Sequential cryogen spraying for heat flux control at the skin surface

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ABSTRACT

Heat transfer rate at the skin-air interface is of critical importance for the benefits of cryogen spray cooling in combination with laser therapy of shallow subsurface skin lesions, such as port-wine stain birthmarks. With some cryogen spray devices, a layer of liquid cryogen builds up on the skin surface during the spurt, which may impair heat transfer across the skin surface due to relatively low thermal conductivity and potentially higher temperature of the liquid cryogen layer as compared to the spray droplets. While the mass flux of cryogen delivery can be adjusted by varying the atomizing nozzle geometry, this may strongly affect other spray properties, such as lateral spread (cone), droplet size, velocity, and temperature distribution. We present here first experiments with sequential cryogen spraying, which may enable accurate mass flux control through variation of spray duty cycle, while minimally affecting other spray characteristics. The observed increase of cooling rate and efficiency at moderate duty cycle levels supports the above described hypothesis of "isolating" liquid layer, and demonstrates a novel approach to optimization of cryogen spray devices for individual laser dermatological applications.

Keywords: convective heat transfer, cooling selectivity, dynamic cooling, evaporative cooling, hypervascular lesions, laser dermatologic surgery, port wine stain.

1. INTRODUCTION

In dermatologic and cosmetic laser treatments, non-specific absorption in epidermal melanin often poses a risk of dyspigmentation, blistering, or scarring, which limits the maximal radiant exposure that can be safely used in a clinical situation. For many indications, such as port wine stain birthmarks (PWS), such limitation adversely affects the success of laser therapy. Pre-cooling of epidermis with cryogenic spray cooling (CSC) allows safe application of laser pulses with higher energy, enabling improved blanching of PWS.[1,2]

Despite the relatively wide clinical use of CSC in recent years, however, quantitative understanding of the involved processes remains incomplete. It is therefore not certain whether existing cryogen spray devices have been optimized for the intended applications. In particular, laser therapy of PWS calls for extremely high spatial selectivity of cooling,[3,4] which requires use of short cryogen spurts (tens to hundreds of milliseconds) and highest possible heat transfer rate across the skin-coolant interface.

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In theory, most efficient cooling occurs when the mass flux of sprayed cryogen matches the evaporation rate at the skin surface. Clearly, the heat extraction is impaired if too little cryogen is sprayed. On the other hand, if the spray mass flux exceeds the evaporation rate, a layer of liquid cryogen may build up on the skin surface, acting as a thermal barrier between the very cold spray droplets and the target surface.[5] However, such considerations do not fully take into account the dynamics of spray droplet impact, which may also affect the cooling efficiency.

Verkruysse *et al*.[6] recently measured cooling rates with straight-tube nozzles of different inside diameters. *Narrow* nozzles had an inside diameters of 0.69 mm, similar to that of a commercial CSC device for PWS treatment (DCD for ScleroPlus, Candela, Wayland, MA), and *wide* ones had a diameter of 1.37 mm. Fast-flashlamp photography revealed that with either nozzle, a layer of liquid cryogen accumulated on the target surface (epoxy tissue model), even at spurt duration as short as 20 ms. It was therefore very surprising that higher cooling rate was observed with *wide* nozzles, which undoubtedly featured higher mass flux (and, incidentally, also a smaller spray cone).

Based on fast-flashlamp photographs, presented in the same article, the authors hypothesized that higher momentum of larger and faster droplets, as produced by the *wide* nozzle, partly or completely removes the liquid cryogen layer, which in turn enhances heat extraction from the substrate.[6] Recent direct measurements in our group have shown that the *wide* (1.37-mm inner diameter) straight-tube nozzles indeed produce significantly larger and faster droplets.[7,8] Further, the fact that spraying with the *wide* nozzle yields a higher heat transfer coefficient was confirmed with independent steady-state measurements using a metal-rod technique,[9] described earlier by Verkruysse *et al*.[6] Most recently, Svaasand *et al*. introduced a metal-disk technique, and determined average heat transfer coefficient in a 100-ms CSC spurt to be 10,800 W/m^{2}K and 7,200 W/m^{2}K for the *wide* and *narrow* nozzle, respectively[10] - in good agreement with earlier results from our grup.[6,9]

