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Simulation of Heat Transfer in Liver Tissue under Microwave Ablation

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Abstract

The understanding of heat transport in human tissues is important for enhanced insight of thermoregulatory mechanism and physiological conditions during hyperthermia treatments such as microwave ablation (MWA). However, the result of heat transfer in human tissue to various therapeutic conditions is not well understood. The modeling of heat transport in target organ can be used as a guideline for the practical treatment. Therefore, it is interesting to investigate on the heat transfer characteristics occurred during MWA process. The modeling of heat transport through the MWA process has been the subject of interest for years, but the application of a porous media model in this field is new. This research is concerned with MWA process of heat transfer in the liver tissue using a 2.45 GHz microwave antenna under various conditions. A complete mathematical model of MWA based on porous media approach is proposed, which uses transient momentum equations (Brinkman model extended Darcy model) and energy equation with electromagnetic wave propagation equation to describe the temperature and blood velocity profiles within the liver tissue. The coupled nonlinear set of these equations are solved using the axisymmetric finite element method (FEM). In particular, the results calculated from a porous media model are compared with the results calculated from a bioheat model as well as the experimental results from previous work in order to show the validity of the simulation results. The obtained results show that the porous media model could be a feasible and potential model for the study of the transport phenomena in liver tissue during MWA process. Moreover, the obtained values provide an indication of limitations that must be considered during MWA thermotherapy.

***Keywords**:* Bioheat model, Finite element, Liver tissue, Microwave ablation, Porous media model

1. Introduction

Liver cancer is a significant worldwide public health issue. Each year, one of millions of people is diagnosed with liver cancer around the world [1]. There are many treatment alternatives for liver cancer. The treatment chosen depends upon the position and size of cancer and the overall health of the patient. In this past, possible treatments for liver cancer are surgery, cryosurgery, radiofrequency ablation and chemotherapy. However, each therapy method is limited by the side effects of the treatment [2]. One of promising alternative liver cancer treatments to degrade the effect is microwave ablation (MWA). This is a process that uses the heat from microwave energy via the microwave antenna to kill cancer cells without damaging the surrounding tissue. Therefore, the patients who have MWA therapy may experience less pain, swelling, and scarring than with traditional surgery. However, the thermodynamic response of liver tissue under MWA treatment is not well understood. In order to gain insight into the transport phenomena in heat transfer occurring within the liver tissue, a detailed knowledge of absorbed microwave radiation as well as temperature distribution is necessary. Thus, it is interesting to investigate the heat transfer effects that occur during MWA process.

The experiment of MWA on liver tissue was proposed [3-4]. However, the experimental for liver cancer therapy on live human beings is difficult because of ethical consideration. Therefore, the modeling of MWA in liver tissue is needed. The heat transfer modeling of liver tissue is important as a tool to investigate the heat transfer characteristics occurred during MWA process that can be used as a guideline for the practical treatment.

Previously, the studies of MWA dealt with homogeneous material and focused on heat conduction within a medium using Pennes's bioheat equation. Pennes's bioheat equation, introduced by Pennes [5] and based on the heat diffusion equation, is frequently used for analysis of heat transfer in biological tissues during thermal therapy. Description of the established bioheat transport models in liver tissue during MWA can be found in the literature [6-8]. Wang et al. [6] evaluated of the treatment effectiveness of a novel coaxial multi-slot antenna for conformal MWA of tumors, the heat transfer was described by the bioheat equation. Liu et al. [7] proposed and designed a microwave antenna with two slots for MWA process. The simulation results found that the new microwave antenna can achieve desired performance characteristic for MWA. Wu et al. [8] evaluated the effect of high frequency microwave (6 GHz and 18 GHz) applied to liver cancer therapy against conventional microwave (915 MHz, 2450 MHz) by a finite element model coupled electromagnetic field and bioheat transfer equation. The results show that the high frequency MWA can cause less collateral damage, more concentrated ablation region and better material response than conventional MWA.

Due to the simplifications and shortcomings of bioheat model, is based on the assumption that all heat transfer between the tissue and the blood occurs in the capillaries [9] and assumes that the temperature of the blood within the capillaries is equal to the body's core temperature [10]. Therefore, other researches have established mathematical bioheat models by extending, modifying bioheat model [11-12]. The study of high temperature tissue MWA using a modified bioheat equation to include the tissue's internal water evaporation during heating has been proposed [11]. The simulation result of the modified bioheat equation was found to be in excellent agreement with the experimental result more than the original bioheat equation. He and Liu [12] developed a parallel finite-difference method based on alternating direction explicit (ADE) scheme to solve three dimensional modified transient bioheat equation for the realistic tissue structure.

In reality, biological tissues are complex structures consisting of cells of different sizes and a microvascular bed in which the blood flow direction contains many vessels and can be regarded as a porous structure. Consequently, the study of heat transport in biological tissue using the anatomical structure of the liver tissue can be represented more accurately via porous media theory. With the advantage of requiring only a few assumptions, porous media models have been applied to analyze the heat transfer in biological tissues, including the liver tissue during thermal ablation in recent years. Chiang et al. [13] demonstrated the potential of incorporating water and water vaporization and transport physics into the simulation of MWA by using porous media assumptions in the tissue domain. CT imaging was used to validate the simulation model. Wang et al. [14] analyzed the characterization of bioheat transport through the annular biological medium using porous media model during radiofrequency ablation therapy. Chaichanyut and Tungjitkusolmun [15] utilized the three-dimensional finite-element models to examine the tissue temperature distributions during and after MWA using a 2.45 GHz four-tine (4T) antenna for hepatic cancer tissue. Although porous media models have been used for heat transfer studies in biological tissues under thermal ablation in previous investigations, they did not utilize porous media modeling in representing the thermal transport of biological tissues such as liver tissue during MWA process due to the complexity of the problem. In addition, there are few studies on the modeling of the heat transport in the liver tissue during MWA process from different thermal models, especially a detailed description of the temperature and blood velocity profiles.

