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Coupling effect of hypobaric pressure and spray distance on heat transfer dynamics of R134a pulsed flashing spray cooling

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ABSTRACT

Cryogen spray cooling (CSC) with R134a has been commonly used in the laser dermatology. Lots of strategies have been proposed to improve the cooling capacity of CSC, among which the hypobaric pressure method (lowering local pressure on the targeted skin) is of great potential. This paper experimentally investigated the coupling effect of hypobaric pressure and spray distance on the surface heat transfer dynamics of R134a pulsed flashing spray cooling. The absolute pressure within the vacuum chamber (i.e. spray back pressure) could be adjusted from 100 kPa to 0.1 kPa, and the spray distance was from 10 mm to 50 mm. It's found that lowering the pressure enhanced the spray angle and droplet evaporation rate. A transitional pressure of 10 kPa was found, under which the spray pattern became much more homogeneous, while droplet diameter and velocity decreased much faster with the reduction of the pressure. At the rather short distance (10 mm), lowering pressure always benefited enhancing the cooling capacity, which produced 2.6 times maximum heat flux with 0.1 kPa than that with the atmospheric pressure (from 247 kW/m^2 to 641 kW/m^2). For other longer spray distances (>10 mm), nevertheless, lowering the pressure slightly helped to increase the maximum heat flux with the pressure larger than the transitional pressure, while further lowering the pressure caused the rapid decrease of the maximum heat flux. The hypobaric pressure should be appropriately chosen in conjunction with spray distance to ensure higher cooling capacity for the CSC. The suitable spray distances coupling with the pressures were recommended.

1. Introduction

PWS is one kind of congenital vascular birthmarks in the dermis that occurs in approximately 0.3–0.5% of infants [1]. The best choice for the treatment of PWS is the laser surgery with the selected wavelength to cause permanent thermal damage to the target blood vessels in the dermis via the principle of selective photothermolysis [2]. However, the competitive absorption of laser energy by the melanin in normal tissue (especially in epidermis) will not only reduce the therapeutic effect but also cause irreversible thermal damage to the epidermis, due to the close absorption peak of laser energy at the selected wavelength (typically 585 nm and 595 nm) between the oxyhemoglobin (HbO_2) and melanin. The efficacy of selective photothermolysis depends on the extent of epidermal pigmentation, optical shielding by blood and PWS vascular anatomy and morphology [1,3]. Generally, high melanin content results in increased nonspecific thermal injuries of epidermis and thus decreased treatment efficacy.

Nelson et al. firstly suggested using CSC to protect epidermis from thermal damage. Prior to the laser irradiation, cryogen (usually R134a with the saturated temperature of about −26.2 °C at atmospheric pressure) is sprayed on the skin surface with a short spurt (less than 100 ms), leading to quick reduction of the skin surface temperature [4]. In this way, CSC can selectively cool down the epidermis and enhance the threshold laser fluence for the epidermis thermal damage, which allows the safe use of higher laser energy [5]. Although the CSC assisted laser therapy has been regarded as the gold standard of the PWS treatment, lots of clinical studies have demonstrated that majority of PWS failed to clear completely (less than 20%) [1,3]. In order to improve the therapy outcome of the PWS, much effort has been conducted in the past ten years to optimize the cooling capacity of the CSC during the laser therapy including the effect of spurt duration [6], spray distance [7,8], spray angle [9] and the initial temperature of the substrate on the heat transfer dynamics [10], *etc.* Their results showed that the spurt duration and spray angle had little effect on the sur-

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face heat flux (q) and heat transfer coefficient (h). In contrary, q and h were largely dependent on the spray distance and the initial temperature of the cooling substrate, where shorter spray distance and higher initial temperature could result in larger heat flux and heat transfer coefficient. Pikkula et al. studied four different spray nozzles on the spray characteristics and the heat transfer dynamics of the CSC [11,12]. Their results showed that the heat removal from the cooling surface was little affected by the different sprays although the distinct nozzles could result in much difference of spray droplets diameter and velocity. Dai et al. and Zhou et al. have comparatively studied the cooling capacity of the CSC using different cryogens of R134a and R404a [13,14]. Their results implied that R404a can enhance the cooling efficacy to some extent because of its lower boiling point (about −46.5 °C at the atmospheric pressure). However, R404a has not been commercially used in the clinical surgery.

Recently, Aguilar et al. suggested a hypobaric pressure-modulatable technique in which a close chamber and a vacuum pump were used to lower the spray pressure and locally induce the vasodilation for the benefit of the easier absorption of the laser energy for the small blood vessels of the PWS skin [15–17]. Moreover, this novel treatment modality is promising to improve the CSC cooling efficacy by reducing the skin surface temperature and increasing the total heat extraction of the skin surface [18]. Their work involved one spray distance and four hypobaric pressures, which has given some basic insight and meaningful guidance for the use of the hypobaric spray cooling in the clinic.

