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Parameter Optimization of Cryogen Spray Cooling for Skin Protection during Hyperthermal Laser Lipolysis

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Abstract
Non-invasive hyperthermal laser lipolysis has attracted researcher's interest because of its obviously advantages. Owing to the competitional absorption of laser energy in skin with other chromophores, it is necessary to develop efficient skin cooling technology, to protect epidermis and dermis from thermal damage. Temperature changes of pigskin epidermis under 1210nm laser irradiation with different energy (6W~12W) and irradiation duration (3s~13s) were obtained by infrared thermal imager. The experimental results showed that the epidermis temperature will exceed the safety threshold of 47°C, except laser energy is 6W and irradiation duration is 3s~5s. For cold protect of skin, multi-pulsed cryogen spraying cooling (MCS) by using R134a was introduced. Numerical simulation results suggested that fat-dissolving can realized with skin cold protection by hyperthermal laser lipolysis with energy of 6W and irradiation duration of 7s, accompanied by MCS with pulse duration of 10ms, pulse interval of 2000ms and pulse number of 5.

Keywords
Hyperthermal laser lipolysis; Multi-pulsed cryogen spraying cooling; In vitro experiment; Numerical simulation

Introduction

Obesity is a nutritional and metabolic disorder caused by excessive accumulation or abnormal distribution of adipocyte, which has become a serious global public health problem. According to World Health Statistics 2021 [1] released by the WHO, the age-standardized prevalence of obesity in adults worldwide has increased 1.5 times with 650 million. For obese patients, effect of weight control simply through exercise and diet therapy is often not ideal, more and more patients hope to achieve body contouring through surgery. Tumescent anesthesia liposuction was introduced in the 1970s, but this invasive surgery may lead to complications such as subcutaneous infection, permanent sensory nerve damage [2]. Subsequently, different non-invasive or minimally invasive lipolysis procedures have been developed as cryolipolysis [3], radiofrequency energy [4], high-intensity focused ultra-sound [5] and laser-assisted lipolysis [4,6].

Since current century, laser lipolysis based on selective photo-thermal effect has attracted the attention of many researchers. Based on the apoptosis mechanism of adipocyte, the methods of laser lipolysis include hyper-thermal (50~65°C) and high-temperature (42~50°C). Considering photo-thermal selectivity, near-infrared lasers are mainly applied in the literature including diode laser (920nm, 924/975nm, 980nm) and Nd:YAG laser (1064nm, 1319nm, 1320nm, 1440nm, 1444nm) [7]. In vitro laser lipolysis is mainly used in high-temperature lipolysis to avoid the thermal damage of normal tissue. Low-energy laser around 635nm was mainly used by researchers early to achieve lipolysis effect via photo-modulation [8]. In 2017, Decorato et al. [9] irradiated in vitro directly via 1060nm laser from onto the skin surface for laser lipolysis, while cooling the skin contact with sapphire window. Moon et al. [10] and Vas

et al. [11] used the combined technology for lipolysis in vitro with 1060nm/635nm and 1064nm/2940nm respectively. To improve the laser energy to achieve in vitro hyper-thermal lipolysis, it is urgent to develop efficient skin cooling technology, which can achieve efficient lipolysis of subcutaneous fat and protect skin tissue from thermal damage.

Our research group has previously proposed a technique of multi-pulse spray cooling coupled with laser lipolysis for 1064nm Nd:YAG laser, which achieved lipolysis effect of 2~4mm below the dermis while protecting epidermis from thermal damage [12]. But the absorption capacity of 1064nm ray by water is higher than that of adipocyte increased risk of tissue damage. In contrast, the absorption capacity of 1210nm ray by adipocyte is greater than water. Cryogen spray cooling (CSC) is to spray R134a with low boiling point and high volatility onto skin surface to instantaneously and selectively refrigerate the skin through phase change boiling heat transfer, which has been widely applied in laser treatment of port wine stains (PWS) [13]. The treatment and cooling object for PWS is blood vessels in dermis and melanin in epidermis respectively, while for laser lipolysis, the treatment object is subcutaneous fat and cooling target of CSC extends from epidermis to dermis. To study the clinical effect of 1210nm laser coupled CSC, it is expected to achieve in vitro non-invasive hyper-thermal lipolysis.

