5 \mu\text{m}$ in this study). The change in radiometric temperature $\Delta S(t) (^{\circ}\text{C})$, due to cooling is computed by integrating the infrared emission over all depths [5]

$$\Delta S(t > 0) = \mu_{\text{film}} \int_{-l(t)}^0 [T(z, t > 0) - T_i] \exp\{-\mu_{\text{film}}[z + l(t)]\} dz + \mu_{\text{skin}} \int_0^{\infty} [T(z, t > 0) - T_i] \exp[-\mu_{\text{film}}l(t) - \mu_{\text{skin}}z] dz. \quad (8)$$

Here, we have assumed that the presence of an infrared attenuating cryogen-ice film (thickness, $l(t)$) makes

Fig. 2. Schematic of instrumentation for measuring the radiometric surface temperature of skin in response to: (a) sapphire contact or (b) cryogen spray cooling.

an additional contribution to the measured radiometric temperature change. Infrared attenuation coefficients of skin and cryogen-ice film are denoted as μ_{skin} and μ_{film} (m^{-1}), respectively. Since sapphire is relatively transparent in detection bandwidth 3–5 μm [11], we neglect contributions to $\Delta S(t)$ due to internal emission.

Substituting expressions for the computed temperature distribution [(3) and (5)] into (8), we obtain the respective predicted radiometric temperature change due to SCC or CSC

$$\Delta S_{\text{SCC}}(t > 0) = -T_1 \left\{ 1 + \eta \left[\frac{\tilde{\mu}_{\text{skin}} \operatorname{erfcx}(\tilde{h}_{\text{SCC}}) - \tilde{h}_{\text{SCC}} \operatorname{erfcx}(\tilde{\mu}_{\text{skin}})}{\tilde{\mu}_{\text{skin}} - \tilde{h}_{\text{SCC}}} \right] \right\} \quad (9a)$$

$$\Delta S_{\text{CSC}}(t > 0) = (T_{\infty} - T_i) \left\{ \left[\frac{1 - \exp[-\mu_{\text{film}} l(t)]}{\tilde{\mu}_{\text{skin}} \operatorname{erfcx}(\tilde{h}_{\text{CSC}}) - \tilde{h}_{\text{CSC}} \operatorname{erfcx}(\tilde{\mu}_{\text{skin}})} \right] \right\} \quad (9b)$$

where $\tilde{\mu}_{\text{skin}} = \mu_{\text{skin}} \sqrt{\alpha t}$.

III. MATERIALS AND METHODS

A. Sapphire Contact Cooling

A contact cooling device, consisting of two circular sapphire windows (each 3 mm in thickness and 20 mm in diameter) separated by an evacuated chamber, was constructed. The evacuated chamber was used to prevent formation of an infrared absorbing film of mist (resulting from water vapor condensation) on the contact sapphire window. A recirculating chiller (T-250, ThermoTek Inc.) delivered water (4 °C; lowest attainable temperature) to a copper coil wrapped around the contact sapphire window, which was cooled to temperatures between 6 °C and 12 °C (Fig. 2). Skin of human volunteers was cooled by bringing fingers or arms in sudden contact with the cold sapphire window within the field of the infrared radiometer.

B. Cryogen Spray Cooling

1,1,1,2 Tetrafluoroethane (Refrigerant 134a; ICE KLEA, Wilmington, DE) [boiling point ≈ -26 °C at 1 atmospheric pressure (atm)], an environmentally compatible, nontoxic, chlorofluorocarbon substitute [12]–[14] was sprayed onto the

Fig. 3. Calibration curves for the infrared detection system: in air (○ ○ ○), and with intervening SCC device present (● ● ●).

fingers of same volunteers. Cryogen, contained in a pressurized steel canister (≈ 5 atm), was delivered through a narrow aluminum tube (inner diameter ≈ 1 mm) connected to an electronically controlled standard automobile fuel injection valve. Cryogen spurt duration, τ (20–100 ms), was controlled by a programmable digital delay generator (DG535, Stanford Research Systems, Sunnyvale, CA). Distance between the targeted skin site and tip of the tube was approximately 10 mm. The cooled site was approximately 7 mm in diameter.

