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Cryogen spray cooling of human skin: effects of ambient humidity level, spraying distance, and cryogen boiling point

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ABSTRACT

Recent studies have shown spray cooling of the skin surface with millisecond cryogen spurts to be an effective method for protecting the epidermis from non-specific thermal injury during various laser mediated dermatological procedures. We have investigated the effects of ambient humidity level, spraying distance, and cryogen boiling point on the resulting radiometric surface temperature. Our findings indicate that: 1) decreasing the ambient humidity level results in less ice formation on the skin surface without altering the radiometric surface temperature during a cryogen spurt; 2) increasing the spraying distance to 85 mm lowers the radiometric surface temperature; and 3) boiling point of the cryogen does not directly affect the surface temperature in the geometries studied.

Keywords: alternative refrigerants, cutaneous hypervascular lesions, dermatology, lasers, port wine stains, rhytides, selective thermal injury

1. INTRODUCTION

Successful laser treatment of hypervascular cutaneous lesions such as port wine stains, hemangiomas, and telangiectasias is based on selective photocoagulation of blood vessels without inducing thermal injury to the epidermis. Protecting the epidermis from laser induced thermal injury may also be beneficial in treatment of facial rhytides. A method to overcome non-specific thermal injury is to spray a short (on the order of milliseconds) cryogen spurt directly onto the skin surface immediately prior to laser irradiation.[1-5]

In contrast to other procedures (e.g., placing ice or a cold substrate such as a sapphire window in contact with skin), cryogen evaporation on the skin surface allows localized cooling of the epidermis without lowering the temperature of targeted blood vessels.[6] Although preliminary studies indicate that thermal injury to the epidermis can be reduced or eliminated by cryogen spray cooling (CSC) while still achieving the therapeutic effect[1,2,4], an understanding of the cryogen evaporation process (both in transit and at skin surface), is essential for optimization of parameters (e.g., cryogen physical properties and spurt duration), and design of the delivery system. To address these issues, we have investigated the dependence of radiometric surface temperature of human skin on: 1) ambient humidity level; 2) spraying distance between the delivery nozzle and surface; and 3) cryogen boiling point.

2. METHODS AND MATERIALS

The experimental setup for CSC and measurements of human skin radiometric surface temperature is shown in Figure 1. Cryogens were contained in pressurized steel reservoirs, and delivered through a 4 cm long tube (diameter ≈ 1 mm) threaded onto the end of an automobile fuel injector. The opening and closing of the injector were controlled by a relay circuit, and a programmable digital delay generator (DG353, Stanford Research Systems, Sunnyvale, CA) was used to set the cryogen spurt duration (5-100 ms).

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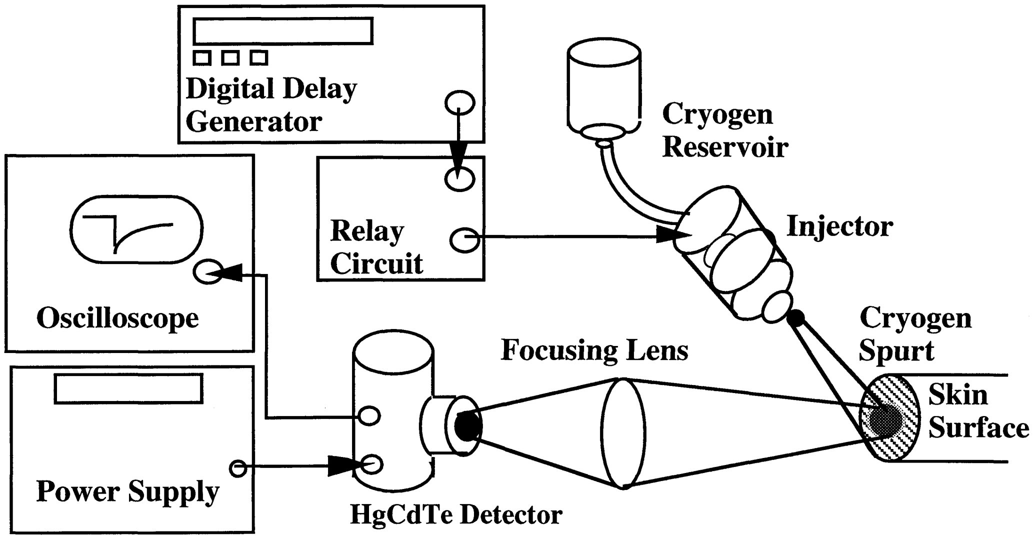

Figure 1. Experimental setup for cryogen spray cooling of skin and measurements of radiometric surface temperature.

