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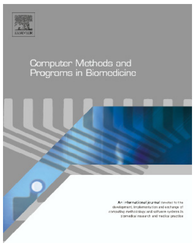

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Anatomical model-based finite element analysis of the combined cryosurgical and hyperthermic ablation for knee bone tumor

Zhi Zhu He[a,*], *Xu Xue*[a], *Jian Xiao*[b], *Jing Liu*[a,c]

[a] *Beijing Key Laboratory of Cryo-Biomedical Engineering & Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China*
[b] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[c] *Department of Biomedical Engineering, School of Medicine, Tsinghua University, Beijing 100084, China*

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ABSTRACT

This paper is aimed at investigating the capacity of using combined cryosurgical and hyperthermic modality for treating knee bone tumor with complex shape. An anatomical model for human knee was constructed and a three-dimensional (3D) finite element analysis was developed to determine temperature distribution of the tissues subject to single freezing (SF), single heating (SH) and alternate freezing–heating (AFH), respectively. The heat fluxes of the probes wall and the ablation volume are particularly tracked to comparatively evaluate the ablation ability of different probe configurations with varied diameter, number and active working length. As example, an effective conformal treatment strategy via one time's insertion while cyclic freezing–heating using multiple probes is designed for a predefined knee bone tumor ablation. Both SF and SH could create large enough ablation volume, while it is hard for them to perform a conformal treatment on irregular and slender knee tumor. As an alternative, AFH could form a flexible and controlled shape and volume of the ablation by changing the size and number of the probes and adjusting their insertion depth. In addition, a thermal protection method is considered to reduce cryoinjury of the health tissue.

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1. Introduction

Cryosurgery is a clinical therapy for treating various tumors through a controlled deep freezing via inserting metal probe to the target diseased tissues [1,2]. It has been demonstrated to be a safe, minimally invasive and cost-effective treatment approach. Since its first introduction to bone tumor clinics by Marcove and Miller [3] in the early 1970s, cryosurgery has become an important adjuvant technique to resection for the treatment of aggressive benign and low-grade malignant bone tumor [4–6]. The primary "open system" technique entailed pouring liquid nitrogen directly into a tumor cavity after curettage and subsequently performed reconstruction of the cavity using implants. However, some reports indicated that such freezing technique could induce serious complications such as skin necrosis, infection, late fractures, delayed healing and nerve injury. Subsequently, a "semi-open system" using

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[*] *Corresponding author at:* P.O. Box 2711, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China. Tel.: +86 10 82543766; fax: +86 10 82543767.
E-mail address: zzhe@mail.ipc.ac.cn (Z.Z. He).

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pressurized spraying technique developed by Dabak [7] could increase the contact area of the coolant with the irregular walls of the cavity to reduce the soft-tissue injury. Recently a “close system” using cryoprobe has been developed to bone tumor treatment by Bickels [8] and Popken [9]. The main advantage of this system is to precisely control the freezing temperature and duration time.

In contrast to freezing therapy, hyperthermia uses high temperature to induce tissue necrosis [10]. Its heating type could adopt heat conduction from high-temperature metal probe or the spatial heating by radio frequency, microwave and high-intensity focused ultrasound, etc. The thermal ablation techniques including radio frequency (RF) [11–13] have also been used to treat bone tumor. Although cryosurgery and hyperthermia widely perform tumor treatment, there also raised serious concerns including incomplete destruction of tumor cell for single freezing and possible tumor cells metastasis induced by single heating. In addition, cryosurgery is often associated with bone resection and only considered as an adjuvant technique for bone tumor treatment. The bone resection would leave defect and must be reconstructed by implants, which would lead to large injury for healthy bone and reduce the quality of life [14,15]. For a “close system” cryosurgery, in fact, only small drilling holes are needed for the cryoprobe to insert into the site of bone tumor. However, quite a few investigations focus on an independent “close system” cryosurgery of bone tumor without resection. The main reason may be that bone tumor often has complex shape and large volume so that freezing is hard to completely destroy the tumor. Thus a powerful conformal ablation strategy is very important for bone tumor treatment.

