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Comparison of Heat Propagation Properties in Different Sizes of Malignant Breast Tumours using Computational Fluid Dynamics

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ABSTRACT

Breast cancer is one of the leading critical illnesses in Malaysia. Typically, patients would undergo a lumpectomy or mastectomy followed by chemotherapy and radiotherapy. However, these treatments have side effects that impact the quality of life. Hyperthermia is a treatment that can kill the tumour with less effect on the other parts of the body. From previous findings, heating the body to a temperature of 40°C to 46°C is an alternative procedure to reduce the side effect of these treatments. This study aims to investigate heat propagation into malignant tumours of different sizes. Three different models of breast tumours with different sizes were modelled. The heat propagation was simulated using the computational fluid dynamic (CFD) method. Three different temperatures were applied to the malignant tumours exposed to infrared and thermocouple heat sources. From the observation, model 14mm demonstrated the highest temperature propagation as compared to the others. The heat propagation in the blood vessel also showed a significant radiation effect as shown in the tumour. However, the velocity and pressure in the blood vessel have no significant changes for all models. In conclusion, the heat propagation via infrared sources managed to penetrate the tumours and the early stage of the tumour experienced better heat propagation as compared to thermocouples.

1. Introduction

A breast tumour is a disease in which the cells in the breast grow out of control. The cells keep growing indefinitely, creating new cells, consequently crowding out normal cells and causing further complications throughout other parts of the body as it spreads malignantly over time [1]. Due to the aggressive nature of the tumour, a person with breast cancer may suffer considerably and affecting their quality of life [2]. One of the grave concerns with breast cancer is that the tumour can grow to a significantly large size before the symptoms begin to appear [3]. Typically, tumour size grows

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linearly with its stage, causing cancer to be diagnosed at an advanced stage. This also posed a problem because different sizes of the tumour must go through different treatments [4]. Therefore, even if the tumour was detected at an earlier stage, it cannot be treated the same as advanced-stage breast cancer [4]. Hyperthermia therapy is an alternative treatment for cancer patient by exposing the body with high temperature. The exposure of high temperature will help in damaging cancer cells as well as reducing the inflammation [5].

Around 85% of all breast cancers are hormone-positive receptors and can be treated by therapies [6]. Furthermore, many breast cancer forms can cause breast lumps, but not in all cases [7]. Owing to these two attributes, this research aims to investigate the properties of heat propagation of malignant breast tumours at different temperatures. Different temperatures are hypothesized to show the difference in the dissipation of heat applied to the breast. In the same context, this study also seeks to compare the heat propagation of breast tumours of different sizes. The size of the tumour can affect heat propagation because of its intrinsic nature to counter external heat. For this, a model of the breast is created with three sizes of the tumour inside the breast for each stage from stage one to stage three. As elaborated, stage one is 14mm, stage two is 32mm and stage three is 55mm tumours. This study will use the Computational Fluid Dynamics (CFD) method which uses the discretization technique in software, therefore determining the heat change as it is applied.

2. Methodology

To obtain the most accurate data simulation for analysis, the method that we used was the CFD method which is commonly used today. A full and complex data set was done for a comprehensive thermal flow analysis after the imposition of the malignant tumour using CFD simulation.

2.1 Tumour and Heat Source Modelling

The first step was to create a breast model by following the breast model by Afify [3]. The model was drawn in SolidWorks Premium 2018 and saved in IGS format. The shape used was the hemispherical shape for the breast with a diameter of 144 mm and the sphere shape for the tumour was modelled after Amri *et al*., [8]. The hemispheric shape was chosen because the symmetrical shape of the model will better allow for simulating the actual structure. The tumour size considered for stage 1 was 14mm, for stage 2 was 32mm and for stage 3 was 55mm, as shown in Fig. 1. The tumour was located at the centre of the breast model because the same coordinates produce the same normalized thermal effect on the tissue as shown in Fig. 2.