This study presents the simulation of temperature and blood velocity profiles within the liver tissue during MWA process. Two-dimension axisymmetric liver tissue model is used in numerical analysis. A complete mathematical model of the process involved in MWA is based on transient momentum equations (Brinkman extended Darcy model) and the transient energy equation coupled with the electromagnetic wave propagation equation to describe the temperature and blood velocity profiles within the liver tissue. The set of governing equations as well as the initial and boundary conditions are solved using the axisymmetric finite element method (FEM) via COMSOL™ Multiphysics program. This study focuses on the differences in heat transfer models within the liver tissue during MWA process. The comparison of heat transfer from using the bioheat model and the porous media model is performed and evaluated. In order to complement the simulation results and to verify the accuracy of the presented numerical models of MWA, the simulated results using a porous media model are compared with the results calculated from a bioheat model as well as the experimental results from previous work in order to show the validity of the simulation results. The obtained values represent the phenomena accurately to determine the temperature increase in the liver tissue during MWA process and allow more general analysis of thermal ablation inputs, and facilitate the analysis of heat transfer contributing to thermal ablation growth.

2. Formulation of the Problem

The goal of MWA is to raise the temperature of the unwanted tissue (tumor) to 50 °C or above, at which cancer cells are destroyed [15]. MWA with microwave frequency as 2.45 GHz have been widely used to clinical surgery. This study uses a single-slot microwave antenna to transfer input microwave power into the liver tissue for the treatment of liver cancer. The single-slot microwave antenna has a diameter of 1.79 mm because this thin antenna is need in interstitial treatments to affect the tissues of the body minimally. A ring-shaped slot 1 mm wide is cut off the outer conductor 5.5 mm from the short circuited tip because the effective heating around the tip of the antenna is very important to the interstitial heating and because the electric field becomes stronger near the slot [16]. The single-slot microwave antenna has three components: an inner conductor, dielectric and outer conductor. The antenna is enclosed in a catheter (made of polytetrafluorethylene; PTFE) for hygienic and guidance purposes. Fig. 1 shows the model geometry of a single-slot microwave antenna. The outer radius of inner conductor, dielectric, outer conductor and catheter in the single-slot microwave antenna are equal to 0.135 mm, 0.335 mm, 0.460 mm and 0.895 mm, respectively. The single-slot microwave antenna operates at the frequency of 2.45 GHz. The dimensions of the single-slot microwave antenna are given in

Table 1, while its dielectric properties are listed in Table 2.

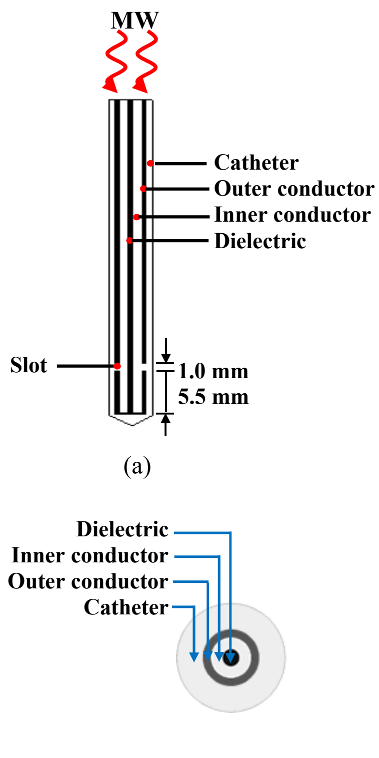

Fig. 1 Schematic diagram of a single-slot microwave antenna (a) Axial schematic of a single-slot microwave antenna and (b) Cross section of the single-slot microwave antenna

Table. 1 Dimensions of a single-slot microwave antenna [17].

Materials	Dimensions (mm)
Inner conductor	0.135 (radial)
Dielectric	0.335 (radial)
Outer conductor	0.460 (radial)
Catheter	0.895 (radial)
Slot	1.000 (wide)

Table 2. The dielectric properties of a single-slot microwave antenna [17].

Properties	Relative permittivity ε_r (-)	Electric conductivity σ (S/m)	Relative permeability μ_r (-)
Dielectric	2.03	0	1
Catheter	2.1	0	1
Slot	1	0	1

Fig. 2 illustrates the computational domain of the problem. The liver tissue is considered as having a cylindrical geometry. It has a 30 mm radius and 80 mm in height and a single-slot microwave antenna is inserted into the liver tissue with 70.5 mm depth [17]. In this study, an axially symmetric model is considered, which minimizes the computation time while maintaining good resolution, and represents the full three-dimensional result. The vertical axis is oriented along the longitudinal axis (axis z) of the single-slot microwave antenna, and the horizontal axis (axis r) is oriented along the radial direction. The model assumes that the single-slot microwave antenna is immersed in a liver tissue.

In an anatomical view, three compartments are identified in the biological tissues, namely, blood vessels, cells and interstitial space [14-15]. The interstitial space can be further divided into the extracellular matrix and the interstitial fluid. However, for sake of simplicity, the biological tissues are divided into two distinctive regions, namely, the vascular region (blood vessels) and the extra-vascular region (cells and the interstitial space) and treat the whole anatomical structure as a fluid-saturated porous medium, through which the blood infiltrates. The vascular region is regarded as a blood phase and extra-vascular region is regarded as a tissue (solid) phase, as illustrated in Fig. 2.

The dielectric properties and thermal properties of tissue (tissue phase) and blood (blood phase) are given in Table 3 where the microwave frequency of 2.45 GHz is considered.

