A Fast Adaptive Power Scheme with Different Heating Modes for Optimal Hyperthermia Treatment

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Abstract

To elevate tissue temperature to therapeutic level fast with optimal power deposition during hyperthermia treatment (HT) is a key treatment processing step. Traditionally we have treated the tumor volume, without considering possible existing thermally significant vessels, using a simple 1st-order temperature-based adaptive power scheme to determine optimal power deposition distributions. The difficulty of that approach when considering single large blood vessel, and proposed a novel fast scheme that could improve upon and substitute for the traditional temperature-based adaptive power scheme has been published by Huang et al [1]. The objectives of this study were to discuss the case with more than one thermally significant blood vessels (i.e. counter-current vessels) within a tumor. In this study, we presented the test of a novel three-coefficient-and two-SCV 5th-order temperature-based adaptive power scheme to resolve the induced large blood vessels problem in 3-D temperature distribution and introduced the parameter, SCV (Sentinel Convergence Value), to handle interior scheme shift. The 7th-order case will be discussed to resolve more convection involved blood vessels in the tumor. Results of the novel adaptive power scheme has shown its robustness to fast approach optimal temperature distribution and power density distribution with high precision in the tumor volume when considering the existence of thermally significant blood vessel. Ultimately, we may be able to effectively calculate the absorbed power density distribution of 3-D biological tissues with a complicated vasculature [2] in the volume.

Keywords: Adaptive power scheme, Hyperthermia, Bio-heat transfer equation, Thermally significant blood vessel.

1. Introduction

Hyperthermia, i.e. elevating temperatures of the tumor to the range of 41e45 _C, is used as a modality adjuvant to radiotherapy or chemotherapy in the various cancer treatment types. It has greatly benefited from the development of hyperthermia treatment planning (HTP) [2]. The planning simulates, either simultaneously or beforehand, the heating process and is a valuable component in monitoring the treatment. However, uncertainties exist during computer simulation; recently Greef et al. [3] showed the impact of tissue perfusion uncertainty, which is one of many uncertainties, during optimization in hyperthermia treatment planning. They also referred to another significant impact on optimization methods when considering large blood vessels and suggested temperature-based optimization is superior to specific absorption rate (SAR)-based optimization.

In locoregional hyperthermia, in case of application to deep-seated tumors, heating is generally applied using phase-array systems such as high-intensity focused ultrasound (HIFU). The amplitude and phase of every applicator transducer are important parameters to be tuned, thus, to optimize the power density distribution or temperature distribution [4,5]. Kolios et al. [6] used HIFU in treatments and showed blood flow cooling of different vessel sizes. Through simulating the heating process, the parameters are determined [7], and the process is a valuable component with which to monitor treatment. Another type of optimization with constraints on both tumor and normal tissues, such as the complaint-adaptive power density optimization, it was used as a tool for HTP-guided steering in deep hyperthermia treatment [8]. Fast response from the computer was a must for hyperthermia treatment.

