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Effects of relative humidity on laser light transmittance during cryogen spray cooling of in vitro skin phantoms

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ABSTRACT

While cryogen spray cooling (CSC) can protect skin epidermis from non-specific thermal damage, spray droplets in-flight and the cryogen/frost layer that forms on the skin surface may pose a potential problem for laser light attenuation due to absorption and/or scattering. Employing a hand piece expressly designed for concurrent light and cryogen delivery on skin phantoms, we studied the effect of relative humidity on light transmittance during and after spray cooling. Cryogen spurts were aimed at a microscope glass slide and a deformable agar phantom preheated at 32°C. According to our results, relative humidity plays a very important role in the light transmission during CSC. Light absorption and/or scattering by the spray droplets in-flight and cryogen/frost layer formation at the surface induced light attenuation values of up to 45%. The higher the relative humidity is, the lower the light transmission.

Keywords: light attenuation, laser surgery, dermatology, port wine stain.

1. INTRODUCTION

The study of light propagation in tissue is central to many medical and biomedical laser applications. In particular, knowledge of the amount of light transported into human skin is important for laser dosimetry of vascular lesion treatments; such as port wine stain (PWS) birthmarks. In dermatologic laser surgery, cryogen spray cooling (CSC) helps to minimize the risk of epidermal damage[1-3] and permits the safe use of higher light doses[4-7]. However, CSC can also be a limiting factor for laser treatments due to optical absorption and scattering of light by the spray droplets and subsequent water condensation/freezing on the sprayed surface. Previous studies have investigated light attenuation in conjunction with CSC. For a typical 30 ms cryogen spurt and 30 ms delay between spurt termination and pulsed laser irradiation, Edris et al.[8] measured a minimum average light transmittance of ~97% through a clear epoxy skin phantom. Pikkula et al.[9] measured transmittance values in the range of 70-95% through a cryogen film sprayed onto a glass cover slip using different combinations of cryogen spurt durations and delay times. However, in both studies, relative humidity remained constant. In this study, we investigate the effect of relative humidity on the light transmission during CSC. Laser light transmittance through a glass slide and an agar skin phantom is measured during multiple cryogen spurt sequences at various relative humidity levels.

2. MATERIALS AND METHODS

1. Agar preparation

Skin phantoms commonly used by researchers in biomedical optics are based on clear agar gels[10]. To reproduce the absorption and scattering properties of biological tissues, these gels may be mixed with a scattering fatty medium (e.g. intralipid)[11] and a water-soluble dye (e.g. India ink)[12]. However, since we are interested in the effect of relative humidity on light attenuation by the cryogen in-flight and deposited on the surface, we did not include scattering and absorbing media into our agar skin phantom.

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Highly purified agar powder (Dickinson and Company, Sparks MD) was dissolved in deionized water in 1% concentration, and heated to a gentle boil on a hot plate. At 40°C, the solution was poured into the mold and left there for a few minutes to reach proper hardening and homogeneous optical properties.

2. Laser light transmittance measurement setup

Continuous laser light emitted by a 633 nm wavelength He-Ne laser (Model 1145P, Uniphase, Manteca CA) and electronically-controlled 1,1,1,2-tetrafluorethane cryogen spurts delivered by a commercial nozzle were coupled onto the hand piece of a commercial laser device and aimed concurrently at either a glass slide or the agar skin phantom. Light transmittance was measured during and after cryogen application. Both sprayed objects were preheated to reach an initial temperature of ~32°C, simulating the average skin temperature. Before each experiment, the sprayed surface was cleaned and sufficient time was provided to allow the glass slide or skin-phantom to return to initial temperature. Identical multiple cryogen spurts (MCS) sequences consisting of five 10 ms cryogen spurts and 60 ms in between spurts were applied to both substrates. To reduce the relative humidity and maintain it at constant levels between 12 and 57% (ambient), the experimental setup was placed inside a custom-made Plexiglas® chamber and either dry air and/or nitrogen gas were used to flush air out (Figure 1).

