Comparative investigation on the spray characteristics and heat transfer dynamics of pulsed spray cooling with volatile cryogens

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Abstract

Cryogen spray cooling with R134a has been widely used in laser dermatology such as port wine stain to prevent unspecific thermal injury due to the absorption of laser energy by melanin in the epidermis. However, R134a spray cooling has shown poor efficacy for darkly-pigmented human skin. This paper presents an experimental study on the spray characteristics and heat transfer dynamics of pulsed spray cooling with three kinds of volatile cryogens (R134a, R407C and R404A), the latter two of which have potential to improve the cooling effect due to their lower saturation temperature. The spray patterns reveal that R404A generates the narrowest spray width and the smallest cooling spot on the cooling surface, which facilitates the accurate control of the cooling area. The R404A spray produces the smallest droplet diameter and the largest velocity, whereas the opposite applies to the R134a spray. The droplet temperature measurements show that R404A spray has the lowest temperature of spray, while the R134a spray has the highest. However, the non-dimensional temperature in the decrease period shows a similar pattern, independent of the cryogens. For the common spray distance in laser surgery (30 mm), R404A spray leads to the lowest surface temperature and highest heat flux, and also removes the most heat from the cooling surface, indicating that R404A has the strongest cooling capacity. Furthermore, R404A spray has the least liquid film resistance time on the cooling surface, implying that it provides the best selectively spatial cooling effect. The results of spray and heat transfer all reveal that R404A possesses significant superiority with regard to pulsed spray cooling for epidermis protection, with the potential of substituting the current R134a in the application of laser dermatology, especially in the case of darkly-pigmented human skin.

1. Introduction

Pulsed Dye Laser (PDL) at a wave length of 585/595 nm has been the common choice for the treatment of vascular skin lesions, such as port wine stain (PWS) [1], based on the principle of selective photothermolysis [2]. The objective of laser treatment for PWS is to cause selective thermal damage to subsurface targets (chromophores) without damaging the overlying normal epidermis [3]. However, the absorption of laser energy by melanin particles in the epidermis will not only reduce the amount of laser energy reaching the disordered blood vessels but also negatively influence the therapeutic outcome, by simultaneously causing irreversible thermal damage to the normal epidermis. Cryogen spray cooling (CSC) of several tens of milliseconds (usually less than 100 ms in clinical surgery) can be introduced in order selectively to decrease the temperature of the superficial layers of skin, with the purpose of minimizing or eliminating laser-induced thermal injury to the epidermis [4–6]. Currently, the standard procedure for the treatment of PWS through PDL aided by CSC is as follows: In order to avoid possible thermal damage of epidermis, a cryogen spurt with a short period of time (<100 ms) will be sprayed to the skin surface before the laser exposure. Then the laser irradiation starts several tens of milliseconds after the end of cryogen spurt. This means that there is no laser energy acting on skin surface before and during the whole cryogen spray and the most period of liquid film resistance time until the start of laser irradiation. Therefore, heat transfer on the surface of cooling substrate can be treated as a non-heat source problem since heat generation from blood perfusion and metabolism can be neglected due to the short process (<0.5 s) of CSC as well as the extremely thin epidermis (<0.1 mm). Besides, cryogen spray cooling is also a technology with increasing interest for electronic cooling and other high heat flux removal applications [7–9].
Cryogen R134a (saturation temperature $= 26.1 \, ^\circ\text{C}$ at atmospheric pressure) is currently the only cooling agent employed in clinical settings. Many studies have been conducted to investigate the surface heat transfer behaviors of CSC with R134a, including the effect of spurt duration [10], spray distance [11,12], spray angle [13], the initial temperature of the substrate [14], spray back pressure [15–17], nozzle size [18,19], etc. Although great progress with regard to improving the therapeutic outcome of PWS has been made in the past ten years for white human skin, nonspecific thermal injuries still commonly occur even when irradiated at a very low radiant exposure due to insufficient heat removal from the epidermis with R134a spray cooling for darkly-pigmented human skin [20,21], since much more melanin is contained in the epidermis. In addition, clinical studies have found that it was rather difficult to clear the disordered blood vessels completely for PWS patients (less than 20%) [22,23]. One important reason is that the R134a spray cannot provide sufficient cooling to the epidermis, which limits the treatment with high laser energy.

New cryogens with a lower saturation temperature and higher volatility are essential for enhancing the cooling capacity of CSC, based on the current spray technique. Alternatively, cryogens R407C and R404A meet the requirement, with a far lower saturation temperature of $-43.6 \, ^\circ\text{C}$ and $-46.5 \, ^\circ\text{C}$ at 1 atm, respectively. Moreover, they share a similar feature with R134a in that they are non-toxic to the human body and friendly toward ozone depletion. Dai et al. [24] first carried out preliminary studies on the heat transfer of R404A spray cooling for the laser dermatology of PWS. They used a 30 $\mu$m diameter thermocouple, embedded at a 100-$\mu$m depth below the phantom surface, to measure the temperature at a long spray distance (85 mm). Their work revealed that R404A spray cooling produced a lower surface temperature than that of R134a, and did not cause any cold injuries to skin within a 300 ms spray duration. In fact, the modelling prediction of tissue freezing by Li et al. during cryogen spray cooling with R134a, R407C and R404A revealed that cold injury did not occur if the spurt duration remained below 3.3 s, 2.2 s and 1.9 s, respectively [25]. Zhou et al. [26] carried out an experimental study on the heat transfer of R404A spray cooling using epoxy resin substrate. They employed a fast-response thin film thermocouple to measure the surface temperature of epoxy resin directly and calculated the surface heat flux and heat transfer coefficient using Duhamel’s theorem. Their results found that the minimum surface temperature appeared at the spray distance of 30 mm, and that a slightly higher heat flux could be obtained for a shorter spray distance.

Although lots of work has been done to investigate the heat transfer dynamics of CSC, little of it concerned the spray’s characteristics and its interaction with surface heat transfer. Furthermore, no study on R407C spray cooling or a comparison of spray and heat transfer between different cryogens has been reported, to the best of our knowledge. Therefore, more efforts should be devoted to developing a better understanding of the complex flashing spray and ensuing heat transfer on the substrate surface for different cryogens. This paper presented a comparative and comprehensive study on both the spray characteristics and heat transfer dynamics of pulsed spray cooling for application in laser dermatology, using the currently employed R134a, and two other new cryogens of R404A and R407C, which have the potential to replace R134a for darkly-pigmented human skin. The spray characteristics, including the spray pattern, droplet diameter, velocity and temperature, and the heat transfer dynamics, including the variations in transient surface temperature, heat flux, heat transfer coefficient and heat removal versus time, are investigated, respectively.

2. Experimental system and numerical methods

2.1. Spray rig

Fig. 1 shows a schematic of the experimental system including the spray rig and the measurement systems. The liquid cryogen is stored in the pressure container, connected with a high pressure N$_2$ bottle. A solenoid valve with a response time of less than 5 ms (B2021SBTTO24DVC by Gems, USA) is used to control the open and closing of the pulsed spray. The straight-tube nozzle made of stainless steel fits tightly into the outlet of the solenoid valve,
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