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Alternative cooling and heating as a novel minimally invasive approach for treating obesity

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ABSTRACT

Patients with obesity often suffer pain and risks arising from complications in their pursuit for a trimmer figure. Therefore, an effective and safe treatment for obesity is urgently needed. In this paper, we propose a novel minimally invasive way to treat the target obesity tissues via alternative cooling and heating produced by a microprobe. The validity of the method was evaluated through both numerical simulation and differential scanning calorimetry (DSC) experiments. Theoretical prediction presents the significant effect of typical surgery and assesses the influence of various temperature boundary conditions on the microprobe to obtain the ideal therapeutic effect. An estimation standard was also established on the basis of cryolipolysis and hyperthermia. The DSC test confirms physical and chemical changes in cells during the cooling and heating process. The treatment planning will be varied with operational target, such as longer or shorter treatment time, one or multiple probes, etc. The 3D reconstruction employing MATLAB shows a simulated destruction area. This work is expected to serve as the foundation for identifying a new cure for obesity.

1. Introduction

The accumulation of excess body fat in the body, not only brings inconvenience to people who suffer from it, but also becomes a major global public health problem. To date, nearly two million Chinese adults are obese, with an overweight percentage of 22.8%. In the developed countries, such as those in Europe and America, this proportion is higher by 30% [1,2]. As a result, the obesity treatment and fat removal have become popular areas of research with worldwide significance.

Many efforts have been made in finding the best treatment for obesity. Surgery is generally accepted as the most effective way for fat removal. In terms of applied methods, it can be categorized into invasive and non-invasive types. As the most famous fat removal method, liposuction can directly remove the adipose tissues and produce an immediate effect after the invasive surgery [3–6]. However, some patients suffer from infection and a syndrome such as massive necrotizing fasciitis caused by subcutaneous damage after surgery [7]. Consequently, the body may fail to function, and fatal complications [8–10], such as blood poisoning, may occur. As an alternative, less invasive methods have been intensively investigated to prevent the side effects of liposuction. These methods include high-intensity focused ultrasound, radiofrequency method, and treatment with infrared light. Although these methods can reduce the probability of infection, they are not effective enough. On the other hand, cryolipolysis, for example, is the latest non-invasive method for fat treatment, but takes at least two months for a full treatment [11–15]. Therefore, to balance the relationship between curative effect and direct injury, we propose a distinct and minimally invasive surgical method, in which alternative cooling and heating is introduced into adipose tissues by an inserted microprobe.

It is well known that the normal living cells cannot survive extreme temperatures. According to the concept of cryolipolysis, temperatures below 277 K can cause inflammatory destruction in adipose tissues. In hyperthermia, on the other hand, a temperature above 316 K would cause the target tissue to spontaneously lose activity, which is a mature principle for tumor treatment [16]. Meanwhile, cell viability is not only associated with temperature, but also related to the temperature changing rate. In cryopreservation, 1 and 40 K/min are acceptable cooling and re-warming rates, respectively [17–19]. Actually, low cooling rate (5–

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Nomenclature

C	heat capacity [J/m^3 °C]
D	diameter of vessel [m]
h	convective heat transfer coefficient [W/m^2 °C]
k	thermal conductivity [W/m °C]
Q_l	latent heat [J/m^3]
Q_m	metabolic heat generation [W/m^3]
t	time [s]
T	temperature [°C]
T_a	artery temperature [°C]
T_b	mean blood temperature [°C]
T_c	body core temperature [°C]
T_f	surrounding air temperature [°C]
T_w	temperature on the microprobe wall [°C]
v	velocity of blood flow [m/s]
x,y,z	Cartesian coordinates [m]
X	location

Greek symbols

ω_b	blood perfusion [ml/s/ml]
Ω	computation domain
ρ_b	density [kg/m^3]
c_b	thermal conductivity [J/kg K]

Subscripts

b	blood
u	unfrozen tissue

180 °C/min) and very high cooling rates (>5000 °C/min) would lead a high viability of cells, which, respectively, allows the cell water outflow to occur completely and thus avoids intracellular crystallization. The rapid heat flow would induce intracellular crystallization and/or vitrification before any water flows out of the cell. In other hands, a rapid cooling rate (180–5000 °C/min) would lead a low viability of cells, which allows the heat flow to prevail over water outflow (in this case, cell water crystallization would occur as water was flowing out of the cell). Crystallization is a critical factor for cell death rate [20]. Therefore, if a rapid cooling rate is applied, the death rate of cells would increase. At the same time, a relatively low re-warming rate can damage cells because of intracellular re-crystallization. Therefore, if a destruction effect is required, temperature changing rate should be induced via a high cooling rate and low re-warming rate.