An integrating sphere (Labsphere, Model IS-040, North Sutton NH) equipped with a pre-calibrated photo-detector (DET210 model, Thorlabs, Newton NJ) was used to collect transmitted light. Measured photocurrent was converted into voltage across a resistance and was acquired at a sampling rate of 1000 Hz with a data acquisition board (Model 100B, GW Instruments, Somerville MA) and stored for further analyses. Software written in LabView (version 7, National Instrument, Austin TX) controlled and synchronized data acquisition from the photo-detector and spray system. The experimental setup is shown in Figure 1.

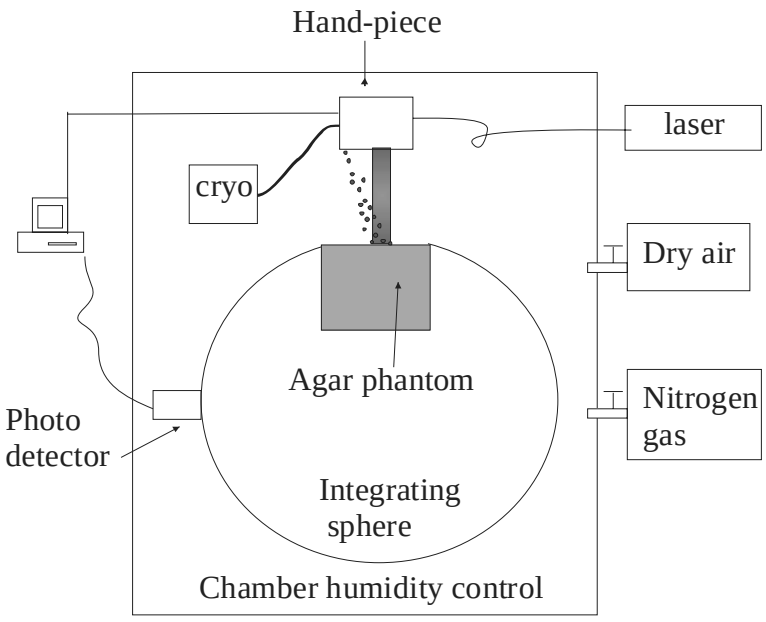

Figure 1: Experimental setup employed to measure dynamic light transmittance during CSC on glass slides and agar phantoms.

3. RESULTS AND ANALISYS

Figure 2 shows the transmittance through the glass slide as a function of time for the MCS sequence described above at four different relative humidity values. It is seen that the light transmittance depends strongly on the relative humidity; the higher the relative humidity is, the lower the light transmittance.

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Figure 3 shows the transmittance as a function of time using the same MCS sequence employed in Figure 2 on a deformable agar phantom. In this case, as well as for the glass slide, we can see an oscillating transmittance, whose amplitude decreases after each cryogen spurt.

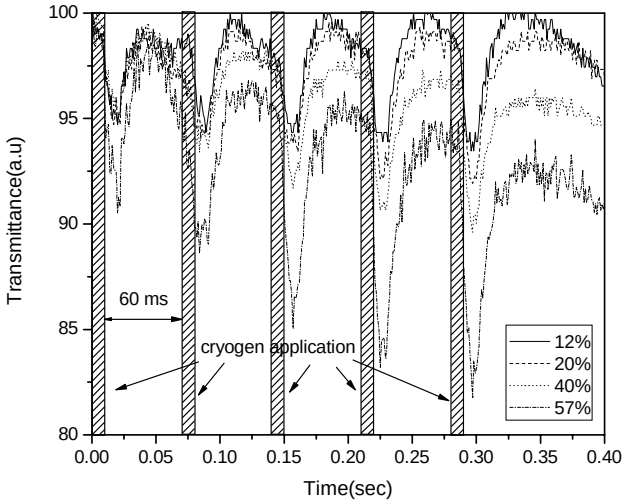

Figure 2: Transmittance as a function of time for the MCS on glass slide: 5 cryogen spurts of 10 ms each and 60 ms delay in between spurts. Note that minimum transmittance is reached after each spurt termination.