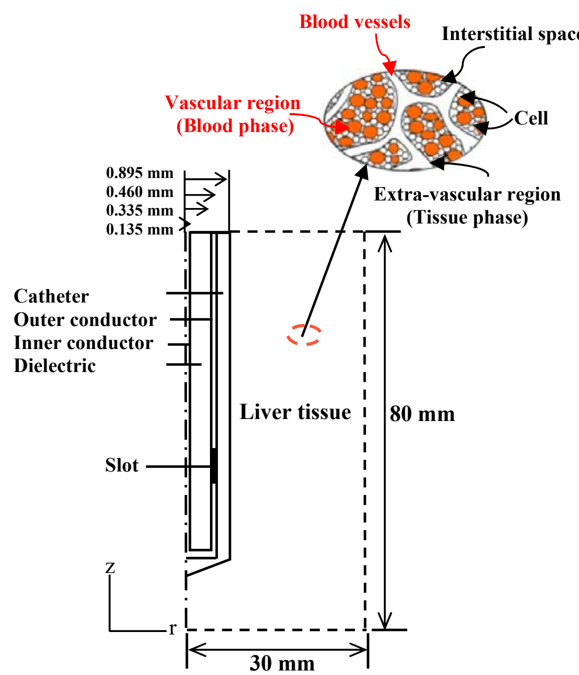

Fig. 2 Axially symmetric model geometry

3. The Formulation of the Mathematical Model

A mathematical model has been formulated to predict the temperature and blood velocity profiles within the liver tissue during MWA process. In this work, the heat transfer phenomena from differences in thermal models i.e. bioheat model and porous media model are systematically investigated. The relevant boundary conditions are described in Fig. 3.

3.1 Electromagnetic Wave Propagation Analysis

The electromagnetic wave propagation model is calculated using Maxwell's equations. The general form of Maxwell's equations for transverse electromagnetic fields (TEM) mode based on the harmonic propagation assumption is demonstrated [18]. To simplify the problem, this research is carried out with the following assumptions:

1. Electromagnetic wave propagation is modeled in 2D axially symmetrical cylindrical coordinates (r-z) [19].
2. An electromagnetic wave, propagating in a single-slot microwave antenna, is characterized by transverse electromagnetic fields (TEM) mode [19].
3. In the liver tissue, an electromagnetic wave is characterized by transverse magnetic fields (TM) mode [19].
4. The induced magnetic field is neglected.
5. The model assumes that the wall of the single-slot microwave antenna is a perfect electric conductor (PEC).
6. The outer surface of the liver tissue is truncated by a scattering boundary condition (the electromagnetic wave can pass through the boundary without reflection) and the electromagnetic wave is confined to the liver tissue.
7. The model assumes that the dielectric properties of the liver tissue are constant.

In this model, the electric field and magnetic field associated with the time-varying transverse electromagnetic (TEM) wave generated by the microwave source propagating in a coaxial cable in the z-direction are expressed in 2D axially symmetric cylindrical coordinates [19]:

Electric field ($\vec{E}$)

$$\vec{E}(r) = r\frac{C}{r}e^{j(\omega t - \delta z)} \qquad (1)$$

Magnetic field ($\vec{H}$)

$$\vec{H}(r) = \varphi\frac{C}{rZ}e^{j(\omega t - \delta z)} \qquad (2)$$

where $C = \sqrt{\dfrac{ZP}{\pi.\ln(r_{outer}/r_{inner})}}$, Z is the wave impedance(Ω), P is the input microwave power (W), r_{inner} is the dielectric inner radius (m), r_{outer} is the dielectric outer radius (m), $\omega = 2\pi f$ is the angular frequency (rad/s), f is the frequency (Hz), $\delta = \dfrac{2\pi}{\lambda}$ is the propagation constant (m^{-1}) and λ is the wave length (m).

For interstitial single-slot microwave antenna during MWA, the magnetic field is purely azimuthal. The electric field is in the radial direction only inside the coaxial cable and in both radial and the axial direction inside the tissue. This allows for the single-slot microwave antenna to be modeled using an axisymmetric transverse magnetic (TM) wave formulation. The vector wave equation is inferred from Maxwell's equation as [19]:

$$\nabla \times \left(\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0} \right)^{-1} \nabla \times \vec{H}_\varphi \right) - \mu_r k_0{}^2 \vec{H}_\varphi = 0 \qquad (3)$$

where ε_0 = 8.8542x10^{-12} F/m is the permittivity of free space, ε_r is the relative permittivity (-), σ is the electric conductivity (S/m), μ_r is the relative permeability (-) and k_0 is the propagation constant in free space (m^{-1}).

Boundary condition for electromagnetic wave propagation analysis

Microwave energy is emitted from the microwave antenna slot, which connected to the microwave generator, and propagates through the single-slot microwave antenna into the liver tissue from the microwave antenna slot. Therefore, the boundary condition for analyzing electromagnetic wave propagation, as shown in Fig. 3, is considered as follows:

At the inlet of the single-slot microwave antenna, TM wave propagation with constant input microwave powers of 10 W is considered. An axial symmetry boundary is applied at r = 0:

$$\vec{E}_r = 0 \qquad (4)$$

$$\frac{\partial \vec{E}_z}{\partial r} = 0 \qquad (5)$$

The first order scattering boundary conditions for $\vec{H}_\varphi$ are used along the outer sides of the liver tissue boundaries to prevent reflection artifacts (low-reflecting boundary condition):

$$\hat{n} \times \sqrt{\varepsilon}\vec{E} - \sqrt{\mu}\vec{H}_\varphi = -2\sqrt{\mu}\vec{H}_{\varphi 0} \qquad (6)$$

where $\vec{H}_{\varphi 0} = C / Zr_{av}$ is the excitation magnetic field and r_{av} is the average value of r_{inner} and r_{outer} (m).

The inner and outer conductors of the single-slot microwave antenna are modeled as the PEC boundary conditions:

$$\hat{n} \times \vec{E} = 0 \qquad (7)$$

3.2 Heat Transfer and Blood Flow Analysis

To solve the thermal problem, the temperature profile and blood velocity profile in the liver tissue have been evaluated by the transient energy equation and transient momentum equations (Brinkman extended Darcy model), respectively. This study is carried out on the heat transfer and blood flow analysis is based upon the following assumptions:

1. Corresponding to the electromagnetic wave propagation analysis, the heat transfer and blood flow analysis in the liver tissue is assumed to be in 2D axially symmetrical cylindrical coordinates (r-z).
2. The liver tissue is assumed to be homogeneous and thermally isotropic and saturated with a fluid (blood) [17].
3. The incompressible Navier–Stokes model is used to simulate the laminar flow conditions inside the blood vessel [20].
4. The LTE assumption between tissue and blood phases is considered [13,15].
5. No phase change occurs in the liver tissue, no energy exchange through the outer surface of the liver tissue, and no chemical reactions occur in the liver tissue.
6. The porosities and thermal properties of the liver tissue are assumed to be constant [17].

