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Effects of Hypobaric Pressure on Human Skin: Implications for Cryogen Spray Cooling (Part II)

Guillermo Aguilar, PhD,[1,2]* Walfre Franco, PhD,[1,2] Jie Liu, MS,[1] Lars O. Svaasand, PhD,[3] and J. Stuart Nelson, MD, PhD[2]

[1]*Department of Mechanical Engineering, University of California, Riverside, California*
[2]*Beckman Laser Institute, University of California, Irvine, California*
[3]*Norwegian University of Science and Technology, Trondheim, Norway*

Background and Objectives: Clinical results have demonstrated that dark purple port wine stain (PWS) birthmarks respond favorably to laser induced photothermolysis after the first three to five treatments. Nevertheless, complete blanching is rarely achieved and the lesions stabilize at a red-pink color. In a feasibility study (Part I), we showed that local hypobaric pressure on PWS human skin prior to laser irradiation induced significant lesion blanching. The objective of the present study (Part II) is to investigate the effects of hypobaric pressures on the efficiency of cryogen spray cooling (CSC), a technique that assists laser therapy of PWS and other dermatoses.

Study Design/Materials and Methods: Experiments were carried out within a suction cup and vacuum chamber to study the effect of hypobaric pressure on the: (1) interaction of cryogen sprays with human skin; (2) spray atomization; and (3) thermal response of a model skin phantom. A high-speed camera was used to acquire digital images of spray impingement on in vivo human skin and spray cones generated at different hypobaric pressures. Subsequently, liquid cryogen was sprayed onto a skin phantom at atmospheric and 17, 34, 51, and 68 kPa (5, 10, 15, and 20 in Hg) hypobaric pressures. A fast-response temperature sensor measured sub-surface phantom temperature as a function of time. Measurements were used to solve an inverse heat conduction problem to calculate surface temperatures, heat flux, and overall heat extraction at the skin phantom surface.

Results: Under hypobaric pressures, cryogen spurts did not produce skin indentation and only minimal frost formation. Sprays also showed shorter jet lengths and better atomization. Lower minimum surface temperatures and higher overall heat extraction from skin phantoms were reached.

Conclusions: The combined effects of hypobaric pressure result in more efficient cryogen evaporation that enhances heat extraction and, therefore, improves the epidermal protection provided by CSC. Lasers Surg. Med. 36:130–135, 2005. © 2005 Wiley-Liss, Inc.

Key words: port wine stains; dermatology; selective photothermolysis; skin vacuum

INTRODUCTION

During laser therapy of hypervascular lesions, such as port wine stain (PWS) birthmarks, telangiectasias, and hemangiomas, skin is irradiated at specific wavelengths to maximize thermal damage to targeted blood vessels, while preventing injury to the overlying epidermis [1]. At the same time, unintentional and localized heating takes place in the epidermis because of absorption of laser energy by melanin which, if not controlled, can lead to complications such as hypertrophic scarring, dyspigmentation, atrophy, or induration [2]. Cryogen spray cooling (CSC) was introduced to cool selectively the epidermis prior to laser irradiation [3]. CSC increases the threshold fluence for epidermal damage allowing the safe use of higher fluences. Despite the clinical implementation of CSC-assisted dermatologic laser therapy, clinical studies have demonstrated that the treatment success rate for most PWS patients is low (<10%), if the ultimate standard is complete blanching of the lesion. Clinical results have shown that dark purple PWS respond well to the first three to five laser treatments, with improved lesion blanching and, thereafter, the lesion color stabilizes at a red-pink color [4,5]. PWS that are initially a red-pink color, such as those of infants and young children, generally respond poorly to laser treatment [6]. Such a treatment failure may be due to limitations in destroying smaller diameter vessels (10–30 μm), since the enclosed blood volume represents but a small fraction of the entire targeted volume; that is, blood and vessel wall/perivascular tissues [7]. It follows that the thermal confinement required to reach threshold damage for permanent PWS blood vessel photocoagulation is insufficient.

