Cooling Efficiency of Cryogen Spray During Laser Therapy of Skin

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Background and Objectives: Cryogen spray cooling (CSC) is used extensively for epidermal protection during laser-induced photothermolysis of port wine stains and other vascular skin lesions. The efficacy of CSC depends critically on the heat transfer coefficient (*H*) at the skin surface for which, however, no reliable values exist. Reported values for *H*, based on tissue phantoms, vary from 1,600 to 60,000 W/m^2 K.
Study Design/Materials and Methods: A simple experimental model was designed and constructed, consisting of a pure silver-measuring disk (diameter 10 mm, thickness ~1 mm), embedded in a thermal insulator. The disk was covered with a 10 μm thick stratum corneum layer, detached from in vivo human skin. The heat transfer coefficient of the stratum corneum/cryogen interface was measured during CSC with short spurts of atomized tetrafluoroethane.
Results: *H* was found to be dependent on the specific design of the cryogen valve and nozzle. With nozzles used in typical clinical settings, *H* was 11,500 W/m^2 K, when averaged over a 100 ms spurt, and 8,000 W/m^2 K when averaged over a 200 ms spurt.
Conclusions: The presented model enables accurate prediction of *H* and thus improve control over temperature depth profile and cooling efficiency during laser therapy. Thereby, it may contribute to improvement of therapeutic outcome. Lasers Surg. Med. 32:137–142, 2003.

Key words: stratum corneum; epidermis; heat transfer coefficient; port wine stains

INTRODUCTION

To date, laser-induced selective photothermolysis is preferred for treatment of various vascular disorders of the skin, such as port wine stains (PWS) and telangiectasia, which are treated with pulsed lasers emitting in the green/yellow wavelength region. This light is strongly absorbed by hemoglobin, whereas other dermal constituents such as proteins and lipids absorb less.

Typical lasers in the clinical use today are flashlamp pumped pulsed dye lasers emitting at 585–595 nm and second-harmonic neodymium doped yttrium–aluminum–garnet (Nd:YAG) lasers at 532 nm. The pulse duration must be sufficiently long to allow heat to diffuse from the lumen to the entire vessel wall, but short enough to prevent thermal damage to perivascular structures [1,2]. Pulse durations used are typically in the range of 0.45–1.5 ms.

The risk of non-selective thermal damage to the epidermis limits the acceptable energy of the laser beam, because even though melanin absorption decays with increasing wavelength, it remains significant over the entire visible and near-infrared spectral regions. Irreversible damage occurs when the epidermal temperature rises above 70°C, i.e., 35°C above normal skin temperature [3].

Limitations of acceptable fluences can be significantly reduced if the epidermis is selectively pre-cooled well below the ambient temperature [3–5]. For example, cooling the epidermis to 0°C will allow for a 'safe' temperature rise of 70°C, thereby increasing the maximum permissible fluence by a factor of $70/35 = 2$.

Moreover, cooling should be spatially selective. This limits the cooling duration to the thermal diffusion time $\tau_e \approx \frac{d_e^2}{\chi_e}$, which is the time required for heat to diffuse through the epidermis [1–6]. Here, d_e is the epidermal thickness and χ_e its thermal diffusivity. For human epidermis, d_e typically is 60–100 μm and $\chi_e = 1.2 \cdot 10^{-7}$ m^2/s [7], thus $\tau_e \approx 30$–80 ms.

Contract grant sponsor: The Air Force Office of Scientific Research; Contract grant sponsor: National Institutes of Health ; Contract grant number: (GM-62177); Contract grant sponsor: The Beckman Laser Institute Endowment.
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L.O. Svaasand and J.S. Nelson have disclosed a potential financial conflict of interest with this sutdy.
Accepted 14 August 2002
Published online in Wiley InterScience (www.interscience.wiley.com).
DOI 10.1002/lsm.10120

Due to the requirement of spatially selective precooling, a technique to spray the skin with 20–100 ms spurts of liquid cryogen has been developed [8]. Spurt duration is controlled with a solenoid valve [8]. Implementation of cryogen spray cooling (CSC) technology into commercial medical lasers has resulted in improved of therapeutic outcome for various dermatological indications, notably PWS [8–11] and hemangiomas [12], leg telangiectasia [13,14], tissue welding [15], rhytides [16,17], and removal of unwanted hair [18,19], and reticular veins [20].