Explicitly, the motivation of this article is carried out in vitro laser lipolysis experiment using streaky pork similar to human adipose tissue. The temperature changes of the adipose tissue epidermis were obtained by infrared temperature measurement, and the effect of hyper-thermal lipolysis was analysed quantitatively. Furthermore, the parameters of laser lipolysis coupled with cryogen spray cooling were obtained by numerical simulation, which provided guidance for in vitro non-invasive hyper-thermal lipolysis.

Experimental system and method

The experimental facility of in vitro laser lipolysis, as shown in Figure 1, consists of a 1210nm laser (BrightLase Ultra-100, QPC laser, USA), an infrared thermal imager (SC620, FLIR System, Inc., USA), an electric thermostatic drying oven (202-2AB, Taiste Instruments Co., Ltd., China), data acquisition and control system.

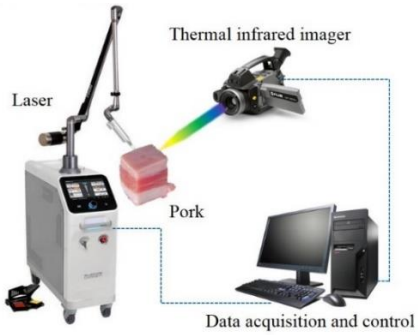


Figure 1. The experimental facility for in vitro laser lipolysis

The energy range of continuous laser is 0~22W, and the laser-spot diameter is adjustable in the range of 0.46 to 2.72cm. The laser fiber probe was fixed 2cm away to vertically incident laser on the surface of the pigskin, forming a laser spot with a diameter of 9mm. Furthermore, real-time temperature responses of the pigskin surface were measured by infrared thermal imager. A data acquisition board of 16-channels (USB-6251, NI, USA) was used to complete the acquisition, transmission and conversion of experimental data. The ambient temperature and humidity were 26°C and 56%, respectively.

Laser energy (*E*) and irradiation duration (*t*) are crucial parameters, both of which should be controlled within a reasonable range to achieve desired therapeutic effect. The influence of different laser energy and irradiation duration on the effect of laser lipolysis was firstly investigated. *E* is fixed at 6W, 9W and 12W, and *t* is adjusted from 3 to 13s in step of 2s.

Mathematical model and numerical method

Multi-layered model for skin

The skin tissue can be simplified into a two-dimensional axisymmetric three-layer homogeneous model, as shown in Figure 2. The rectangle computational area of 12mm (r_k) × 17.1mm (z_k) is divided into epidermis, dermis and subcutaneous fat layer, with the thickness of 0.1mm, 2mm and 15mm, respectively. It is assumed that each layer has homogenous optical and thermophysical properties [12].

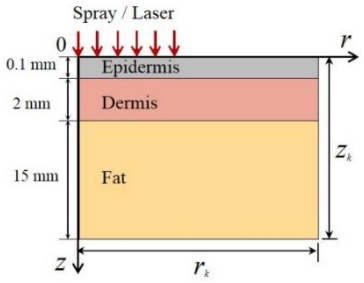


Figure 2. Computational domain of the homogeneous multi-layer skin model

Bio-heat transfer model

During the short duration of laser irradiation, blood perfusion and metabolic heat production can be ignored. Simplified Pennes Bio-heat transfer equation [14] was employed to calculate the temperature distribution in skin and subcutaneous fat tissue under laser irradiation:

$$\rho_i c_i \frac{\partial T_i(r,z,t)}{\partial t} = k_i \nabla^2 T_i(r,z,t) + \frac{Q_i(r,z)}{t_p} \qquad i = e,d,s \tag{1}$$

where T_i and t are the temperature and time. ρ, c and k are the density, specific heat and heat conductivity, separately. The subscripts e, d, and s denote epidermis, dermis, and subcutaneous fat, respectively. t_p is the laser pulse width, and Q is the laser energy per unit volume absorbed by tissue, which can be determined by:

