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Phys. Med. Biol. **51** (2006) 113–120 doi:10.1088/0031-9155/51/1/008

Effect of ambient humidity on light transmittance through skin phantoms during cryogen spray cooling

Julio C Ramirez-San-Juan[1,2], Bernard Choi[1], Walfre Franco[3], J Stuart Nelson[1] and Guillermo Aguilar[3]

[1] Beckman Laser Institute and Medical Clinic, University of California, Irvine, CA 92612, USA
[2] Department of Optics, INAOE, AP 51 and 216, CP 72000 Puebla, Pue, Mexico
[3] Department of Mechanical Engineering, University of California, Riverside, CA 92521, USA

E-mail: gaguilar@engr.ucr.edu

Received 26 May 2005, in final form 9 October 2005
Published 14 December 2005
Online at stacks.iop.org/PMB/51/113

Abstract

Cryogen spray cooling (CSC) is a technique employed to reduce the risk of epidermal damage during dermatologic laser surgery. However, while CSC protects the epidermis from non-specific thermal damage, it might reduce the effective fluence reaching the target chromophore due to scattering of light by the spray droplets and subsequent water condensation/freezing on the skin surface. The objective of this work was to study the effect of ambient humidity (ω) on light transmittance during CSC. An integrating sphere was employed to measure the dynamics of light transmittance through a deformable agar phantom during CSC. The study included two representative CSC spurt patterns studied using four ω: 57, 40, 20 and 12%. Results show that during CSC, as ω increased, light transmittance decreased. For the highest humidity level (57%) studied, light transmittance reached a minimum of 55% approximately 30 ms after spurt termination. In a controlled environment with $\omega = 12\%$, light transmittance reached a minimum of 87% approximately 30 ms after spurt termination. The reduced light transmittance immediately after spurt termination was most likely because of scattering of light caused by condensation of water vapour due to aggressive cooling of ambient air in the wake of the cryogen spurt.

(Some figures in this article are in colour only in the electronic version)

Introduction

In dermatologic laser surgery, cryogen spray cooling (CSC) can minimize the risk of epidermal thermal damage (Nelson *et al* 1995, 1996, Ramirez-San-Juan *et al* 2005, Fried and Walsh 2000) and permits the safe use of higher light doses (Chang and Nelson 1999, Kelly *et al* 2002, 2003). However, CSC may reduce the effective fluence reaching the target chromophore due

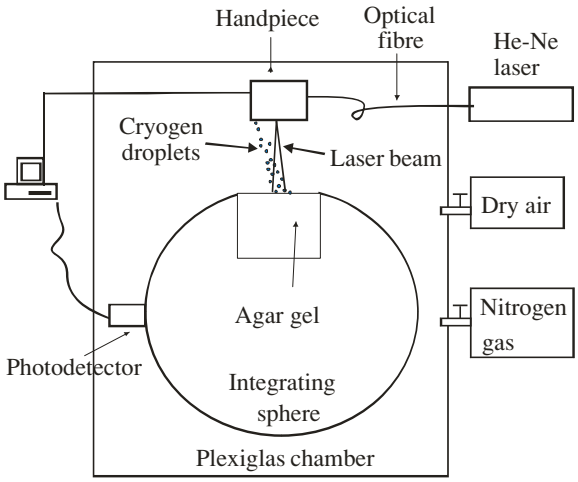

Figure 1. Experimental set-up used to measure light transmittance through skin phantoms during CSC.

to scattering of light by the spray droplets and subsequent water condensation/freezing on the sprayed surface. Previous studies (Edris *et al* 2003, Pikkula *et al* 2002, Choi *et al* 2002) have investigated light attenuation in conjunction with CSC. For a typical clinical application of a 30 ms cryogen spurt duration and a 30 ms delay time between spurt termination and pulsed laser exposure, Edris *et al* (2003) measured a minimum average light transmittance of ∼97%. Pikkula *et al* (2002) measured transmittance values in the range of 70–95% using various combinations of spurt durations and delay times. A limitation of the aforementioned studies was that both assumed constant ambient humidity (ω) and employed rigid skin phantoms. In reality, ω in the operating suite or laboratory may change throughout the day. Majaron *et al* (2001) studied the influence of ω on the cooling rate and efficiency of CSC, and concluded that epidermal protection during CSC-assisted laser dermatologic surgery can be further improved by controlling the influence of ω. Furthermore, CSC on human skin produces an indentation on the skin surface where liquid cryogen accumulates (Basinger *et al* 2004). In this study, we investigated the effect of ω on light transmittance through deformable skin phantoms during CSC with representative single and multiple spurt patterns at different ω.

