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Numerical simulation of effect of vessel bifurcation on heat transfer in the magnetic fluid hyperthermia

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HIGHLIGHTS

- A 3D multiphysical heat and mass transfer model for tumor hyperthermia is proposed.
- The effect of bifurcation vessel on the planning of MFH treatment strategy is studied.
- Low-concentration, big-volume, and diffuse injection improve temperature uniformity.
- High concentration and injection density is appropriate to treated tissue near vessel.
- Small bifurcation angle causes a decrease in tissue temperature in the angle region.

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ABSTRACT

This research aimed to analyze the mass and heat transfer mechanisms in magnetic fluid hyperthermia (MFH) treatment, revealing the effect of blood flow in a blood vessel bifurcation on the accurate spatial control of the thermal dose. A three-dimensional multiphysical model was developed to obtain the blood flow velocity distribution, concentration distribution of magnetic fluid, and temperature distribution of the treated tumor tissues. The calculated results demonstrate that the structure, size, and position of a bifurcation vessel greatly affect the selection of injection parameters for MFH treatment. The injection parameters considered in this study are the concentration of magnetic fluid, injection volume, arrangement of injections within the targeted tissues, and distance between the injection site and bifurcation. Diffuse injection patterns, large volumes, and low concentrations generally decrease the temperature differences within the tissues. To achieve uniform heating, high injection density and high-concentration magnetic fluids may be applied to the area near the vessel in order to reduce the cooling effect of blood flow. However, a more diffuse injection pattern is advantageous if the distance between the injection site and blood vessel is relatively short for the purpose of eliminating the heating effect of magnetic fluids.

1. Introduction

Magnetic fluid hyperthermia (MFH) is a novel and promising hyperthermia approach for the treatment of human cancer [1]. Compared with other well-developed hyperthermia methods, such as RF ablation, ultrasonic hyperthermia, and microwave ablation [2–4], MFH has unique advantages and considerable potential for clinical application. These features were discovered during heating mechanism investigations [5], animal experiments [6,7], and clinical treatments [8,9]. Magnetic nanoparticles have an extraordinarily high focused heating effect on target tumor tissues in contrast to surrounding tissues due to the surface and small size effects of the nanoparticles. MFH easily enables the selective heating of different target tissues with different morphologies at various depths in order to avoid excessive damage to normal tissues and treatment-related side effects [10]. However, MFH is not widely applied in clinical treatments due to the difficulty in the accurate determination of temperature distribution within target tissue, precise control of thermal dose, and uniform heating.

As of this writing, most investigations, as well as clinical applications, have focused on the heating effects and specific absorption rates (SAR) of magnetic fluids. Rosensweig et al. [11] calculated the heating rates of various magnetic particle-containing samples subjected to an alternating magnetic field. Jordan et al. [12] applied a solid-state physical model in order to study the relationship of the heating effects of magnetic fluids with the SAR. Xu et al. [13]

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Nomenclature

C	concentration
c	specific heat
D	diffusion coefficient
d	diameter of the vessel
J	volumetric flow rate
K	Boltzmann constant
L	hydraulic conductivity
l	lengths of the vessel
P	specific absorption rate (SAR)
p	pressure
Q	heat generation
q	heat generation per unit volume
R	mean radius of nanoparticles
S	surface area
T	temperature
U	blood velocity
w	blood perfusion rate

Greeks

θ	bifurcation angles
ϕ	volume flow rate
σ_{T}	osmotic reflection coefficient
η	dynamic viscosity
ρ	density
υ	viscosity
λ	conductivity coefficient
π	osmotic pressure

Subscript

0	main vessel
1,2	branch vessel
b	blood
i	interstitial
l	lymphatic
m	metabolism
t	tissue
v	vasculature

experimentally determined the crucial factors that can increase the SAR of magnetic fluids. Goya et al. [14] analyzed the magnetic carriers and the most promising strategies for the targeted delivery of magnetic nanoparticles. Hergt et al. [15] and Oirechchtaigh et al. [5] explored the physical mechanism of the heat production of magnetic fluid, in which numerous animal experiments and clinical studies were conducted to prove that MFH is effective. Mitsumori et al. [16] applied a dextran magnetite complex to rabbits for liver tumor treatment, thus discovering its potential feasibility. Jordan et al. [6,9] reported the first clinical application of MFH in the treatment of human cancer, whereby temperature variation had been conducted in experimental models of mouse mammary carcinoma.

