An Analysis of Temperature Distribution and Ablated Volume in the 3-D FEM Tissue Model with Blood Vessel during Radio-Frequency Ablation

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Abstract
The current treatment for a brain tumor has many methods such as surgery or chemotherapy but often the treatments may affect the patient or treatment is still limited in some aspects. A promising technique for brain tumor treatment is radio-frequency ablation. Radio-frequency ablation utilizes alternating current (AC), typically at about 500 kHz, to destroy unwanted tissues by heating to temperatures exceed 45°C to 50°C. The objective of this research is to study the treatment of brain tumor during radio-frequency ablation with computer simulation through finite element method (FEM) for solving the problem. A three-dimensional FEM model of brain tissue with a brain tumor and blood vessel is considered. Three types of blood vessels i.e. aorta, main veins and terminal veins are studied. The electric current equation and time-dependent bioheat transfer equation coupled with time-dependent convective blood vessel heat transfer equation are solved to predict temperature distribution and ablated volume within brain tissue model. The simulation results are compared with the simulation results from previous work to verify the accuracy of the presented model. The effects of the blood vessel are included and not included in the brain tissue model, types of blood vessel and treatment time during radio-frequency ablation on the temperature distribution and ablated volume are investigated. The outcomes indicated that size of blood vessel results in heat sink effects which increase with the velocity of blood flow. The aorta causes more heat sink effects than main veins and terminal veins, respectively; thereby the ablated area and ablated volume in case of the aorta is higher than one in case of main veins and terminal veins, respectively. In addition, the temperature value increases with greater treatment time. The results from this study provide the basis for planning the radio-frequency ablation of brain tumor, leading to approaches of medical practice process improvement.

Keywords: Ablated volume, Brain tissue, Radio-frequency ablation, Finite element analysis
1. Introduction
The human brain is the command center for the human nervous system. It is responsible for controlling activities of body, motion, homeostasis such as heartbeat, blood pressure or balancing temperature, and so forth related to cognition, thought, memory, emotion, even decision making. A Brain tumor is one of the diseases concerned with the brain in which abnormal cells uncontrollably form in the tissue of the brain. It can be either benign tumors or cancerous tumors and can start within the brain or spread from elsewhere which is cancerous [1]. The Risk factor of brain tumor includes family history, head injury, infections, environmental risks such as exposure, radiation or electromagnetic field and metastases that spread from any types of cancer such as lung cancer, breast cancer, colon cancer, kidney cancer etc. [2-3]. A Brain tumor can cause many symptoms regardless of whether a benign tumor or cancerous tumor it is such as headache which is an early symptom of brain tumor and reflects increased intracranial pressure, a seizure which causes loss of consciousness and some symptoms reflect the location, size or growth of tumor such as weakness, loss of vision, loss of hearing or impairment of language [1]. Diagnosis of brain tumor is usually by magnetic resonance imaging (MRI). Brain tumor whether benign or cancerous, start within the brain or spread from elsewhere is usually treated by surgery, radiation and chemotherapy – alone or combination based on a case-by-case basis and depend on the number, size and location of a brain tumor [4]. There are risks, side effects and limitations for each type of treatment. The alternative treatment option is radio-frequency ablation.

Radio-frequency ablation is one of the thermal treatment techniques that are employed in the destruction of the tumor. Radio-frequency ablation can be used to treat tumors in the liver, the lungs, kidneys, bones, breasts, the brain as well as other organs [5-9]. During radio-frequency ablation, alternating current (AC) with high frequency (about 500 kHz) is delivered into tumorous tissue through an electrode inserted percutaneously under image guidance into the tissue. The alternating electrical currents then move across the inserted electrode to the ground pad. The movement of ion against friction results in Joule heating, so the tissue temperature is raised [8-9]. The goal of this technique is to elevate the tissue temperature beyond 50 °C to cause the irreversible death of tumorous cells and coagulative necrosis [8-11]. Slightly increasing in temperature in approximately 1°C in the human brain can affect properties of single neurons and neural network function [12]. An increase of approximately 1 – 5 °C in human organs temperature can cause brain lesions. In addition, increases to approximately 40 °C for an extended period of time may lead to tissue damage [12-13]. The study examined the effect of radio-frequency by experiment such as the experimental treatment in the human brain will encounter the problem due to research ethics. Therefore, the computer simulation will be an alternative study which will help reduce the limitations from the experimental methods.

