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Authors
Aguilar, Guillermo
Vu, Henry
Nelson, J Stuart

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NOTE

Influence of angle between the nozzle and skin surface on the heat flux and overall heat extraction during cryogen spray cooling

Guillermo Aguilar[1,2], Henry Vu[2] and J Stuart Nelson[2]

[1] Department of Mechanical Engineering, University of California, Riverside, CA 92521, USA
[2] Beckman Laser Institute, University of California, Irvine, CA 92612, USA

E-mail: gaguilar@engr.ucr.edu

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Abstract

High speed video imaging and an inverse heat conduction problem algorithm were used to observe and measure the effect of the angle between the nozzle and surface of a skin phantom on: (a) surface temperature; (b) heat flux q; and (c) overall heat extraction Q during cryogen spray cooling (CSC). A skin phantom containing a fast-response temperature sensor was sprayed with 50 ms cryogen spurts from a commercial nozzle placed 30 mm from the surface. The nozzle was systematically positioned at angles ranging from 5° to 90° (perpendicular) with respect to the phantom surface. It is shown that angles as low as 15° have an insignificant impact on the surface temperature, q and Q. Only exaggerated angles of 5° show up to 10% lower q and 30% lower Q with respect to the maximal values measured when nozzles are aimed perpendicularly. This study proves that the slight angle that many commercial nozzles have does not affect significantly the CSC efficiency.

1. Introduction

Light absorption by epidermal melanin during vascular lesion dermatologic procedures, such as the laser therapy of port-wine stain (PWS) birthmarks, causes two problems affecting the therapeutic outcome: unintended thermal injury and reduction in energy reaching the targeted blood vessels (Nelson *et al* 1995). As currently practiced, cryogen spray cooling (CSC) prevents epidermal damage in skin types I–IV. However, CSC does not sufficiently protect patients with darker skin types (V and VI) (Chang and Nelson 1999). For this reason, we and other groups have pursued the search for new nozzle designs and methods in an attempt to improve CSC cooling efficiency (Verkruysse *et al* 2000a, Torres *et al* 2001, Aguilar *et al* 2002, 2003a, Dai *et al* 2003, Vu *et al* 2004).

To facilitate comparison and interpretation of CSC experiments with clinical results, most spray nozzles used in the laboratory are chosen with a geometry similar or identical to those used by commercial devices. However, these nozzles are not always aimed at the sprayed surface at the same off-perpendicular angle with respect to the skin surface (∼60°–80°) as with most commercial laser devices (e.g., Candela, Cooltouch™, Fotona). For instance, some studies (Anvari *et al* 1996, 1997, Hoffman *et al* 1997, Verkruysse *et al* 2000b, Edris *et al* 2003) have used nozzles at a slight off-perpendicular angle with respect to the skin surface (∼60°), while others have aimed the nozzles perpendicularly (90°) at the sprayed surface (Torres *et al* 1999, 2001, Aguilar *et al* 2001a, 2001b, Pikkula *et al* 2001, Tunnell *et al* 2002).

The reason for the angled nozzle design used by commercial devices is to allow the laser beam to be aimed perpendicularly at the skin to ensure a spot size of uniform light intensity. However, this is inevitably achieved at the expense of asymmetric cryogen spray deposition. While off-perpendicular impingement of spray droplets may have certain advantages, such as enhanced 'flushing' (convection) of pre-deposited cryogen (Verkruysse *et al* 2000a, Aguilar *et al* 2001b) and, therefore, increase the overall cooling efficiency, such a geometry may produce uneven heat extraction across the sprayed surface, diminished droplet penetration through the pre-deposited cryogen layer and shallower skin indentations due to lower spray momentum (Basinger *et al* 2004), all of which have been shown to result in lower cooling efficiency.

Although prior studies have shown that perpendicular jet impingement leads to larger heat extraction compared to off-perpendicular impingement (Ortiz and Gonzalez 1999, Karl and Frohn 2000), they have involved purely convective heat extraction and, occasionally, evaporation driven by surface heating as opposed to the simultaneous convective and surface-and-self-driven evaporative process resulting from CSC of human skin. Inasmuch as the issue of nozzle angle has been a subject of speculation in the literature and at academic medical symposia for quite some time since the introduction of CSC, the purpose of this study is to show, definitively, whether or not the angle of commercial nozzles with respect to the skin surface has a significant influence on the heat flux and overall heat extraction.