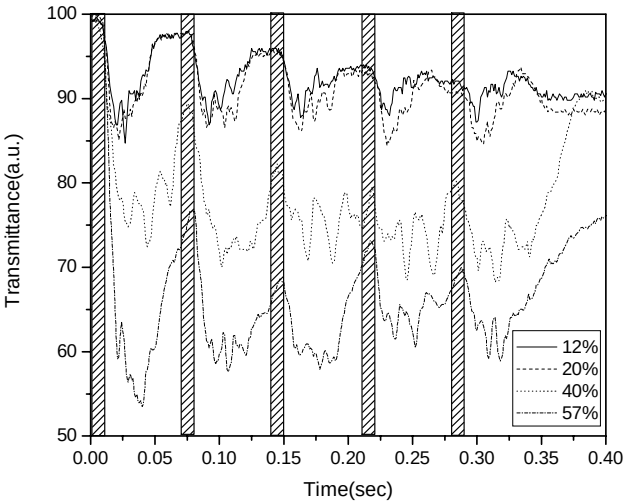

Figure 3: Transmittance as a function of time for the MCS on agar deformable phantom. Note that although transmittance is qualitatively the same, the minimum transmittance through the agar phantom for higher relative humidity is lesser than those measured with the glass slide.

For the glass slide (Figure 2), a local minimum is reached around 10 ms after each cryogen spurt and each local minimum is lower than the previous one. However, for the agar phantom (Figure 3) the transmittance reaches local minima around 30 ms after each cryogen spurt termination, which means that the strongest attenuation of light would

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occur exactly during the application of each laser pulse for sequences with 30 ms delay between spurt termination and laser irradiation.

Note that the effect of humidity on the transmittance is strong under normal atmospheric conditions (57% relative humidity inside an A/C laboratory in UC Riverside, CA), reaching minima of 85 and 65% for the glass slide and agar phantom, respectively. However, as the relative humidity is reduced, light transmission increases. This observation has important practical implications. Normal air-conditioned rooms have a relative humidity that varies between 30-50%, for which transmittance decreases between 30-45% according to our measurements on the agar phantom. In contrast, under a controlled environment with relative humidity of ~12%, only a maximum of 10% reduction in transmittance was measured.

During flight, cryogen droplets quickly change their temperature from 23°C inside the container to ~-50°C on the surface of the sprayed object[13]. This drastic change of temperature implies a drastic change in the density of cryogen and, therefore, a corresponding change in the refractive index[14]. While the transmittance reduction due to the dispersive cloud of cryogen droplets in-flight and of those that bounce off the substrate surface, as well as the formation of a cryogen layer and condensed/frozen water on the sprayed surface may be present regardless of the sprayed object, we believe that the larger transmittance reduction for the agar phantom compared to that of the glass slide is due to addition of two other dispersive sources: (1) enhanced accumulation of cryogen by indentation and (2) freezing of internal water. Cryogen accumulation was first reported by Basinger et al[15], who studied the effect of skin indentation on heat transfer during CSC application. According to this study, the indentation generated by the impingement of cryogen on a gel (polyacrylamide) phantom causes cryogen accumulation and, therefore, thicker cryogen layers as compared with rigid phantoms. Furthermore, it is known[8,9] that the thickness of the cryogen film plays an important role in light attenuation, the thicker the cryogen film is, the lower the light transmission. Freezing of internal water is just a speculation based on observations of a turbid upper surface of the agar phantom, which results immediately after cryogen was sprayed on it.
In summary, these experimental observations suggest that the refractive index variation of flying droplets as a function of temperature, along with the droplets that travel toward and bounce off the substrate surface, the formation of a cryogen layer[15] and the water that condenses/freezes around the cryogen cone spray and layer[16] form a dynamic cloud that is highly dispersive.