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*Correspondence to: Guillermo Aguilar, PhD, Department of Mechanical Engineering, University of California, Riverside, CA 92521. E-mail: gaguilar@engr.ucr.edu.
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Significant improvement in the therapeutic outcome of PWS laser treatment could be achieved by modifying skin physiology with an intentional, controlled, and temporary method, such that smaller vessels are dilated and, as a result, the blood volume fraction (BVF) is increased immediately before laser exposure. A previous study showed that it was possible to increase the BVF in distal extremities by blocking venous return proximally using a blood pressure cuff of 13 kPa (4 inHg) [8]. Therefore, it was possible to use 40% less radiant exposure, compared to an identical laser exposure without the pressure cuff, to induce the same amount of purpura after just one 0.45-millisecond laser pulse (585 nm). However, this procedure has inherent drawbacks, such as the discomfort caused by venous obstruction and the difficulty of using the procedure for therapy of head/neck and trunk PWS lesions. To remedy these drawbacks, we developed a new method wherein PWS blood vessel dilation is attained locally, faster, and more reliably by a small suction cup that creates local hypobaric pressure on the skin surface [9].

Herein, we demonstrate that a local hypobaric pressure offers several advantages for the enhancement of CSC efficiency, such as and reduced local humidity, a shorter jet length, and a stretched and convex skin surface. All these phenomena combined are likely to positively impact the therapeutic outcome of CSC-assisted PWS laser therapy under local hypobaric pressure.

MATERIALS AND METHODS

Suction Cup and Vacuum Chamber

A short round Plexiglas® tube, 25.4 mm (1 in) inner diameter was used to build a suction cup that fits firmly around the handpiece of a laser medical device and seals tightly when pressed gently against the skin (see Part I [9] for more details). A vacuum hand pump (9963K21, McMaster-Carr, Los Angeles CA) was operated to remove the air within the cup and a built-in manometer indicated the hypobaric pressure reached. Laser irradiation was not employed for these experiments, and short cryogen spurts at various hypobaric pressures were released onto the dorsal side of a volunteer's hand. When needed a small valve released the cup from the skin surface after the procedure.

A 279-mm inner diameter by 343-mm high ($11'' \times 13.5''$) cylindrical acrylic vacuum chamber (Terra Universalm, Inc., Anaheim, CA) was constructed with an optical breadboard base, electrical motors, and pressure gauges to position and operate cryogen spray valves and nozzles under controlled hypobaric pressure. Vacuum was generated within the chamber initially at an atmospheric pressure, that is, the hypobaric pressures in this text are relative to atmospheric pressure (0 inHg).

Imaging

A high-speed (HS) 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 at rates between 250 and 1,000 frames per second of: (a) short cryogen spurts impinging on in vivo human skin under atmospheric and hypobaric pressures (within the suction cup); and (b) spray cones generated within the vacuum chamber by a commercial nozzle with inner diameter (I.D.) of 0.4 mm. The purpose ofthese videos was to observe the effects of hypobaric pressures on the cryogen-skin surface interactions and on the spray cones and spray atomization, respectively.

Temperature Measurements and Heat Transfer Computations

The surface temperature variations of a skin phantom induced by sprays released at atmospheric and hypobaric pressures were measured using a fast-response temperature sensor, consisting of a type-K thermocouple attached to a piece of silver foil (3.42 mm × 3.50 mm and 90-μm thick) placed on top of an epoxy substrate. Temperature data were acquired at a sampling rate of 2 kHz using instruNet hardware (GW Instrumentsm, Inc., Somerville, MA) and LabVIEW software (National Instruments, Austin, TX). To compute surface temperatures T, heat flux q, and total heat extraction Q, we used a one-dimensional inverse heat conduction problem, described in detail by Beck et al. [10] and previously employed by the authors in a similar study [11]. A more detailed discussion on the use of this algorithm for CSC can be found in Tunnell et al. [12].

RESULTS

Figures 1 and 2 show images of short cryogen spurts impinging on the dorsal side of a volunteer's hand, which was colored black using a non-toxic erasable marker to improve image contrast. Spurts were aimed from a distance (z) between 20 and 30 mm. The frame shown in Figure 1 was taken 30 milliseconds after a 100-millisecond spurt was initiated under atmospheric pressure and demonstrates obvious skin indentation. In contrast, Figure 2 shows a sequence of six frames taken at 0, 32, 64, 100, 128, and 160 milliseconds during and after a 100-millisecond spurt was released inside the suction cup attached to the skin. Hypobaric pressure before spurt initiation was 10 in Hg (34 kPa). The skin was initially drawn up by suction within the cup and, during spurt deposition, gradually

