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Measurements of Laser Light Attenuation Following Cryogen Spray Cooling Spurt Termination

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Background and Objectives: Cryogen spray cooling (CSC) is used to minimize the risk of epidermal damage during laser dermatological surgery. However, while CSC can protect the epidermis from non-specific thermal damage, the cryogen film on the skin surface may pose a potential problem of laser light attenuation due to optical scattering.
Study Design/Materials and Methods: This study is focused on measuring the light transmittance changes that occur following cryogen spurt termination. The wavelengths studied were chosen for their clinical relevance to treatment of hypervascular skin lesions (594 nm) and laser-assisted hair removal (785 nm). Following delivery of cryogen spurts to the surface of an epoxy skin phantom, continuous records of light transmittance for 594 and 785 nm were obtained using an integrating sphere-based light collection apparatus.
Results: Shortly after spurt termination, there was negligible light attenuation by the cryogen film at the two wavelengths studied.
Conclusions: For the typical clinical use of a 30 milliseconds spurt duration and 30 milliseconds delay between spurt termination and delivery of the laser pulse, a minimum average transmittance value of ~97% was measured. Lasers Surg. Med. 32:143–147, 2003.
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Key words: cryogen spray cooling; transmittance; laser surgery; dermatology; skin

INTRODUCTION

The clinical objective of laser dermatologic surgery is to maximize thermal damage to target chromophores while minimizing injury to overlying skin. Unfortunately, for many skin types, the threshold light dosage for epidermal injury due to melanin absorption can be very close to the threshold for permanent removal of target chromophores, thus precluding the use of higher light dosages. A valuable method to overcome the aforementioned problem is to cool selectively the superficial layers of the skin. Although, melanin absorption will result in heat production during laser exposure, cooling the epidermis can prevent its temperature elevation from exceeding the threshold for thermal injury.

The novel method of achieving selective epidermal protection with “dynamic” or cryogen spray cooling (CSC) is well established and in current use for laser treatment of selected dermatoses [1–8]. However, while CSC can protect the epidermis from non-specific thermal damage, the cryogen film that forms on the skin surface may pose a potential problem of laser light attenuation due to optical scattering. Laser light passes through the cryogen film at a certain time after spurt termination, depending on the user-specified delay time before irradiation. Therefore, light attenuation by the liquid cryogen film depends on the interval between spurt termination and laser irradiation.

Previous studies [9–12] have investigated light transmittance in conjunction with CSC; reported values of light transmittance ranged from 80% [9] to >97% [11]. However, these studies provide limited information on possible transmittance changes following CSC spurt termination. Choi et al. [13] evaluated time-resolved transmittance changes and correlated them with the events of CSC. A limitation of the latter study was that only pseudo-collimated light was measured. In practice, light that is forward scattered by the cryogen film should also enter the skin and thus contribute to the overall therapeutic effect.

The purpose of this study was to evaluate laser light attenuation by the liquid cryogen film formed on the surface of model human skin following cryogen spurt termination. The wavelengths studied were chosen for their clinical relevance to treatment of hypervascular skin lesions (594 nm) and laser-assisted hair removal (785 nm). Following delivery of cryogen spurts to the surface of an epoxy skin phantom, continuous records of light transmit-

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tance for 594 and 785 nm were obtained. An integrating sphere-based light collection apparatus was used to detect the transmitted light.

MATERIALS AND METHODS

A solid block of epoxy resin (RBC#3100, RBC Industries, Inc., Warwick, RI) was constructed to serve as the skin phantom. The block had an estimated thermal diffusivity of ~0.07 mm^2/s, within 36% of the value for human skin (0.11 mm^2/s [14]). The block was mounted onto a copper plate ($100 \times 80 \times 0.5$ mm^3) with a 12.7-mm diameter hole in the center (Fig. 1). The plate temperature was controlled by a thermoelectric cooler (Model CP1.0-17-05L, Melcor Corporation, Trenton, NJ) and maintained at 32°C to approximate *in situ* conditions. To monitor the bulk epoxy block temperature, a type K surface mount thermocouple was fastened onto the block with thermally conductive silicon paste (Model OT201, Omega Engineering, Inc., Stamford, CT) and connected to a bench top temperature controller (Model CSC32, Omega Engineering, Inc., CT).