Materials and methods

Skin phantom preparation

Highly purified agar powder (Dickinson and Company, Sparks, MD) was dissolved in a mixture of deionized water (90%) and glycerol (10%) to achieve a 1% concentration. The mixture was heated to a gentle boil on a hot plate. The heated solution was poured into a glass beaker and allowed to solidify over a few minutes forming a transparent gel.

Laser light transmittance measurement set-up

The experimental set-up was similar to that employed by Edris *et al* (2003). The beaker containing the skin phantom was placed at the entrance port of an integrating sphere (Labsphere, Model IS-040, North Sutton, NH) equipped with a photodetector (DET210, Thorlabs, Newton, NJ) (figure 1). Before insertion into the integrating sphere, the phantom

was pre-heated to 32 °C with a heating plate to approximate the temperature of *in vivo* human skin. The phantom surface was irradiated with 633 nm He–Ne laser light delivered via the standard optics of a commercial laser handpiece, producing a circular spot of ∼7 mm in diameter.

Medical grade, Food and Drug Administration approved cryogen (1, 1, 1, 2-tetrafluoroethane, with a boiling temperature of −26.2 °C at atmospheric pressure) contained in a pressurized steel canister was delivered to the phantom surface through an electronically controlled solenoid valve installed in the commercial handpiece. The spraying distance was 31 mm, which is similar to that employed during clinical treatments. The sprayed circular spot was ∼8 mm in diameter.

The experiment described above was performed at four ω: (1) 57%, which corresponds to the inside of an air-conditioned laboratory at the University of California Riverside; (2) 40%, which corresponds to the inside of the same air-conditioned laboratory one week later; (3) 20%, inside a Plexiglas chamber where the water vapour was removed by dry air; and (4) 12%, inside a Plexiglas chamber where the water vapour was removed using a mixture of dry air and nitrogen gas. The measured uncertainty in ω throughout the study was 5%.

Methods

In each experiment, the skin phantom was continuously irradiated with 633 nm He–Ne laser light. A single 10 ms cryogen spurt or a sequence of multiple cryogen spurts (MCS) was applied to the phantom and the corresponding light transmittance dynamics measured. The MCS is similar to that employed in some commercial devices and consisted of five 10 ms spurts with 60 ms intervals between each spurt. The signal from the photodetector was acquired with a data acquisition board (Model 100B, GW Instruments, Somerville, MA) at a sampling rate of 1 kHz. Software written in LabVIEW (Version 7, National Instruments, Austin, TX) was used to control CSC and data acquisition. After each measurement, lens tissue was used to clean the phantom surface, and the phantom was re-heated to the pre-experimental temperature of 32 °C. The purpose of using high water concentration, low thermal diffusivity and deformable agar gels at 32 °C as skin phantoms was to set experimental conditions similar to those in clinical procedures.

For some experiments, high-speed video images were acquired (Fastcam PCI, Photron Inc., San Diego, CA) to record a side view of cryogen deposition on the phantom surface.

Results

High-speed video imaging permitted observation of CSC dynamics as a function of ω. Figures 2 and 3 show time-series of side view images of cryogen sprays aimed at the phantom during the MCS sequence at $\omega = 40$ and 20%, respectively. Both sets of images were obtained from the high-speed video during application of the first cryogen spurt of the MCS sequence. At $\omega = 40\%$, scattered laser light between the phantom surface and the handpiece was evident because of combined light attenuation by highly scattering cryogen droplets in flight from the nozzle to the agar phantom (figures 2(b), (c) and (d)) and water vapour arising and saturating the atmosphere due to aggressive cooling of ambient air in the wake of the cryogen spurt (figures 2(c), (d), (e) and (f)). In figure 2(g), these phenomena are no longer present. At $\omega = 20\%$, the light attenuation by the cryogen droplets in flight is shown in figures 3(b), (c) and (d); however, the presence of the cloud of water vapour in the wake of the cryogen spurt is not evident at all.