2. Methods

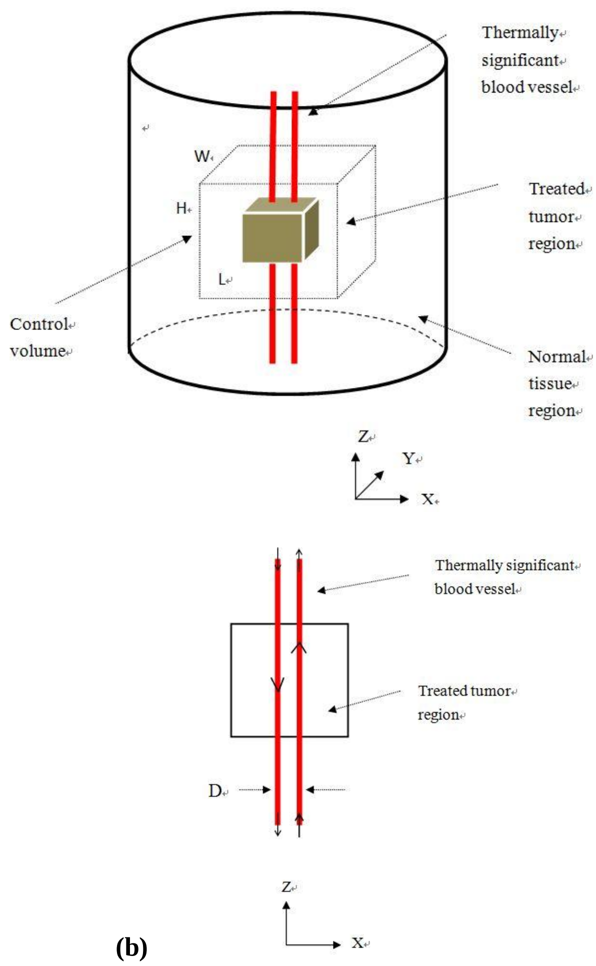
2.1 Geometry model

To present our studies, we used two thermally significant blood vessels counter-currently passing through a tumor region at the center as shown in Figure 1.(a). The tumor volume was a 1-cm cube located in the center of the domain. The domain of control volume in the study was 4-cm (H) by 4-cm (W) by 4-cm (L), for it sufficiently described the temperature distributions around the tumor. The geometric model illustrates two thermally significant blood vessel counter-currently passing through a treated tumor region at the center, with blood moving upward as shown in Fig. 1(a), and the projection view on X-Z plane of Fig. 1(b) is shown in Fig. 1(b). The information on significant blood vessel sizes and average mass flow rates are shown in Table 1 [6].

Table 1. Significant vessel diameters and average flow rates from Kolios et al [6].

Blood vessel diameter (mm)	Average velocity (cm/s)
1.4	10.5
1.0	8.0
0.8	7.5
0.6	6.0
0.4	5.5
0.2	3.4

(a)



(b)

Figure 1. (a) The geometric model illustrates a pair of thermally significant blood vessels counter-currently passing through a treated tumor region at the center, with blood moving upwardly. (b) A projection view on the centric X-Z plane of figure 1.(a) illustrating a thermally significant blood vessel. (0, 0) in X-Z coordinate indicates blood vessel at the boundary entering the control volume.

2.2 Mathematical and numerical modelings

Considering thermally significant blood vessel, blood temperature needs to be calculated. Therefore, combined tissue and blood vessel models were used in the study. The tissue temperature is described by Pennes bio-heat transfer equation. That is,

$$\nabla\bullet(k\nabla T(x,y,z)) - \dot{w}_b c_b (T(x,y,z) - T_a) + q_s = 0 \quad (1)$$

where k, c_b, $\dot{w}_b$, and q_s are the thermal conductivity of soft tissue, specific heat of blood, blood perfusion rate and absorbed thermal power density (which is identical to P_n in Equation (3)), respectively. ▽ is the differential operator. Conduction occurs in all three directions (x, y and z) in the tissue matrix, and the outer control volume surface is held at a constant reference temperature (i.e. identical to the inlet artery temperature).

The convective energy equation is solved for the blood vessel model. That is,

$$m_b c_b \frac{\partial T_b(x,y,z)}{\partial x_i} = Nu \cdot k_b \pi (T_w(x,y,z) - T_b(x,y,z)) + q_s \pi R_{bv}^2 \quad (2)$$

where m_b is the blood mass flow rate at vessel segment along x_i. x_i is the coordinate axis which is x, y or z axis. The vasculature consists of straight vessel segments. Nu, k_b, R_{bv} and T_w are Nusselt number, thermal conductivity in blood, radius of blood vessel and blood vessel wall temperature. We assume an average uniform velocity profile of blood fluid in vessel, and fully developed flow, as studies showed insignificant difference when comparing results with those of using non-uniform profile in vessel. The vessel heat transfer coefficient was calculated using a constant Nusselt number, which is 4.0, as studies [9] indicated there was no significant difference in the range of ±10% of 4.0.