Experiments were performed inside a visibly transparent chamber (≈ 85×50×40 cm, respective length, height, and width) under controlled ambient humidity levels. Lowered ambient humidity levels were achieved by flushing the chamber with nitrogen gas. An electrical hygrometer (RH411, Omega Engineering, Stamford, CT) placed inside the chamber was used to measure the humidity level. A circular opening on a side wall, sealed with a neoprene gasket, allowed placement of volunteer's forearm inside the chamber for experimentation.

A single element liquid nitrogen cooled infrared HgCdTe detector (MDD-10E0-S1, Cincinnati Electronics, Mason, OH), optically filtered at the cold stop by a 10.6-14 μm bandpass filter, was mounted on a three axis micropositioner and positioned inside the chamber to measure the skin radiometric surface temperature. The infrared detection system was calibrated by measuring output voltage of the detector as a function of the surface temperature of a copper block coated with highly emissive black paint. The copper block was heated by resistive elements from 23 to 70 °C while measuring its surface temperature with a precision thermistor (8681, Keithley Instruments, Cleveland, OH). Detector was calibrated before each set of experiments.

Skin sites on fingers of volunteers were sprayed, and the radiometric surface temperature measured while varying the: 1) humidity level (60, 30, and 5% ± 5%); 2) spraying distance (≈ 8-100 mm); or 3) cryogen (Table 1). All cryogens are considered non-toxic and environmentally compatible replacements for chlorofluorocarbons.[7]

Table 1. Cryogens used in spray cooling of skin.

Cryogen	Composition (by weight)	Boiling Point (°C) at atmospheric pressure
R-134A	100% Tetrafluoroethane	-26
R-407C	52% Tetrafluoroethane 25% Pentafluoroethane 23% Difluoromethane	-43
R-404A	4% Tetrafluoroethane 44% Pentafluoroethane 52% Trifluoroethane	-48

3. RESULTS AND DISCUSSION

3.1. Effect of Ambient Humidity Level

Inasmuch as water vapor present in air undergoes condensation upon interaction with cryogen droplets to form ice, which is subsequently deposited on skin surface, we have investigated the effect of ambient humidity level during CSC. Radiometric surface temperature during a cryogen spurt was not affected when reducing the ambient humidity level to a minimum of 5% (Figure 2). Increasing the humidity level resulted in more ice formation on skin surface as evidenced by broadening of the quasi-equilibrium state corresponding to a phase transition. Distinct temperatures at which phase transition occurred were noted. For example in Figure 2, two phase transitions occur at 0 °C which corresponds to melting of ice, and at approximately -6 °C which may be due to a binary mixture of liquid cryogen and ice.

3.2. Effect of Spraying Distance

Increasing the spraying distance from 8 to 85 mm resulted in reduction of radiometric surface temperature by an additional 10 °C during a 50 ms R-134A spurt (Figure 3). Increased distance may allow sufficient time for the core of droplets to cool substantially before striking the skin surface as the outer layers evaporate in flight. Further reduction in the radiometric surface temperature was not achieved when increasing the spraying distance to 100 mm.

At short spraying distances (< 35 mm), no ice formation was observed as confirmed by: 1) visual inspection of the skin surface; and 2) absence of the quasi-equilibrium state in the recorded radiometric signal. A phase transition was observed at approximately -9 °C for spraying distances of 85 and 100 mm.

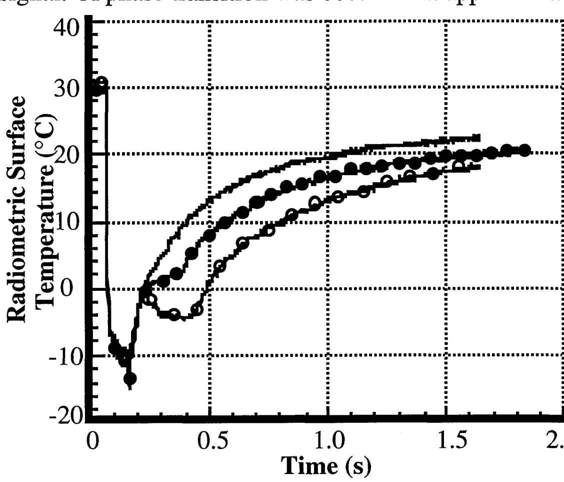

Figure 2. Effect of various humidity levels, 5 (—), 30 (—•—), and 60 (—o—) % on radiometric surface temperature.
Cryogen: R-134A; spraying distance: 50 mm; spurt duration: 80 ms.