The Pennes’ bioheat model is widely used for modeling the heat transfer in human tissues during radio-frequency ablation to investigate the interaction of radio-frequency and heat transfer. In 2002, Tungjitkusolmun et al. [14] determined tissue temperature distribution during radio-frequency ablation using the finite element method (FEM). A three-dimension model of a four-tine radio-frequency probe, liver tissue and a large blood vessel was constructed. The effects of the presence of a blood vessel and its distance to probe were studied. The results showed that the blood vessel acted as a heat sink and the adjacent tissue was cooled down when it was near the probe. Zhu et al. [15] investigated a numerical model coupling the transport of electrical current, heat and the evaporation process in the tissue. The findings showed that the largest specific absorption rate happens at the edge of the circular surface around the electrode. In addition, the time duration between the beginning of the evaporation was 65 s and the cooling situations of the inside agent greatly affect the water loss pattern. Huang [16] computational study focused on the effects of blood vessels on the formation of the thermal lesion during radio-frequency ablation. The finite difference method was used to solve both Pennes’ bioheat transfer equation and convection-diffusion equation for a three-dimensional model of liver under several conditions of blood flow, the dimension of blood vessel and location of the blood vessel. The results showed that small blood vessel produced thermal lesion region like a tail, which could hurt the normal tissues. Zorbas et al [17] simulated radio-frequency ablation in computational models of human liver, lung and kidney in order to study the effect of realistic geometry in the treatment outcome. It was shown
that the ablation with the conventional single electrode inside the tumor must be careful in voltage and time setting in order to achieve effective treatment because of the difference in an ablated zone in various body sites. Singh et al. [18] studied on three-dimensional FEM models of breast cancer ablated by radio-frequency by varying applied voltages, tissue thermogenic capacities and sizes of a blood vessel. Integrating the bioheat equation with blood flow conservation was solved. The results showed that the increase in thermogenic capacity due to an increase in tumor volume caused an increase in treatment time.

Although a bulk amount of research has developed models to study on radio-frequency ablation, it was found that most of them have no regard for the complexity of organs such as including of different types of the blood vessel. In addition, most studies have mainly focused on the modeling of heat transfer within homogeneous tissue but do not include a tumor in a model. In fact, having different types of blood vessel as well as blood flow velocity and embedded brain tumor are affected by the treatment outcome. Therefore, in order to provide adequate information on the appropriate treatment of radio-frequency ablation process, it is essential to consider all of the previously mentioned parameters in the analysis. This research aims to study the treatment of brain tumor during radio-frequency ablation with computer simulation through FEM for solving the electrical-thermal problem. A cylindrical geometry of brain tissue which has spherical tumor included and Y-shape blood vessel included with a four-tine radio-frequency probe is considered. There are three different types of blood vessel considered, all of which have different diameters as well as blood flow velocity. The coupling of electrical current equation, time-dependent bioheat transfer equation and time-dependent convective blood vessel heat transfer equation is explained to predict temperature distribution and ablated volume within brain tissue model. The simulation results are compared with the simulation results from previous work to verify the accuracy of the presented model. The effects of a blood vessel which is included and not included in the brain tissue model, types of blood vessel and treatment time on the temperature distribution and ablated volume are studied. The results from this study provide the knowledge of heat transfer within brain tissue with blood vessel during radio-frequency ablation. It can be used as a guideline to treat brain tumor during radio-frequency ablation.

