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Effects of Metabolic Heat on The Temperature Distribution of Human Hands Affected by Sarcoma Tumors Given Interstitial Hyperthermia Therapy

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Abstract: In the medical world, heat transfer studies can be used as tumor therapy. At a temperature of ≥40ºC, a tissue will stop growing and die. One therapy that uses this concept of heat transfer is interstitial hyperthermia therapy. The high temperature given will certainly have an impact on the normal tissue around the tumor. Thus, the use of interstitial hyperthermia therapy requires the ability to adjust the right heat source, both based on space, time, and other supporting factors, such as metabolic heat, so that optimal success will be obtained. This study analyzes the influence of metabolic heat on the distribution of temperature in the human hands in interstitial hyperthermia therapy under unsteady conditions. The Pennes bioheat equation and the finite element numerical method are used to determine the value of the temperature distribution. This study was conducted for 600 seconds and variations in metabolic heat values were used in the form of 0 W/m^3; 368,1 W/m^3; 500 W/m^3; 800 W/m^3 and 1200 W/m^3. In this study, metabolic heat influences temperature distribution that occurs in the interstitial treatment of hyperthermia therapy. This is because metabolic heat will provide heat from the inside so that the temperature in the tissue will increase.

Keywords: Heat Transfer, Interstitial Hyperthermia Therapy, Unsteady, Pennes' Bioheat Equation, Finite Element Method, Metabolic Heat

Highlight:
1. How heat transfer mechanisms may play a role in tumor treatment?
2. What is the role of metabolic heat in metabolic heat in the treatment of tumors on the hands?
3. How is interstitial hyperthermia treated with temperature distribution in the affected hand of the tumor?

1. Introduction

Metabolism plays an important role in the thermoregulation of the human body. A person's metabolic rate varies according to the person's physical activity. Active people have a higher metabolic rate than less active people. This increase in metabolism creates energy in the form of heat and is used to maintain body temperature as usual[1)]. Various studies have been conducted, metabolic heat is proven to influence heat transfer that occurs in the human body in the process of hyperthermia. The process of hyperthermia is a process of giving heat temperature beyond normal temperature, usually aimed at turning off the tissue that is detrimental to the human body, such as tumors. The higher the metabolic heat value in the human body, the higher the temperature that occurs in the hyperthermal process will be higher as well[2)].

The term for the science that studies heat transfer in living things is known as bioheat transfer. This science aims to know, analyze and study thermodynamic processes that occur in living things. In 1948, Harry H. Pennes introduced a mathematical equation that can be used in knowing the heat transfer that occurs in the human body, namely the Pennes equation. The Pennes equation assumes that the temperature of blood flow in the vein is equal to the temperature in the tissue or it can be said that the heat transfer in the blood vessels is ignored. Although the concepts used in these equations are unrealistic, there have been widespread applications in various areas of bioheat for inherent simplicity and pragmatic results[3)].

One of the medical cases involving the process of heat transfer in its settlement is the treatment of tumors. Tumors not only grow on epithelial tissues (tissues that protect internal organs) but can also grow on mesenchymal tissues (tissues forming connective tissue such as in bones, cartilage, nerves, muscles, joints, and blood vessels). Mesenchymal tissues account for more than two-thirds of the total body weight. Tumors in mesenchymal tissues are commonly known as sarcoma tumors[4)].

Various methods can be done in dealing with sarcoma tumor tissues, one of which is interstitial hyperthermia

therapy. Interstitial hyperthermia therapy utilizes heat sourced from electromagnetic field energy to damage tumor tissues[5]. This type of thermal therapy uses a needle antenna that is high-frequency and is directly implanted into tumor tissues. Therefore, pathological tissue can be easily heated to a therapeutic temperature (40 °C - 46 °C)[6].