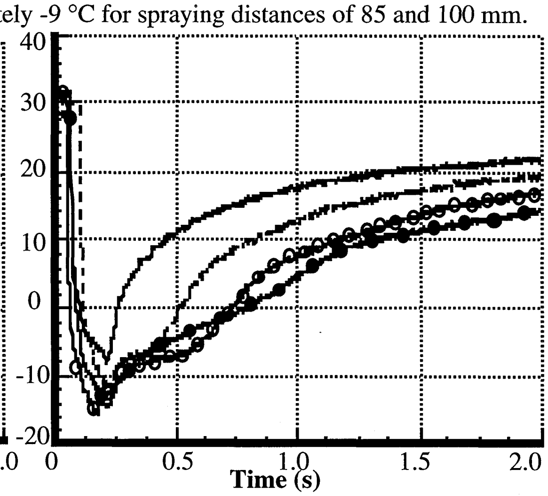

Figure 3. Effect of spraying distance, 8 (—), 50 (—•—), 85 (—o—), and 100 (- - -) mm on radiometric surface temperature.
Cryogen: R-134A; ambient humidity level: 60%; spurt duration: 50 ms.

3.3. Effect of Cryogen Boiling Point

In general, boiling point of the cryogen did not have a considerable effect on the radiometric surface temperature. For a relatively short spraying distance of 8 mm, only an additional 5 °C radiometric surface temperature reduction was obtained when spraying the skin with R-407C or R-404A instead of R-134A (Figure 4a). Almost identical surface temperature profiles were obtained after termination of R-134A and R-404A spurts.

For a relatively long spraying distance of 80 mm, lower radiometric surface temperature was obtained when spraying the skin with R-407C (Figure 4b). Regardless of the spraying distance, ice formation was minimal or absent with R-404A, and further reductions in surface temperature were not achieved.

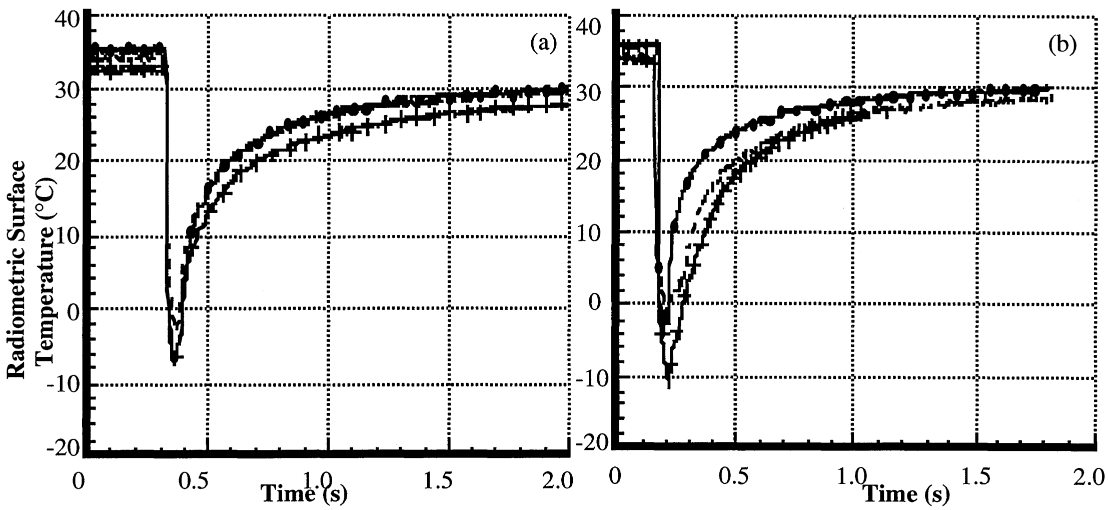

Figure 4. Effect of cryogen boiling point on radiometric surface temperature for spraying distances of: (a) 8, and (b) 80 mm. Cryogens: R-134A (- - -), R-407C (—+—), and R-404A (—•—); ambient humidity level: 60%; spurt duration: 80 ms.

4. CONCLUSIONS

Altering the ambient humidity level did not change the resulting radiometric surface temperature during a cryogen spurt; however, the amount of ice formation was affected. Whether ice formation is clinically desirable requires further investigation. Increasing the spraying distance resulted in lowered surface temperature, and more ice formation when using R-134A or R-407C. Additional radiometric surface temperature reductions were not achieved by changing the cryogens used in these experiments. Our findings underscore the importance of investigating the thermodynamics of cryogen evaporation process for successful design of delivery systems, and optimization of CSC parameters.

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