2. Materials and methods

2.1. Cryogen delivery

A commercial nozzle identical to that incorporated into various Candela laser devices (GentleLASE®, Smoothbeam™, Vbeam® and C-beam™) was used in this study. The nozzle consisted of a stainless steel tubing with an approximate inner diameter of 0.5 mm. The nozzle was aimed at the surface of a skin phantom containing a fast-response temperature sensor (described below) at seven different angles, ranging from 90° (perpendicular) to 15° in decrements of 15° (i.e., 90°, 75°, 60°, 45°, 30°, 15°) plus one exaggerated nozzle angle of 5° (figure 1).

The nozzle-to-surface distance was kept constant at 30 mm (analogous to the Candela devices) for all experiments. Three 50 ms spurts of tetrafluoroethane (R-134a, boiling temperature $T_b = -26$ °C at atmospheric pressure) were delivered for each of the seven angles tested permitting the averaging of surface temperature variations for identical experiments as well as to check for consistency.

2.2. Imaging

A high speed camera (Photron Fastcam PCI 10K, Itronics, Westlake Village, CA) with a 90 mm zoom lens (V-HQ Macro MC 90 mm f/2.5, Elicar, Japan) was used to acquire digital images of

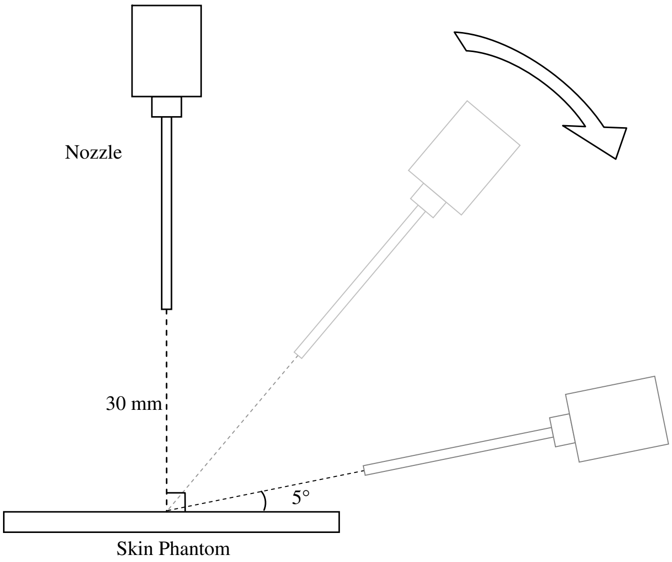

Figure 1. Schematic diagram of the experimental setup. Spray angles were varied from 90° (perpendicular) to 5°.

spray impingement on *in vivo* human skin at two angles: 90° (perpendicular) and 65°. Image sequences were captured at a rate of 500 frames per second and pixel resolution of 512 × 240. The target was the dorsal hand coloured with a black marker to improve the image contrast.

2.3. Surface temperature measurements

The surface temperature sensor consisted of a miniature type-K thermocouple (∼50 μm bead diameter) placed underneath a thin (20 μm) layer of aluminium foil (48 mm × 41 mm), which was positioned on top of a 5.7 mm thick bar of polymethylmethacrylate resin (Plexiglas®). The sensor was sized to encompass the entire sprayed area so temperature measurements represent average values. Small strips of 50 μm thick cellulose tape (Scotch tape®) were placed between the aluminium foil and Plexiglas®, forming a square box around the thermocouple bead to provide electrical insulation and mechanical support. Thermal paste was applied around the bead to ensure good thermal contact. The purpose of this sensor was to provide a skin-like thermal substrate, so that surface heat flux (q) and overall heat extraction (Q) were on the same order of magnitude as those expected for human skin. The thin aluminium foil coupled with the miniature sensor provided 'real-time' surface temperature measurements. Published thermal properties (provided by RBC Industries Inc, Warwick, RI and www.matweb.com) of materials used to build the sensor are shown in table 1. The thermal properties of dermal human skin (Duck 1990) are also given for reference.

The thermocouple signal was conveyed via an analog channel of an SCXI-1000 chassis to a PCI-6024E data acquisition card (National Instruments, Austin, TX) and temperature data were ultimately displayed to the user and recorded at a sampling rate of 4 kHz through a custom-made Labview program. This acquisition rate is more than appropriate because the response time of the aluminium foil attached to the thermocouple sensor was estimated to be on the order of 5–8 ms. The sensor was allowed to return to ambient temperature between each experiment.