In view of the above, heat transfer coefficient of the commercial CSC devices could likely be increased by modifying the atomizing nozzle geometry, which is currently similar to our *narrow* nozzle. Another possibility would be to adjust the distance between the nozzle and skin surface for optimal heat transfer coefficient at the cryogen-skin interface.[11] However, both these variations strongly affect other spray characteristics, such as spray temperature, covered area, etc, which makes seeking for optimal configuration a rather complicated task.[7,8,11] Preliminary tests revealed, for example, that *wide* nozzle sprays caused a significant amount of patient discomfort, hardly acceptable for routine clinical use.[6]

Therefore, we propose and investigate below an alternative approach to control the cryogen spray deposition with possibly much less effect on other spray characteristics. Using the *narrow* nozzle design, which - apart from depositing too much cryogen - seems to work well in clinical practice, we try to maximize the cooling rate and efficiency by sequential spraying, *i.e.*, application of a series of very short spurts with varying delays between them. The hypothesis is that, if the presence of liquid layer is indeed limiting heat transfer across the skin surface, an appropriate reduction of cryogen flux should result in increased cooling rate and efficiency.

Finally, quantitative assessment of heat transfer coefficient during CSC has lately been rather controversial, with values determined using various techniques ranging from around 2,000 W/m^{2}K[12,13] up to 40,000 W/m^{2}K,[14,15] admittedly obtained with somewhat different atomizers and spraying conditions. In the present study, we use the metal-disk technique,[10] which is relatively simple, fast, and accurate.

2. INSTRUMENTATION AND METHOD

2.1. Cryogen spray device and settings

All measurements were performed with 1,1,1,2 tetrafluoroethane (C$_2$H$_2$F$_4$, also known as R134a), the same cryogen as used in clinical instruments and in other similar studies. It has a boiling temperature of –26 °C and is kept in a steel canister at the saturation pressure (6.6 bar at 25 °C). A high-pressure hose connects the canister with the electronically controlled solenoid valve (*i.e.*, automobile fuel injector). Attached to the valve body is the atomizing nozzle, which consists of a stainless steel tube with inner diameter of 0.69 mm (length: 32 mm), similar to that of a commercial CSC device intended for PWS therapy (DCD for ScleroPlus, Candela, Wayland, MA). The spraying distance was fixed at 60 mm.
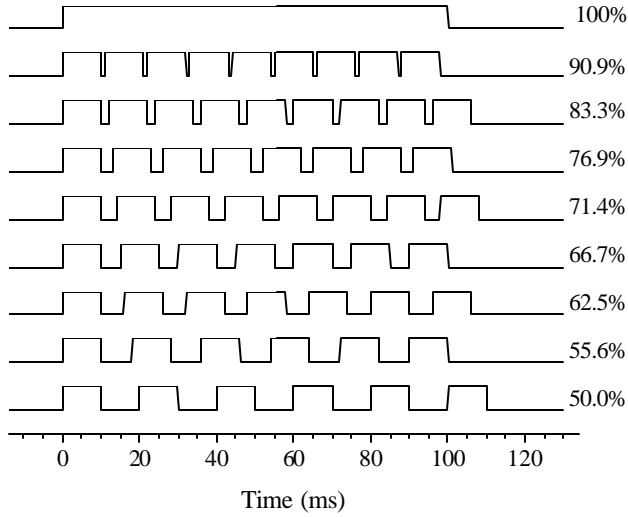
Figure 1: Schematic representation of spraying sequences used in this study. Six to nine 10-ms cryogen spurts were applied in a time interval of 100–110 ms, yielding duty cycles from 50.0 to 90.9% (marked next to each sequence). A single 100-ms spurt is used as a reference.