Light transmittance dynamics following CSC spurt termination were investigated at two wavelengths ($\lambda = 594$ and 785 nm). For $\lambda = 594$ nm, HeNe laser (Model 1677, Uniphase, Manteca, CA) was used. To avoid saturation of the light detector, a linear polarizer was used to attenuate incident power for the 594 nm wavelength. For $\lambda = 785$ nm, a diode laser (Model HL7851G, Thor Labs, Newton, NJ) was used.

Transmitted light was collected by an integrating sphere (Model IS-040, Labsphere, North Sutton, NH) equipped with a silicon photodiode that was calibrated for both wavelengths. The voltage output of the photodiode was acquired with a connector block (Model BNC-2110, National Instruments, Austin, TX) connected to a data acquisition board (Model PCI-MIO-16E-4, National Instruments). Software written in LabVIEW (Version 6i, National Instruments) controlled data acquisition. A sampling rate of 1,000 Hz was used, and 10,000 samples were acquired for each measurement. This study focused only on the first 250 ms of acquired data.

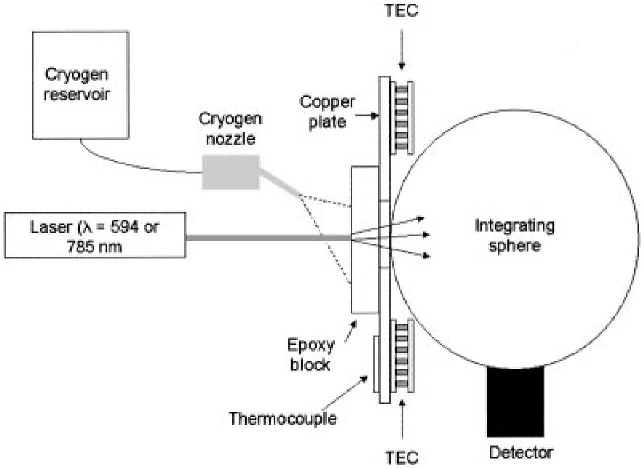

Fig. 1. Schematic of experimental apparatus to measure light transmittance dynamics after cryogen spray cooling (CSC). Light propagated from the laser through the cryogen spurt or liquid cryogen pool, through the epoxy block, and into the integrating sphere. The thermoelectric coolers (TEC) and thermocouple were used to maintain a constant epoxy block temperature of 32°C.

Cryogen (1,1,1,2-tetrafluoroethane, $T_b = -26.2°C$ at atmospheric pressure) contained in a pressurized steel canister was released by an electronically controlled solenoid valve (Series 99 by Parker Hannifin Corp., General Valve Division, Fairfield, NJ) through a 0.5-mm diameter nozzle positioned 40 mm from the epoxy block at an angle of 15° with respect to the surface normal. This atomizing valve–nozzle arrangement is the same as that used in the Candela (Wayland, MA) Dynamic Cooling Device^{TM} (DCD), which has been incorporated with the following lasers: SPTL1-b^{TM}, ScleroPLUS^{TM}, V-Beam^{TM}, C-Beam^{TM}, GentleLASE^{TM}, GentleLASE PLUS^{TM}, GentleYAG^{TM}, and SmoothBeam^{TM}. Tetrafluoroethane, the only cryogenic compound currently FDA approved for use in dermatologic laser surgery, is a non-flammable, non-toxic, environmentally compatible freon substitute, which does *not* deplete atmospheric ozone or contribute to global warming [15].

Cryogen spurts durations (τ_{cry}) of 10, 20, 30, 50, and 100 ms were obtained using a programmable digital delay generator (DG535, Stanford Research Systems, Sunnyvale, CA). Transmitted light was determined for each of the following user-specified delay times (τ_d) following cryogen spurt termination: 0, 10, 20, 30, 50, and 100 ms. For each τ_{cry} and τ_d, three trial were performed and the results averaged. After each measurement, lens cleaning tissue soaked with methanol was used to clean the epoxy surface and sufficient time provided to allow the block to return to the preset temperature (32°C).

RESULTS

A summary of average percentage transmittance values for wavelengths of 594 and 785 nm as functions of τ_{cry} (10, 20, 30, 50, and 100 ms) and τ_d (0, 10, 20, 30, 50, and 100 ms) following cryogen spurt termination is shown in Table 1. Immediately after spurt termination ($\tau_d = 0$) and at $\tau_d = 10$ ms, the minimum average transmittance values measured for 594 and 785 nm were 82% and 73%, respectively. However, at $\tau_d = 20$ ms, the minimum average transmittance values measured for 594 and 785 nm were 99% and 95%, respectively. A minimum average transmittance value of 97% was determined for the typical clinical use of a τ_{cry} of 30 ms and τ_d of 30 ms for both wavelengths under study (Fig. 2).