However, despite intensive research on CSC, the value of the heat transfer coefficient, H, between the liquid cryogen layer and the skin has remained uncertain. The reason for this is that in vivo measurement of a thermal distribution confined to the epidermal layer is a challenging task. Given the steep thermal gradients and short cooling times with CSC, the use of inserted thermocouples becomes impractical. For example, the wire diameter of the smallest commercially available micro-thermocouple is ~25 μm, with a bead diameter of ~60 μm, which is comparable to the epidermal thickness. Also, thermal conductivities of thermocouple metals are typically two to three orders of magnitude larger than that of human skin. Therefore, inserted thermocouples significantly perturb the thermal distribution in the epidermis. Thermocouple readings represent tissue temperatures only when thermal gradients have become sufficiently small. Because of these uncertainties, reported values for H cover a wide range, i.e., 1,600–60,000 W/m^2 K [3].

This paper presents a novel technique based on a metallic disk detector for measuring H, during short cryogen spurts. It is demonstrated that such a detector can be designed to have similar chemical/mechanical surface characteristics to those of the stratum corneum, with a similar heat flux to the cryogen-sprayed surface as in the case of human skin.

MATERIALS AND METHODS

Cryogen Spray

The cryogen (1,1,1,2 tetrafluoroethane, R 134a) spray was delivered with an automobile gasoline engine fuel injection valve for (Injector # 57031, Borg Warner®, Chicago, IL), and spurt durations were 100 and 200 ms. The valve was connected to a container of liquid cryogen via a high-pressure hose. The container was mounted upside down in order to deliver liquid cryogen to the valve. The container was maintained at room temperature, which corresponds to a cryogen pressure of 670 kPa. Two different custom built nozzles (32 mm long with 0.7 and 1.4 mm bores, respectively) were used, as well as two commercial nozzles (Dynamic cooling device, DCD®, incorporated in GentleLASE® and ScleroPLUS® lasers, Candela Corp., Wayland, MA). The finely dispersed spray of cryogen droplets had a conical geometry with an opening angle of 17°. The spray diameter at the detector disk, positioned 50 mm from the nozzle, was ~15 mm. The spray droplet temperature was measured with a 300 μm bead diameter thermocouple, inserted directly in the cryogen spray. The measured temperature of the spray was −55°C, well below the boiling point of R134a (−26.2°C at 1 atm) [21].

Model

A disk-shaped body of a high thermal conductivity metal (99.9% pure silver), was partly embedded in a thermal insulator; for practical reasons epoxy resin was used. The disk temperature was measured by a Chromel–Alumel thermocouple (Omega, Stamford, CT, 130 μm wire diameter and 300 μm bead) soft-soldered to the lower surface (60% Sn and 40% Pb). The upper disk surface was exposed to cryogen with a spray diameter ~50% larger than that of the disk. Disks had a 10 mm diameter and a thickness d_m of 0.7, 1.0, or 2.0 mm. The small ratio between thickness and diameter ensures that the temperature distribution and heat flow in the disk can be treated as one-dimensional. The measuring model is schematically illustrated in Figure 1.

Detector Surface Preparation

In order to simulate the in vivo human skin surface and test the influence of chemical composition on heat extraction during CSC, one disk was covered with a layer of human stratum corneum (SC). The preparation started by depositing a thin layer of low-viscosity ethylcyanoacrylate glue onto the disk surface, which was then pressed (~100 kPa) against the flexor surface of a male volunteer's forearm for about 30 seconds. Removal of the disk from the skin resulted in the detachment of the SC from the epidermis. The study protocol described was approved by the Institutional Review Board (IRB) at the Norwegian University of Science and Technology, Trondheim, Norway.

The disk surface was inspected under an optical microscope to ensure a continuous SC layer. The total layer thickness was determined to be $d_{SC} \approx 10$ μm, which matches the reported thickness SC thickness on human extremities, i.e., 12.7 ± 4.2 μm [22]. The aforementioned procedure provided a disk detector with a surface texture and physicochemical properties resembling those of human skin.

When using a non-covered silver surface, the disk detectors were roughened with a fine steel brush to resemble skin texture, since macroscopic structure of the disk surface may affect heat transport mechanisms (e.g., adhesion) in the metal–cryogen boundary layer.