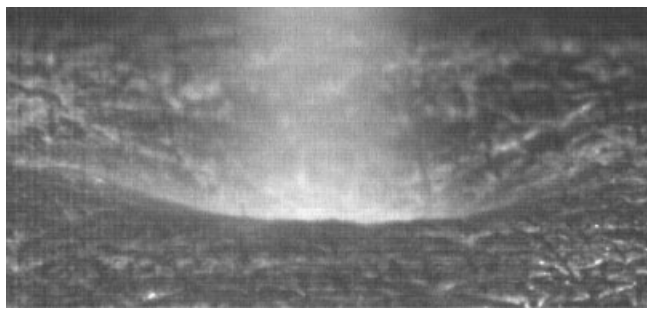

Fig. 1. Typical frame from an in vivo CSC spray impingement video. The frame corresponds to 30 milliseconds into a 100 milliseconds spurt. Nozzle-to-skin distance, $z = 30$ mm, I.D. = 0.4 mm which is similar to that used during clinical procedures.

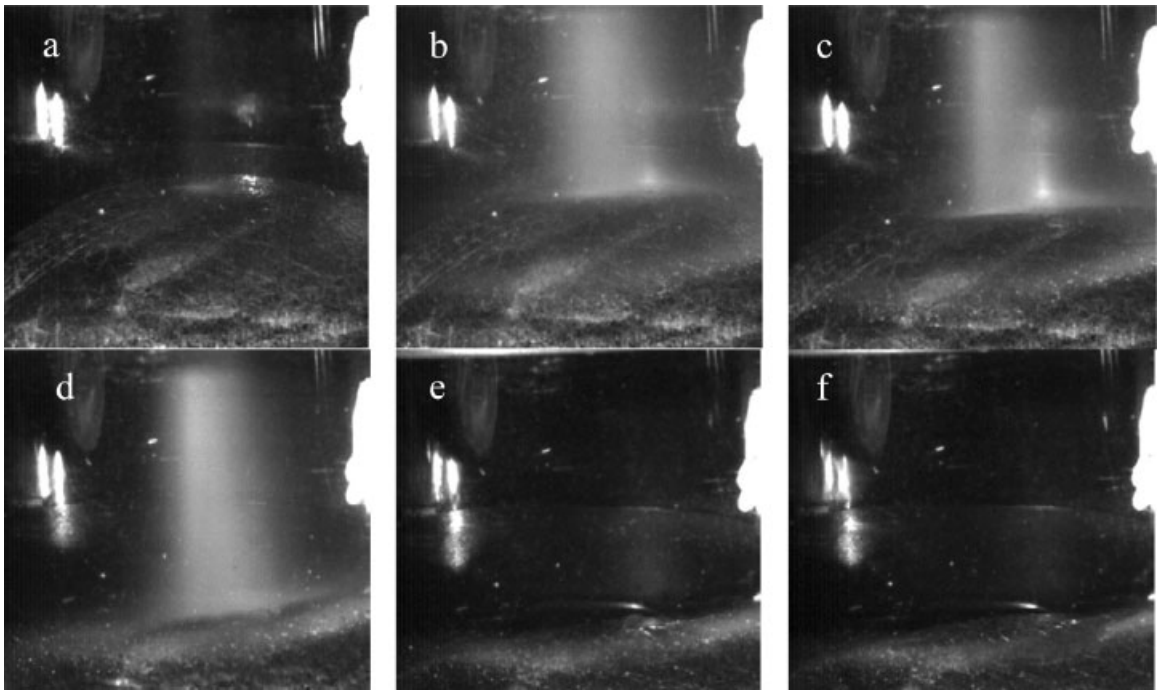

Fig. 2. Frames from an in vivo CSC spray impingement video. Frames (**a**)–(**f**) correspond to 0, 32, 64, 100, 128, and 160 milliseconds during and after a 100-millisecond spurt, $z = 20$ mm. Initial hypobaric pressure was 10 inHg.

displaced downwards until it eventually detached from the cup. Note that 60 milliseconds after the spurt ($t =$ 160 milliseconds), there was no significant frost formation (frame *f*). Less frost formation was observed for similar experiments with higher hypobaric pressures of 15 and 20 inHg (not shown). These observations were consistent with relative humidity measurements taken during experiments within the vacuum chamber at various hypobaric pressures (Table 1).

