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Journal
Physics in Medicine and Biology, 48(1)

ISSN
0031-9155

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Publication Date
2003-01-07

DOI
10.1088/0031-9155/48/1/401

INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **48** (2003) N1–N6 PII: S0031-9155(03)53461-3

NOTE

Effects of mass flow rate and droplet velocity on surface heat flux during cryogen spray cooling

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Received 13 September 2002
Published 16 December 2002
Online at stacks.iop.org/PMB/48/N1

Abstract
Cryogen spray cooling (CSC) is used to protect the epidermis during dermatologic laser surgery. To date, the relative influence of the fundamental spray parameters on surface cooling remains incompletely understood. This study explores the effects of mass flow rate and average droplet velocity on the surface heat flux during CSC. It is shown that the effect of mass flow rate on the surface heat flux is much more important compared to that of droplet velocity. However, for fully atomized sprays with small flow rates, droplet velocity can make a substantial difference in the surface heat flux.

1. Introduction

Unintended light absorption by epidermal melanin poses two obstacles during laser dermatologic surgery. First, a significant portion of the incident light being absorbed by epidermal melanin potentially causes thermal damage therein and, second, less energy reaches the target chromophores (Nelson *et al* 1995). As currently practised, CSC prevents epidermal damage in skin types I–IV. However, for patients with darker skin types (V and VI), CSC does not provide sufficient protection (Chang and Nelson 1999, Anvari *et al* 1995). Therefore, to extend the benefits of CSC to patients with darker skin types, cooling efficiency must be improved.

Understanding the fundamental spray parameters that influence heat extraction from the surface of human skin is a requisite to improving cooling efficiency. Recent studies have shown that CSC efficiency can be increased by optimizing the nozzle-to-skin distance

(Aguilar *et al* 2001a), nozzle diameter (Anvari *et al* 1995, Verkruysse 2000, Aguilar *et al* 2000) and by spraying cryogen in a sequence of short spurts (Majaron 2002). However, such changes influence mass flow rate ($\dot{m}$), average cryogen droplet diameter (d), velocity (v), temperature (T) and number of droplets per unit volume (C), which can affect surface heat flux (q).

In previous studies (Verkruysse 2000, Aguilar *et al* 2001b), we have conducted systematic experiments to investigate the influence of each of the above parameters on q. It has been shown that higher q (or heat transfer coefficient, h) is achieved with sprays produced by nozzles with an inner diameter (D_N) of 1.4 mm as compared to those produced by nozzles with $D_N =$ 0.5–0.8 mm. It may be hypothesized that the difference is due to the larger and faster droplets produced by nozzles with $D_N = 1.4$ mm, which penetrate deeper into the liquid cryogen layer formed on the skin surface during CSC. In a subsequent study (Karapetian *et al* 2002) using various nozzle geometries, no perceptible correlations of d and T to the total heat removed (Q) and maximum heat flux ($q_{\max}$) were noted. Furthermore, contrary to results reported by Pikkula *et al* (2001), who suggested that a variation in $\dot{m}$ has only a modest impact on q, our studies showed that $\dot{m}$ strongly correlates with Q and $q_{\max}$ (Karapetian *et al* 2002), where a three-fold increase in $\dot{m}$ led to an identical increase in Q and an 11-fold increase in $q_{\max}$. Similar trends in the effect of $\dot{m}$ on steady state q have been observed in studies of water sprays cooling a hot plate (Ciofalo *et al* 1999, Schmidt and Boye 2001).

All of the aforementioned studies helped elucidate the most important parameters affecting q, although several questions remain unanswered. For instance: (1) can faster (higher v) droplets penetrate deeper into the liquid cryogen layer and considerably increase q? or (2) is a larger q simply a consequence of a larger $\dot{m}$? or (3) if both parameters are involved, what are their relative contributions? The present study addresses these questions.

Ideally, the most appropriate way to determine the influence of selected spray parameters on $q_{\max}$ is to vary only one parameter in each study. This is a challenging task because CSC spray parameters are correlated to a certain extent. However, we have determined that their interdependency can be minimized through changes in nozzle geometry. By varying nozzle length (L_N) while keeping D_N constant, we have shown (Aguilar *et al* 2000) that v may be affected significantly with almost no effect on d and T. Since any variation in L_N may slightly alter $\dot{m}$, we have used a metering valve to adjust $\dot{m}$. Therefore, using nozzles of different L_N and D_N and adjusting $\dot{m}$, we could examine the relative influence of v and $\dot{m}$ on $q_{\max}$, while maintaining other spray parameters constant.