Spraying sequences used in this study are illustrated in Figure 1. For sequential spraying, individual spurt durations are constant at $t_s = 10$ ms, while the delays between consecutive spurts, t_d, are varied from 1 to 10 ms. This way, the duty cycle of the sequence, defined as $r = t_s/(t_s + t_d)$, is varied from 91% down to 50%. The number of spurts is adjusted to keep the duration of the whole sequence between 100 and 110 ms, in order to ease comparison with the reference 100-ms non-sequential spurt.

2.2. Measurement of heat flux across the sprayed surface

A custom device was built to measure the heat transfer across the sprayed surface, as described in Svaasand et al.[10] In short, the device consists of a small disk made of pure, highly conducting metal, embedded in a block of thermal insulator. The upper surface of the disk, roughened with sand paper to approximate skin surface, is sprayed with cryogen, and disk temperature is measured by a thermocouple attached to its lower surface. Heat flux across the sprayed surface of the disk, j_q, can then be expressed as:

$$j_q \approx \frac{\rho c V}{A} \frac{dT}{dt} \approx \rho c d \frac{dT}{dt},$$ (1)

where ρ, c, V and A represent the density, specific heat, volume, and exposed surface area of the metallic disk, respectively, T marks its temperature, and d is its thickness. Equation (1) assumes that temperature T is uniform over the whole metal disk. This assumption is justified if the diffusion time across the disk thickness, $t_d \approx d^2/\alpha$ (where α stands for thermal diffusivity of the metal), is much smaller than the disk's relaxation time τ, given by[10]

$$\tau \approx \frac{\rho c d}{h}.$$ (2)

Here, h marks the heat transfer coefficient, as defined by convective ("Robin") boundary condition at the cooled surface:[16]

$$j_q \approx h (T - T_c).$$ (3)

We used high-purity copper (Cu-110: $\rho \approx 8,920$ kg/m^3, $c = 390$ J/kg K, $\alpha = 1.14 \times 10^{-4}$ m^2/s) to make a disk with a 7-mm diameter and thickness of $d = 0.42$ mm. This yields an appropriately short diffusion time $t_d \approx 1.5$ ms, and relaxation time equal to $\tau = 150$–300 ms for the h values in the range of 5,000–10,000 W/m^2 K. Since measurement errors of 10% or more can result from heat conduction across the back surface of the metallic disk, when fully embedded in an epoxy block,[10] we cast only a thin epoxy plate around the disk (of the same thickness as the disk itself), and supported everything by a block of polyurethane foam with very low thermal conductivity (see Fig. 2). This approach reduces heat-loss error for our detector to

<1%. In order to ensure optimal thermal contact, the thermocouple (type K, 300-?m bead) was soldered to the back surface of the copper disk. Temperature data were acquired using an A/D converter board and dedicated software (instruNet, Omega Engineering, Stamford, CT) at a sampling rate of 1000 Hz.
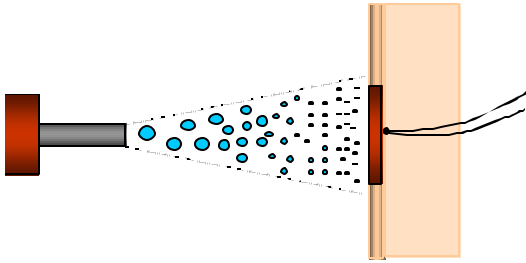

Figure 2: Scheme of the detection device, consisting of a copper disk embedded in a thin epoxy plate and supported by a polyurethane foam. The thermocouple bead is soldered to the back side of the copper disk, while its front surface is exposed to cryogen spraying..

By equating Eqs. (1) and (3), heat transfer coefficient can be calculated from acquired temperature scans as:

$$h \ ? \ \frac{? \, c \, d}{(T \, ? \, T_c)} \, ? \frac{dT}{dt} ? . \tag{4}$$

The described technique in principle enables assessment of heat transfer dynamics, expressed as $h(t)$, with temporal resolution limited by the heat diffusion time t_d.