Figures 3a show individual frames from videos of the spray cone produced by the same commercial nozzle within the vacuum chamber under atmospheric (a) and various hypobaric pressures (b–d): 10, 15, and 20 inHg, respectively (34, 51, and 68 kPa). These frames correspond to 100 milliseconds into a 1-second spurt, which is more than the time required for the spray cone to develop fully [13]. Note how the spray cone widened as pressure was reduced and the high intensity central core became shorter

TABLE 1. Variation of Relative Humidity With Hypobaric Pressure Within Experimental Vacuum Chamber

Hypobaric pressure (in Hg)	Relative humidity (%)
0 (atmospheric)	31
5	27
10	24
15	22
20	22

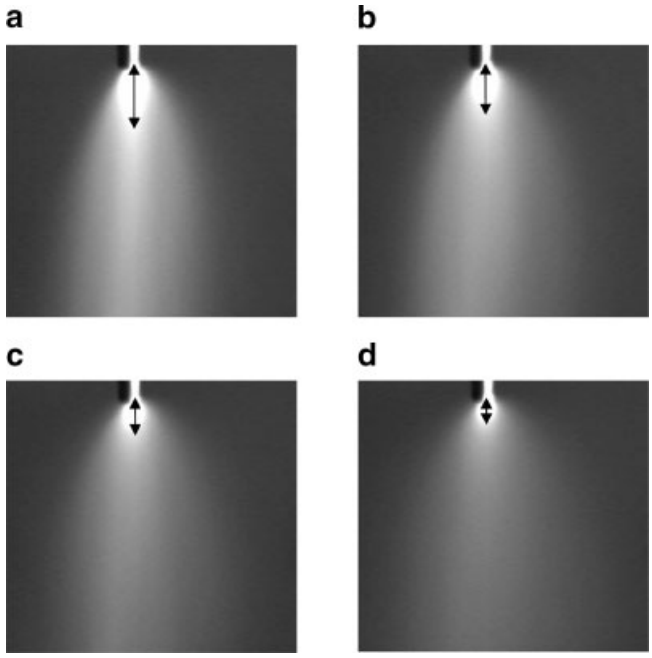

Fig. 3. Frames from videos of CSC spurts released within the vacuum chamber under (**a**) atmospheric and (**b**) 10, (**c**) 15, and (**d**) 20 in Hg of hypobaric pressure. Each frame corresponds to 100 milliseconds into a 1-second spurt. Arrows indicate approximate jet length based on the region of intense light reflection.

in length and width, suggesting a much more homogeneous atomization at hypobaric pressures. Furthermore, the jet length of spray (indicated by the arrows) decreased as pressure was reduced implying an enhancement in liquid evaporation.

Figure 4 shows skin phantom surface temperatures as a function of time under atmospheric pressure and 5, 10, 15, and 20 in Hg (17, 34, 51, and 68 kPa) of hypobaric pressure. Minimum temperatures decreased and the time when they were reached was prolonged for lower pressures (higher hypobaric pressures). This suggests that evaporation of liquid cryogen under hypobaric pressure was enhanced due to larger adiabatic expansion upon release from the pressurized tank (~7 bar) to a lower pressure environment. Note, however, that the cooling rates for all hypobaric pressure curves were lower than that at atmospheric pressure. This explains why the maximum surface heat fluxes were reduced with respect to that at atmospheric pressure, as shown in Figure 5. Nevertheless, the areas under the curves in Figure 5 increased as pressure decreased. Consequently, overall heat extraction at the skin model surface was enhanced by lowering pressures, as shown in Figure 6.

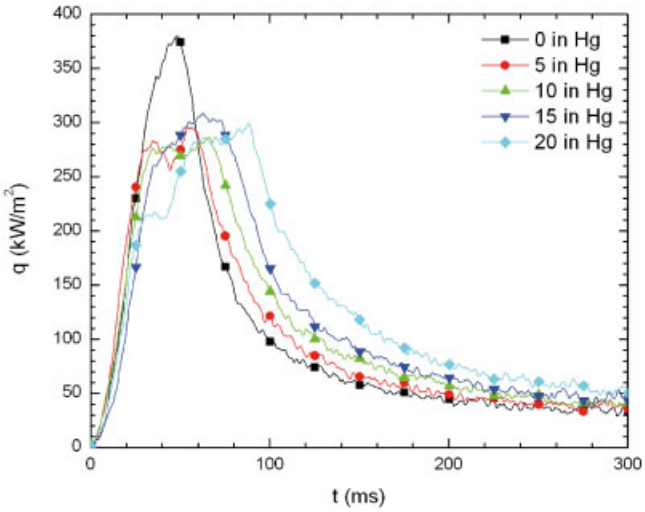

Fig. 5. Skin phantom surface heat fluxes as a function of time for 0 (atmospheric), 5, 10, 15, and 20 inHg of hypobaric pressure. [Figure can be viewed in color online via www.interscience.wiley.com.]