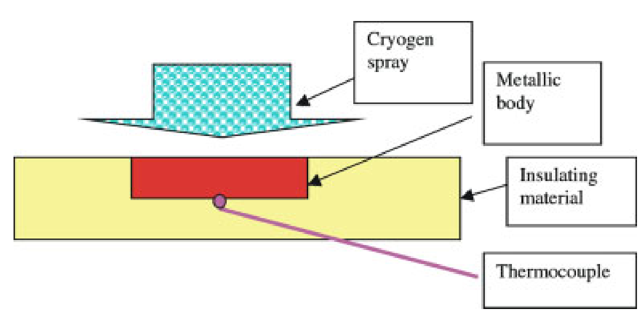

Fig. 1. Schematics for measuring heat transfer coefficients.

Measurement of the Heat Transfer Coefficient

Measurements were analyzed on a time scale when of the disk temperature can be taken to be uniform. For the silver disk ($\chi_m = 1.7 \times 10^{-4}$ m^2/s) with a thickness $d_m =$ 0.7 mm, the time required to equalize its temperature is $t > d_m{}^2/\chi_m \approx 3$ ms [23]. Under this provision, the disk temperature dynamics, $T(t)$, is given by

$$\rho_m C_m V_m \frac{dT}{dt} = a_m H(T_c - T) \quad (1)$$

where ρ_m, C_m, V_m, and a_m are, respectively, density, specific heat per unit mass, volume, and surface area of the disk. The cryogen spray temperature, T_c, was measured to be -55°C [21].

For constant H, the solution of Equation 1 is

$$T(t) = (T_c - T_o)\left(1 - e^{-\frac{t}{\tau_m}}\right) + T_o \quad (2)$$

where T_o is the initial disk temperature at $t = 0$, and τ_m represents the thermal relaxation time of the disk, $\tau_m = \frac{\rho_m C_m d_m}{H}$. The heat transfer coefficient can, therefore, be determined by monitoring the disk temperature during CSC (Eq. 2), using

$$H = \frac{\rho_m C_m d_m}{\tau_m}. \quad (3)$$

The low thermal conductivity of the dehydrated SC and its adverse effect on heat extraction from the detector must be considered in the analysis. The thermal admittance of the SC, A_{SC}, will thus be coupled in series with H, which corresponds to the thermal admittance through the boundary layer where the temperature changes from T_c to the surface temperature of the SC layer. In other words, the disk detector senses the thermal resistance of the SC layer (R_{SC}), coupled in series with the thermal surface resistance at the SC–cryogen interface. The latter is defined as the inverse of the corresponding heat transfer coefficient ($1/H_{SC}$)[25], which can be assessed from the experimentally determined value, H^*, using

$$\frac{1}{H_{SC}} = \frac{1}{H^*} - R_{SC}. \quad (4)$$

The thermal admittance is defined as $A_{SC} = \kappa_{SC}/d_{SC}$, or $R_{SC} = d_{SC}/\kappa_{SC}$ where κ_{SC}denotes the thermal conductivity of the SC, taken to be $\kappa_{SC} = 0.2$ W/mK, i.e., similar to that of keratinous fibers ($\kappa_{wool} = 0.18$ W/mK) [23]. It will not be necessary to correct for the thin ($\sim 1 - 2$ μm) adhesive layer between the SC and the silver surface, because the thermal conductivities of acrylic and SC are similar [23].

Insulation Considerations

The epoxy resin surrounding the detector disk is not an ideal insulator. Therefore, so it might be necessary to correct the analysis for heat exchange during the measurement. Heat diffuses a distance of $\sim\sqrt{\chi_i t}$ in the insulating-material during time t. The ratio between the thermal energy supplied by the insulation and the energy simultaneously extracted from the CSC can be approximated by

$$F \approx \frac{\rho_i C_i \sqrt{\chi_i t}}{\rho_m C_m d_m} \quad (5)$$

where $\rho_i C_i$ is the specific heat per unit volume of the insulating material, and χ_i is its thermal diffusivity.

The thermal diffusivity and conductivity of a typical epoxy resin are, respectively, $\chi_i = 1.1 \cdot 10^{-7}$ m^2/second and $\kappa_i = 0.14$W/mK [24], and the corresponding values for silver are $\chi_m = 1.7 \cdot 10^{-4}$ m^2/s and $\kappa_m = 425$ W/mK [23]. The resulting ratio becomes $F \approx 0.05$ for a 1 mm thick silver disk and a 100 microseconds CSC. As a result, the H obtained using Equations 1 and 2 are underestimated by the same amount. All values presented in Tables 1 and 2 are corrected accordingly.