C. Temperature Measurements

Emission in the 3–5 μm spectral range was collected with an InSb infrared focal plane array (IR-FPA) camera (Amber Engineering Inc., Goleta CA) configured for unit magnification. The IR-FPA camera system acquired 30–400 infrared emission images per second from skin, and was externally triggered by the digital delay generator. The infrared signal collected by each detector element in the IR-FPA was digitized with a 12-b (0–4095) A/D converter, and stored in a computer.

The infrared detection system was calibrated for temperature changes above and below the ambient value (23 °C). Average pixel values over a circular region (≈ 1 -mm diameter; 800 pixels) were measured as a function of the surface temperature of: 1) an aluminum block coated with highly emissive ($\epsilon \approx 0.97$) black paint (TC-303 black, GIE Corp., Provo, UT) and heated by a resistive element from 23 °C to 75 °C; and 2) a thermoelectric cooler (ITI FerroTec, Chelmsford, MA) coated with the same black paint, and cooled to -20 °C. Simultaneously, a surface mount precision thermistor (8681, Keithley Instruments, Cleveland, OH) measured the temperatures of the aluminum block and thermoelectric cooler. Calibrations were performed with and without room temperature SCC device placed against the aperture. Responsivity (ratio of pixel value to temperature) of the infrared detection system was higher with the SCC device present (Fig. 3). We attribute this effect to background emission specularly reflected from the sapphire window surface, resulting in an additional signal component detected by the IR-FPA.

Fig. 4. Measured ($\circ \circ \circ$) and theoretical (—) values of radiometric surface temperatures in response to SCC. Parameters used in computing the predicted results were $h_{SCC} = 2000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = 12^{\circ}\text{C}$, and $\mu_{\text{skin}} = 10 \text{ mm}^{-1}$.

IV. RESULTS

A. Measured and Theoretical Radiometric Temperatures

Examples of measured and predicted radiometric surface temperature profiles in response to SCC are presented in Fig. 4. Measurements represent average temperatures in an approximately 2-mm-diameter circular skin surface region. Theoretical values shown are for $h_{SCC} = 2000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, and $T_{\infty} = 12^{\circ}\text{C}$. Considering that water is the major constituent of skin, we used $\mu_{\text{skin}} = 10\text{--}20 \text{ mm}^{-1}$, characteristic of liquid water in the $3\text{--}5 \mu\text{m}$ spectral region [15].

We attribute the discrepancy between measured and theoretical values at early times to: 1) a thin infrared absorbing mist layer that sometimes formed on the contact surface of the cold sapphire window; and 2) difficulty in determining the exact time of contact between the sapphire window and skin surface. The cold (relative to skin surface temperature) mist provides an additional signal component detected by the IR-FPA at early times; as the mist and skin surface reach an equilibrium temperature, good agreement between measured and theoretical values is obtained.

Inasmuch as the sapphire window temperature, and thermal contact at the sapphire-skin interface were variable, steady state surface temperature in response to SCC ranged between $14\text{--}19^{\circ}\text{C}$. Reasonable agreement between measured and theoretical values was obtained by proper selection of h_{SCC} , T_{∞} , and μ_{skin} . In general, h_{SCC} ranged between $2000\text{--}10000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, indicating variability in thermal resistance at the sapphire-skin interface. Value of T_{∞} ranged between $6\text{--}12^{\circ}\text{C}$.

In contrast to SCC, rapid temperature reductions to values between 5°C and -9°C (average temperatures in approximately a 2-mm-diameter circular skin surface region) were obtained in response to CSC ($\tau = 20\text{--}100 \text{ ms}$) [Fig. 5(a)]. After the cryogen spurt was terminated, the radiometric temperature returned to ambient values. Increased spurt duration resulted in a longer time to return to baseline temperature.