The numerical scheme used to calculate the temperatures was a black and red vectorization finite difference SOR method with upwind differencing used for the vessels. The numerical details are described by Huang [9]. The property values used in treated tumorous and non-treated normal tissues were k = 0.5 W m^{-1}℃$^{-1}$, c = c_b = 4000 J kg^{-1}℃$^{-1}$ and ρ = 1000 kg m^{-3}. For blood, k_b is identical to k. In this study, a finite difference nodal spacing of 1 mm was used. The boundary temperature was set to 37$^{\circ}C$ at the outer control volume surfaces. Inlet temperatures of vessel to the control volume were also set to 37$^{\circ}C$.

2.3 Proposed adaptive power optimization scheme

An adaptive optimization scheme was employed to find optimal PD distribution in the treated tumor region during hyperthermia treatment. The optimal PD was reached as tissue temperatures were close to ideal temperatures with respect to CV, through calculation of mathematical models of tissue and blood vessel described in Sec. 2.2. The flow chart of adaptive scheme, finer resolution optimization scheme, to reach ideal temperature at the treated volume is shown in Figure 2. Adaptive absorbed power density scheme based on temperature and convergence value (CV) is,

if (CV > **1st SENTINEL CV**) then
$P_n(x,y,z)=P_{n-1}(x,y,z)+coef1*(T_{ideal}(x,y,z)-T(x,y,z))$
else if (CV > **2nd SENTINEL CV**) then
$P_n(x,y,z)=P_{n-1}(x,y,z)+coef3*(T_{ideal}(x,y,z)-T(x,y,z))^3$
else
$P_n(x,y,z)=P_{n-1}(x,y,z)+coef5*(T_{ideal}(x,y,z)-T(x,y,z))^5$
end if

where *P* is absorbed power density (Wm^{-3}) , n is the iteration number, T_{ideal} is ideal temperature and one of important values, sentinel CV (SCV), introduced above is defined as a value which makes adaptive power schemes shifted to fast approach terminal (or desired) CV with less iteration. The above scheme listed three coefficients (coef1, coef3 and coef5), two SCVs and fifth order temperature-based scheme. The coefficients and SCVs will be determined and described in the next result section. Depending on required precision (i.e. CV), the scheme shifted (i.e. based on SCV) to different order of temperature-based scheme.

From Figure 3, the case for treated tumor volume having 0.2-mm diameter vessel inside, it appeared insignificant more iterations required than the treated tumor without vessel case to reach CV (=0.05 or 5%). However, the treated tumor volume having 0.8-mm vessel inside increased at least 13 times in iteration than that without thermally significant vessel inside to reach CV (=0.05 or 5%). It can be expected that more iterations will be required if higher accuracy (such as 2.5% of convergence criterion) of results or higher mass flow rate of blood vessel is needed. This situation caused significant time to process adaptive iterations, which is inefficiency.

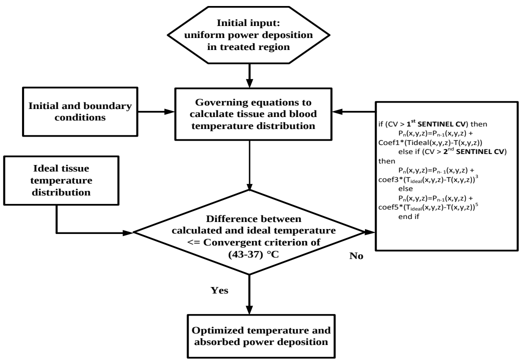


Figure2 The flow chart of finer resolution adaptive power optimization scheme to reach ideal temperature at the treated region.