Alternatively, embedding the silver disk in a different material could reduce this systematic error. For example, insulating foam materials, such as expanded polyurethane, have much lower thermal conductivities, close to that of air ($\kappa_i = 0.025$ W/mK). With the volumetric specific heat in the range of $\rho_i C_i = 25$ kJ/m^3, the corresponding thermal diffusivity equals $\chi_i = \frac{\kappa_i}{\rho_i C_i} = 1 \cdot 10^{-6}$ m^2/s [23]. The fractional thermal energy supplied by the surrounding/supporting material would thus be reduced to only $\sim$0.3% during 100 microseconds CSC.

RESULTS

A typical temperature response, $T(t)$, of a disk detector with an uncovered silver surface is shown in Figure 2a. The continued decrease in temperature for $\sim$50 ms after the end of a 100 ms spurt is due to evaporation of the liquid cryogen layer, deposited on the disk surface [24]. In order to verify whether the disk relaxation time, τ_m (and, thereby, H) varies during the spurt, Figure 2b displays the function $\ln((T - T_c)/(T_o - T_c))$ vs. time for $T_o = 13.5$ °C and $T_c = -55$ °C. The logarithmic plot falls on a straight line, in particular during the latter half of the spurt, thus demonstrating a constant value of H in that time interval. Since the heat transfer rate gradually decreases during the spurt, this observation indicates that H is rather independent on the heat transfer rate.

The average H was determined to be 7,600 W/m^2 K; after correcting for heat diffusion from the insulation

TABLE 1. Average Heat Transfer Coefficient for a 100 ms Long Cryogen Spurt From Different Spray Nozzles

Nozzle	H (W/m^2 K)
0.7 mm bore, 32 mm long	7,200
1.4 mm bore, 32 mm long	10,800
GentleLASE®	7,400
0.5 mm bore, ~30 mm long	
ScleroPLUS®	6,600
0.8 mm bore, orifice <1 mm thick	

Distance from nozzle to disk 50 mm. Uncoated disk (bare silver surface).

TABLE 2. Comparison of Heat Transfer Coefficients for CSC as Measured Using the Disk Detector Covered With Human Stratum Corneum (Top Row) and With Exposed Silver Surface (Bottom Row)

Disk	Heat transfer coefficient, average over 100 ms	Heat transfer coefficient, average over 200 ms
SC covered surface, measured	$H^* = 7{,}300$ W/m^2 K	$H^* = 5{,}700$ W/m^2 K
SC covered surface, corrected for SC thickness	$H_{SC} = 11{,}500$ W/m^2 K	$H = 8{,}000$ W/m^2 K
Exposed silver surface	$H = 11{,}000$ W/m^2 K	$H = 7{,}900$ W/m^2 K

Nozzle: 1.4 mm bore, 32 mm long; Distance from nozzle to disk 50 mm.

during the measurement, according to Equation 5, the value becomes about 8,000 W/m^2 K.

Results for two custom built nozzles and the two commercial nozzles are given in Table 1. These results yield a heat transfer coefficient in the range of 6,000–11,000 W/m^2 K, where the lower values are for the narrow bore nozzles [25].

The values in Table 2 illustrate the effect of covering the disk detector with a 10 μm thick layer of human stratum corneum. The upper row gives the measured values, corresponding to an effective heat transfer coefficient, H^* in Equation 4. The middle row gives H of the stratum corneum/cryogen spray interface, corrected after accounting for the thermal resistance of the SC layer using Equation 4. The lower row gives results from separate measurements, performed using a disk with uncovered silver surface.

The first data column presents H values averaged over the first 100 ms of CSC, and the last column the corresponding values for 200 ms. The differences between the values in these two columns may, in part, represent the influence of ambient water condensation and frost formation on the detector surface [3,24]. No frost formation was observed at spraying times less than 100 ms in normal, ambient air. The values in Table 2 represent averages from ten series of measurements carried out with three different detectors (disk thickness 0.7, 1, and 2 mm) and a spraying distance 50 mm. The values were reproducible with a typical deviation from the mean value of less than 10%.