3. RESULTS

Figure 3a presents temperature data as acquired during and after cryogen spray cooling of the copper disk with a continuous 100-ms spurt ($r = 1.000$; thicker line), and two sequential sprays with duty cycles of $r = 0.833$ and $r = 0.714$ (see the legend). All spraying sequences start at time $t = 0$ and last for 100–110 ms, as depicted in Fig. 1. It suffices to consider disk temperatures at time $t = 100$ ms in order to realize that, under conditions used in this experiment, *lowering the duty cycle (r) increases CSC rate and efficiency.* As illustrated in Figure 3b, which presents minimal temperatures of each scan as a function of the corresponding duty cycle, such a trend holds systematically from $r = 1.0$ to $r \, ? \, 0.7$, but is reversed at lower duty cycles.
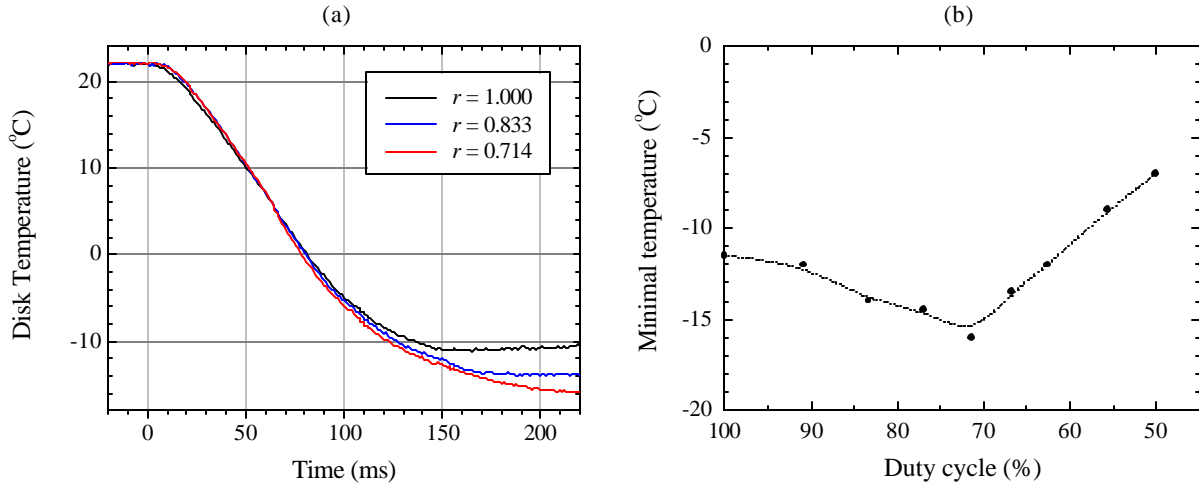
Figure 3: (a) Temperature of the copper disk as measured during CSC with a continuous 100-ms spurt and two sequential sprays with select duty cycles r (see the legend). All spraying sequences start at time $t = 0$ (as depicted in Fig. 1). (b) Minimal temperatures obtained with such sequential sprays plotted as a function of the (decreasing) duty cycle.