2. The formulation of the mathematical model

In this research, a numerical analysis of the electrical current equation, time-dependent bioheat transfer equation and time-dependent convective blood vessel heat transfer equation within the heterogeneous brain tissue is studied.

2.1. The simulation models

The three-dimensional finite element model is used in this study to analyze electrical-thermal problem within human brain tumorous tissue which blood vessel included and not included during radio-frequency ablation. The model of a problem can be divided into four sections: brain tissue, brain tumor, Y-shape blood vessel and radio-frequency probe (RF probe) as shown in Figure 1. The model of brain tissue is a cylindrical shape and has a diameter of 100 mm and a height of 120 mm [14] as shown in Figure 1(a). For another section, the brain tumor is modeled to be 50-mm diameter spherical shape within the brain tissue model as shown in Figure 1(b). The effects of a blood vessel which is included and not included in the brain tissue model, types of blood vessel and treatment time on the temperature distribution and ablated volume are considered. The blood vessel is modeled to be Y-shape looking alike branches of the human blood vessel. The angle between two branches of the Y-shape blood vessel is 30 degree. The length of the blood vessel is 100 mm. The diameter of the blood vessel depends on the types of blood vessel. The blood vessel will be considered in the case that includes blood vessel effect as shown in Figure 1(c). The study uses a four-tine electrode RF probe to transfer electrical current into a brain tumor. Figure 1(d) shows that the RF probe consists of two parts: a trocar and four-tine electrode. The trocar is made from stainless steel and has a diameter of 1.83 mm and a length of 60 mm. The four-tine electrode is made from Nickle-Titanium (Ni-Ti) and has a diameter of 0.53 mm as shown in Figure 1(c). The distance from the distal trocar to the distal
The RF probe is inserted into the brain tissue with 60 mm depth. The distal trocar is at the center of the brain tumor and parallels 31.38 mm away to the centerline of Y-shape blood vessel as shown in Figure 2.

Table 1 illustrates the dimensions of model components.

Figure 1. The physical domains of the problem: (a) overall model for human brain tissue during radio-frequency ablation (b) brain tumor (c) Y-shape blood vessel (d) Four-tine electrode of RF probe and (e) electrode

2.2. Governing equation

Mathematic analysis being relevant to this research consists of the electric current equation, heat transfer and blood flow. The system of governing equation is solved numerically using FEM in order to predict temperature distribution and ablated volume in human brain tissue during radio-frequency ablation, as follows;

2.2.1. Electric current

In radio-frequency ablation, an electric current through RF probe causes the electric field in the tissue. The nearby region from the RF probe has the strongest field and causes resistive heating around the electrode. Thus, the electric field is solved by the generalized Laplace equation [12]:

\[ -\nabla \cdot (\sigma \nabla V) = Q_i \]

where \( \sigma \) is the electrical conductivity (S/m), \( V \) is potential (V) and \( Q_i \) is the current source (A/m\(^2\)).
The boundary conditions for the electric current analysis as follows: the outer surface of brain tissue is assumed to be ground ($V = 0$), the potential at electrode surfaces is $V_0$ ($V = V_0$) and the surface between the brain tissue and the brain tumor is considered as a continuity boundary condition, as shown in Figure 3.

2.2.2. Heat transfer

The Pennes’ bioheat equation with the metabolic heat source and the external heat source applied to the brain tissue can be written as [12]:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \left( \rho c_p \right)_b \omega_b (T_b - T) + Q_{met} + Q_j$$

where subscript $b$ represents the blood, $\rho$ is the density (kg/m³), $c_p$ is the specific heat (J/kg·°C), $k$ is the thermal conductivity (W/m·°C), $\omega_b$ is the blood perfusion (1/s), $Q_{met}$ is the metabolic heat source (W/m³), is neglected since it was small [14], $Q_j$ is the external heat source generated by electric current (W/m³) and have relations as Equation (1), $T$ is the tissue temperature (°C) and $T_b$ is the blood temperature (assumed to be uniform throughout the tissue at 37 °C).