$$Q(r,z) = E \times \frac{A(i,j)}{\Delta V} \tag{2}$$

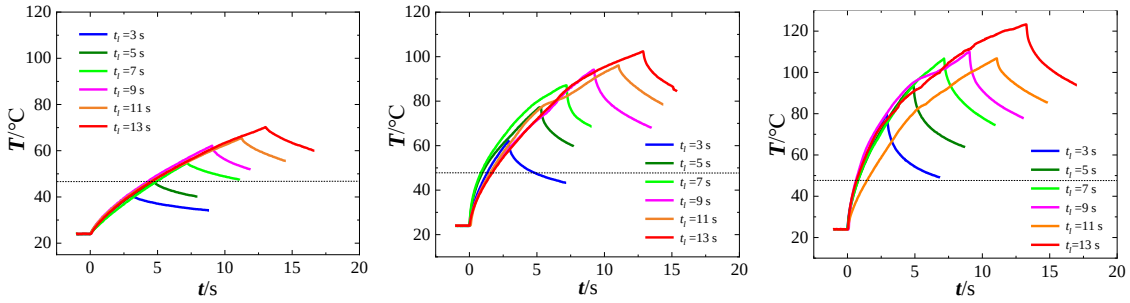
where E is the energy of photon, $A(i,j)$ is the photon deposition amount per computational cell and ΔV is the cell volume. MCS is implemented simultaneous with laser irradiation to prevent skin tissue from thermal injury. For MCS, the surface heat flux obtained from the experiment can be used for the second kind of boundary conditions on the skin tissue surface (z=0) [15]:

$$-k_e \left.\frac{\partial T}{\partial z}\right|_{z=0} = q(t) \tag{3}$$

where the $q(t)$ is the surface heat flux.

Results and Discussion

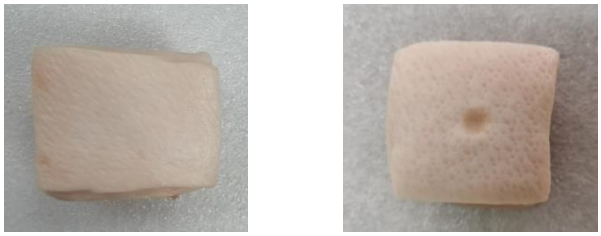
The temperature variations of laser spot center measured via infrared thermal imager are presented in Figure 3. The temperature of laser center rises with the increase of irradiation duration and decreases immediately after the termination of laser irradiation. For fixed laser energy, T_{max} of pigskin surface increases with increasing irradiation duration. Irradiated with laser energy of 6W, 9W and 12W, the highest temperatures of pigskin surface at t=13s are 70°C, 102°C and 123°C, respectively. T_{max} will increase with the increase of laser energy under same irradiation duration. As can be seen from Figure 3, temperatures of pigskin surface are all higher than the safety threshold (47°C) of epidermis [16] except for E=9W and t=3s.



(a) E=6W (b) E=9W (c) E=12W

Figure 3. Temperature variation of laser irradiation center on pig-skin surface with duration

The appearance changes of pigskin after laser irradiation are shown in Figure 4 when E=12W. There is no obvious change in pigskin surface when t≤7s (Figure 4(a)). When t≥9s, lightly yellow thermal lesion appears (Figure 4(b)). Table 1 summarizes the temporal thresholds for appearance change of pigskin surface and damage of fat tissue after laser irradiation with different energy. According to Table 1, pigskin surface has been thermally damaged under the laser irradiation duration larger or equal to 9s, 9s and 11s, when laser energy is 6W, 9W, and 12W, respectively. Thus, auxiliary cooling technique is needed to protect normal skin tissue from thermal damage to keep efficiency of hyper-thermal lipolysis.