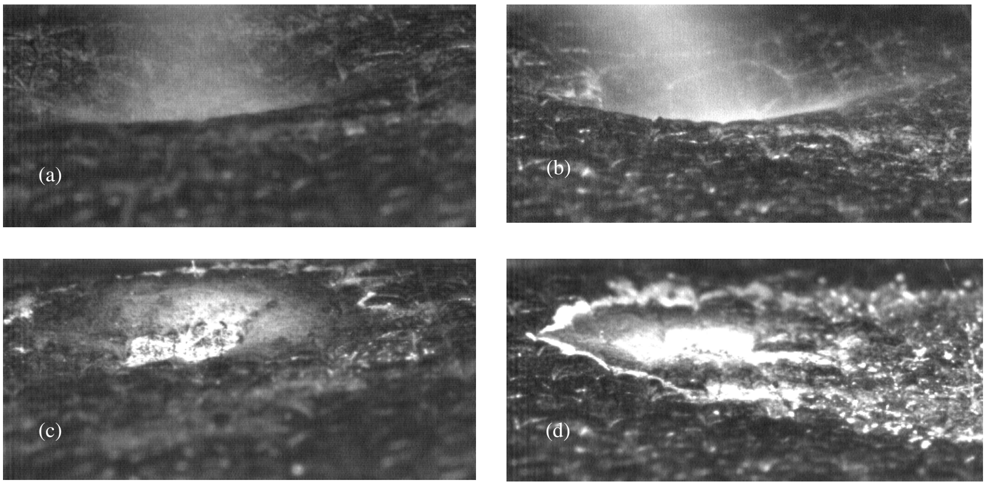

Figure 2. Images of a cryogen spurt impinging at 40 ms into a 100 ms spurt on the dorsal side of a hand blackened (for contrast). The spray nozzle was aimed at (a) 90° (perpendicularly) and (b) 65°. Frost formation resulting 90 ms after the end of the spurt for the nozzle impinging at (c) 90° (perpendicularly) and (d) 65°.

Table 1. Thermal properties and thicknesses of layers used in the temperature measurement sensor. Human dermal skin properties (Duck 1990) are provided for reference.

Properties	Al foil	Scotch tape®	Plexiglas®	Dermis
Thickness (mm)	0.020	0.050	5.7	–
k (W (m K)$^{-1}$)	205	0.19–0.25	0.19–0.24	0.54
ρ (kg m^{-3})	2710	1160–1400	1150–1190	1150
c (J (kg K)$^{-1}$)	896	1400	1300–1500	3700
α_{avg} (m^2 s^{-1})	844×10^{-7}	1.22×10^{-7}	1.31×10^{-7}	1.26×10^{-7}

2.4. Inverse heat conduction problem algorithm

The CSC dynamics can be simplified to a one-dimensional heat conduction problem if uniform heat transfer over the sprayed surface is assumed, in which case an inverse heat conduction problem (IHCP) algorithm can be employed. We used the sequential function specification method (SFSM) of (Beck *et al* 1985) which estimates q as a piecewise constant function of time at each time step. This method has been previously employed in similar studies (Aguilar *et al* 2003b, 2003c) and a more detailed discussion of its application to CSC can be found elsewhere (Tunnell *et al* 2002). Q was simply computed by integrating q over time.

3. Results and discussion

An example of the asymmetry of spray deposition is seen in figures 2(a)–(d). Figures 2(a) and (b) show images of impinging spurts on the dorsal side of the hand as the nozzle was aimed at 90° and 65°, respectively. It is apparent from these images that off-perpendicular spray impingement causes some droplets to bounce off the skin indentation away from the nozzle. As mentioned above, this is likely to produce an uneven heat extraction during cryogen deposition, also suggested by the images shown in figures 2(c) and (d), which show the frost that forms 90 ms after spurt termination for the 90° and 65° cases, respectively. As discussed

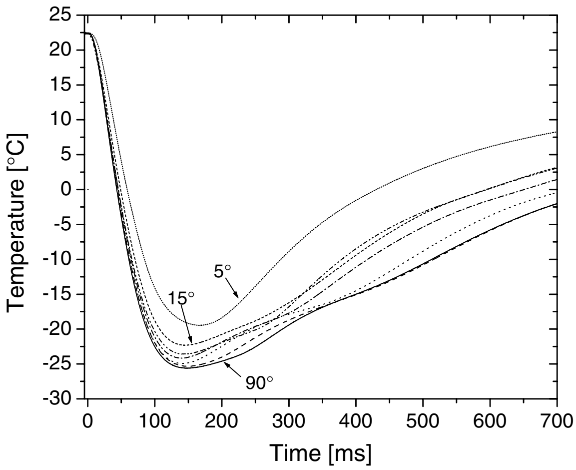

Figure 3. Surface temperatures as a function of time for 50 ms cryogen spurts aimed at the surface at seven different angles (5°, 15°, 30°, 45°, 60°, 75° and 90°), and 30 mm away from the surface.