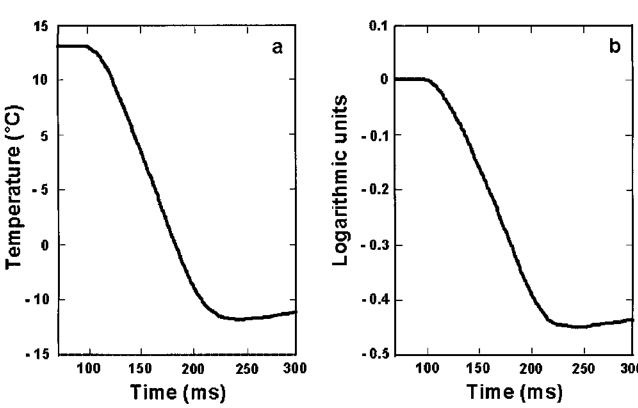

Fig. 2. **a**: Temperature response of a silver disk exposed to a 100 ms long cryogen spurt. Valve opens at time 0.1 seconds and closes at 0.2 seconds. Nozzle bore 0.7 mm, spraying distance 50 mm; air humidity 40%. **b**: Logarithmic display (see text for details).

The results given in Table 2 demonstrate that the values of H for CSC on a bare silver disk are very close to those obtained for spraying the stratum corneum. The results from spraying a silver surface are therefore expected to be representative for the corresponding values in the case of skin cooling.

DISCUSSION

The brief derivation of Equation 4 implies neglecting the specific heat of the SC layer. This applies only if the heat transfer time across this layer is much less than that for the metal disk, i.e.,

$$d_l \ll \sqrt{\frac{\chi_l}{\chi_m}}\, d_m. \qquad (6)$$

Since the thermal diffusivity of silver is about a thousand times larger than that of the SC, this condition requires that the layer thickness should be much less than 3% of the disk thickness. Thus, a SC layer of ~10 μm thickness should be quite acceptable.

Heat transfer mechanisms in the surface–spray interface layer may, in principle, also depend on the heat flux across the cooled surface. Consequently, the H values obtained using a metallic disk detector may not be representative for cryogen spraying of human skin, if the surface heat flux in these two systems differs by a large amount.

The amount of heat (Q_e) transferred across the skin surface during a CSC of duration τ can be roughly estimated as

$$Q_e \approx \rho_e C_e \sqrt{\chi_e \tau}(T_c - T_n) \qquad (7)$$

where ρ_e and C_e are density and specific heat per unit mass of the skin, respectively.

Since the thermal relaxation time of our disk detector is selected to match approximately the cooling duration, the

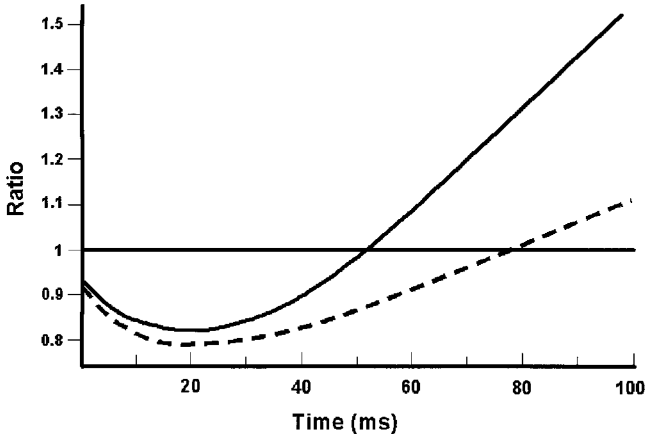

Fig. A1. Ratio between instantaneous heat flux to the skin surface and to the metallic disk surface. Time in seconds. $T_n = T_i = 35°C$, $T_c = -55°C$, $H = 5{,}000$ W/m^2 K. Upper curve, disk thickness $d_m = 0.15$ mm and lower curve $d_m = 0.2$ mm.

corresponding amount of heat transferred to the surface of the metallic body (Q_m) becomes

$$Q_m \approx \rho_m C_m d_m (T_c - T_o). \quad (8)$$

Thus, approximately the same amount of thermal energy will be extracted from a 0.15–0.2 mm thick silver disk of the same initial temperature as that of normal skin ($T_o = T_n$) for spurt duration of 100–200 ms as in the case of skin. Note that, whereas the total amount of heat transferred to the skin surface is determined by the thermal diffusivity, the corresponding heat transport in the disk is independent of the diffusivity and determined only by the specific heat and disk thickness.