Tumor tissues will be damaged if exposed to high temperatures with a critical point of about 40 °C. This is due to differences in the physiological characteristics of normal cells and tumor cells. Tumor cells have a chaotic form of blood vessels, or sensitive hypoxia areas and have a low PH[7,8]. This damage results in the denaturation of proteins leading to changes in molecular dredges and changes in the shape of enzyme complexes in the synthesis and repair of a cell's DNA[9,10]. For normal tissue, the tissue will not be damaged if given a temperature of up to 44 °C for 1 hour[11]. While in the central nerve tissue, hyperthermia damage is found, but only irreversible [12]. In peripheral tissues there will be functional damage and will recover within 4 weeks[13].

However, damage from hyperthermia therapy cannot always be avoided for higher temperatures, such as burns (in 25% of patients with breast cancer)[14,15]. Temperatures that are too high, subcutaneous fat, or muscle tissue produce a feeling of distress, which is not felt by therapy patients. Subcutaneous fat burns are seen in 3-12% of patients treated with deep hyperthermia[16]. Thus, the use of interstitial hyperthermia therapy requires the ability to adjust the right heat source, both based on space, time, and other supporting factors, so that optimal success will be obtained[17].

Based on the description above, there is still no research on the effect of metabolic heat on the distribution of temperature in the human hand when applied interstitial hyperthermia therapy for sarcoma tumor therapy in unsteady conditions. To find out the temperature distribution that occurs, the Pennes equation and the finite element numerical method are used. Geometric conditions used in the form of 2D asymmetry consisting of 5 layers of skin on the human hand, sarcoma tumors, and antennae on interstitial hyperthermia therapy.

2. Material and Method

The research conducted is a simulation of heat transfer that occurs in the hands of humans when applied to interstitial hyperthermia therapy and heat coming from the environment is ignored. This heat transfer is calculated by the equation of bioheat Pennes assisted by the numerical finite element (FE) method. A finite element (FE) is a numerical method in which a problem is divided into a certain number of elements (finite) to represent the problem that the actual number of elements is infinite (continuum). This numerical method is used to determine the temperature distribution in the hands of humans affected by sarcoma tumors during interstitial hyperthermia therapy. The study also looked for the influence of metabolic heat on the distribution of temperature that occurs in the hands of humans in unsteady conditions. The metabolic heat value used is 0 W/m^3; 368,1 W/m^3; 500 W/m^3; 800 W/m^3 and 1200 W/m^3.

2.1 Pre-processing

Pre-processing is the initial stage of the complete process of this study. The steps in pre-processing are:

- Parameter defining

a) Thermal properties

Parameters of thermal properties of human hand tissue and sarcoma tumors are shown in Table 1[18,19]. Hand tissue consists of several layers, in the form of epidermis, dermis, fat, muscle, and bone.

Table 1 - Thermal properties of the tissue

	Density ρ (kg/m^3)	Thermal Conductivity k (W/mK)	Specific Heat c_p (J/gK)
Epidermis	1200	0,24	3598
Dermis	1200	0,45	3300
Fat	937	0,21	3258
Muscle	1000	0,5	4000
Bone	1920	0,44	1440
Sarcoma tumor	1079	0,52	3540

Table 2 - Thermal properties of blood and other components

	Symbol	Value	Unit
Specific heat of blood	c_b	4200	J/gK
Blood density	ρ_b	1000	kg/m^3
Blood perfusion rate	ω_b	0,0002	ml/ml.s
Arterial blood temperature	T	37	ºC
Time	Δt	600	s
Frequency	F	2,45	GHz
Power	P	1	W

b) Design geometry

The geometry of the design used is a 2D asymmetry in the form of human hands, tumor tissue, and an antenna of the hyperthermia process. Figure 1 is the geometric shape of the research conducted and figure 2 is the shape of the antenna used. For geometric dimensions can be seen in Table 3[20]

Table 3 - Geometry dimensions

	Value (mm)
Epidermis	0,08
Dermis	2
Fat	10
Muscle	20
Bone	8
Major axis of sarcoma tumor	15
Minor axis of sarcoma tumor	10
Radius in conductor	0,135
Radius in outer conductor	0,47
Radius in inner conductor	0,595
Catheter radius	0,895
Air slot size	1