The physical model of the cryogen-ice film on skin surface gives good agreement with infrared thermal measurements

Fig. 5. (a) Measured values of radiometric surface temperature in response to 20 ($\circ \circ \circ$), 40 ($\triangle \triangle \triangle$), 60 ($\bullet \bullet \bullet$), 80 ($\square \square \square$), and 100 ($\blacklozenge \blacklozenge \blacklozenge$) ms tetrafluoroethane spurts. Comparison of predicted (—) and measured values ($\circ \circ \circ$) in response to: (b) 40- and (c) 80-ms spurts. Parameters used in computing the theoretical results were: $h_{CSC} = 40000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = -7^{\circ}\text{C}$, $\mu_{\text{skin}} = 12 \text{ mm}^{-1}$, and $\dot{l} = 1 \mu\text{m} \times \text{ms}^{-1}$. Values of μ_{film} were 50 and 55 mm^{-1} in (b) and (c), respectively.

[Fig. 5(b) and (c)]. We used $h_{CSC} = 40000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, associated with a liquid-vapor phase transition [10], $T_{\infty} = -7^{\circ}\text{C}$, and $\dot{l} = 1 \mu\text{m} \times \text{ms}^{-1}$ consistent with a measured rate of cryogen-ice film formation [5] to fit the experimental results. Since no values of the infrared attenuation coefficient of liquid tetrafluoroethane have been reported, we assumed $\mu_{\text{film}} =$

Fig. 6. Computed values of radiometric surface temperature in response to various values of: (a) $h_{CSC} = 80\,000$ (—), $40\,000$ (---), and $4\,000$ (· · ·) $W \times m^{-2} \times K^{-1}$ while fixing $T_{\infty} = -7^{\circ}C$, $\mu_{skin} = 12\,mm^{-1}$, $\mu_{film} = 50\,mm^{-1}$, and $\dot{l} = 1\,\mu m \times ms^{-1}$; (b) $\mu_{film} = 60$ (—), 50 (---), and 40 (· · ·) mm^{-1} while fixing $h_{CSC} = 40\,000\,W \times m^{-2} \times K^{-1}$, $T_{\infty} = -7^{\circ}C$, $\mu_{skin} = 12\,mm^{-1}$, and $\dot{l} = 1\,\mu m \times ms^{-1}$; (c) $\mu_{skin} = 20$ (—), 12 (---), and 10 (· · ·) mm^{-1} while fixing $h_{CSC} = 40\,000\,W \times m^{-2} \times K^{-1}$, $T_{\infty} = -7^{\circ}C$, $\mu_{film} = 50\,mm^{-1}$, and $\dot{l} = 1\,\mu m \times ms^{-1}$; and (d) $\dot{l} = 1.75$ (—), 1 (---), and 0.35 (· · ·) $\mu m \times ms^{-1}$ while fixing $h_{CSC} = 40\,000\,W \times m^{-2} \times K^{-1}$, $T_{\infty} = -7^{\circ}C$, $\mu_{film} = 50\,mm^{-1}$, and $\mu_{skin} = 12\,mm^{-1}$.

40–60 mm^{-1} , consistent with values for the absorption coefficient of ice in the 3–5 μm spectral region [16].

B. Sensitivity Analysis

To investigate the influence of various parameters in fitting the experimental data, sensitivity studies were performed. Increasing h_{CSC} from 4000 to 40 000 $W \times m^{-2} \times K^{-1}$ resulted in lower radiometric temperatures for early times, whereas a value as high as 80 000 $W \times m^{-2} \times K^{-1}$ had a negligible effect [Fig. 6(a)]. For $h_{CSC} = \infty$, measured values differed considerably from those predicted indicating that the mechanical contact between the sapphire window and skin surface was a key determining factor in the resulting temperature profile.