The Pennes’ bioheat equation is frequently used to describe heat transfer and the temperature distribution in biological tissue.

The convective heat transfer equation applied to the blood vessel can be written as:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T = \nabla \cdot (k \nabla T)$$

where $\rho$ is the density of blood (kg/m³), $c_p$ is the specific heat of blood (J/kg·°C), $u$ is the velocity of blood (cm/s), $k$ is the thermal conductivity of blood (W/m·°C) and $T$ is the blood temperature (°C).

The boundary conditions for the heat transfer analysis as follows: the outer surface of brain tissue is set to be body temperature of 37 °C and the velocity field of blood in Z-axis is constant ($u_z = u_0$). Corresponds to the electric current analysis, the surface between the brain tissue and the brain tumor and the surface between the brain tissue and the blood vessel is considered as a continuity boundary condition, as shown in Figure 3.

Figure 2. Dimensions and position of physical domains of the problem
2.3. Material and tissue properties
The electrical and thermal properties of the components and tissues in this study i.e. electrode, trocar, blood vessel, brain tissue and brain tumor are shown in Table 2.

| Components     | Materials | \( \rho \) (kg/m\(^3\)) | \( c_p \) (J/kg·°C) | \( k \) (W/m·°C) | \( \sigma \) (S/m) |
|----------------|-----------|---------------------------|----------------------|------------------|-----------------|
| Electrode      | Ni-Ti     | 6450                      | 840                  | 18               | \( 1 \times 10^{8} \) |
| Trocar         | Stainless Steel | 21500                 | 132                  | 71               | \( 4 \times 10^{6} \) |
| Blood vessel   | Blood     | 1000                      | 4180                 | 0.543            | 2.54            |
| Tissue (Brain) | Brain     | 1038                      | 3650                 | 0.53             | 0.76            |
| Tissue (Tumor) | Tumor     | 1040                      | 3960                 | 0.57             | 2.09            |

In addition, there are three types of blood vessel included in this study, namely, aorta, main veins and terminal veins. The parameters such as the diameter of the blood vessel and velocity of blood depend on types of blood vessel. Blood vessel parameters used in the calculation are shown in Table 3.

| Types of blood vessel | Diameter (mm) | Velocity (cm/s) |
|-----------------------|---------------|-----------------|
| Aorta                 | 10            | 50              |
| Main veins            | 2.4           | 1.5             |
| Terminal veins        | 0.28          | 0.8             |
3. Calculation procedure
The temperature distribution and the ablated volume in a human brain during radio-frequency ablation are investigated through a finite element model. The triangular elements and the Lagrange quadratic elements are used to estimate the temperature through each element in the three-dimension model. This study uses an element-independent formulation to solve the problem. To obtain a reasonable estimate, a fine mesh is specifically identified in a sensitive area. The matrix of governing equations with the boundary and initial conditions are solved numerically by the FEM via COMSOL™ Multiphysics program to demonstrate the phenomenon that occurs in the human brain treated by radio-frequency ablation. A grid independence test is carried out to identify the appropriate number of elements that are required. This mesh independence test led to a mesh with approximately 400,000 elements. It is reasonable to suppose that, with this element number, the accuracy of the results will be independent of the number of elements.

This study will systematically investigate the impacts of blood flow and types of a blood vessel on temperature distribution and ablated volume in tumorous human brain tissue during radio-frequency ablation. There are effects of blood vessel included and not included in the model and three types of blood vessels, namely aorta, main veins and terminal veins to be considered.

4. Results and discussion
In the present study, the three-dimensional model is used to analyze coupling of electrical-bioheat transfer and blood flow within tumorous human brain tissue which blood vessel included and not included during radio-frequency ablation.