DISCUSSION

In regards to the effects of hypobaric pressure on CSC spray/surface interactions, it can be noted in Figure 1 that the skin may be significantly indented upon spray impingement. This indentation may be as deep as 2 mm and might adversely affect CSC efficiency, as documented in a recent study by Basinger et al. [14]. Local hypobaric pressure induces the formation of a convex surface (Fig. 2a), which minimizes cryogen "pooling" that otherwise would occur on an indented surface; the former is expected to result in more efficient heat extraction during CSC. We are currently conducting experiments to determine the effects of convex surfaces on heat extraction. Furthermore, the depletion of air within the suction cups also removes water vapor, which as surface temperature decreases, condenses, and freezes, and has an adverse effect on heat extraction during [15] and after [16] CSC deposition.

An additional benefit of the vacuum-assisted procedure is that upon release within the cup, cryogen evaporates and expands, increasing the pressure inside the cup and, thus, loosening the tight skin seal. This may be an important design consideration for more professional handpieces that incorporate suction cups, since no pressure release valve

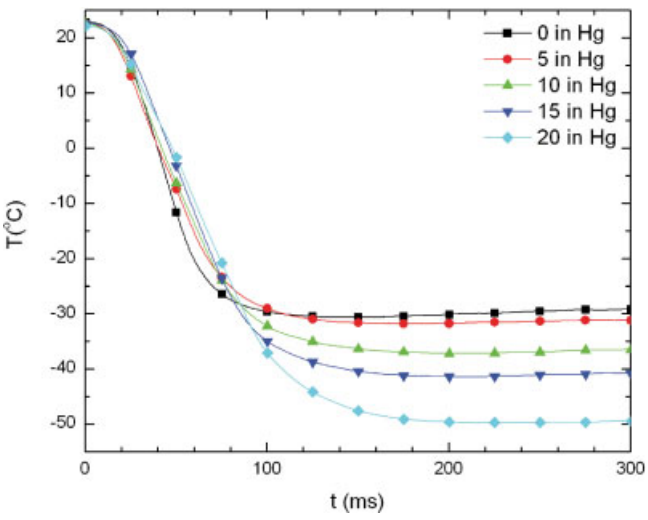

Fig. 4. Skin phantom surface temperatures as a function of time for 0 (atmospheric), 5, 10, 15, and 20 inHg of hypobaric pressure. [Figure can be viewed in color online via www.interscience.wiley.com.]

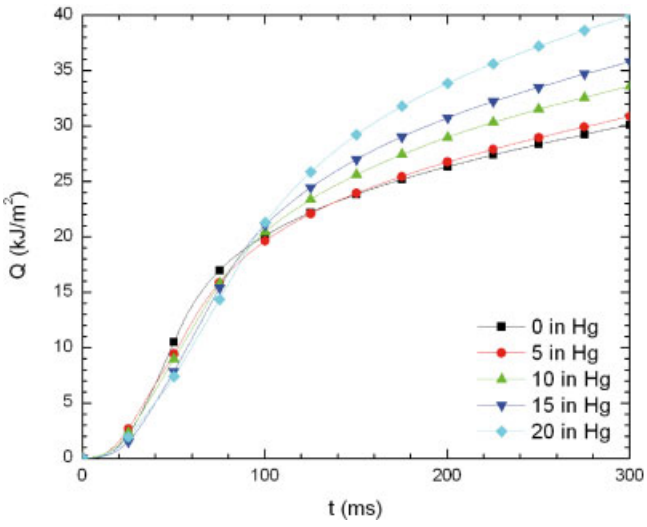

Fig. 6. Skin phantom surface heat removal as a function of time for 0 (atmospheric), 5, 10, 15, and 20 inHg of hypobaric pressure. [Figure can be viewed in color online via www.interscience.wiley.com.]

may be necessary. However, if the cup volume is too small and the cryogen released during a spurt is too great, the cup may be released before the laser pulse is delivered, which may have at least two detrimental effects. First, cryogen delivered after the cup is released may induce skin indentation and frost formation, which occurs under ambient atmospheric pressure [16] and, second, if the time lapse between the end of the spurt and laser irradiation is comparable to the relaxation time of the dilated vessels, the advantage of temporarily dilating them may be lost.