There are two important background factors when solving a system of finite difference equations of thermal transport phenomena (conduction and convection) in the case. The first is the initial temperatures are uniform 37 ℃ in the treated tumor volume. This made adaptive temperature-based power increment increasing gradually, as well as for temperature distributions. The second is the cooling effect by the blood vessel. Particularly the impinging point of blood vessel on treated tumor volume was the most difficult region to reach ideal temperature. Hence the amplification of temperature difference (i.e. between ideal and calculated temperatures) near high thermal gradient region would speed up iterative results and we proposed improved schemes.

The traditional scheme was the first order temperature-based adaptive absorbed power density scheme which was identical to the one published by Huang et al [1], and the scheme was employed to calculate temperature distributions on biological tissues without considering impact of thermally significant blood vessels. It was the following:

$$P_{n+1}(x,y,z)=P_n(x,y,z)+\Delta P(x,y,z) \quad (3)$$

$$\Delta P(x,y,z)=Coef*\Delta T(x,y,z) \quad (4)$$

$$\Delta T(x,y,z)=T_{ideal}-T(x,y,z) \quad (5)$$

where *P* is absorbed power density (Wm^{-3}), which is a function of space, *Coef* is 10000 (i.e. coef1 in the proposed scheme), n is the iteration number and ΔT is the difference of ideal temperature and calculated temperature. The *Coef* has been tried with different values, and was chosen based on smoothly converging rate (without considering optimal solutions at low CV, which value is described in Eqn. 6, and higher blood flow rate). The ideal temperature in the scheme stands for 43℃ in the treated tumor region in this study.

Conditional statement in the chart, shown in Figure 2, introduced an important adaptive process for the heated tumor volume. That was, evaluation criterion shown in Equation (6),

$$\frac{\sqrt{\dfrac{\sum_{all\ target\ nodes}((\Delta T(x,y,z))^2}{total\ number\ of\ target\ nodes}}}{(43-37)\ ^oC} \le convergence\ value\,(CV) \quad (6)$$

2.4 Difficulty of reaching optimal temperature and power density deposition

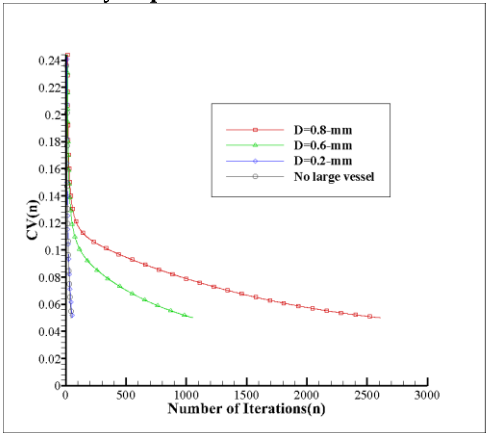


Figure 3. Comparison of CV(n) at number of iterations (n), using the traditional adaptive 1st-order temperature-based optimization scheme, for the tumor volume with and without a pair of counter-current blood vessels with identical mass flow rate flowing in both blood vessels. The sizes of pair vessels are 0.2-mm, 0.6-mm and 0.8-mm in diameter.

A pair of large blood vessels within a tumor revealed increasing difficulty of obtaining optimal temperature fast as size of vessels becomes larger. For vessel sizes of D=0.8-mm and 0.6-mm, the time needed to reach optimal temperature with CV=0.05 have been doubled as compared with the single vessel case, but for the smaller size of vessels such as D=0.2-mm, it remained the same (speed).　This described increased blood vessel convection in tumor that leads more difficult in power deposition.

3. Results

3.1 Temperature and power density distributions at target CV = 0.05

Figures show temperature and power density distributions at the central X-Z plane located at y = middle of 4-cm in length.