4.1. Verification of the model
To verify the accuracy of the present model, the result in case of the blood vessel is not included in human brain tissue is validated against the computer simulation results obtained by Tungjitkusolmun et al., 2002 [14]. The validation model is a three-dimensional model having a cylindrical shape (100-mm diameter and 120-mm length). The four-tine RF probe is fully deployed and situated in the middle of the hepatic tissue model. The average applied power is 60 W for 8 min, the average voltage is 30 V and impedance is 60 Ω. Table 4 shows the validation results which are the ablated zone dimensions (at a temperature of 50 °C) in the same positions with the results of validation model when a blood vessel is not included in tissue. The diagram of a typical lesion and the parameters measured is shown in Figure 4. It is found that the simulated results correspond closely with the Tungjitkusolmun et al study. [14]. Some certain mis-match involved in the simulation is caused by some difference in the numerical scheme.

| Case                        | W1 (mm) | W2 (mm) | D1 (mm) | D2 (mm) | R1 (mm) | R2 (mm) |
|-----------------------------|---------|---------|---------|---------|---------|---------|
| Tungjitkusolmun et al., 2002 | 21.0    | 21.0    | 17.6    | 18.5    | 11.8    | 11.8    |
| Present Study               | 22.02   | 21.90   | 17.00   | 16.45   | 13.29   | 13.29   |

Figure 4. The diagram of a typical lesion and the parameters measured of validation model from Tungjitkusolmun et al., 2002 [14]
4.2. Effects of blood vessel

In this study, the models of three different types of blood vessel included in brain tissue, namely, aorta, main veins and terminal veins which have different diameters and blood flow velocity as shown in Table 3 undergone radio-frequency ablation are investigated to discuss the effects of blood vessel included and not included in the model and effects of the difference between each type of blood vessel. The computer simulation of radio-frequency ablation is performed based on the power of 15 W for a treatment time of 480 s via a four-tine electrode RF probe. Brain tumor has 50 mm diameter and distance between the center of brain tumor and the centerline of blood vessel included in the brain tissue is 31.38 cm. Figure 5 (a) - (d) illustrate temperature distribution within brain tissue on the x-z plane which various types of blood vessel included, i.e. aorta, main veins, terminal veins and no blood vessel included, respectively, undergone radio-frequency ablation. The red bound in temperature distribution identifies the margin in which temperature is 50 °C isotherm. The 50 °C isotherm correlates with coagulation zone boundary within acceptable accuracy and the region inside the red bound is called an ablated zone. The hot spot zone with the highest temperature occurs at the four-tine electrode tips and decreases with distance. In cases that blood vessel included in brain tissue, the results show that the temperature distributions and ablated zones are asymmetric around the electrode because they converge to the blood vessel. The asymmetry in temperature distributions and ablated zones occurs more in case of the aorta, main veins and terminal veins, respectively. Considering cases of blood vessel included, the temperature distribution and ablated zone within brain tissue are affected by blood flow due to heat sink effect. Aorta causes the larger temperature distribution and ablated zone with a higher temperature than main veins and terminal veins, respectively, because its higher blood flow velocity results in more influential to heat transfer within brain tissue during radio-frequency ablation. In case of no blood vessel included, radio-frequency ablation creates symmetric larger temperature distribution and ablated zone within brain tissue than cases of blood vessel included because it is not disturbed by a blood vessel.