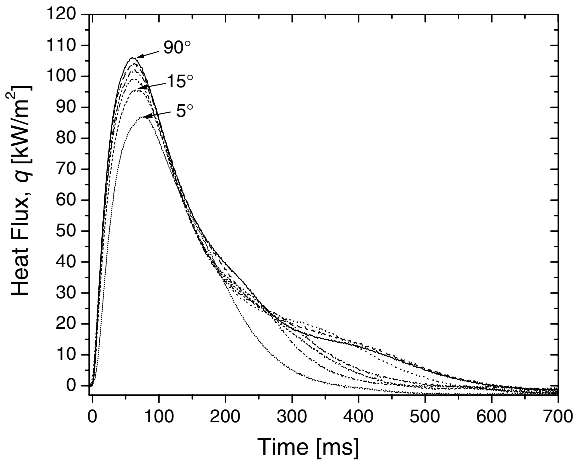

Figure 4. Heat fluxes (q) as a function of time computed through the IHCP algorithm, corresponding to all temperature curves shown in figure 3.

in detail by Majaron *et al* (2001), the frost shown herein is not formed until most of the cryogen has evaporated, but since it appears precisely on the area that was previously occupied by the cryogen and remains on the surface for a relatively long time, it serves as a good indication of the symmetric and asymmetric sprayed areas for the angles of 90° and 65°, respectively.

Figure 3 shows the average of three surface temperature measurements as a function of time for each of the seven angles. Note that both the rate at which temperature drops and the minimum temperature reached for the 90° angle are, respectively, the fastest and lowest with respect to all other angles studied. However, the differences between all curves are small, except for the 5° angle which shows the slowest rate of decrease and the highest minimum temperature reached which is about 7 °C above the 90° angle.

Figure 4 shows the heat flux (q) calculations for each of the temperature curves shown in figure 3, using the IHCP algorithm described above. As can be seen, the maximum heat flux difference corresponding to angles varying between 15° and 90° is almost insignificant (<5%)

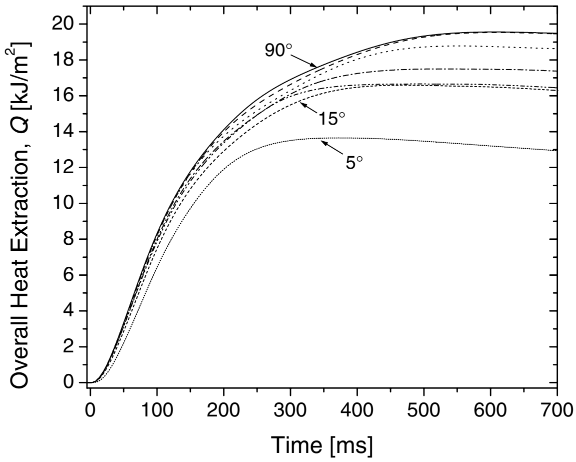

Figure 5. Overall heat extractions (Q) as a function of time computed by integrating q for all curves shown in figure 4.

for times up to 200 ms. Admittedly, larger differences exist for later times (>200 ms), but this may be attributed to the post-cooling period, in which frost formation and subsequent melting occur. Only the 5° angle shows a 10% difference in the maximum q from the perpendicular.

Finally, figure 5 depicts the overall heat extraction (Q). As for q, insignificant differences are observed for all angles between 15° and 90° although a clearer distinction between all curves is appreciable for times >200 ms, due to the integral nature of Q. Only the 5° angle shows a 30% lower Q with respect to the maximal values measured when the nozzle is aimed perpendicularly.

4. Conclusion

The surface temperature, heat flux q and overall heat extraction Q produced by commercial cryogen nozzle devices positioned at angles ranging from 5° to 90° were measured. It was shown that angles as low as 15° relative to the skin surface do not have any major impact on the average surface temperature, q and Q. Only exaggerated inclinations of 5° show up to 10% lower maximal q and 30% lower maximal Q. The homogeneity of the heat flux across the sprayed surface is still an issue not yet resolved. However, this problem still exists for the case of perpendicular as well as non-perpendicular nozzle angles and we are presently working on this issue.

All these results indicate that the potential CSC efficiency enhancement due to the conceived 'flushing' induced by angled nozzles is small, suggesting that perpendicular spray impingement effectively deposits the smallest amount of cryogen on the targeted surface as a result of higher droplet momentum and penetration through the pre-deposited cryogen layer—effects which have proven to enhance CSC efficiency.

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