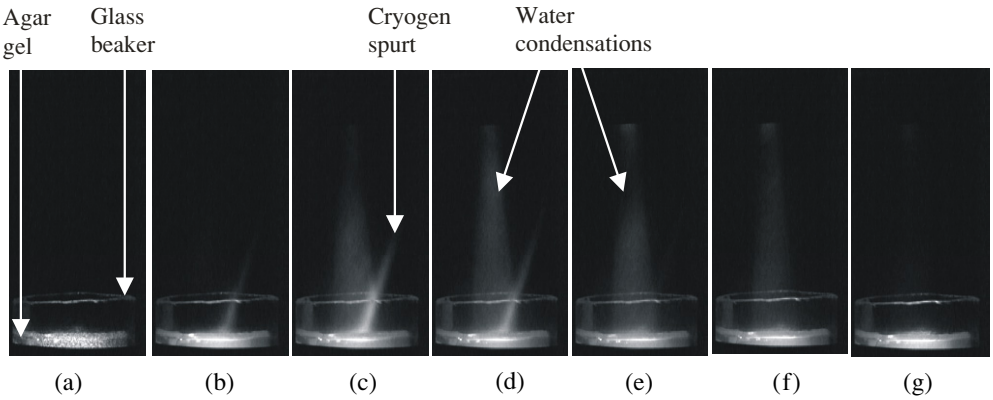

Figure 2. Time-series images of side views of the region between handpiece and skin phantom for $\omega = 40\%$ during application of the first cryogen spurt of the MCS sequence. Image (a) corresponds to the time just before the spurt application. Images (b), (c) and (d) show light scattering due to the cryogen spurt and images (c), (d), (e) and (f) show the scattering cloud generated by water vapour. In part (g), both phenomena are no longer present. A similar behaviour was observed for each cryogen spurt during the MCS sequence application. The time elapsed between each image is ∼6 ms.

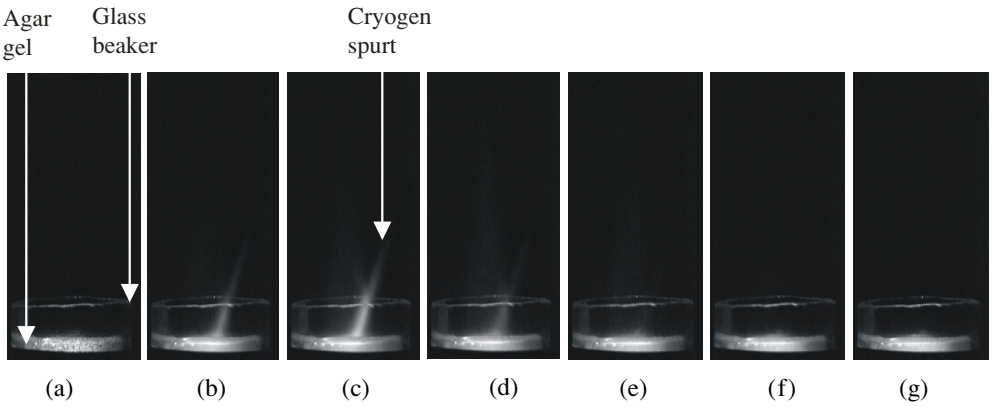

Figure 3. Time-series images of side views of the region between handpiece and skin phantom surface for $\omega = 20\%$ during application of the first cryogen spurt of the MCS sequence. Image (a) corresponds to the time just before the spurt application. Images (b), (c) and (d) show light scattering due to the cryogen spurt. At this ω the scattering cloud generated by water vapour is not evident. A similar behaviour was observed for each cryogen spurt during the MCS sequence application. The time elapsed between each image is ∼6 ms.

During CSC, as ω increased, light transmittance decreased. Figure 4 shows time-resolved transmittance during CSC with a single 10 ms cryogen spurt at four ω: 57, 40, 20 and 12%. As cryogen droplets impinged on the phantom surface, a rapid decrease in light transmittance was noted. With relatively low ω, the effect of ω on light transmittance did not appear to be significant; nevertheless, as ω increased, the transmittance progressively decreased. The minimum light transmittance corresponded to the highest ω.