In general, all the researches for the optimization of CSC mentioned above especially by Nelson and Aguilar group indeed have made great contributions to improve the PWS treatment efficacy and deep understanding of heat transfer characteristics of pulsed cryogen spray cooling. The motivation of the present study is to provide further investigation into the physical mechanism of the surface heat transfer dynamics triggered by the impact of the pulsed flashing spray using R134a under vacuum conditions, in which larger spray back pressure range (from 0.1 kPa to 100 kPa) and multiple spray distances (from 10 mm to 50 mm with the interval of 10 mm) are systematically considered. Besides, the results of this research would provide references for the high power thermal management such as electronics, avionics and electro-optics, demanding high heat flux but relatively low cooling surface temperature [19,20].

2. Experimental facility and data processing

2.1. Spray system

Fig. 1(a) shows the schematic of the experimental system. It consists of several subsystems including the cryogen spray system, the vacuum system, the high speed camera system (CCD), the phase Doppler particle analyzer (PDPA) system, surface temperature measurement system, and data acquisition and control system. The spray system has a pressure container for the storage of R134a cryogen (Dupont, USA) with the pressure of about 0.6 MPa at the room temperature of 20 °C, a fast response solenoid valve (B2021SBTTO24DVC by Gems, USA) which can open or close within 5 ms, a straight tube nozzle made of a stainless steel and its geometry resembling that of commercial nozzles used in the clinical devices with length of 63.5 mm and inner diameter of 0.81 mm (The schematic of nozzle is shown in Fig. 1(b)). The nozzle is perpendicular to the substrate surface, which is different with that of clinical use with 30 degree inclination angle. However, Aguilar's study found that the angle (between the axis perpendicular to the substrate surface and the nozzle line) ranged from 0° to 75° had insignificant impact on the surface temperature and heat flux of CSC [9]. So our study is comparable with the real condition in commercial laser device. The vacuum system includes a small test vacuum chamber (250 mm × 250 mm × 250 mm) with three transparent glass windows used for the measurements of CCD and PDPA, a large vacuum chamber with the volume of 0.2×10^{9} mm^3 connected to the test vacuum chamber which keeps the pressure relatively constant during the spray (The pressure has a little increase of no more than 0.06 kPa in the 50 ms spray), and a vacuum pump (PT 70F by Leybold, Germany) which extracts gas from the vacuum chamber and the minimum value of pressure within the vacuum chamber can be reached about 0.1×10^{-3} kPa. A pressure transducer (PTX7517 by GE, US) is installed inside the test vacuum chamber ranged between 0 and 103 kPa with the accuracy of ±0.2%. A one-dimensional positioned with space resolution of 0.1 mm is set inside the test vacuum chamber to adjust the distance between the nozzle and cooling substrate. The data acquisition and control system mainly consists of a computer and a DAQ board (NI: M-6251, USA), which not only captures the temperature and pressure signals but also generates pulsed signals to control the open or close of solenoid value. In the following of the paper, the absolute pressure in the test vacuum chamber is called as the spray back pressure or abbreviated to pressure.

2.2. Spray imaging

With scattered illumination by a high power Xe lamp (PLS-SXE300, China), a high-speed video camera (MotionXtra HG-100, USA) with shutter speed of 997 μs is used to record the spray pattern. The schematic of the scattered illumination is showed in Fig. 1(c). The camera and the lamp are positioned in the same horizontal plane, with the camera viewing perpendicularly to the spray axis. The angle (α) between the camera axis and the lamp axis is about 90°. The light from the lamp will be scattered into the camera by the liquid droplets, resulting in the spray image. Consequently the spray image is determined by the intensity of the scattered light. The camera is placed about 500 mm from the spray axis, which can catch the field of view of about 40 × 30 mm^2. All pictures are taken at the speed of 1000 fps and the same resolution of 1024 × 768 pixels.

2.3. Droplet diameter and velocity measurements

A phase Doppler Particle Analyzer (PDPA by TSI, US) is used to measure the velocity and diameter of the droplets in the spray of R134a simultaneously (Fig. 1(d) shows the photograph of PDPA measurement). The PDPA generates four interfacing laser beams of two wavelengths, 514.5 nm (Channel one) and 488 nm (Channel two). Two beams focus on a probe volume, typically smaller than 1 mm^3. The diameter and velocity of droplets can be measured simultaneously. When droplets go through the probe volume, these beams are interfaced and a Doppler signal with a frequency shift proportional to the droplet velocity is generated. The phase difference between the signals collected by adjacent detectors is proportional to the droplet diameter. Before taking the measurements, the optimum values of the PDPA parameters have to be selected including the diameter range (0–1.0 mm), velocity range (0–100 m/s) and the laser power (1.0 W).

2.4. Temperature measurement method

The temperature measurement method is schematically shown in Fig. 2. A epoxy resin substrate (50 mm × 50 mm × 5 mm) is used as cooling substrate due to its similarity of thermal property with that of human skin [21–24]. The thermal properties of epoxy resin are shown in Table 1 and the thermal properties of epidermis are