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Effective heating for tumors with thermally significant blood vessels during hyperthermia treatment

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HIGHLIGHTS

- ► Cooling effects by blood flow during hyperthermia treatments could be improved.
- ► The preheating strategy places zone on the blood vessel next to treated tumor region.
- ► Higher preheating zone temperature and longer preheating zone length are helpful.
- ► The preheating could prevent extreme required power deposition in the tumor region.
- ► We proposed the preheating strategy using a single blood vessel and vascular model.

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ABSTRACT

Significant cooling effect by blood vessels, particularly in treated tumor region, during hyperthermia treatment has been recognized by researchers. The present study investigated a heating strategy, using a preheating zone and adaptive optimization, to effectively reduce the cooling effect as thermally significant blood vessels flowed through treated region during hyperthermia treatment. The preheating zone is located in a vessel's entrance region adjacent to treated tumor and the heating strategy attempted to elevate blood temperature before blood flowing into the treated region. We numerically calculated blood and tissue temperatures using 3-D models and the goal of treatment was to reach a uniform therapeutic temperature in the tumor region using the proposed heating strategy. Results showed first, for large blood vessels, the heating strategy effectively elevated blood temperature at the entrance of treated tumor and reduced total tumor power deposition. Consequently, it helped to reach the ideal treated temperature on tumor more effectively, and avoided extreme power deposition due to the cooling effect of blood vessels entering the treated region. For small blood vessels, the preheating zone could further improve the treatment result. Secondly, heating flowing blood with adaptive optimization results in a unique phenomenon along blood flow paths. That is a strong convective nature of blood flow, which creates high thermal gradients in the treated region. Thus, it plays a different and significant role in adaptive optimization process as compared to thermal diffusion of solid tissues.

1. Introduction

Reaching uniform target temperature in the treated region is the desirable goal of tumor hyperthermia. However, complicated biological vasculature inside human body made the treatment hard to reach this kind of temperature distribution [1,2]. Thus, to

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Nomenclature

c	specific heat capacity, J kg^{-1} °C^{-1}
CV	convergence value
D	diameter of blood vessel, mm
H	length of control volume in z direction, cm
k	thermal conductivity, W m^{-1} °C^{-1}
L	length of control volume in x direction, cm
L_{pre}	the preheating zone length, mm
m	mass flow rate, kg s^{-1}
n	the iteration number
Nu	Nusselt number of blood vessels
P	absorbed power deposition, W m^{-3}
R	radius of blood vessel, mm
T	temperature, °C
$\dot{w}$	perfusion rate, kg m^{-3} s^{-1}
W	length of control volume in y direction, cm
x	coordinate in the x direction
y	coordinate in the y direction
z	coordinate in the z direction
ΔC_n	cost function increment at nth iteration
ΔT	temperature difference, °C

Greek symbols

π	mathematical constant
ρ	density, kg m^{-3}

Subscripts

pre	preheating zone
b	blood
bv	blood vessel
i	index of node number; index of level number of blood vessels
ideal	ideal temperature in the treated tumor or desired temperature in the preheating zone
n	iteration
s	absorbed source power
w	vessel wall

reach the goal requires precise absorbed power deposition with optimization during treatment. Recently Huang et al. [3] presented a 3-D vascular model with optimization to treat the specific interior tumor. The paper addressed significant cooling effect by large blood vessels at the entrance to the treated region, particularly for those vessels flowing into the region. Historically, the cooling effect generated by thermally significant blood vessels has been investigated by many researchers. At first, blood could carry heat out and mix with warmer tissue temperatures and Pennes [4] studied the cooling effect by proposing a blood perfusion term in the mathematical formulation. Pennes equation is an approximation to the temperature field without considering impact of large blood vessels. Chen and Holmes [5] investigated micro-vascular contributions in tissue heat transfer. They presented important properties of vascular compartments which described vascular thermal impact in their bio-heat equation. In 1980, Chato [6] investigated heat transfer of blood vessels and indicated that large arteries have significant impact on the temperature distribution of surrounding tissue. Continued from Chato's work, during 1990s, Huang [7] used a 3-D tissue and blood vessel model to numerically investigate the impacts of large blood vessels on hyperthermia cancer treatments, and Huang et al. [8] developed analytical solutions of Pennes bio-heat transfer equation with a blood vessel by neglecting axial conduction effect. Baish [9] presented heat transport by countercurrent blood vessels in the living tissues. Crezee and Lagendijk [10,11] experimentally verified temperature profiles around large artificial vessels in the perfused tissues.

Rawnsley et al. [12] illustrated the experimental blood temperature data measured in the thighs of anesthetized greyhound dogs under hyperthermic conditions heated by scanned focused ultrasound. Furthermore, Kolios et al. [13] presented ultrasonic lesion formation in rat liver with short ultrasound exposure time, approximately 8 s, which showed that blood flow played an important role in the thermal dose distribution. Lin et al. [14] used external ultrasound power and optimization to treat a cubic tumor region. Tharp and Roemer [15] showed an optimized power deposition with finer resolution during hyperthermia treatment. However, they did not consider the impact of blood flow in the treated region. Huang et al. [3] investigated optimized temperature and absorbed power density distributions using vascular model involving blood flows.

The concept of preheating blood has been raised by Crezee and Lagendijk [11,16], and Roemer [17]. They suggested preheating the large vessels before they enter the heated volume as a solution to the cooling effect of large vessels. In this study, we proposed a heating strategy to optimally realize the idea.

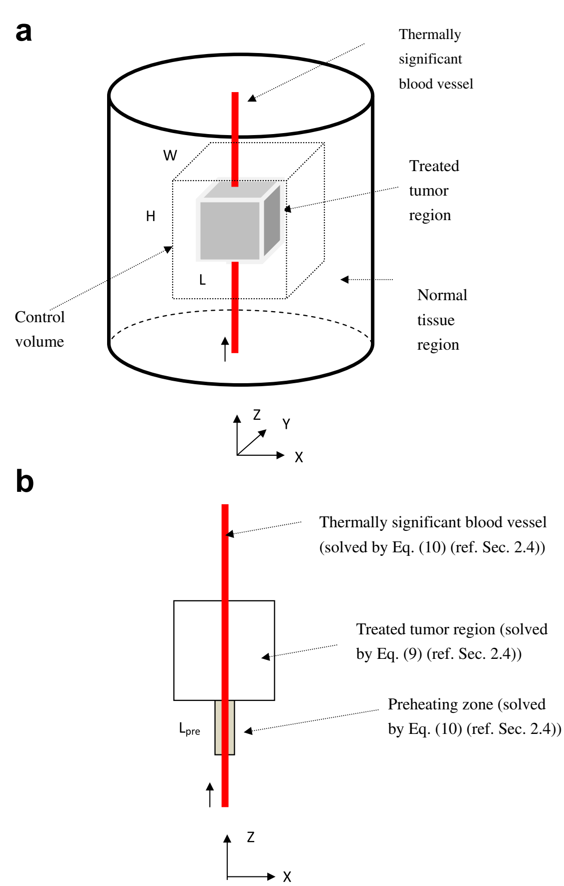

Fig. 1. (a) Shows the geometric model illustrating a thermally significant blood vessel passing through a treated tumor region at the center with blood flowing upward. (b) A projection view on X–Z plane of Fig. 1(a) indicates a preheating zone with length (L_{pre}) and temperature (T_{pre}) on a thermally significant blood vessel.