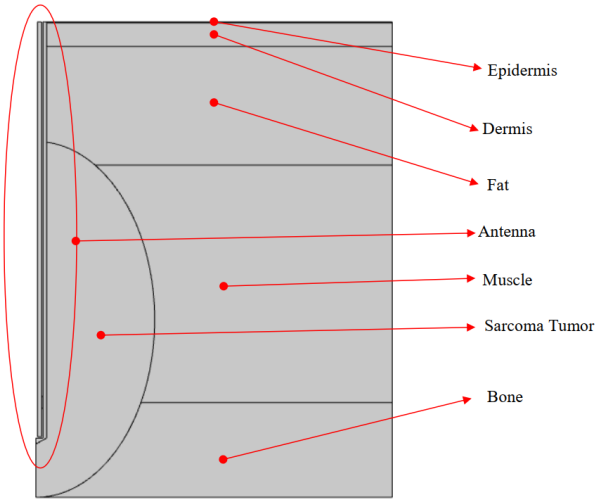

Fig 1 : Research geometry design

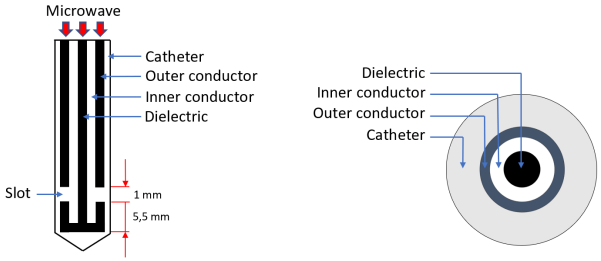

Fig 2 : Antenna design

c) Electrical properties

Electrical parameters of human body tissues, tumors, and antenna are shown in Table 4[20)]

Table 4 - Electrical properties

	Relative Permittivity ε_r	Relative Permeability μ_r	Electrical Conductivity σ (S/m)
Epidermis	38	1	1,46
Dermis	38	1	1,46
Fat	10,8	1	0,27
Muscle	52,7	1	1,74
Bone	5,3	1	0,095
Sarcoma tumor	40	1	1
Dielectric	2,03	1	0
Catheter	2,06	1	0
Air slot	1	1	1

- Determination of governing equation

The governing equation used is the Pennes equation under unsteady conditions, here is the formula used[6,21)]:

$$\rho c \frac{dT}{dt} = k\nabla^2 T + \rho_b c_b \omega_b (T_a - T) + Q_m + Q_e \quad (1)$$

ρ is the mass of the tissue type, ρ_b is the mass of the blood type, c is the specific heat of the tissue, c_b is the specific heat of the blood, T is the temperature of the blood, T_a is the temperature of the arteries, t is the time, Q_m is the metabolic heat and Q_e is the external heat produced from interstitial hyperthermia therapy. The external heat is as follows:

$$Q_e = \frac{\sigma|\hat{E}|^2}{2} \quad (2)$$

σ is electrical conductivity and E is the electric field

- Meshing

The meshing process is a discrete process of elements so that analysis can be calculated on smaller elements[22)]. In addition, the development of the shape and number of mesh used should be carefully observed, as it determines the amount of convergence that occurs. Where the number of convergence is what will determine the accuracy of the completion of the simulation carried out[23)].

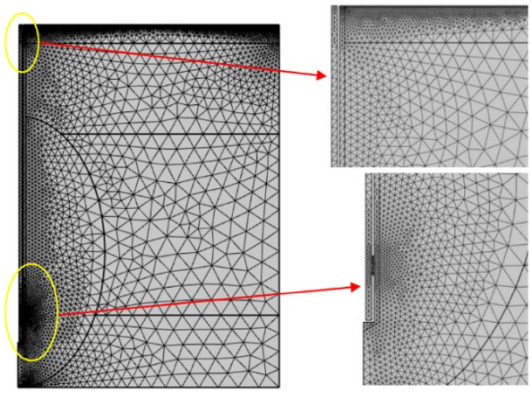

Fig 3 : Meshing

- Determination of node

Node is a point or an area to be researched or analyzed. In this study, geometry was divided into 11 nodes, at the position of the value r = 1 mm and the distance between the node Δz = 3.33 mm. Here is the position of the node that will be done for research