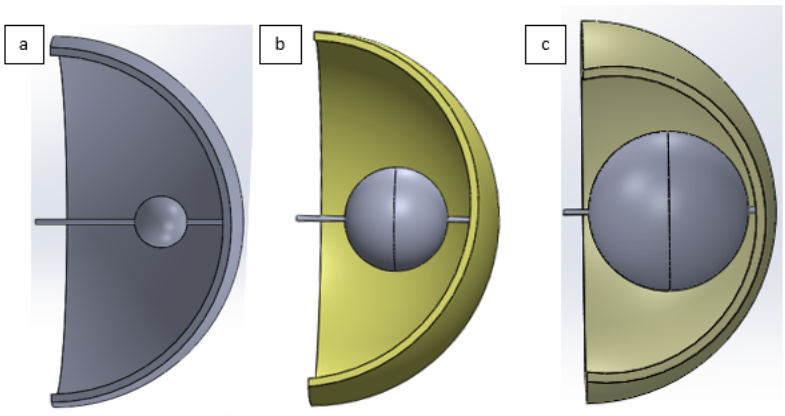

Fig. 1. Schematic diagram of the three different sizes of tumour (a) 14mm, (b) 32mm, and (c) 55mm

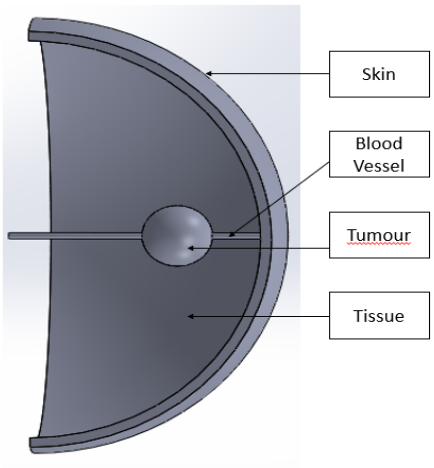

Fig. 2. Tumour location at the breast model

Next, the model was imported into Ansys Fluent to generate the mesh. In Ansys, Grid Independent Test (GIT) was performed to evaluate the best mesh for the simulation. For these models, the body sizing was done to the tumour model because this study is focusing tumour heat propagation. The sizing 0.3 mm was chosen with 9,678 nodes so that we can obtain a lower error from the GIT [6-7].

For heat sources, there were two heat sources used for this research which are thermocouples and infrared. For thermocouples, the heat was applied to the surface of the breast model and transferred heat to the surrounding tissue. The tissue is divided into two which are normal and abnormal. An abnormal tissue will produce high temperatures compared to the normal tissue [8]. When the heat is applied to the tissue, the tumour will produce a higher temperature compared to the surrounding tissue because the tumour has an intrinsic heat generation capability. Another heat source used was the infrared placed 1 meter from the tissue surface [9]. Based on the frequency applied, the abnormal tissue reacted and produced the Specific Absorption Rate (SAR) value which is related to the heat generation of the tumour. The frequencies applied were 1.8, 2.4, 5.0 and 8.9 GHz and produced descending order values of SAR which were 22, 20, 8.1 and 1.1 mW/kg. Based on the SAR, the values were used in Pennes Bioheat Equation to generate temperature distribution from the tumour. For an infrared heat source, a user-defined function (UDF) code was used to solve the equation inside the Ansys fluent for heat generation of the tumour. The UDF code solved the transient Pennes bioheat equation.

For this research, only the tissue and tumour are considered and the heat generation of the tumour amounting to 8,750,000 W/m^3 was to be obtained from the verification method of the research [10]. Table 1 showed the physical properties of the tumour and tissue.

Table 1
The values of Reynolds number and velocity

	Tissue	**Tumour**
Density (kg/m^3)	1090	1090
Specific heat (J/kg.K)	3421	3421
Thermal conductivity (W/m.k)	0.49	0.49

Afterwards, the model analyses were run in the solver process. The solver was completed when the calculation converged or reached the iteration time limit. The solver was using a pressure-based value while the velocity formulation was using absolute value. The time used was transient with a

time step size of 0.1 seconds while the number of exposure times was 1800 seconds. The calculation was run until it has completed and reached convergence. The temperature contour was used to show the temperature distribution by the tumour after the surrounding tissues were heat-applied. Legend showed the value of the highest and the lowest temperature that gain from the contour.