DISCUSSION

A solid block of epoxy resin was used as the phantom because its thermal diffusivity is similar to that of human skin. The block was warmed and maintained at 32°C to approximate in situ human skin before CSC. In many previous studies [9,11–13], glass at room temperature was used as the substrate to investigate the thermodynamics of

TABLE 1. Percent Transmittance Values (Mean ± SD) for 594 and 785 nm Wavelengths as Functions of τ_{cry} and τ_d Following Cryogen Spurt Termination

	Transmittance (%)					
τ_d (ms)	0	10	20	30	50	100
$\lambda = 594$ nm						
τ_{cry} (ms)						
10	89 ± 1	84 ± 2	99 ± 0	99 ± 2	100 ± 0	100 ± 1
20	83 ± 1	84 ± 2	99 ± 2	100 ± 2	100 ± 1	100 ± 1
30	83 ± 2	83 ± 2	99 ± 1	99 ± 1	99 ± 1	100 ± 1
50	82 ± 0	82 ± 2	100 ± 2	100 ± 1	99 ± 2	100 ± 1
100	84 ± 4	87 ± 2	100 ± 1	100 ± 1	99 ± 2	99 ± 1
$\lambda = 785$ nm						
τ_{cry} (ms)						
10	87 ± 2	75 ± 2	98 ± 1	99 ± 1	100 ± 1	100 ± 1
20	79 ± 3	75 ± 1	99 ± 2	99 ± 2	100 ± 1	100 ± 1
30	73 ± 1	74 ± 1	98 ± 3	97 ± 2	99 ± 2	100 ± 1
50	75 ± 1	76 ± 2	95 ± 1	96 ± 1	95 ± 2	100 ± 1
100	74 ± 1	73 ± 1	95 ± 1	97 ± 1	95 ± 1	96 ± 0

CSC. However, dynamics of the cryogen film layer may be dependent on the temperature profile and composition of the substrate under study. Preliminary studies in our laboratory suggest that both the drop in transmittance during CSC and subsequent frost formation depend on both substrate temperature and composition (unpublished data).

Transmittance measurements based on collimated light alone [9,12,13] may portray an unrealistically low expectation for therapeutically useful transmitted light. Therefore, diffuse (e.g., scattered) and collimated light should be included in transmittance measurements following CSC. The present study utilized an integrating sphere to collect both diffuse and collimated light passing through the liquid cryogen film and epoxy block. Theoretical modeling and measurement of collimated and diffuse light propagation are currently underway to explore further this topic.

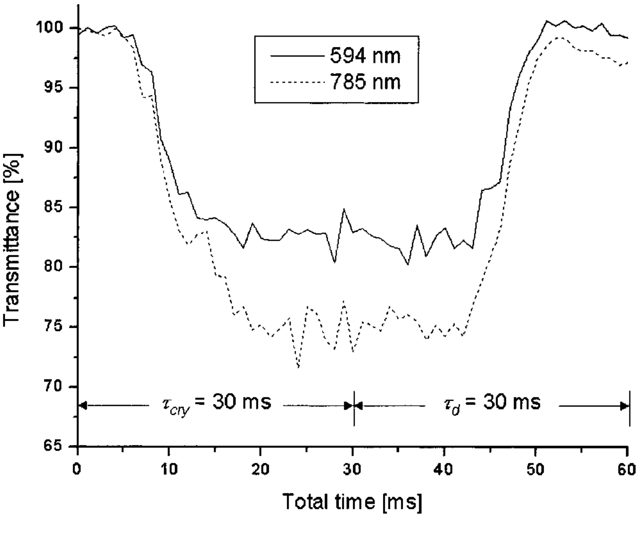

Fig. 2. Average percentage transmittance values for 594 and 785 nm wavelengths as functions of $\tau_{cry} = 30$ ms and $\tau_d = 30$ ms following cryogen spurt termination

The main cooling mechanism of CSC is a rapid evaporation of cryogen, which extracts the necessary latent heat from the skin [16,17]. In practice, liquid cryogen is "atomized" into a fine spray, and directed on to the skin surface. During flight, spray droplets cool rapidly due to the evaporation of cryogen. Therefore, the droplet temperature when impinging on the skin surface is typically between −50 and −60°C. The temperature of the epidermis is rapidly reduced as it is supplying the latent heat of cryogen evaporation. As the skin temperature decreases, the heat flux becomes insufficient to vaporize subsequent impinging droplets. At this stage, cryogen begins to build up and forms a layer of liquid film that remains on the skin surface after spurt termination. Consequently, cooling continues for a much longer time than the actual user-specified spurt duration. The presence of liquid cryogen on the skin surface after spurt termination constitutes *de facto* skin cooling during and after laser exposure. The temperature of this layer approaches the boiling temperature of tetrafluoroethane ($T_b = -26.2°C$).