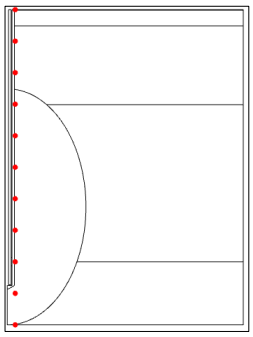

Fig 4 : Defining research node

2.2 Solver

The solver process is the process of solving the governing equation assisted by the numerical method of finite element (FE). There are two studies conducted, in the form of electromagnetic wave equations and bioheat transfer.

2.3 Pre-processing

In the post-processing stage, an analysis of the results and discussion of the nodes given and the distribution of temperature that occurs from metabolic heat variations.

3. Results

3.1 Effect of Metabolic Heat on Temperature Distribution in The Human Hand When Applied Interstitial Hyperthermia Therapy

Metabolic heat is heat stored in the human body. Metabolic heat is commonly used in the thermoregulation system of the human body. Metabolic heat plays an important role in the distribution of temperature in the tissues of the human body, this is because metabolic heat will provide heat from within so that the temperature in the tissues will increase[1]. In this study, the variation in metabolic heat value used was 0 W/m^3; 368,1 W/m^3; 500 W/m^3; 800 W/m^3, and 1200 W/m^3, with 11 nodes scattered from the epidermis tissue up to the bone, at a value of r = 1 mm. The time used in analyzing the temperature distribution is 600 seconds. Here's a graph that can be presented from this study.

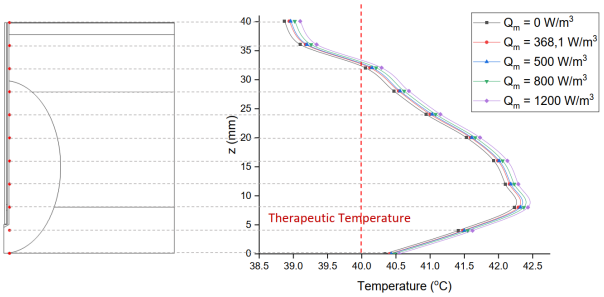

Fig 5 : Comparison of the temperature distribution in the human hand along the line r = 1 mm and the value of t = 600 s based on variations in metabolic heat in the human body

Based on the graph above, the highest temperature distribution value is at a metabolic heat value of 1200 W/m^3, followed by a metabolic heat value of 800 W/m^3; 500 W/m^3; 368,1 W/m^{3}and the lowest temperature distribution value is at a metabolic heat value of 0 W/m^3. This is following the basis of existing theories, that one of the factors that influence changes in temperature in the human body is metabolic heat[2].

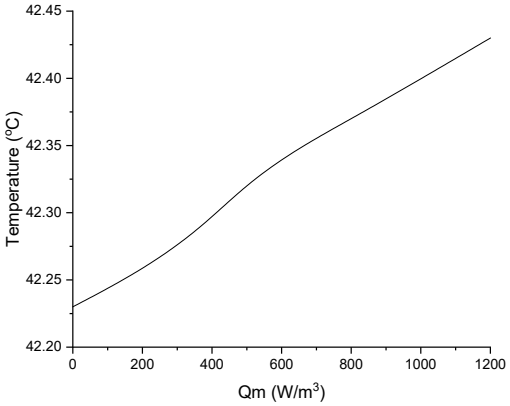

Fig 6 : The effect of metabolic heat on temperature changes that occur in the human body when applied to interstitial hyperthermia therapy

Figure 6 shows a graph of the influence of metabolic heat on temperature changes that occur at r = 1 mm and z = 8 mm when applied interstitial hyperthermia therapy. The x-axis displays the metabolic heat value and the y-axis displays the temperature value. Based on the graph, it can be seen that the temperature value will increase as the metabolic heat value increases. However, the effect of metabolic heat on temperature increases that occur is not too great when compared to the heat produced from

interstitial hyperthermia therapy. The large increase in temperature that occurs for each increase in metabolic heat of 1000 W/m^3 is 0,167 ^{o}C