2. Materials and methods

A total of eight nozzles in combination with a solenoid valve (Series 99 by Parker Hannifin Corp., General Valve Division, Fairfield, NJ) were used to produce 100 ms cryogen spurts. The eight nozzles consisted of two sets of straight stainless steel tubing with L_N of 8 and 65 mm with four different D_N (0.57, 0.83, 1.08 and 1.33 mm). Cryogen (tetrafluoroethane, boiling temperature $T_b = -26.2\ ^\circ$C at atmospheric pressure) was delivered through a standard high-pressure hose. A metering valve (SS-SS2-VH by Swagelok, Solon, OH) was inserted between the cryogen container and solenoid valve to adjust $\dot{m}$. The cryogen in the container was maintained at saturation pressure (670 kPa at 25 °C). For each pair of nozzles with the same D_N, the metering valve was used to control flow so that two nozzles of different L_N provide the same $\dot{m}$.

An experimental temperature sensor similar to those reported previously Aguilar *et al* 2000, Majaron *et al* 2002, Svaasand *et al* 2002) was used to measure $q_{\max}$ for all nozzle geometries. The temperature sensor consisted of a silver disc (10.48 mm diameter, 0.4 mm

thickness) thermally insulated by epoxy resin ($k_T = 0.218$ W m^{-1} K^{-1}). The top surface of the disc was exposed to a 100 ms cryogen spurt and the disc temperature was measured by a 300 μm bead diameter, type-K thermocouple soldered to the bottom side. This temperature sensor operates under the assumption of lumped capacitance, which means the disc temperature is assumed to vary uniformly during the cryogen spurt. Therefore, q is proportional to the time variation in temperature $\left(\frac{\mathrm{d}T_{\mathrm{disc}}}{\mathrm{d}t}\right)$ and, similarly, $q_{\max}$ is proportional to $\left|\left(\frac{\mathrm{d}T_{\mathrm{disc}}}{\mathrm{d}t}\right)\right|_{\max}$. The latter represents the maximum rate of change in the disc temperature during the spurt. Before measuring q, a digital camera (Elicar, Japan) was used to visualize the spray cone and then position the nozzles at a distance where the sprayed area closely matched the temperature sensor's surface area (A).

To compute $\dot{m}$, a 12 oz cryogen container was connected to each of the eight nozzles with L_N/D_N geometries and 100 ms spurts were repeated 30 to 50 times. The container weight before and after each series of spurts was recorded.

A Phase Doppler Particle Analyzer (PDPA by TSI Inc, St. Paul, MN) was used to obtain local v and d, at a distance of 25 mm from the nozzle tip. Further details concerning PDPA operation can be found elsewhere (Bachalo 1980).

3. Results and discussion

Images of spray cones showed little variation in the sprayed area (A) among the eight different L_N/D_N configurations. At an axial distance of 25 mm, all the spray cone diameters were approximately 11 mm. This confirmed that most of the cryogen droplets that reached the surface contributed to cooling the sensor.

For each nozzle, i.e. a specific L_N/D_N configuration, mass flow rate ($\dot{m}$) measurements were carried out five times, showing good reproducibility. Considering all sources of error, a 5% uncertainty was estimated for all values of $\dot{m}$.

Figure 1 shows the dependence of $q_{\max}$ on $\dot{m}$. Squares and circles correspond to measurements taken with L_N of 8 and 65 mm, respectively. Data points represent the average