Prior to evaporation, the cryogen film that forms on the skin surface may pose a potential problem of laser light attenuation due to optical scattering. Light attenuation by the liquid cryogen film depends on the interval between spurt termination and laser irradiation. A summary of transmittance values for wavelengths of 594 and 785 nm as functions of τ_{cry} and τ_d following cryogen spurt termination is shown in Table 1. The reduction in average transmittance values during τ_{cry}, immediately ($\tau_d = 0$) after spurt termination and at $\tau_d = 10$ milliseconds, is most likely due to the presence of highly scattering cryogen droplets in flight from the spray nozzle to the skin surface as well as splashing of the liquid cryogen pool due to recently deposited and rebounding droplets. By $\tau_d = 20$ ms, the lowest average transmittance values measured for 594 and 785 nm were 99% and 95%, respectively. A minimum average transmittance value of 97% was determined for the typical clinical use of a τ_{cry} of 30 ms and τ_d of 30 ms for both wavelengths under study (Fig. 2). Therefore, light attenuation by the liquid cryogen film does not appear to pose a major clinical or operational problem during treatment of hypervascular skin lesions and laser-assisted hair removal.

During CSC and immediately after spurt termination ($\tau_d = 0$–20 milliseconds), total light transmittance was lower at 785 nm as compared to 594 nm. Since light scattering is known to decrease with increasing wavelength, these results seem to be counterintuitive. However, the source of this discrepancy may be due to beam divergence for the two sources used. HeNe lasers are characterized by a minimal beam divergence angle (e.g., angle of incidence is approximately 0° with respect to the surface normal), whereas laser diodes typically emit beams that are highly divergent (e.g., angle of incidence $\geq 0°$). Due to optical scattering, cryogen droplets in flight, or those rebounding from the epoxy surface, will increase the spread of the angle of incidence. Therefore, since 785 nm photons are characterized by a higher angle of incidence, such photons may be scattered to even greater angles in the presence of cryogen droplets, increasing the probability of scattering outside of the integrating sphere field of view. These droplets would also be present after spurt termination (e.g., at $\tau_d \geq 0$) due to the 5–10 milliseconds jitter in the user-specified spurt duration due to imperfect synchronization between the electronics and nozzle closure [18]. In summary, the difference in light transmittance between 594 and 785 nm may be due to the larger beam divergence of the latter. Future experiments will be performed to confirm this hypothesis.

A layer of frost has been observed to form on the skin surface following cryogen spurt termination. Experiments studying CSC in a controlled atmosphere have proven conclusively that this frost forms primarily as a result of condensation of ambient water vapor on the cooled surface of human skin [18]. This phenomenon occurs approximately 100 ms after the end of a τ_{cry} of 30 ms delivered by the commercial Candela Dynamic Cooling Device^{TM}. Therefore, the incident laser light dose delivered for therapy is not affected by optical scattering due to frost because τ_d is regularly chosen to be much shorter than 100 ms to avoid losing the spatial selectivity of CSC. However, during clinical implementation, the laser handpiece typically is moved manually from a given site to an immediately adjacent spot. Frost that forms after CSC of one site may still be present during laser irradiation of the adjacent site. Since results obtained by Choi et al. [13] suggest that total light transmittance through frost is fairly low (less than 50%), it is important for the clinician to maneuver the handpiece to avoid irradiating through any frost that is inadvertently present from previous sites. A future study is planned to investigate light transmittance dynamics during CSC of adjacent sites.

CONCLUSIONS

This study simulated *in situ* human skin conditions with the use of a heated epoxy block to measure light transmittance changes that occur following cryogen spurt termination. Shortly after spurt termination, there was negligible light attenuation by the cryogen film at the two wavelengths studied. For the typical clinical use of a 30 ms spurt duration and 30 ms delay between spurt termination and delivery of the laser pulse, a minimum average transmittance value of at least ~97% was measured.

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