3.2 Effect of Antenna Air Slot Distance on Temperature Distribution in Human Hands with Unsteady Conditions

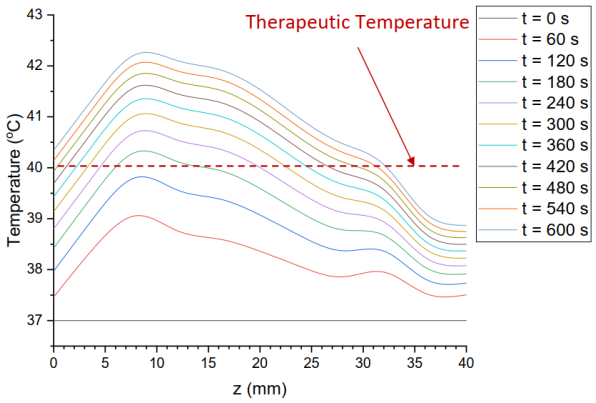

Fig 7 : Temperature distribution in the human hand along the line r = 1 mm and value Qm = 0 W/m^3

An unsteady condition is a condition in the form of temperature changes influenced by time. From the graph above, you can see that the temperature value will increase over time. This is because in the governing equation used, the temperature value is directly proportional to the amount of time. Therefore, the longer interstitial hyperthermia therapy is applied, the greater the temperature value produced[6]. Low metabolic heat values in interstitial hyperthermia therapy will make the duration required in achieving therapeutic temperatures will be longer. However, this will make it easier to control the large value of temperature distribution that occurs in each body tissue. If the metabolic heat value is high, the tumor tissue will more quickly reach therapeutic temperature. However, the normal tissue around the tumor can at any time experience therapeutic temperatures and make the tissues in the tissue die[24].

The results show that the highest temperature value is at node 3 (value z = 8.016 mm) and the lowest is at node 11 (value z = 40.08 mm). This is due to the influence of the node distance to the heat source or antenna air slot. An antenna air slot is a place where heat escapes from the interstitial hyperthermia therapy. The temperature that occurs in the body tissue will be smaller as it gets farther away from the antenna air slot and the greatest temperature value will occur in the tissue closest to the antenna air slot[25].

3.3 Analysis of The Contours of Temperature Distribution in Each Variation of Metabolic Heat

This study was conducted in the hands of humans with 2D asymmetric geometric shapes. From figure 8, you can see the contour shape of the temperature distribution at the metabolic heat value of 0 W/m^3; 368,1 W/m^3; 500 W/m^3; 800 W/m^3, and 1200 W/m^3 in 600 s. Each temperature contour has a similarity, in the form that the therapeutic temperature (≥40 ^{o}C) occurs right in the tumor and there is an increase in temperature with each increase in metabolic heat value. This therapeutic temperature will be used to kill tumor tissue. However, some parts of the tumor tissue do not reach therapeutic temperature and some normal tissues that reach therapeutic temperature. This shows that the therapy performed is less than optimal. This is due to the laying of a heat source or antenna air slot that does not correspond to the geometric shape of the existing tumor[25].

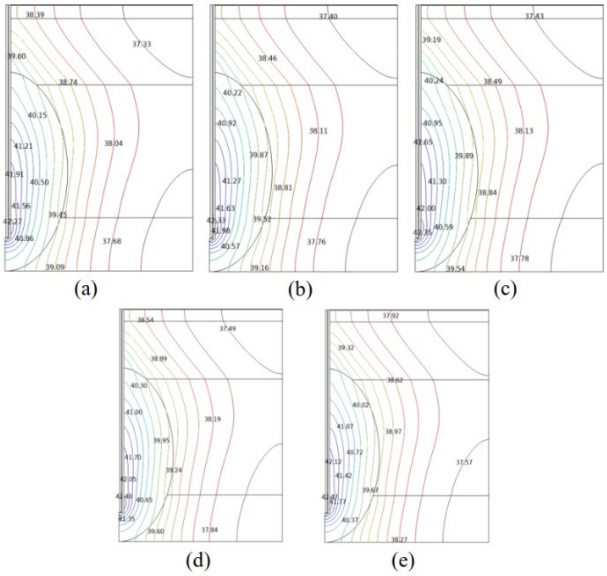

Fig 8 : Contour shape of temperature distribution that occurs in the 600s, (a) Q_m = 0 W/m^3; (b) Q_m = 386,1 W/m^3; (c) Q_m = 500 W/m^3; (d) Q_m = 800 W/m^3; (e) Q_m = 1200 W/m^3