Recently, freezing and heating have been combined to improve output of tumor treatment [16–20]. As far as heating intensity is concerned, typical representatives of freezing–heating systems are cryoprobe-apparatus with internally circulated high-velocity fluids (deep low-temperature liquid nitrogen and high-temperature water vapor) designed by Liu’s group [19] and a similar freezing system but with radiofrequency heating from Xu’s group [16]. Researches have indicated that freezing immediately followed by a rapid and strong heating of the target tissues can effectively improve the ablation effects [16,19,21]. In addition, an induced larger thermal stress during AFH process also significantly enhances mechanical injury of tumor cell [19] and microvasculature [21]. However, it is noteworthy that an improper operation would weaken the treatment effect due to counteraction between freezing and heating.

In this work, we investigate the ability of AFH system developed in our previous work [19] to knee bone tumor treatment. An anatomical CAD model of human knee is applied to perform a 3D finite element analysis on the temperature evolution of tissues during SF, SH and AFH processes. We evaluate the ablation effect of different probe configurations and design an effective conformal treatment strategy to induce necrosis on the predefined knee bone tumor. In addition, the thermal effects of large blood vessels and thermal protection measure are also investigated. The paper structure is organized as follows: The geometric and mathematical models of 3D finite element analysis are described in the Section 2. The simulation results about the ablation effects for SF, SH and AFH strategy are presented in the Section 3. The final Section 4 summarizes all the key physics in current work.

2. Geometric and mathematical model

2.1. *Geometric model*

An anatomical CAD model of human knee (Fig. 1) has been established in our previous work [22]. The tissue structures are composed of skin, large arterial and venous vessels, muscle and bones, which contain femoral, patella, tibia and fibular, respectively. The shape and size of all the components’ geometry and their mutual positions in this model refer to knee anatomical structure and images from magnetic resonance imaging (MRI) and computed tomography (CT). Taking the femoral as example, we firstly obtain the characteristic size and shape of femoral from MRI and CT, which is then input to the software Solidworks Office Premium 2007. Based on femoral morphology, Solidworks could build the complex structure of femoral. Finally, all the components merge together to form a complete anatomical CAD model of knee. The main feature of the anatomical CAD model is to not only accurately characterize the complex structure of the bone located at the knee joint and also easily establish the finite element model for numerical simulation. In addition, large arterial and venous vessels are considered in the model to predict a more close to reality bioheat transfer in human knee. In fact, the real knee is more complex than that in current geometry model. Ligament, cartilage and tendon, which have small volume and considerably irregular shape, are hard to be mapped by a feasible mesh. Although these structures are not explicitly defined by separate mesh sets, we consider the temperatures distribution of some critical structures based on their positions, and analyze potential injury during treatment.

The bone tumors often occur at the distal femur. Meller [4] has reported 440 cryosurgical treatments for bone tumor, where about 87 cases were located at the distal femur. In current work, we thus predefine a large ellipsoidal bone tumor at the left distal femur (shown in Fig. 1(C)). Based on the specific position of the bone tumor, four configurations of probes considering their diameter and number are illustrated in Fig. 2 (A–D), which denotes case number from 1 to 4. The real probe shape is illustrated in Fig. 2(E). For SF and SH, the active probe part is assumed as contact part with bone. Its length denoted by Lp is about 37 mm. For AFH, Lp = 15 mm is assumed for all the probes. The probes were inserted to the left bottom of femur through the desired drilling holes along z axis. The probes’ positions are on the center or circumference of a predefined circle with diameter 15 mm. Its center position on the x–y plane is (−23 mm, 36 mm) and perpendicular to z axis. The position P of the probes tip for cases 1–4 in z axis is on the plane $z = -10$ mm, while it locates on the plane $z = -13$ mm for the central probe of case 4. In addition, the probes could move along z axis to form a desired shape of ablation domains.

2.2. *Governing equation*

During freezing or heating process, the target tissue would undergo a dramatic temperature change. The solidification of

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