2.1 Equations

For an infrared heat source, the transient Pennes bioheat equation was adopted to heat transfer model in biological tissues. The equation for calculating the temperature that would be gained by the tumours after certain energy was applied to the tumour and produced SAR was given as follows:

$$\rho C = \nabla . (k \nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \quad (1)$$

where Q is the tissue density (kg/m3), C is the heat capacity of tissue (J/kg K), k is the thermal conductivity of tissue (W/m K), T is the tissue temperature (℃), T_b is the temperature of blood (℃), ρ_b is the density of blood (kg/m3), C_b is the heat capacity of blood (J/kg K), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolism heat source (W/m3), and Q_{ext} is the external heat source (electromagnetic heat-source density) (W/m3). The external thermal source term is equal to the electromagnetic champ's resistive heat, defined as electromagnetic power absorbed as given by

$$Q_{ext} = \frac{1}{2} \sigma_{tissue} |\bar{E}|^2 = \frac{\rho}{2} . SAR \quad (2)$$

The SAR can be obtained by:

$$SAR = \frac{\sigma}{\rho} |E|^2 \quad (3)$$

Here, *E* is the RMS value of the induced field in (V/m), *σ* the conductivity of tissue in (S/m), and *ρ* the mass density of tissue in kg/m^3.

For heat sources by infrared, the SAR value is used with different temperatures applied. SAR is the reaction of the tumour to the frequency applied by the heat source. The temperature used is 38℃ for SAR 22mW/kg, 40℃ is for 8.1mW/kg and 41℃ is for 1.1mW/kg. SAR value has come from the infrared value and the tissue properties. Each of the temperatures is tested for all sizes of the tumour to figure out the temperature distribution of the tumour. The SAR value is got from infrared which is a place from 1 meter from the tissue based on [12]. The net input power that was used was 1mW and the actual acceptable limit of 2mW/kg averaged over 10g of tissue exposed to EM (electromagnetic) radiation is much less than the SAR values [23].

3. Results

Based on figure 3 and figure 4 below, the breast model with a tumour size of (a) 14mm (b) 32mm and (c) 55mm at the centre was stimulated by three different temperatures stated 40-degree, 50-degree and 60-degree for the thermocouple heat source and 38-degrees, 40-degrees and 41-degrees for an infrared heat source. The temperature contour showed the temperature distribution after applying the heat. Based on Chaplain *et al*., [11], the abnormal tissue temperature was higher than the normal tissue. A tumour is classified as abnormal tissue and it has heat generation inside which explained the gains in temperature. The method that we applied for this study was verified with the

research by Kandlikar *et al*., [12] with the tumour inside the tissue in a cube shape. For this result, the thermocouple with tumours 14mm, 32mm and 55mm has a different result of heat propagation. The infrared with tumours 14mm, 32mm, and 55mm also has a difference in heat propagation.

The results are outlined in Figures 3 and Figure 4. The simulation results show that in a heat source using a thermocouple, the tumour size influenced the amount of heat from inside the tumour as well as the heat propagated to the surrounding tissues. In a 14mm tumour, the heat generated inside the tumour was around 2.28e2 to 2.42e2, while heat propagated to the surrounding tissues was around 2.55e2 to 2.96e2. In a 32mm tumour, the heat inside the tumour stands between 2.98e2 and 4.12e2, while heat propagated to the surrounding tissues was below 2.98e2. In a 55mm tumour, the heat inside the tumour was below 2.79e2, while the surrounding tissues were heated to a temperature up to 3.79e2. This shows that using a thermocouple, the surrounding tissues receive much more excessive heat if the tumour was bigger. But the best temperature achieved using a thermocouple was if the tumour was 32mm in size.