Figure 4 presents the dynamics of heat flux across the cooled surface, $j_q(t)$, as calculated using Eq. (1) from temperature scans acquired during and after three CSC spurts with varying duty cycle r (same events as in Fig. 3a). With the continuous spurt ($r = 1.000$; thicker line), the heat flux stalls at $j_q = 48$ W/cm^2 after ? 40 ms of spraying. With sequential spraying, exhibiting a *lower average cryogen mass flux*, it *stalls at a higher value* of 50 W/cm^2 (at $r = 0.833$). At an even lower duty cycle of $r = 0.714$, it increases for another 30 ms to reach a peak value of $j_q = 56$ W/cm^2.
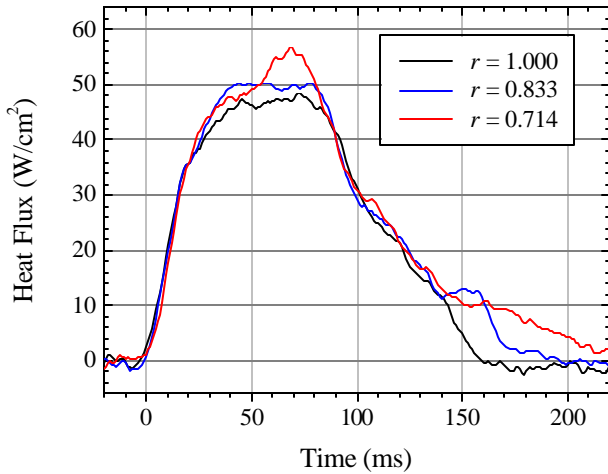

Figure 4: Dynamics of heat flux across the cooled surface, $j_q(t)$, as calculated using Eq. (1) from copper disk temperature scans in Fig. 3a.

Finally, heat transfer coefficient, h, closely related to physical mechanisms involved in heat transfer across the cooled surface, can be calculated from acquired copper-disk temperature scans using Eq. (4). Figure 5 presents the result for one continuous and two sequential CSC spurts (same as analyzed in Figs. 3a and 4). In this calculation, the cryogen temperature was set to $T_c = -57$?C, as measured at the target distance in a stationary spray (using a bare thermocouple in dry atmosphere).[8,10,11] To our knowledge, the same assumption of constant T_c throughout the CSC event was made in all recently published analysis on the same problem.

The presented results show that the heat transfer coefficient (h) varies markedly during CSC with either a continuous or sequential spraying. Further, they show that h values reached with decreasing duty cycles of sequential sprays are increasingly higher than those obtained with a continuous 100-ms spurt – a trend, which is reversed at $r \approx 0.7$. The maximal value reached is $h \approx 9{,}200$ W/m^2 K (at $r = 0.714$), 12% higher than that obtained with the non-sequential spurt (8,200 W/m^2 K).
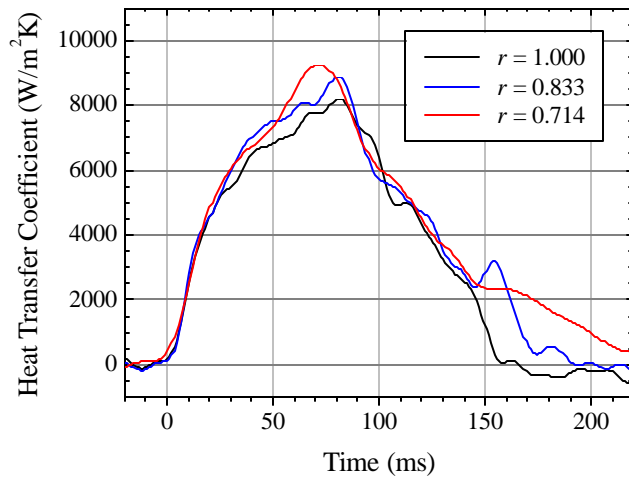

Figure 5: Heat transfer coefficient at the cooled surface, h, as calculated from the copper-disk temperature scans in Fig. 3a using Eq. (4).

4. DISCUSSION

In the presented experiments, the metallic-disk detection technique proved to provide reliable measurements of heat flux (j_q) and heat transfer coefficient values (h) at the surface dynamically cooled with CSC, in good quantitative agreement with earlier results obtained in our group using other experimental approaches.[6,9] While the metal-disk approach is certainly prone to specific systematic errors (such as the heat-loss error, discussed in Sect. 2.2), its high repeatability makes it sensitive enough to reliably detect small variations in cooling dynamics, induced by rather small modifications of CSC conditions - such as sequential spray's duty cycle in this study.