3.2.1 Bioheat model

The transient bioheat equation effectively describes how heat transfer occurs within the human tissue, and the equation can be written as

$$\rho c\frac{\partial T}{\partial t}=\nabla\cdot(k\nabla T)+\rho_b c_b\omega_b(T_b-T)+Q_{met}+Q_{mw} \tag{8}$$

where ρ is the tissue density (kg/m^3), c is the specific heat (J/kg.°C), k is thermal conductivity of tissue (W/m. °C), T is the tissue temperature (°C), T_b is the temperature of blood at 37 °C, ρ_b is the density of blood (kg/m^3), c_b is the specific heat of blood (J/kg.°C), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolism heat generation (W/m^3) and Q_{mw} is the external heat source from microwave energy (W/m^3).

The first term on the left hand side of Eq. (8) denotes the transient term, while the first, second, third and fourth terms on the right hand side of Eq. (8) denote heat conduction term , blood perfusion term, metabolic heat source term (Q_{met} = 33,800 W/m^3) [8,21] and external heat source term from microwave energy (Q_{ext}), respectively. The external heat source is equal to the resistive heat generated by the electromagnetic field as follows [17]:

$$Q_{mw}=\frac{\sigma|\vec{E}|^2}{2} \tag{9}$$

When to apply microwave radiation to the un-wanted tissue or cancer cell through the antenna, the microwave energy is absorbed by the cancer cell becomes heat and causes the temperature of this cancer cell to increase. The knowledge of microwave interaction with cancer cell has been a topic of interest for studies of MWA process [22-23].

Boundary condition for heat transfer analysis using bioheat model

The heat transfer analysis is considered only in the liver tissue domain, which does not include the single-slot microwave antenna. An axial symmetry boundary is applied at r = 0. The outer sides of the liver tissue boundaries are fixed temperature at 37 °C.

The boundaries between of the single-slot microwave antenna and liver tissue are considered as insulating boundary conditions:

$$\hat{n}\cdot(k\nabla T)=0 \tag{10}$$

The initial temperature is assumed to be the same at the body core temperature at 37 °C [24].

$$T(t_0)=\text{ 37 °C} \tag{11}$$

In addition, this study utilized the pertinent thermal model based on the porous media theory to investigate the heat transfer behavior of the liver tissue during MWA.

3.2.2 Porous media model

Energy Equation: The temperature profile in the liver tissue during MWA process is obtained by solving the conventional heat transport equation where the metabolism heat generation term and the external heat source term from microwave energy are included. The governing equations describing the heat transfer phenomenon based on porous media approach are given by [17]:

$$(\rho c)_{eff}\frac{\partial T}{\partial t}+(\rho c)_b\left(u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}\right)= k_{eff}\left(\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{met}+Q_{mw} \tag{12}$$

where

$$(\rho c)_{eff}=(1-\phi)(\rho c)_t+\phi(\rho c)_b \tag{13}$$

$$k_{eff}=(1-\phi)k_t+\phi k_b \tag{14}$$

subscripts eff , t and b represent the effective value, tissue phase and blood phase, respectively.

The first and the second terms on the left hand side of Eq. (12) denotes the transient term and convection term due to blood flow, respectively. The first, second and third terms on the right hand side of Eq. (12) denote heat conduction term, metabolic heat source term (Q_{met} = 33,800 W/m^3) [8,21] and external heat source term from microwave energy (Q_{ext}), respectively. The external heat source is calculated by Eq. (9).

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Momentum Equations: The Brinkman model extended Darcy model was first developed by Brinkman [25] and used to represent the blood flow within the liver tissue. Using standard symbols, the governing equations describing the heat transfer phenomenon are given as follows [17]:
Continuity equation:

$$\frac{\partial u}{\partial r}+\frac{\partial w}{\partial z}=0 \tag{15}$$

Brinkman equation:

$$\frac{1}{\phi}\left(\frac{\partial u}{\partial t}\right)+\frac{1}{\phi^2}\left(u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho_b}\left(\frac{\partial p}{\partial r}\right)+\frac{\nu}{\phi}\left(\frac{\partial^2 u}{\partial r^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{u\nu}{\kappa} \tag{16a}$$

$$\frac{1}{\phi}\left(\frac{\partial w}{\partial t}\right)+\frac{1}{\phi^2}\left(u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}\right)=-\frac{1}{\rho_b}\left(\frac{\partial p}{\partial z}\right)+\frac{\nu}{\phi}\left(\frac{\partial^2 w}{\partial r^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{w\nu}{\kappa}+g\beta(T-T_b) \tag{16b}$$

where u and w are the blood velocity components (m/s), ϕ is the tissue porosity (the volume fraction of the vascular space) (-) [26], p is the pressure (Pa), ν = 3.78x10^{-7} m^2/s is the kinematics viscosity, β = 1×10^{-4} 1/K is the coefficient of the thermal expansion and κ is the permeability (m^2).

Boundary condition for heat transfer and blood flow analysis using porous media model

As shown in Fig. 3, the boundaries of liver tissue correspond to the assumption are considered as follows:

An axial symmetry boundary is applied at r = 0 for heat transfer and blood flow analysis as:

$$\hat{n}.\bar{u}=0 \tag{17}$$

$$\hat{n}\cdot\left(-pI+(1/\phi)\eta\left(\nabla\cdot\bar{u}+(\nabla\cdot\bar{u})^T\right)\right)=0 \tag{18}$$

The surroundings of the liver tissue are fixed temperature at 37 °C and the boundaries for blood flow analysis are considered an open boundary condition:

$$\hat{n}\cdot\left(-pI+(1/\phi)\eta\left(\nabla\cdot\bar{u}+(\nabla\cdot\bar{u})^T\right)\right)=-F_0\hat{n} \tag{19}$$

where η is the dynamic viscosity (Pa.s) and F_0 is the normal stress (N/m^2)

The boundaries between of the single-slot microwave antenna and liver tissue are considered as insulating boundary conditions as well as the bioheat model:

$$\hat{n}\cdot\left(k_{eff}\nabla T\right)=0 \tag{20}$$

Furthermore, the outer surface between of the single-slot microwave antenna and liver tissue is rigid body, a no slip boundary conditions are applied for the Brinkman equations:

$$\bar{u}=0 \tag{21}$$

Corresponding to the bioheat model, the initial temperature is assumed to be the same at the body core temperature at 37 °C:

$$T(t_0)= 37\ ^\circ\text{C} \tag{22}$$

In addition, the initial condition for the blood velocities and pressure are:

$$u(t_0)=0 \text{ m/s},\ w(t_0)= 0 \text{ m/s and } p(t_0)=0 \text{ Pa} \tag{23}$$

In this work, the dielectric properties and thermal properties are assumed to be constant that are not temperature dependent because of it has a little bit change with this temperature range during MWA process. [15,17].