(a) No lesions (t≤7s) (b) Thermal lesions (t≥9s)

Figure 4. The appearance of pigskin under different irradiation duration (E=12W)

Table 1. Temporal thresholds for appearance change of pigskin surface and fat tissue after irradiation

Laser energy (E)	Skin surface		Fat tissue
	No lesion	Thermal lesion	
6W	t ≤ 9s	t ≥ 11s	t ≥ 11s
9W	t ≤ 9s	t ≥ 11s	t ≥ 9s
12W	t ≤ 7s	t ≥ 9s	t ≥ 9s

In order avoid the risk of epidermis thermal damage by 1210nm laser, the effect of MCS and laser coupling on pig skin is evaluated by numerical simulation. Under the laser irradiation (E=6W, t_l=7s), the results of numerical simulation were compared with the measured results of pigskin surface temperature at the center of laser spot over time. As shown in Figure 5, the numerical simulation results are in good accordance with the experimental results, which verifies the validity of the skin tissue light propagation and heat transfer model.

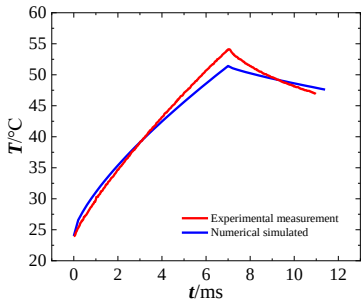
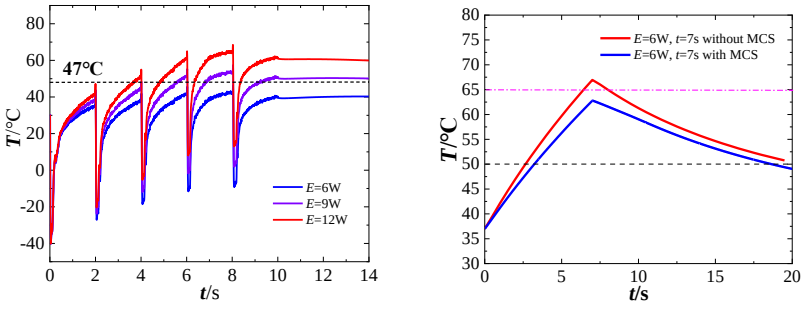


Figure 5. The comparison between the numerical simulation results and experimental results of temperature variation in laser irradiation center with time (E=6W, t_l=7s)

The change of skin tissue temperature with time was numerically simulated by fixing the laser irradiation time (t_l=7s), changing the laser power (E=6, 9, 12W), and supplemented by MCS (Δt_p=10ms, Δt_d= 2000ms, n_p=5). As can be seen from Figure 6(a), MCS can significantly reduce the epidermis temperature and make the epidermis temperature below the safety threshold of 47°C during the laser irradiation with E=6W, t_l=7s. Figure6(b) shows the temperature change over time at 2.1mm subcutaneous fat under E=6W, t_l=7s laser irradiation with or without MCS. Although fat reached the lowest lipolysis threshold of 50°C in the absence of MCS, it also exceeded the highest safety threshold of 65°C. Fat can be in the range of lipolysis temperature threshold to achieve lipolysis after the action of MCS. Therefore, MCS with proper parameter is an effective cold protection method for in vitro 1210nm laser lipolysis with high energy.



(a) Skin surface (b) At 2.1mm under the skin

Figure 6. Temperature changes of surface and internal with MCS (Δt_p=10ms, Δt_d= 2000ms, n_p=5)

Conclusions

In this paper, the in vitro laser thermal response experiment for pig skin was carried out to measure the temperature changes of pig skin surface during 1210nm laser irradiation. It is found that When the laser energy E=6W with laser irradiation time t_l>5s, and the laser energy E≥9W with laser irradiation time tl≥3 s, the external surface temperature of pig skin exceeded

the safety threshold of 47°C, which caused the risk of thermal damage to the surrounding normal skin tissue. The MCS (Δt_p=10ms, Δt_d=2000ms, n_p=5) and the laser (E=6W, t_l=7s) were coupled and synchronized by numerical simulation. The results show that the coupled parameters not only satisfy the skin surface temperature below the safe threshold, but also ensures the safe fat-dissolving temperature of the fat layer. MCS is a kind of cold protection technology with good application prospect for non-invasive hyperthermal laser lipolysis.

Acknowledgments

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