Based on a more rigorous analysis of the same effect (see Appendix), the results in Figure A1 show the difference between instantaneous values of the heat flux across the skin surface and across the disk surface. The upper curve shows that in the case of a heat transfer coefficient of $H = 5{,}000$ W/m^2 K, the heat flux from skin is 20% less than that from a 0.15 mm thick silver disk after 20 ms, whereas it is about 50% higher after 100 ms. The corresponding values for a 0.2 mm thick disk are 25% less after 20 ms and 10% higher after 100 ms. In case of a lower H, such as 1,000 W/m^2 K, the corresponding difference will be less that 10% for both disk thicknesses. Thus, the proper selection of disk thickness (and possibly also the initial disk temperature) enables a heat flux similar to that of skin.

The detailed expression for the dependence on H on the spatial and temporal distribution of the cooling within the skin is given in the Appendix (see Eq. A1).

CONCLUSIONS

The described model for measurement of H during CSC yields reproducible and relatively accurate values. The values of H during a 100 ms spurt of tetrafluoroethane onto the stratum corneum were determined to be up to 11,500 W/m^2 K. The values of H are well above the thermal admittance of epidermis, i.e., for an epidermal thickness of $d_e = 60 - 100$ μm and thermal conductivity in the range of $\kappa_e = 0.16 - 0.25$ W/mK [7]. The epidermal thickness rather than the heat transfer coefficient therefore limits cooling of the entire epidermis. The measured value of H is thus near optimal for epidermal protection during laser dermatologic surgery.

The requirements for an efficient protection of the epidermis in regions of the body where the thickness might vary substantially from, is that H should be larger than the admittance, i.e., thus, as the thickness of the layer to be protected increases, the spurt duration must be longer and in the range of $\tau_e \approx \frac{d_e^2}{\chi_e}$. However, the cooling requirement can be relaxed since the thermal admittance now is correspondingly smaller. In clinical practice, this will ensure that the protection by cooling is optimized for the specific lesion, and thereby contribute to improved treatment protocols.

ACKNOWLEDGMENTS

The authors acknowledge support from the Air Force Office of Scientific Research, National Institutes of Health (GM- 62177), and the Beckman Laser Institute Endowment. The methodology described in this manuscript is contained within U.S. Patent Number 5,814,040—Apparatus and Method for Dynamic Cooling of Biological Tissues for Thermal Mediated Surgery—awarded to J. Stuart Nelson, M.D., Ph.D., Thomas E. Milner, Ph.D., and Lars O. Svaasand, Ph.D., and assigned to the Regents of the University of California.

APPENDIX

The temperature distribution in a surface-cooled semi-infinite medium with a heat flux at the boundary given by $H(T_c - T)$, can be expressed [25] as

$$T(x,t) = \left(erfc\,\frac{x}{2\sqrt{\chi_t t}} - e^{\frac{H}{\kappa_t}x + \left(\frac{H}{\kappa_t}\right)^2 \chi_t t}\, erfc\left(\frac{x}{2\sqrt{\chi_t t}} + \frac{H}{\kappa_t}\sqrt{\chi_t t}\right)\right) \times (T_c - T_n) + T_n. \quad (A1)$$

Here, x and t denote, respectively, the distance from the surface and the time after onset of cooling. T_n and T_c are, respectively, the initial normal tissue temperature and the temperature of the impinging cryogen droplets; κ_t and χ_t are, respectively, the thermal conductivity and diffusivity of the tissue.

The instantaneous value of the heat flux j to the skin surface during CSC can be expressed from Equation A1

$$j = -\kappa_t \frac{\partial T}{\partial x}\bigg|_{x=0+} = He^{\left(\frac{H}{\kappa_t}\right)^2 \chi_t t}\, erfc\left(\frac{H}{\kappa_t}\sqrt{\chi_t t}\right)(T_n - T_c) \quad (A2)$$

The corresponding heat flux j_m to the metal disk can be expressed from Equation 1

$$j_m = \frac{\rho_m C_m d_m}{\tau_m} e^{-\frac{t}{\tau_m}} (T_o - T_c). \quad (A3)$$

An example of the ratio between the flux to the skin surface and the corresponding flux to the metal surface, i.e., j/j_m, is shown in Figure A1.

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