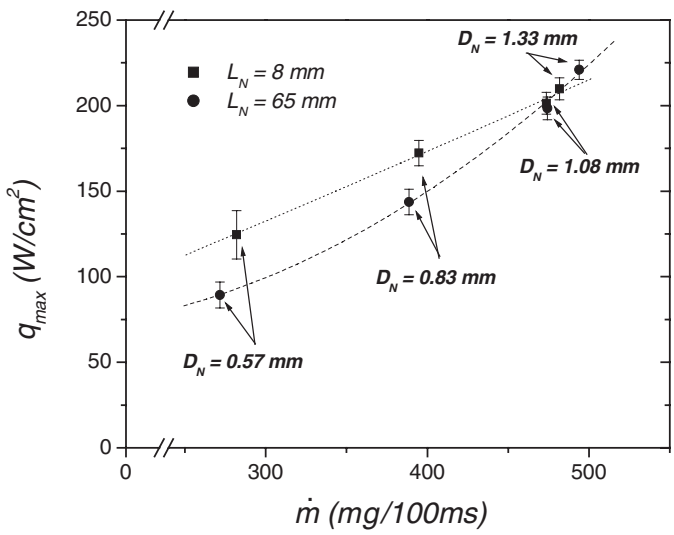

Figure 1. $q_{\max}$ as a function of $\dot{m}$ during a 100 ms spurt. Squares and circles correspond to measurements taken with L_N of 8 and 65 mm, respectively.

Table 1. Variation of d, v, and $q_{\max}$ with nozzle parameters L_N and D_N.

	D (μm)		v (m s^{-1})			$q_{\max}$ (W cm^{-2})		
D_N (mm)	$L_N = 8$ mm	$L_N = 65$ mm	$L_N = 8$ mm	$L_N = 65$ mm	$\frac{v_{8\ \mathrm{mm}}}{v_{65\ \mathrm{mm}}}$	$L_N = 8$ mm	$L_N = 65$ mm	$\frac{q_{\max\,(8\ \mathrm{mm})}}{q_{\max\,(65\ \mathrm{mm})}}$
0.57	12.59	13.26	57.6	39.7	1.45	124.5	89.3	1.39
0.83	13.65	13.15	70.9	41.7	1.70	172.3	143.7	1.20
1.08	15.26	14.27	72.6	53.4	1.36	201.4	198.4	1.02
1.33	18.29	17.16	55.3	28.2	1.96	209.9	221.0	0.95

of five measurements taken with each nozzle. Note that for each group of nozzles of the same L_N, $\dot{m}$ increases proportionally with D_N, and, in turn, $q_{\max}$ increases with $\dot{m}$, illustrating the effect that $\dot{m}$ has on $q_{\max}$.

We now focus on the dependence of $q_{\max}$ on v, as $\dot{m}$ was held constant (<5% variation) for each pair of nozzles with identical D_N but different L_N (8 and 65 mm). Table 1 shows that for each D_N the variation in d is minimal (<6%) as L_N was changed from 8 to 65 mm. With minimal variations observed in A, d and $\dot{m}$, it was expected that C also varied minimally. In contrast, for each D_N there was a large variation in v between nozzles with L_N of 8 and 65 mm, with the ratio $\frac{v_{8\ \mathrm{mm}}}{v_{65\ \mathrm{mm}}}$ ranging from 1.36–1.96 (table 1, column 6). At 25 mm from the nozzle tip, we observed that nozzles with $D_N = 1.33$ mm produce 'jet-like' sprays that are not fully atomized. This may explain the decrease in the values of v for nozzles with $D_N = 1.08$ and 1.33 mm (table 1, columns 4 and 5) because the PDPA acquires data only for atomized portions of sprays.

The influence of v on $q_{\max}$ can be inferred by comparing $\frac{v_{8\ \mathrm{mm}}}{v_{65\ \mathrm{mm}}}$ to the corresponding ratio $\frac{q_{\max\,(8\ \mathrm{mm})}}{q_{\max\,(65\ \mathrm{mm})}}$ (table 1, columns 6 and 9, and also from figure 2, which shows these ratios as a function of D_N). Figure 2 illustrates the ratios of v and $q_{\max}$. For the nozzles with $D_N = 0.57$