4. Calculation Procedure

In this study, the FEM is used to analyze the transient problems. The coupled model of electromagnetic wave propagation, heat transfer and blood flow analysis are solved by the FEM using COMSOL^{TM} multiphysics, to demonstrate the phenomena that occurs within the liver tissue during MWA. The computational scheme starts with computing an external heat source term by running an electromagnetic wave propagation calculation and subsequently solves the time-dependent temperature and blood velocity in the liver tissue using thermal properties. All the steps are repeated until the required heating time is reached. The description of the temperature and blood velocity profiles, Eq. (8), (9) – (23) requires specification of the temperature (T), velocities components ($(\bar{u}=(u,w))$) and pressure (p). These equations are coupled to the electromagnetic wave propagation equations (Eq. (1) – (7)) by Eq. (9). The axisymmetric FEM model is discretized using triangular elements with the Lagrange quadratic shape functions. In order to obtain a good approximation, a fine mesh is specified in the sensitive areas. The system of governing equations as well as initial and boundary conditions are solved with the Unsymmetric Multifrontal Method (UMFPACK) solver to approximate temperature and blood velocity variation across each element. The number of elements where solution is independent of mesh density is found to be around 20,325 elements. It is reasonable to confirm that, at this number of element, the accuracy of the simulation results is independent from the number of elements through the calculation process.

Table 3 The dielectric properties and thermal properties of tissue phase and blood phase [11,19,27]

Properties	Relative permittivity ε_r (-)	Electric conductivity σ (S/m)	Thermal conductivity k (W/m. °C)	Density ρ (kg/m^3)	Specific heat c (J/kg.°C)
Tissue phase (t)	43.00	1.69	0.497	1,030	3,600
Blood phase (b)	58.30	2.54	0.450	1,058	3,960

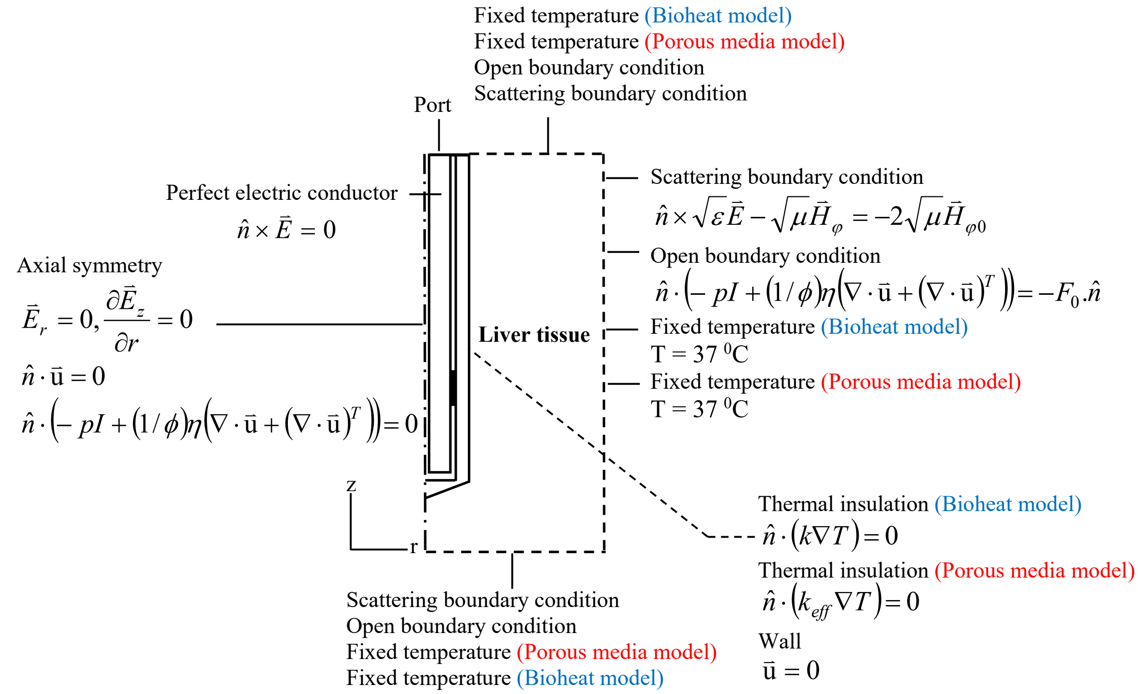

Fig. 3. Boundary conditions for analysis

5. Results and Discussion

5.1 Verification of the Model

To verify the accuracy of the presented mathematical model of MWA, the resulting data of the present model is validated against the simulation results and experimental results with the same conditions, obtained by Yang et al. [11]. Fig. 4 shows the geometry of the validation model. In the validation case, the microwave power of 75 W with frequency of 2.45 GHz and the initial liver tissue temperature of 8°C are selected. The radius of single-slot microwave antenna is 1.25 mm. It is inserted 20 mm deep into liver tissue. The axially symmetrical model is used to analyze the MWA process and the heating duration is 50 s. Fig. 5 shows the validation results of the liver tissue temperature by using bioheat model against the simulation results obtained by Yang et al. [11], with respect to the heating time of MWA at the positions of 4.5 mm and 9.5 mm away from the single-slot microwave antenna. It is found that the simulated results from the bioheat model are corresponded closely with the simulated results from bioheat model obtained by Yang et al. [11].