Some investigators also attempted to predict the nanoparticle concentrations and temperature distributions in tumor tissues. Candeo [17] studied the influences of nanoparticle sizes, concentrations, and magnetic field intensities on the temperature distribution within tissues. Bagaria et al. [18] considered the effects of the distribution of magnetic particles on the temperature variation during MFH. Y.G. Lv et al. [19] simulated the influences of the frequency and strength of the alternating EM field, as well as the heating effects of particle sizes, concentrations, and microstructures. D. Su et al. [20] concluded that the quantity and distribution of particles are essential to the temperature distribution in treated tumor tissues without blood vessels. Pavel et al. [21] explored the impact of a blood vessel located beside the tumor and the effect of the ferromagnetic nanoparticle dose on the tumor temperature. Kolios et al. [22] found that reducing the volumetric flow through the vessels is the most promising strategy for reducing the localized cooling of large vessels.

Achievements in oncological research indicate that many solid tumors are connected to or pass through the complicated blood vessel system [23]. According to Murray [24], the bifurcated structure of human blood vessels has dichotomous characteristics, i.e., two daughter branches extend from a father vessel. Motomiya et al. [25] investigated the fluid velocity in the human carotid artery bifurcation. Liu et al. [26] studied the role of bifurcated blood vessels in microwave ablation hyperthermia. Dughiero et al. [27] established a 3D model with a vessel bifurcation to analyze the heating effect of thermo-seeds.

In MFH, the mutual effect of the nanoparticle transport and heat transfer processes, as well as the existence of vessel bifurcation, complicated the temperature prediction and increases the difficulty in thermal dose control for uniform heating. Therefore, investigations into this present study address the heat and mass transfer mechanisms in treated tumor, as well as the effect of vessel bifurcation on injection parameter selection, for the purpose of gaining valuable information in planning a uniform heating strategy.

2. Modeling

2.1. Physical model

The model consisted of a cubic region of healthy tissue with an edge length of 8 cm. The shape of the tumor tissue was assumed to be irregular, approximating the volume of a sphere with a diameter of 2.4 cm, as shown in Fig. 1(a). An applied Y-type bifurcation is shown in Fig. 1(b) The flow behavior of blood is necessarily affected by the shape of the vessel, therefore the basic parameters of vessel bifurcation are essential to be determined.

In Fig. 1, a Y-type bifurcation was applied, which consisted of a main vessel and two branch vessels. Calculations were made using Murray's proposed law of $d_0^x = d_1^x + d_2^x$ in describing the relationship [24], where x is assumed to be 3, according to Murray [28].

Based on the minimum energy consumption principle, the relationship between bifurcation angle of two branches and vessel diameters [29] can be expressed as

$$\cos\theta_1 = \frac{\left(1+\alpha^3\right)^{4/3} + 1 - \alpha^4}{2\left(1+\alpha^3\right)^{2/3}} \qquad \cos\theta_2 = \frac{\left(1+\alpha^3\right)^{4/3} + \alpha^4 - 1}{2\alpha^2\left(1+\alpha^3\right)^{2/3}} \tag{1}$$

where $\alpha = d_2/d_1$.The maximum vessel length-to-diameter ratio is found to be about 35, and the average value is 10 [30]. The distribution of bifurcation angles is approximately normal with a mean value of 44.3° and range of 10°–86° [31]. Based on the aforementioned principles and experimental data, a defined set of bifurcation vessels was given different lengths, diameters, and angles to analyze the cooling effects on the temperature distribution of surrounding tissues.

Four injection layers were arranged along the blood flow direction (Z-axis). The distance between layers 1 and 2, 2 and 3, as