Increasing μ_{film} from 40 to 60 mm^{-1} influenced the radiometric temperature during the 10–60-ms interval [Fig. 6(b)]. Changing μ_{skin} from 10 to 12 mm^{-1} had minimal effect on the radiometric temperature [Fig. 6(c)], but when increased to 20 mm^{-1} , lower values resulted during the first 60 ms.

The rate of cryogen-ice film build up ($\dot{l}$) had an appreciable effect on the radiometric temperature change; considerably lower temperatures were achieved as $\dot{l}$ was increased from 0.35 to 1.0 and 1.75 $\mu m \times ms^{-1}$, respectively [Fig. 6(d)].

C. Computed Thermal Responses

Computed values of heat flux, and total energy removed per unit skin surface area in response to SCC and CSC, are presented in Fig. 7. We have assumed a “best” case for SCC by using $h_{SCC} = 10\,000\,W \times m^{-2} \times K^{-1}$ corresponding to relatively minimal thermal resistance at the sapphire-skin interface, and $T_{\infty} = 4^{\circ}C$. For CSC, we have assumed $h_{CSC} = 40\,000\,W \times m^{-2} \times K^{-1}$, and $T_{\infty} = -7^{\circ}C$.

When cryogen is sprayed onto the skin surface, the immediate heat flux q is approximately four times greater than conductive cooling using a cold sapphire window [Fig. 7(a)]. As skin surface temperature becomes closer to that of the sapphire window or the cryogen-ice film, the thermal gradient and, subsequently, heat flux diminish over time. However,

Fig. 7. Computed values of (a) heat flux and (b) total energy removed per unit skin surface area in response to SCC (---) and CSC (—). We assumed $h_{\text{SCC}} = 10000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = 4^{\circ}\text{C}$ for SCC, and $h_{\text{CSC}} = 40000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = -7^{\circ}\text{C}$ for CSC.

Fig. 8. Isothermal contours in response to (a) SCC and (b) CSC. We assumed $h_{\text{SCC}} = 10000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = 4^{\circ}\text{C}$ for SCC, and $h_{\text{CSC}} = 40000 \text{ W} \times \text{m}^{-2} \times \text{K}^{-1}$, $T_{\infty} = -7^{\circ}\text{C}$ for CSC.

total energy removed per unit skin surface area Q continues to increase. For example, Q due to CSC is approximately four and two times greater than by SCC immediately and 100 ms after cooling, respectively [Fig. 7(b)].

The relationship between depth of skin cooling and sapphire contact time or cryogen spurt duration is demonstrated with isothermal contour plots (Fig. 8). When a cold sapphire window ($T_{\infty} = 4^{\circ}\text{C}$) is placed on the skin surface, reducing the temperature at $z = 100 \mu\text{m}$ to 10°C requires approximately 2 s of contact time; deeper tissue structures (up to $500 \mu\text{m}$) are cooled to temperatures between 10°C and 20°C [Fig. 8(a)].

When cryogen is sprayed onto the skin surface, temperature reductions to approximately between 0°C and 20°C are obtained for $10 \leq z \leq 100 \mu\text{m}$ when the spurt duration is 40 ms [Fig. 8(b)]. Temperatures of deeper tissue structures (e.g., located in $z \geq 200 \mu\text{m}$) are not reduced substantially even when the spurt duration is longer (e.g., 100 ms). In conclusion, with CSC, cooling remains localized in the epidermis while leaving the temperature of deeper structures unaffected.

V. DISCUSSION

Inducing spatially selective photocoagulation in multilayered composite biological tissues is the objective in many thermally mediated therapeutic procedures that utilize microwave, infrared, or visible electromagnetic radiation. For example, successful laser treatment of cutaneous hypervascular malformations such as PWS is based on selective photothermal destruction of targeted blood vessels without thermal damage to the normal overlying epidermis. Selective cooling of superficial tissue is a technique to protect the epidermis from laser induced thermal injury. In this study, we have investigated the effectiveness of a cooled sapphire window, and a short cryogen spurt for selective cooling.