The simulation results from this study illustrate that the temperature distribution and ablated zone from radio-frequency ablation are influenced by heat sink effects due to convective heat transfer by blood flow. The electric field is created between two electrodes, one is percutaneously inserted into the tumor and another is a ground pad. The high-frequency AC is delivered into the tissue and induces Joule heating that leads to irreversible destruction of the tumor cell at a higher temperature above 50 °C. When the bulk motion of blood flow occurs near the region in which radio-frequency ablation is conducted, the heat generated by Joule heating from radio-frequency ablation is carried and dispersed. Heat is first transferred from ablated zone to surface of a blood vessel by conduction and then carried away from the surface by convection. This is by combined effects of conduction within blood flow due to randomness of blood flow and the bulk of blood flow that removes heated blood which is adjacent to the surface of a blood vessel and replaces with cooler blood. The blood flow enhances heat transfer, since it carries cooler bulk of fluid into contact, initiating rate of heat conduction at a number of sites in the fluid. The rate of heat transfer by convection strongly depends on fluid (blood) velocity. The higher fluid velocity leads to a higher rate of heat transfer. Considering the blood vessels included in this study, the aorta has a larger diameter with higher blood flow velocity than main veins and terminal veins, respectively, as shown in Table 3. Therefore, the rate of heat transfer due to heat sink effects in the aorta is higher than the main veins and terminal veins, respectively. It results in more hot spot zone with higher temperature in the aorta than main veins and terminal veins, respectively. In addition, heat sink effects result in the region between near electrode and blood vessel has a higher temperature and leads to asymmetric ablated zone compared with the case that no blood vessel included. The asymmetric ablated zone with a high temperature between the near electrode and blood vessel occurs more in case of the aorta and less in case of main veins and terminal veins, respectively, corresponding to the rate of heat transfer resulted by heat sink effects. Furthermore, the radio-frequency ablation raises the temperature in tissue by Joule heating, being the process where the energy of electric current flows through a conductor and converted into heat due to the passage of it through resistance. The blood has higher electrical conductivity than brain tissue as shown in Table 2, AC delivered into the tissue is consequently diverted toward blood flow. Therefore, more Joule heating occurs in the region between the near electrode and the blood vessel.
along with the blood vessels, especially the nearby site to the electrode, results in the asymmetric ablated zone with a high temperature in these regions.

Figure 5. Temperature distribution within brain tissue on an x-z plane based on the power of 15 W for a treatment time of 480 s via four-tine electrode radio-frequency probe for each type of blood vessel included (a-c) or not included (d).

Temperature trends obtained at three points around the tumor during radio-frequency ablation based on the power of 15 W for a treatment time of 480 s via four-tine electrode RF probe are exhibited in Figure 6(a) – (d) for the case of the aorta, main veins, terminal veins included and no blood vessel included, respectively. The three points i.e. R1, R2 and R3 are exhibited in Figure 7. Temperature trends show that the temperature at all points increases along the treatment time for all cases. The temperature distributions in cases of blood vessels included are asymmetric as they converge to the blood vessel. In case of aorta included, the temperature trend at R3 is higher than R1 and R2, respectively, while in cases of main veins and terminal veins, temperature trends at R3 are slightly higher than the R1 but significantly higher than R2. This result is consistent with the temperature distribution and ablated zone in Figure 5. The temperature trend at the point which near the blood vessel (R3) is the highest as a result.
of the effects of Joule heating caused by the diverted passage of radio-frequency electric current toward blood flow due to higher electrical conductivity of blood compared with brain tissue as well as heat sink effects due to convective heat transfer by blood flow. The aorta which has a larger diameter with a higher velocity of blood flow results in more heat sink effects than main veins and terminal veins, respectively. Thus, the temperature trend at R3 in case of the aorta is higher than the main veins and terminal veins, respectively. Considering two other points (R1 and R2), since the point R1 is nearer to the electrode tip in which the highest temperature occurs as shown in Figure 5, the temperature trend at the point R1 is higher than one at R2 in all case. It is because blood flow is included and effects in these cases that the temperature trends at R1 and R2 are also in agreement with the temperature trend at R3. For the case of no blood vessel included, the temperature trend at R3 is about the same high as one at R1 because of no heat sink effects from blood flow, whereas the temperature trend at R2 is lower than the others because of the further distance from the electrode tips. The result agrees with the temperature distribution in Figure 5. The temperature distributions in case of no blood vessels included are symmetric as there is no heat sink effect by blood flow. The temperature trend at R3 is lower than one in the cases of blood vessels included while the temperature trend at R1 and R2 to be close to the temperature trend at R1 and R2 in the cases of blood vessels included. This is because there are no heat sink effects due to convective heat transfer by blood flow as well.