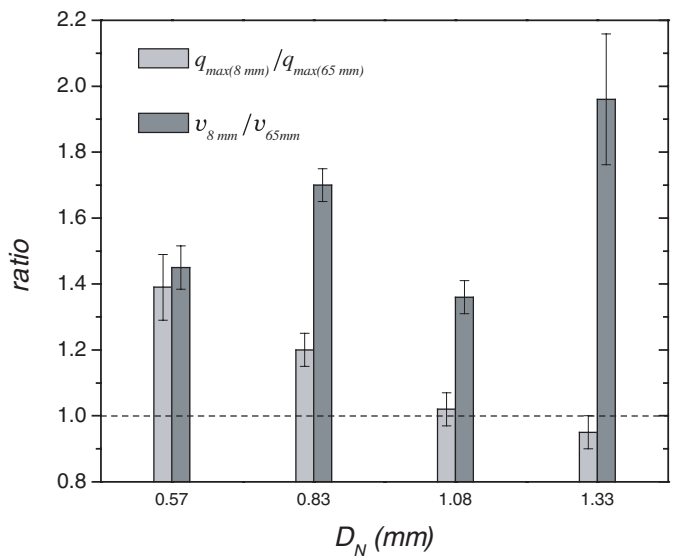

Figure 2. Ratios of the indicated parameters ($q_{\max}$ and v) between two nozzles of identical D_N when L_N is changed from 8 mm to 65 mm.

and 0.83 mm, increases in v result in substantial increases in $q_{\max}$. For the nozzles with $D_N =$ 1.08 and 1.33 mm, however, the large increases in v result in minimal differences in $q_{\max}$.

Using fast flash lamp photography, Aguilar *et al* (2000) showed that nozzles with $D_N =$ 1.4 mm produced 'jet-like' (not atomized) sprays, while nozzles with $D_N = 0.5$–0.8 mm produced 'cone-like' (fully atomized) sprays. It is interesting to contrast these results with our previous work (Verkruysse *et al* 2000, Aguilar *et al* 2001b), where the higher q measured for nozzles of larger D_N was attributed to larger as well as faster droplets, which presumably could penetrate better through a residual liquid cryogen layer formed on the surface during CSC. This layer may suppress a more dynamic convective and evaporative cooling by isolating the surface from colder incoming droplets. This is supported in this study by the 'cone-like', fully atomized sprays produced by nozzles with $D_N = 0.57$ and 0.83 mm, which are more likely to form a layer of liquid cryogen. For these sprays, droplets with higher v disrupt this layer and enhance $q_{\max}$. In contrast, for 'jet-like' (not atomized) sprays produced by nozzles with $D_N =$ 1.08 mm and 1.33 mm, the impinging jet prevents the liquid cryogen layer from forming in the first place, and the influence of v on $q_{\max}$ diminishes.

Our results complement our previous hypothesis (Karapetian 2002) that larger $\dot{m}$ also results in more liquid cryogen deposition on the surface, which indirectly produces higher lateral fluid velocity in the liquid cryogen layer and thus increased $q_{\max}$. Higher $\dot{m}$ also lowers the cryogen liquid layer temperature by quickly replenishing it with incoming droplets that are colder than the cryogen boiling temperature due to evaporative cooling during flight (Aguilar *et al* 2001a). For optimized CSC, it appears that it is more important to focus on depositing a larger mass of cryogen in the shortest possible time, than on designing nozzles that produce larger and faster droplets.

4. Conclusion

It is shown that the effect of cryogen mass flow rate ($\dot{m}$) is dominant on the maximum surface heat flux ($q_{\max}$) within the range of mass flow rates studied ($\sim$2.7–5.0 mg ms^{-1}), as evidenced by the 1.7 and 2.5 increase in $q_{\max}$ measured for the 8 and 65 mm long nozzles, respectively. Increasing the average droplet velocity (v) of fully atomized sprays between 45% and 70% enhances $q_{\max}$ by 20–40%. In contrast, a 36–96% increase in v of jet-like sprays has a negligible effect on $q_{\max}$. Therefore, for dermatologic laser therapies that require optimal CSC, nozzles should be designed to produce higher $\dot{m}$ rather than larger and faster droplets. The end result will be an improvement in CSC efficiency that may extend the benefit to all patients, particularly those with darker skin types.

Acknowledgments

This work was supported by the National Institutes of Health (GM62177 to JSN and HD42057 to GA). Institutional support from the Office of Naval Research, National Institutes of Health and the Beckman Laser Institute Endowment is acknowledged. We also acknowledge a grant from the National Science Foundation for the purchase of the PDPA system (CTS-9901375 to EJL). Helpful discussions with Drs Bernard Choi and John Viator are greatly appreciated.

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