According to our infrared thermal measurements, the contact at the sapphire-skin interface is a determining factor in the resulting temperature profile. For relatively good thermal contact (i.e., minimal thermal resistance at the sapphire-skin interface), temperature reductions to approximately $14\text{--}19^{\circ}\text{C}$ are achieved at the surface. Poor thermal contacts (i.e., large

thermal resistance at sapphire-skin interface) results in higher temperatures (16 °C) at the surface.

Apart from the difficulty of placing the sapphire window in contact with the skin surface for short times (less than 1 s), the resulting temperature reductions are relatively minimal even for good thermal contacts. Inasmuch as laser induced epidermal temperature increases of 30–70 °C can be achieved during treatment of PWS [17], SCC may not reduce the temperature sufficiently within the epidermis immediately prior to pulsed irradiation. More importantly, however, sustained cooling does not confine the temperature reduction to the epidermis. Consequently laser energy is used first to “rewarm” the cooled targeted blood vessels, and then induce a sufficient temperature increase required for photocoagulation.

Infrared thermal measurements show surface temperature reductions to between 5 °C and –9 °C are obtained within 20–100 ms by CSC (Fig. 5). Liquid cryogen droplets (b.p. $\approx$ –26 °C) strike the “hot” (30 °C) skin surface and undergo evaporation. Temperature reductions are obtained as a result of skin supplying the latent heat of vaporization to cryogen droplets. Since relatively large temperature reductions are obtained within milliseconds, cooling remains localized to the epidermis.

Inasmuch as water vapor present in the surrounding air undergoes condensation upon release of the cryogen into the atmosphere, variable quantities of ice can be formed at skin surface based on the relative humidity level. Results of preliminary experiments performed in an atmospheric water vapor control chamber indicate that lowering the relative humidity level to 5% results in elimination of ice at skin surface [18].

Whether ice elimination is clinically desirable, however, requires further investigation. Nevertheless, reducing or eliminating ice minimizes the scattering of laser light by the cryogen-ice film which is formed over the skin surface. A reduction of 10%–15% in light transmission ($\lambda = 585$ nm; a commonly used wavelength for laser treatment of PWS) through the cryogen-ice film has been reported for tetrafluoroethane spurts ranging between 5–100 ms [19].

Although laser treatment of PWS with irradiation parameters $\lambda = 585$ nm, pulse duration (τ_p) $\approx$ 0.5 ms, and dosage (D) = 5–10 J $\times$ cm $^{-2}$ has yielded successful results in some cases, improved therapeutic outcome in a greater proportion of patients with large blood vessel diameters (> 100 μ m) may be expected by using alternative wavelengths, longer pulse durations (1–10 ms), or higher light dosages [20]–[25]. Unfortunately, laser irradiation utilizing alternative parameters can result in more heat generated within the epidermis. In such a situation, a single cryogen spurt immediately prior to pulsed laser irradiation may not be sufficient to protect the epidermis from thermal injury. Additional cryogen spurts during and possibly after laser irradiation may be required to remove a sufficient amount of heat to protect the epidermis from subsequent hypertrophic scarring, atrophy, and changes in normal skin pigmentation. Further studies aimed at improving treatment of PWS and other cutaneous hypervascular malformations utilizing CSC in conjunction with laser irradiation are currently underway.

VI. CONCLUSION

Measurements utilizing infrared radiometry show contact cooling with a sapphire window reduces the skin surface temperature from 30 to approximately 14–19 °C, depending on temperature of the sapphire window, and the thermal at sapphire-skin interface. CSC with tetrafluoroethane results in rapid (within milliseconds), and large (on the order of 30 °C) surface temperature reductions. Computational results indicate when a cryogen spurt is sprayed onto the skin surface: 1) the amount of heat flux and total energy removed per unit skin surface area are at least doubled; and 2) spatially selective epidermal temperature reduction is achieved.

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