Compared to the earlier used technique with thermocouple-embedded epoxy block, the strength of the metal-disk approach arises primarily from avoidance of the inverse analysis of the heat diffusion dynamics. In presence of experimental noise, the ill-posedness of such analysis imposes a sizeable uncertainty onto the best-fit result (in terms of average h), even without taking into account its dependence on numerous inaccurately known experimental parameters, such as individual thermocouple depths and thermal properties of the epoxy substrate. (The latter are not only difficult to determine accurately for a specific epoxy sample, but can change dynamically when cooled - much more than for a pure metal).[6] In addition to substantially reducing or altogether eliminating some further sources of measurement errors (related to the size of thermocouple bead vs. strong thermal gradients in epoxy substrate, heat flux along the thermocouple wires vs. heat transfer through the epoxy, etc.), the metallic-disk approach enables dynamical determination of surface heat flux, $j_q(t)$, and heat transfer coefficient $h(t)$. The temporal resolution of such analysis is in principle limited only by the heat diffusion time t_d, which can be brought down to ≈ 1 ms.

It is critical, however, to ensure optimal thermal contact between the thermocouple bead and the metal disk. As illustrated by the following example, an insufficient - albeit still rather good - thermal contact can induce time delays that significantly affect the results. Figure 6a presents two metal-disk temperature scans, acquired simultaneously with two thermocouples during a 100-ms CSC spurt. One thermocouple was soldered to the back side of the disk, while the other was dipped into thermal paste, pressed into a tiny bore on the back surface of the disk, and fixed with a drop of epoxy glue. Figure 6a demonstrates how the time-lag in the "glued thermocouple" scan converts to severely underestimated heat transfer coefficient. Without the direct comparison, it would be very difficult to recognize the error in "glued thermocouple" data. (In this example, a 99.9% pure silver disk with thickness of 0.7 mm was used, yielding $t_d \approx 3$ ms and $\tau \approx 260$ ms at $h = 5{,}000$ W/m^2 K.)
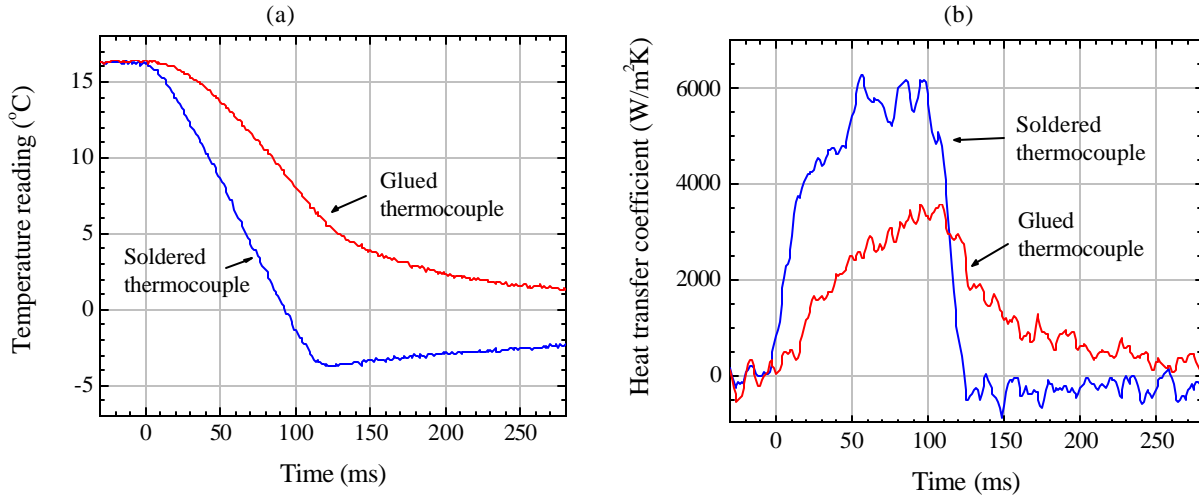
Figure 6: (a) Temperature scans during a continuous 100-ms CSC spurt acquired simultaneously with two thermocouples, one soldered and the other one glued to the back side of the metallic disk (see text for details). (b) Heat transfer coefficient, h, as calculated from the temperature scans in Fig. 6a using Eq. (4).