Figure 5 shows the time-resolved transmittance during the MCS sequence at each of the four ω. In this graph, an oscillating transmittance behaviour was observed. As in the single cryogen spurt experiments (figure 4), transmittance decreased as ω increased. At a given ω,

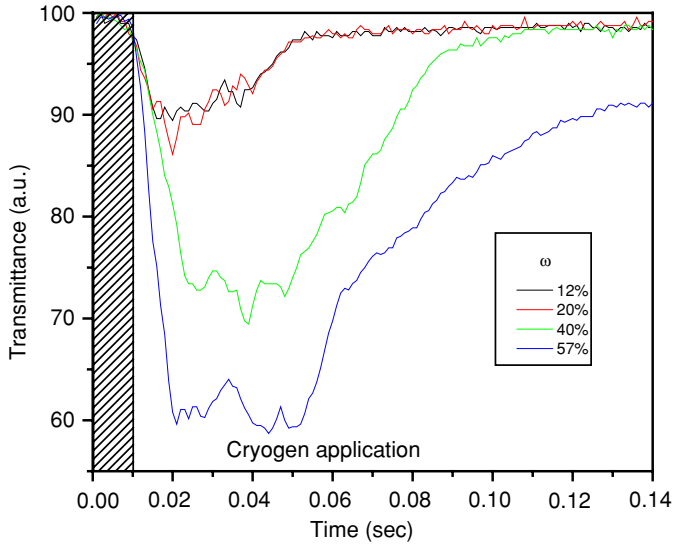

Figure 4. Time-resolved transmittance during CSC with a single 10 ms cryogen spurt (vertical bar) at four ω. At low ω ($< 20\%$), the effect on light transmittance appears negligible; however, for higher ω, the effect becomes more prominent.

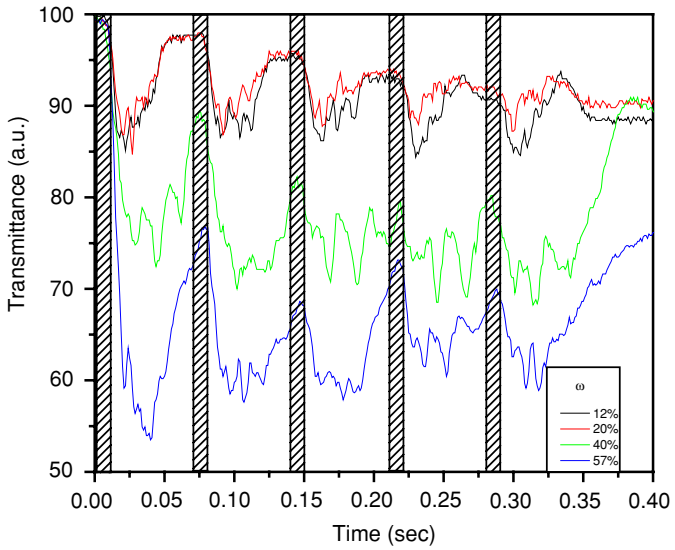

Figure 5. Time-resolved transmittance during CSC with a MCS sequence of five 10 ms cryogen spurts (vertical bars) with a 60 ms delay time between each spurt, at four ω. Light transmittance reaches a local minimum between successive cryogen spurts, approximately 30 ms after spurt termination.

the minimum transmittance between each spurt was similar, suggesting that the effect of ω on droplet–surface interaction effects such as droplet deposition and rebound, and water vapour condensation is not cumulative.

Discussion

The purpose of the experimental design was to include most of the complexity of cryogen-skin interactions. Since the mechanical properties of skin are a function of age, anatomical location, and history (what the skin has experienced in time), the skin deformation during CSC is highly variable. However, deformations between 1 to 3 mm in depth always occur upon the impact of CSC sprays, as documented in a previous study (Basinger *et al* 2004). The deformation observed in agar during CSC, approximately 2 mm in depth, is similar to that of human skin.

Previous studies (Edris *et al* 2003, Pikkula *et al* 2002, Choi *et al* 2002) have investigated light attenuation in conjunction with CSC. For the typical clinical application of a 30 ms cryogen spurt duration and a 30 ms delay time between spurt termination and pulsed laser exposure, Edris *et al* (2003) measured a minimum average light transmittance of ∼97%. The authors proposed that the reduction in average transmittance values during CSC after spurt termination is most likely due to the presence of highly scattering cryogen droplets in flight from the nozzle to the skin surface as well as the splashing of the liquid cryogen pool due to recently deposited rebounding droplets. Pikkula *et al* (2002) measured transmittance values in the range of 70–95% using various combinations of spurt durations and delay times and proposed the cryogen film on the sprayed surface as a source of light attenuation due to optical absorption: the thicker the cryogen film, the lower the light transmittance.