3.4 Comparison of Temperature Changes in Interstitial Hyperthermia Therapy

The results of the temperature distribution in this study will be compared with the results of temperature distribution in the research conducted by Gas P. and Kurgan. Research conducted by Gas P. and Kurgan discussed the analysis of comparison of distribution data that occur from differences in geometric defining forms, in the form of 2D and 3D. Gas P. and Kurgan conducted interstitial hyperthermia therapy research in liver tissue which was solved by Pennes equations and numerical methods of finite element (FE). Here is the form of temperature data that occurs in the liver at the position of node z = 16 mm and r = 0.895 mm carried out by Gas P. and Kurgan[26]:

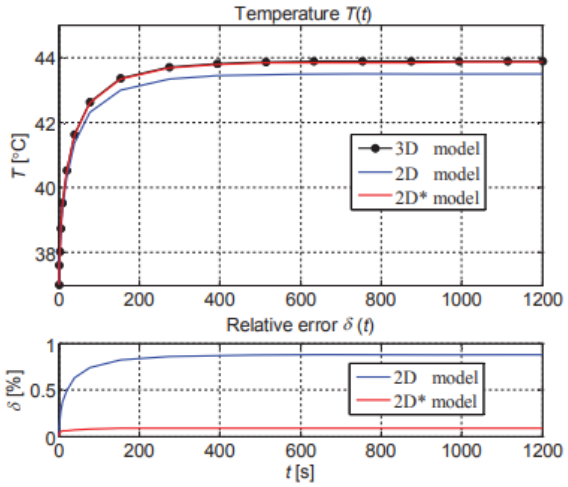

Fig 9 : Temperature distribution in the research of Gas P. and Kurgan in the position of node z = 16 mm and r = 0,895 mm

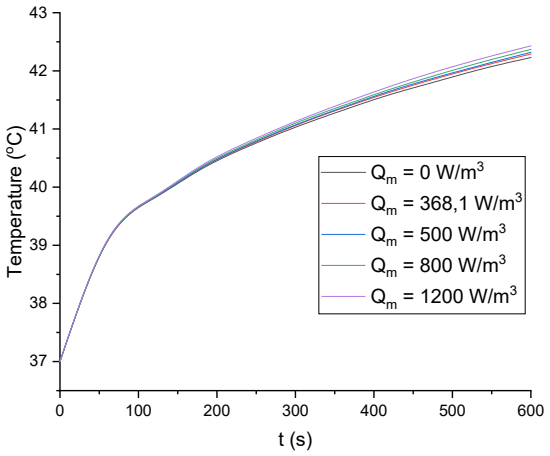

Fig 10 : The temperature distribution in the human hand along the line z = 15 mm and the value of Qm = 0 W / m^3

Figure 10 is the distribution of temperature in human hands at the value r = 1 mm and the value z = 8 mm. The two charts above show the similarity of trends when applied to interstitial hyperthermia therapy. The similarity of this trend is in the form of a rapid increase in temperature at the beginning and then the later the increase that occurs is more stable.

4. Conclusion

The conclusions obtained from this study are the form of metabolic heat influence the distribution of temperature in the human hand's given interstitial hyperthermia therapy. The higher the metabolic heat value will cause the higher the value of temperature distribution that occurs in the human body. However, the effect of metabolic heat on the increase in temperature that occurs is not too great when compared to the heat produced from the interstitial hyperthermia therapy process. In addition, the temperature distribution is also influenced by the length of interstitial hyperthermia therapy. The longer the time done, it will make the resulting temperature higher as well.

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