The results of this study demonstrate that sequential CSC with appropriate duty cycle (r) can increase cooling rate and efficiency as compared to continuous spraying of same duration. Under conditions of this study, such a trend holds systematically from $r = 1.0$ to r ? 0.7, but is reversed at lower duty cycles (see Fig. 3). This is in perfect agreement with spray cooling theory in general,[5] and our hypothesis of "isolating" liquid cryogen layer on the cooled surface, in particular.[6]

Heat flux across the cooled surface (j_q) varies substantially during both continuous and sequential CSC (Fig. 4). The curves obtained with various duty cycles start to differ approximately 20 ms into the cryogen spurt – most likely indicating the buildup of liquid cryogen layer. Regardless of the duty cycle, heat flux starts decreasing at time t ? 80 ms – more than 20 ms before the end of the cryogen spurt! Since this time corresponds to the time when the disk temperature crosses 0 ?C (see Fig. 3a), we can attribute this effect to deposition of frost from ambient water vapor, which is associated with substantial deposition of latent heat to the detector disk.[17]

The presented formal analysis of heat transfer coefficient dynamics - using Eq. (4) and the assumption of constant cryogen temperature T_c - shows that h varies markedly during CSC in both continuous and sequential mode (Fig. 5). Further, it confirms that the h values reached with sequential sprays can be significantly higher than with the continuous 100-ms spurt. This result is even more interesting if we consider that the mass of sprayed cryogen is decreasing (roughly proportionally) with the duty cycle (r). By using appropriate sequential CSC, the cooling efficiency can be thus improved even more than the cooling rate itself.

We are not aware of any plausible physical explanation for the relatively slow increase of $h(t)$ during first 70–80 ms of CSC, as evidenced by Fig. 5. Therefore, we believe that this is an artefact of the assumption of constant cryogen temperature, T_c. We hypothesize that the similarly slow increase in $j_q(t)$ during first 40 ms (Fig. 4) in fact results from gradually decreasing spray temperature, rather than slowly increasing $h(t)$. This would correspond well to our measurements of spray development time on the order of 30 ms.[7,8] We have recently undertaken a more rigorous analysis of heat transfer coefficient dynamics, using Eq. (4) in combination with dynamic measurements of spray temperature, $T_c(t)$. Preliminary results indicate that heat transfer coefficient values exceed 20,000 W/m^{2}K during first 10–20 ms of the spurt, but are quickly brought down to the 8,000–12,000 W/m^2 K range, presumably due to buildup of the liquid layer and deposition of latent heat due to water condensation and freezing on the metallic disk.[17]

Finally, maximizing the heat transfer rate may not be the ultimate goal in CSC used with laser tratment of deeper subsurface targets (e.g., hair removal). For such targets, it may be beneficial to use a prolonged, but less aggressive heat extraction,

which would provide sufficient epidermal protection while minimizing the risk of epidermal cryo-injury.[3,17] Sequential spraying with suitably low duty cycles may offer an attractive way to adapting CSC for such appications.

5. CONCLUSIONS

With some CSC devices, sequential spraying can be used to increase the cooling rate, as compared to continuous spraying of the same duration. Under our experimental conditions, duty cycles around $r = 0.7$ yielded a >10% increase in heat flux across the cooled surface – while presumably utilizing ?30% less cryogen mass. All observations support the hypothesis of "isolating" liquid cryogen layer when using a 0.7-mm straight nozzle at a 60-mm working distance. In addition, the results demonstrate a paramount influence of ambient water condensation on heat flux balance at the sprayed surface, even during 100-ms cryogen spurts. In summary, sequential CSC offers a novel and practical approach to optimization of cryogen spray devices for individual laser dermatological applications.

ACKNOWLEDGEMENTS

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