![Graphs showing temperature trends](image)

**Figure 6.** The temperature trends evaluated at three points (R1, R2 and R3) within brain tumor based on the power of 15 W for a treatment time of 480 s via four-tine electrode radio-frequency probe for each type of blood vessel included (a-c) or not included (d)
Table 5 shows a comparison of the ablated area and ablated volume from a computer simulation of radio-frequency ablation in cases of the aorta, main veins, terminal veins and no blood vessel included. Figure 8 illustrates a diagram of the measured dimension of the ablated zone. The results show that heat sink effects due to convective heat transfer by blood flow dominate restricted ablated area and ablated volume. Because 50 °C isotherm (as the boundary of the ablated zone) is limited by blood vessel and heat dissipates in the directions perpendicular to the electrode, W1 is used to calculated ablated area and ablated volume in this study. Considering cases of blood vessel included, the results show that ablated area and ablated volume in cases of the aorta is larger than main veins and terminal veins, respectively, because aorta produces a broader area of temperature distribution due to its higher blood flow velocity. However, the ablated area and ablated volume in case of no blood vessel included are higher than cases of blood vessel included because it is not disturbed by a blood vessel. This result corresponds to the temperature distribution and ablated zone in Figure 5.

Figure 7. The points where temperature trends are evaluated within the brain tumor (R1 - R3).

Figure 8. Diagram of a measured dimension of the ablated zone

Table 5. The ablated area and ablated volume from a computer simulation of radio-frequency ablation in cases of the aorta, main veins, terminal veins and no blood vessel included.

| Blood Vessel   | Diameter of tumor (mm) | Power (W) | Time (s) | W1 (mm) | W2 (mm) | D1 (mm) | D2 (mm) | Ablated area (cm²) | Ablated volume (cm³) |
|----------------|------------------------|-----------|----------|---------|---------|---------|---------|-------------------|----------------------|
| Aorta          | 50                     | 15        | 480      | 30.436  | 26.309  | 23.388  | 26.315  | 29.10215          | 118.1004             |
| Main veins     | 50                     | 15        | 480      | 30.411  | 30.113  | 23.638  | 27.050  | 29.05436          | 117.8096             |
| Terminal Veins | 50                     | 15        | 480      | 30.209  | 30.722  | 23.657  | 27.086  | 28.66966          | 115.4776             |
| No vessel      | 50                     | 15        | 480      | 30.680  | 30.619  | 23.358  | 27.056  | 29.57063          | 120.9636             |
5. Conclusions
This numerical study presents the three-dimensional finite element analysis of radio-frequency ablation in the brain tumor using a four-tine electrode. The model of cylindrical brain tissue which spherical brain tumor embedded is constructed. The effects of blood vessel included and not included on temperature distribution and ablated volume within brain tissue are investigated. There are three types of blood vessel including aorta, main veins and terminal veins. The results reveal that blood vessel results in heat sink effects that dissipate heat from surrounding tissue. The aorta causes more heat sink effects than main veins and terminal veins, respectively, because the higher velocity of blood flow leads to a higher rate of convective heat transfer by blood flow. Therefore, the temperature distribution within aorta is higher than main veins and terminal veins, respectively. In addition, the results indicated that ablated area and ablated volume in cases of the aorta is larger than the main veins and terminal veins, respectively, because aorta produces a broader area of temperature distribution due to its higher blood flow velocity. Nevertheless, the ablated area and ablated volume in case of no blood vessel included are higher than cases of blood vessel included since it is not disturbed by a blood vessel. Even though it is found that temperature distribution and ablated zone in case of no blood vessel included are symmetric and broader than cases of blood vessel included, consideration of blood vessel and its influences is very essential because it is consistent with radio-frequency ablation in clinical treatment. This simulation can be applied to use in clinical brain tumor treatments by radio-frequency ablation as a guideline for treatment planning.

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