4. CONCLUSIONS

Relative humidity affects light transmission during CSC. The higher the relative humidity is, the lower the light transmission. The effect of relative humidity together with cryogen attenuation at the agar surface induces light attenuation values of up to 45%.
Due to a variety of relative humidity in different geographical locations or even in the same location during the day, it may be necessary to implement some kind of humidity control during CSC application that helps reduce light attenuation.

5. ACKNOWLEDGMENTS

The Arnold and Mabel Beckman Fellows Program at the University of California, Irvine, supported BC; JSN received support from the National Institutes of Health (GM62177, AR48458 and AR47551); GA received support from the National Institutes of Health (HD42057).

REFERENCES

1. Nelson JS, Miller TE, Anvari B, Tanenbaum BS, Svaasand LO and Kimel S; Dynamic epidermal cooling during in conjunction with laser-induced photothermolysis of port wine stain blood vessels; Laser Surg Med 1996; 19:224-229.

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2. Aguilar G, Wang GX and Nelson JS; Effects of spurt duration on the heat transfer dynamics during cryogen spray cooling; Phys Med Biol 2003; 48:2169-2181.
3. Nelson JS, Miller TE, Anvari B, Tanenbaum BS, Svaasand LO and Kimel S; Dynamic epidermal cooling during in conjunction with laser-induced photothermolysis of port wine stain blood vessels; Laser Surg Med 1996; 19:224-229.
4. Chang CJ and Nelson JS; Cryogen spray cooling and higher fluence pulsed dye laser treatment improve port-wine stain clearance while minimizing epidermal damage; Derm Surg 1999; 25: 767-772.
5. Kelly KM, Nanda VS and Nelson JS; Treatment of port wine stain birthmarks using 1.5-msec pulsed dye laser at higher fluences in conjunction with cryogen spray cooling; Derm Surg 2002; 28: 309-313.
6. Kelly KK, Svaasand LL and Nelson JS; Optimization of laser treatment safety in conjunction with cryogen spray cooling; Arch Derm 2003; 139 (10): 1372-1373
7. Fried NM and Walsh JT Jr; Cryogen spray cooling during laser tissue welding; Phys Med Biol 2000; 45: 753-763
8. Edris A, Choi B, Aguilar G and Nelson JS; Measurements of laser light attenuation following cryogen spray cooling spurt termination; Laser Surg Med 2003; 32:143-147.
9. Pikkula BM, Domankevitz Y, Tunnel JW and Anvari B; Cryogen Spray Cooling: Effects of cryogen film on heat removal and light transmission; Proc. SPIE 2002; 4609: 50-56.
10. Cubeddu R, Pifferi A, Taroni P, Torricelli A and Valentini G; A solid Phantom for photon migration studies; Phys Med Biol 1997; 42:1971-1979.
11. Staveren v, Moes CJM, van Marle J Prahl SA and van Gemert MJC; Light scattering in intralipid-10% in the wavelength range 0f 400-1100 nm; Appl Opt 1991; 34: 4507-4514.
12. Madsen SJ, Wilson BD, Patterson MS, Park YD, Jacques SL and Hefetz Y; Experimental test of a simple diffusion model for the estimation of scattering and absorption coefficients of turbid media from time-resolved diffuse reflectance measurements; Appl Opt 1992; 31:3509-3517.
13. Aguilar G, Majaron B, Pope K, Svaasand LO, Lavernia E and Nelson JS, Influence of Nozzle-to-skin distance in cryogen spray cooling for dermatologic laser surgery; Laser Surg Med 2000; 28:113-120.
14. *Principles of Optics* by Max Born and Emil Wolf, 17 th edition, 1999; Cambridge University Press, United Kingdom.
15. Basinger B, Aguilar G and Nelson JS; Effect of skin indentation on heat transfer during cryogen spray cooling; Laser Surg Med 2004; 34: 155-163.
16. Majaron B, Kimel S, Verkruysse, Aguilar G, Pope K, Svaasand LO, Lavernia E and Nelson JS; Cryogen spray cooling in laser dermatology: Effects of ambient humidity and frost formation; Laser Surg Med 2001; 28:469-476.