Spurts released under atmospheric pressure (Fig. 3a) show a higher intensity of reflected light—more noticeable within the spray cone center, which presumably denotes a greater number and size of droplet particles in that region. Conversely, as pressure within the chamber decreases, it is evident that the jet length shortens (indicated by the arrows) and a much more homogeneous and presumably finer atomization is achieved [17] (Fig. 3b), resulting in more uniform deposition of cryogen over the skin cross-sectional area. This phenomenon occurs because the exit velocity of the expelled cryogen jet increases, producing higher shear stresses with the surrounding steady gas, and because lower ambient pressure induces a greater adiabatic expansion of the cryogen droplets, which enhances evaporation.

At the same distance from the nozzle, however, the spray droplets may be smaller and slower, an issue that may be detrimental to heat extraction, as shown previously by Karapetian et al. [18]. It should be noted that the rate of change of surface temperatures when a skin phantom is sprayed under hypobaric pressures (5, 10, 15, and 20 in Hg) is lower as compared to atmospheric pressure (Fig. 4). However, it may also be noted that the minimum surface temperatures reached under hypobaric pressures are lower than those under atmospheric pressure. This is an indication that two evaporating and competing phenomena are occurring simultaneously. First is the evaporation rate of droplets in-flight, which is increased by lower pressures and thus reduces the size and velocity of cryogen droplets reaching a target at the same distance. Consequently, the cooling rates of droplets in-flight and the maximum or critical heat flux for the experiments performed at atmospheric pressure are faster and greater, respectively, than those at hypobaric pressures (Fig. 5). This result could have a detrimental effect on heat flux if the cryogen mass deposition was already at or near optimum under atmospheric pressure. Second is the evaporation rate of the deposited cryogen, which is also increased at lower pressures. This has a positive effect on total heat extraction because it enhances the evaporation of the liquid film, which then extracts a larger amount of heat from the skin. This is corroborated by the fact that even though the maximum heat flux is higher under atmospheric pressures, the total surface heat extraction increases with lower pressures (Fig. 6).

Finally, it is worth noting that a complementary feasibility study (Part I) indicated that about 35% lower fluence is needed to induce the same level of purpura intensity and subsequent PWS lesion blanching. This suggests that less efficient CSC may be required for laser therapy under hypobaric pressures as compared to that at atmospheric pressure. In fact, CSC may have to be adjusted to prevent overcooling. Conversely, maintaining the same or better cooling efficiency may allow safe use of even higher laser fluences. It is important to note, however, that while overcooling poses a higher risk for epidermal and dermal cryo-injury [19], variation of spurt duration [11], nozzle-to-surface distance [20] and/or nozzle geometry [13], could be easily adjusted during CSC under hypobaric pressure to avoid overcooling.

CONCLUSIONS

It was observed that the skin bulges within the suction cup forming a convex surface leading to the deposition of a thinner cryogen layer and, consequently, higher heat fluxes. Insignificant frost formation is observed during and after cryogen deposition on human skin under hypobaric pressures since air humidity is decreased during the suction process. A larger adiabatic expansion induces better and more homogeneous atomization, which increases the liquid cryogen evaporation rate; the combination of all these effects lowers surface temperatures and increases total heat extraction. We recognize that the distance between the spray nozzle and skin must be adjusted to account for the enhanced evaporation of droplets in-flight. Finally, implementation of hypobaric pressures during laser therapy is straight-forward and should be pursued as an adjunct for those lesions that are initially a red-pink color (such as those of infants and young children) and for poorly-responding PWS, which are believed to be composed primarily of small capillaries (10–30 μm in diameter) that must be dilated for proper thermal confinement during laser exposure. Further studies are underway to optimize the relevant parameters, such as pressure, and cooling and timing of laser irradiation.

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