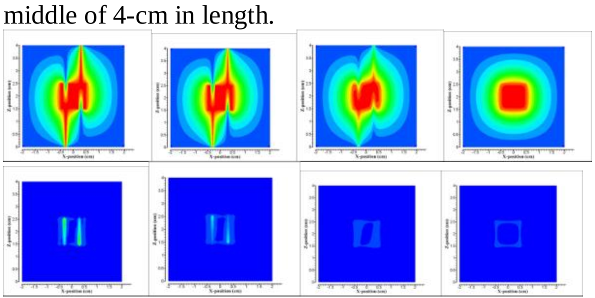


Figure 4 (Top row) temperature distributions and (bottom row) their corresponding absorbed power density distributions in the centric X-Z plane, which consists of a pair of thermally significant counter-current blood vessels of 0.8, 0.6, 0.2-mm diameter and none from left to right, respectively, within the tumor volume. The set CV is 0.05. The distance between parallel counter-current blood vessels is 6-mm.

3.2 Target CV 0.025 indicated difficulty of reaching optimal solutions for higher precision results.

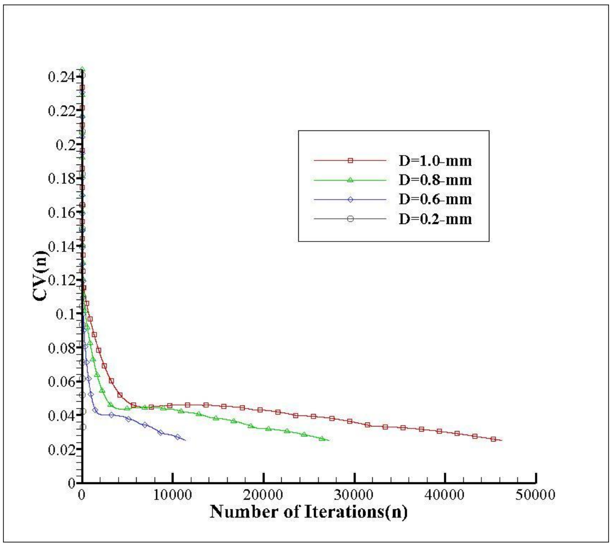


Figure 5 Comparison of CV(n) and number of iterations (n) For (a) The traditional one coefficient power readjustment scheme with coef1 = 10,000 for different vessel sizes D = 0.6, 0.8 and 1.0-mm of two identical large blood vessels (with 6-mm in distance) in the tumor volume.

4. Discussions

Figure 5 showed that A pair of large blood vessels within a tumor revealed increasing difficulty of obtaining optimal temperature fast as size of vessels becomes larger. For vessel sizes of D=0.8-mm and 0.6-mm, the time needed to reach optimal temperature with CV=0.05 have been doubled as compared with the single vessel case, but for the smaller size of vessels such as D=0.2-mm, it remained the same (speed).　This described increased blood vessel convection in tumor that leads more difficult in power deposition.

5. Conclusions

A new robust adaptive power scheme need to be developed in order to fix time consuming searching for optimal power density distribution. The 7th-order power scheme will be considered due to increased convection impact within the tumor.

6. Acknowledgements

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7. References

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快速適應演算能量加熱方式以不同策略來尋求最佳熱治療腫瘤組織之研究

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摘要

在熱治療腫瘤組織規劃時, 藉由最佳熱能置入, 快速提昇組織溫度到治療溫度, 是一個重要的治療處理步驟。傳統上, 針對治療腫瘤組織, 使用簡單的一階溫度變因適應熱能方式來決定最佳熱能置入分佈, 沒有考慮可能存在有熱意義的血管之情況。這個研究目地, 顯示其傳統方式治療計算上的困難度(耗時), 而將提出一個新快速適應演算能量加熱方式, 可改進而取代傳統依溫度為主的適應演算能量加熱方式治療。在這研究, 我們提出一個新的三係數和二守衛收斂參數(SCV)五階溫度變因適應演算能量加熱方式, 來解決大血管在三維溫度分佈所引發冷卻的問題和提出守衛收斂參數(SCV), 用於處理系統內部收斂結構改變。
關鍵字：適應演算能量加熱方式, 熱治療腫瘤, 生物熱傳方程式, 熱意義之血管