In addition, the simulated results from the porous media model and bioheat model are compared with the experimental results obtained by Yang et al. [11]. Fig. 6 shows the validation results of the liver tissue temperature by using porous media model and bioheat model, with respect to the heating time of MWA at the positions of 4.5 mm and 9.5 mm away from the single-slot microwave antenna and the heating duration is 50 s. It is found that the simulated results of the porous media model agree well with the corresponding experimental results with similar trends in temperature distribution over the same approximate time range at both positions, especially at the end stage. This is due to the fact that the porous media model is based on convective heat mode coupled with conduction heat mode, while the bioheat model is manly governed by conduction heat mode. In addition, at the position of 9.5 mm away from the single-slot microwave antenna, the temperature distribution matches the experimental results better than the temperature distribution at the position of 4.5 mm. Therefore, the developed model based on porous media approach is reasonable and can be used effectively for this problem. This is important to obtain the approaching realistic tissues modeling during MWA.

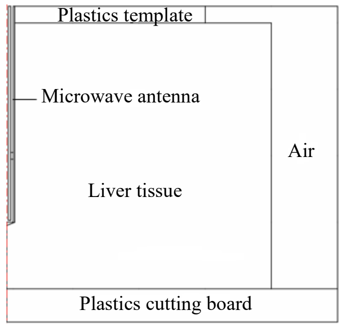

Fig. 4 Geometry of the validation model obtained by Yang et al. [11]

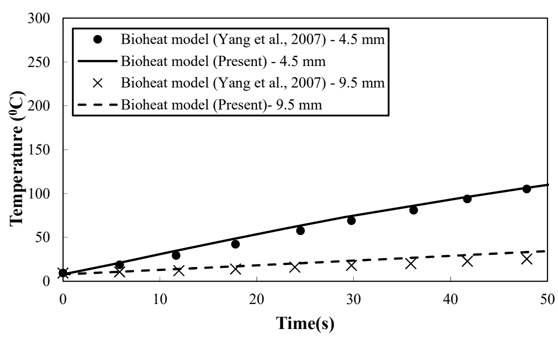

Fig. 5 The validation results of the liver tissue temperature from the bioheat model with the liver tissue temperature from bioheat model, against Yang et al. [11].

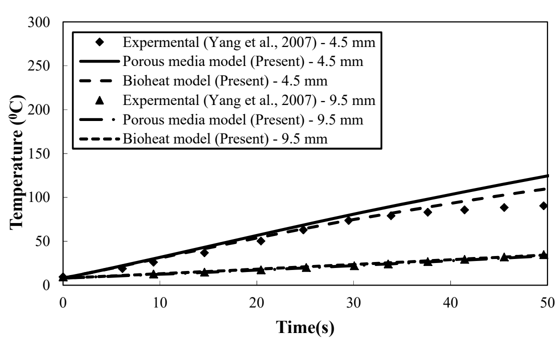

Fig. 6 The validation results of the liver tissue temperature from the porous model and bioheat model with the liver tissue temperature from experimental results, against Yang et al. [11].

This study demonstrates the simulation of temperature and blood velocity profiles within the liver tissue during MWA process.

5.2 Temperature Profile

Predicting the temperature profile play an important role in study of MWA process. In order to simulate the temperature profile as well as heat transfer within the liver tissue, the coupled model of transport phenomenon of electromagnetic wave propagation, heat transfer and blood flow are analyzed. The combination of these phenomena has an effect in which the microwave energy can be absorbed by the liver tissue and then converted into heat. In this section discusses the temperature profile in liver tissue during MWA process from using a developed model based on bioheat model and porous media model. The simulated results of the temperature profile in liver tissues based on a frequency of 2.45 GHz, input microwave power of 10 W and the tissue porosity of 0.6 are shown in Fig. 7. Fig. 7(a) shows the temperature profile in liver tissues calculated using bioheat model and Fig. 7(b) calculated using porous media model, for heating times of 30 s, 120 s, and 300 s, respectively. It is found that in both models, the temperature value increases as time increasing. In addition, the temperature profile forms a nearly ellipsoidal shape around the slot and the highest value occurs in the vicinity of the single-slot microwave antenna and decreases with the distance. It is found that by using the different heat transfer models, the distribution patterns of temperature at a particular time is the same, but the maximum value are quite different. The obtained results show that the maximum temperature increases calculated from both heat transfer models are capable of destroying cancer in liver tissue (cancer cells start to die at about 50°C [15]). Consider the comparison between the temperature increases, obtained from the two models, it can be seen that the results from porous media model, always give a slightly lower than that of bioheat model. It is found that at the heating time of 300 s, the maximum temperature are 86.551 °C and 95.431 °C in case of using porous media model and bioheat model, respectively or with maximum difference between two models is 9.31 %. Nevertheless, the volumetric heating pattern within liver tissue calculated using porous media model displays a wider region as compared to the result calculated using a bioheat model. The porous media model provides a wider region of heat dissipation to the liver tissue around the single-slot microwave antenna because of the effect of natural convection within the pores on heat transfer. The presences of natural convection heat transfer in liver tissue based on porous media model leads to an infiltrated flow of blood phase through the tissue pores far away from the hot spot zone. These patterns arise from the fact that the maximum temperature calculate using bioheat model (narrow heat region) always higher than case of using porous media model (wider heat region). This natural convection effects influences the characteristic to the liver tissue temperature, which is expected to occur in the realistic physiological condition.