In this paper, we introduce the method which has been successfully applied in the tumor treatment to implement both thermal ablation and cold devastation on the adipose tissue [21,22]. The work is dedicated to investigating the ablation and apoptotic behavior during the implementation process. Numerical simulation presents the treatment process and reveals that temperature can be employed as the sole assessment criterion for the target tissue. Meanwhile, the result of the parametric study documents the adaptability and validity of the proposed method. Additionally, the differential scanning calorimetry (DSC) experiment confirms the injury characteristics of alternative cooling and heating damage by thermal property analysis, and further illustrates the effectiveness of the treatment.

2. Material and methods

2.1. Heat transfer model and calculation domain

In an actual surgery, to maximally utilize the effective section of the surgical probe, the microprobe is supposed to be inserted parallel to the skin surface (Fig. 1(a)), which appears as the best way. The human body is prescribed as a three-layer model consisting of muscle, fat, and skin. For simplification, a 3D rectangular geometry with dimensions of 0.04 m × 0.08 m × 0.07 m (Fig. 1(b)) is selected as the analyzed spatial domain. Given the alternative cooling and heating process in the treatment, the microprobe is inserted into the middle of the fat layer and can be simplified as a cylinder of 55 mm length and 2.5 mm radius. In addition, the 40 mm long black part of the microprobe (Fig. 1(b)) serves as the effective section which introduces various temperatures on the wall. For convenience, the domain inside the microprobe is deemed vacant and the point depicted in Fig. 1(b) is the origin of the coordinates (0,0,0).

To determine the ablation and apoptotic effects on the adipose tissue and the temperature distribution around the microprobe location, we adopt the Pennes bioheat equation [23], which describes the influence of blood flow upon temperature distribution in the tissue in terms of heat sinks or sources with variable temperatures:

$$\rho c\frac{\partial T(X,t)}{\partial t} = \nabla K(X)\cdot\nabla[T(X,t)] + \rho_b c_b \omega_b(X)[T_a - T(X,t)] + Q(X,t) \quad X = \Omega \tag{1}$$

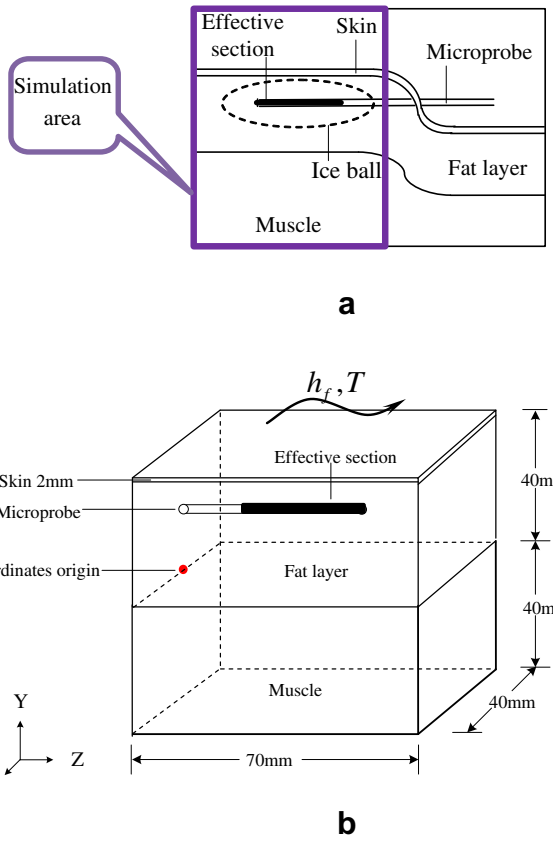

Fig. 1. (a) Sketch of a prescribed actual surgery. (b) Schematic of the calculation domain.