Even when the two aforementioned mechanisms of light attenuation, (1) presence of recently deposited and rebounding cryogen droplets and (2) formation of a thick cryogen layer, could be present in this study, figures 4 and 5 suggest that the reduced light transmittance during CSC application was most likely due to mechanisms associated directly with ambient humidity (ω): (3) presence of a highly scattering cloud because of water vapour arising and saturating the atmosphere due to aggressive cooling of ambient air in the wake of the cryogen spray (figure 2); (4) water condensation and probably frost formation on the phantom surface; (5) increased cryogen layer accumulation due to surface indentation (Basinger *et al* 2004); and (6) freezing of the phantom surface due to the internal humidity of the agar phantom.

Mechanisms 1, 2, 5 and 6 are independent of ω and should be present in all the experiments performed in this study, even at low ω. This means that the minimum light transmission due to these four mechanisms is, 87% ($\omega = 12$–20%) as seen in figures 4 and 5. For higher ω, mechanisms 3 and 4 become dominant and the light transmittance progressively decreases, reaching a minimum of 70% and 55% for $\omega = 40\%$ and 57%, respectively.

Transmittance reached a minimum value approximately 30 ms after termination of each cryogen spurt (figures 4 and 5). In practice, a 30 ms delay time between spurt termination and laser irradiation is commonly used by clinicians. Therefore, our results suggest that with these CSC parameters the laser pulse may be applied at the time of minimum light transmittance.

Measurements of time-resolved transmittance during the MCS sequence showed an oscillating behaviour at each of the four ω (figure 5). The frequency of the observed modulations may be comparable to the characteristic frequency (or time scale) of the following phenomena: (i) light attenuation by discrete cryogen droplets in flight from the nozzle to the agar phantom and the formation of water vapour arising and saturating the atmosphere, both present in each spurt of the MCS sequence; (ii) non-steadiness of short cryogen spurts, which may take as long as 20 ms to fully develop (Aguilar *et al* 2003); (iii) inherent opening and closing valve dynamics, which we estimate in the order of a few milliseconds; (iv) mechanical vibrations of the feeding lines and nozzle assembly as cryogen flows through; and (v) inherent dynamics of flow development within feeding lines and nozzle assembly. In addition, at the surface level, (vi) the liquid cryogen is deposited as a circular layer that initially expands, reaches a maximum spread diameter and then shrinks to disappear (evaporation).

Subsequently, there is formation of ice in the form of rings that also shrink and disappear as they melt. It is important to note, however, that while the first five phenomena listed above could be related to the oscillations observed in figure 5 because they take place in the time span of a few milliseconds, the ice ring formation and shrinking occurs over hundreds of milliseconds or an even longer time scale (Majaron *et al* 2001), and thus is unlikely to be the cause of the oscillations.

An important difference between the experiments conducted in this study and clinical applications is laser power. We employed a low-power laser (30 mW) while clinical lasers are typically in the kW range. Pikkula *et al* (2002) employed several clinical lasers (including the SmoothBeam^{TM}) at different wavelengths to determine light attenuation through the cryogen film deposited on a glass cover slip. In the particular case of the SmoothBeam^{TM}, the transmittance reported was ∼93%, such that if there were any kind of high power-cryogen interaction, it would be, in the worst case scenario, responsible for only 7% of the light attenuation. High-power laser-skin interactions, however, are expected to be more significant than high-power laser-cryogen interactions because the heat generated within the tissue by a high-power laser has an effect on the mechanical and thermal interactions between cryogen and skin. Nevertheless, the enhanced water vapour formation produced by high humidity levels and its effect on the light transmittance reported herein would still exist regardless of the laser power and the heat generated by a high-power laser would only affect laser-skin interactions long after CSC.

Conclusions

Employing an agar skin phantom, we studied the effect of ambient humidity (ω) on light transmittance during CSC. During CSC, as ambient humidity (ω) increases, light transmittance decreases. With the highest ω (57%) used in this study, light transmittance reached a minimum of 55% approximately 30 ms after spurt termination because of water vapour arising and saturating the atmosphere due to aggressive cooling of ambient air in the wake of the cryogen spray and on the phantom surface. Due to a wide variety of ω in different global locations or even in the same location throughout the day, it may be desirable to implement some type of humidity control in the operating suite or laboratory during CSC application to keep the humidity below 20% to help maximize light transmittance.

Acknowledgments

The authors would like to thank Jie Liu from the LTPBA at UC Riverside for the technical video support and acknowledge the Fondo de Repatriaciones CONACYT-México (JCR), the Arnold and Mabel Beckman Fellows Program (BC) and the National Institutes of Health (HD42057 and A Ward Ford Research Grant) to GA and (GM62177, AR48458 and AR47551) to JSN.

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