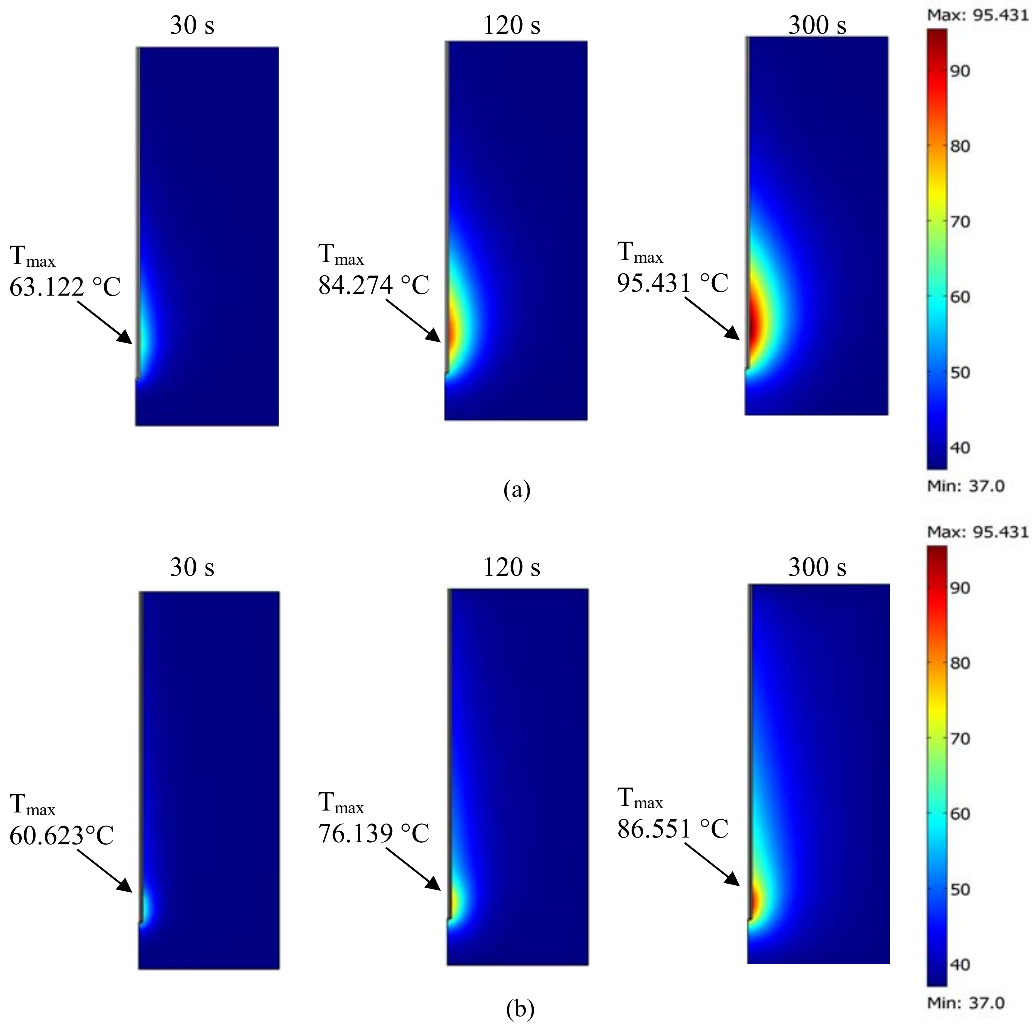

Fig. 7. The temperature profile in liver tissue at various time based on a frequency of 2.45 GHz, input microwave power of 10 W and tissue porosity of 0.6 calculated using;
(a) bioheat model and (b) porous media model.

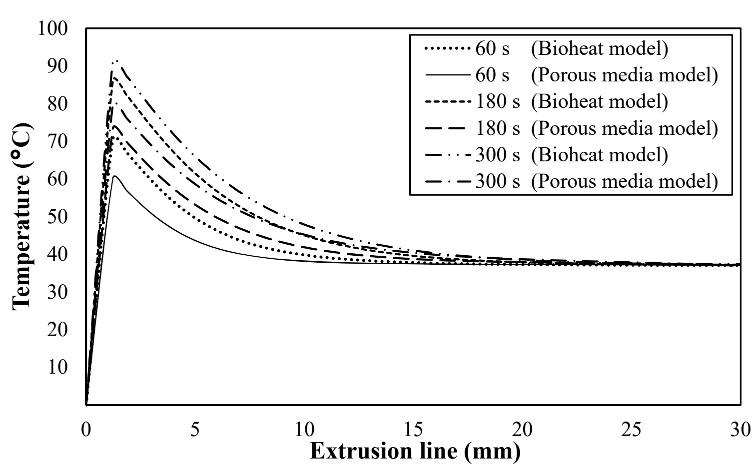

Fig. 8 The temperature distribution in liver tissue along the extrusion line based on a frequency of 2.45 GHz, input microwave power of 10 W and tissue porosity of 0.6 at various times.

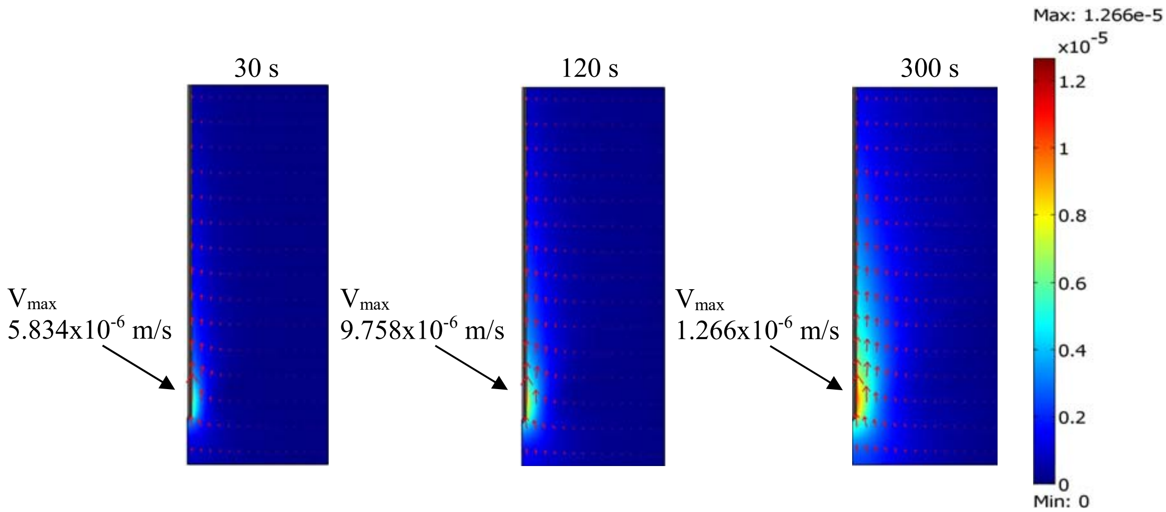

Fig. 9 The blood velocity profile in liver tissue at various time based on a frequency of 2.45 GHz, input microwave power of 10 W and tissue porosity of 0.6 calculated using the porous media model

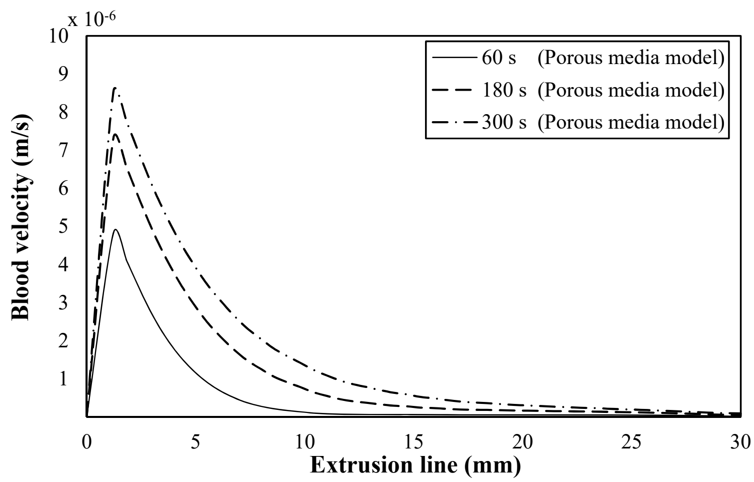

Fig. 10 The blood velocity distribution in liver tissue along the extrusion line based on a frequency of 2.45 GHz, input microwave power of 10 W and tissue porosity of 0.6 at various times.

Fig. 8 shows the temperature distribution in liver tissue at z = 16 mm (insertion depth of 64 mm or the center of slot) based on a frequency of 2.45 GHz, input microwave power of 10 W and the tissue porosity of 0.6 at various times calculated using bioheat model and porous media model. From the Fig. 8, it is seen that the temperature distribution of two models have a similar trend with a difference in magnitude. The temperature quickly increases along the extrusion line to a maximum temperature value at the slot exit. After that the temperature values gradually decreases and approach to steady state. The comparison between temperature distribution obtained from the two models, it can be seen that the porous media model, always gives a lower temperature than that of the bioheat model. Moreover, it is found that the temperature difference between the two heat transfer models increases as time increasing. The temperature difference between two heat transfer models obviously occurs at the hot spot zone. This is because the large temperature gradient produced by a microwave power causes a strong effect of natural convection which provides a buffer characteristic to the liver tissue temperature. Besides the microwave power, the magnitude of dielectric properties and thermal properties in liver tissue will directly affect the amount of temperature gradient within the liver tissue.

5.3 Blood Velocity Profile

The blood velocity profile in liver tissue at various time based on a frequency of 2.45 GHz, input microwave power of 10 W and the tissue porosity of

0.6 calculated using the porous media model is shown in Fig. 9. The blood flows as it is driven by the effect of buoyancy due to microwave energy. The blood velocity profiles have a trend corresponding to the temperature profile (Fig. 7(b)). The buoyancy effect is stronger near the tip and the slot of the single-slot microwave antenna, leads to a high blood velocity region at near the tip and the slot of the single-slot microwave antenna. The blood velocity profile forms a nearly ellipsoidal shape around the slot. Further, it reaches highest values in the vicinity of the slot of single-slot microwave antenna and decreases with the distance from the single-slot microwave antenna axis. The warmer blood with lower density rise near the slot of the single-slot microwave antenna, while the surrounding colder blood with higher density displaces the rising warmer blood in the immediate vicinity of the slot single-slot microwave antenna. The blood velocity increases rapidly in the early time of heating and reaches a maximum value in a short time. These blood velocity profiles vary corresponding to the temperature gradient within the liver tissue (Fig. 7(b)). It is found that the blood velocity value increases as time increasing corresponds to the temperature value increases. This is because a temperature gradient produced by a microwave power causes a strong effect of natural convection which provides a buffer characteristic to the liver tissue temperature during MWA process.

Fig. 10 shows the blood velocity distribution in liver tissue at z = 16 mm (insertion depth of 64 mm or the center of slot) based on frequency of 2.45 GHz, input microwave power of 10 W and porosity of 0.6 at various times. The blood velocity distributions have a trend corresponding to that of temperature distributions (Fig. 8). The blood velocity quickly increases along the extrusion line and reaches its maximum value near the slot exit, and gradually decreases and approach to zero at the outer boundary of the liver tissue where no effect of propagating wave occurs. Moreover, it is found that the blood velocity value increases as time increasing.

6. Conclusions

Clinical treatment with MWA needs an accurate control of the lesion generation in order to ensure cancer tissue destruction and to minimize damage to normal liver tissue. Computer simulation is necessary for predicting the temperature and blood velocity profiles during MWA process. For effective treatment, an accurate mathematical model represented electromagnetic wave propagation, heat transfer and blood flow of biological tissue is needed. In this study, a complete mathematical model of MWA process using porous media approach is proposed, which uses transient momentum equations (Brinkman model extended Darcy model) and transient energy equation coupled with electromagnetic wave propagation equation to describe the temperature and blood velocity profiles within the liver tissue during MWA process using a single-slot microwave antenna. The temperature distribution results calculated from a porous media model and bioheat model are compared with the experimental results from previous work in order to show the validity of the numerical results. The obtained results show that the porous media model could be a feasible and potential model for the study of the transport phenomena in liver tissue during MWA process. It is found that the temperature profile from a developed model based on porous media approach displays a wider region with a slightly lower maximum temperature as compared to the result calculated using a bioheat model. It is seen that the temperature distribution of two models have a similar trend with a difference in magnitude. The temperature quickly increases along the extrusion line to a maximum temperature value at the slot exit. After that the temperature values gradually decreases and approach to steady state. Moreover, it is found that the blood velocity profiles and blood velocity distribution by using porous media model have a trend corresponding to the temperature profile and blood velocity distributions, respectively.

In next step of research, the formulation of a three-dimensional modeling for approaching realistic liver tissue under MWA therapy will be performed.

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8. References

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