Using infrared as the source of heat, it was observed that the tumour size also influences the amount of heat inside the tumour and the heat propagated to the surrounding tissues. In a 14mm tumour, the heat inside the tumour was between 2.33e2 and 2.45e2, while the heat propagated to the surrounding tissues was between 2.67e2 and 3.01e2. In a 32mm tumour, the heat generated inside the tumour was around 1.32e3 to 3.45e3, while the heat propagated to the surrounding tissues was below -1.51e3 K. In a 55mm tumour, the heat generated inside the tumour was below 2.86e2 K and the heat propagated to the surrounding tissues was between 3.077e2 K and 3.29e2 K. This results suggested that infrared source can heat the tumour better than thermocouple, with heat propagation to the surrounding tissues higher as well, except in 32mm tumour size where the heat propagation was lower to the surrounding tissues. As with thermocouples, the greatest temperature achieved was in a 14mm tumour.

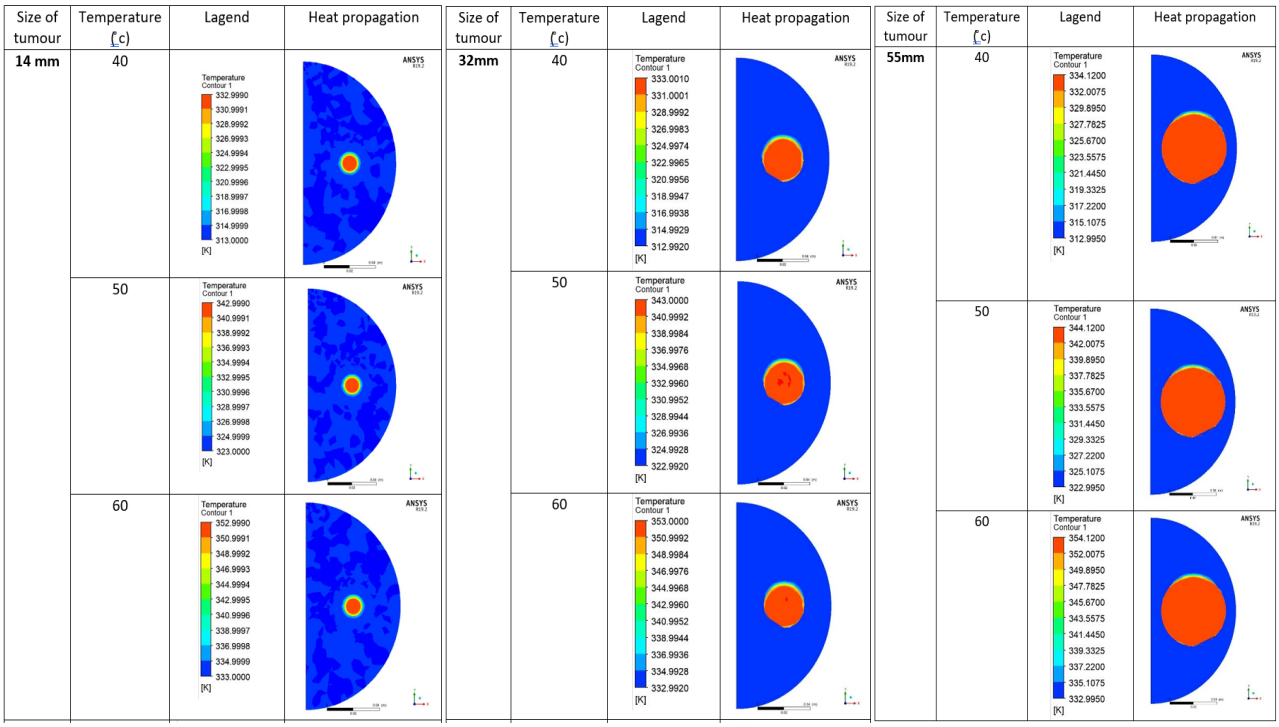

Fig. 3. The thermocouple heat source at the tumours 14mm, 32mm and 55mm location at the breast model

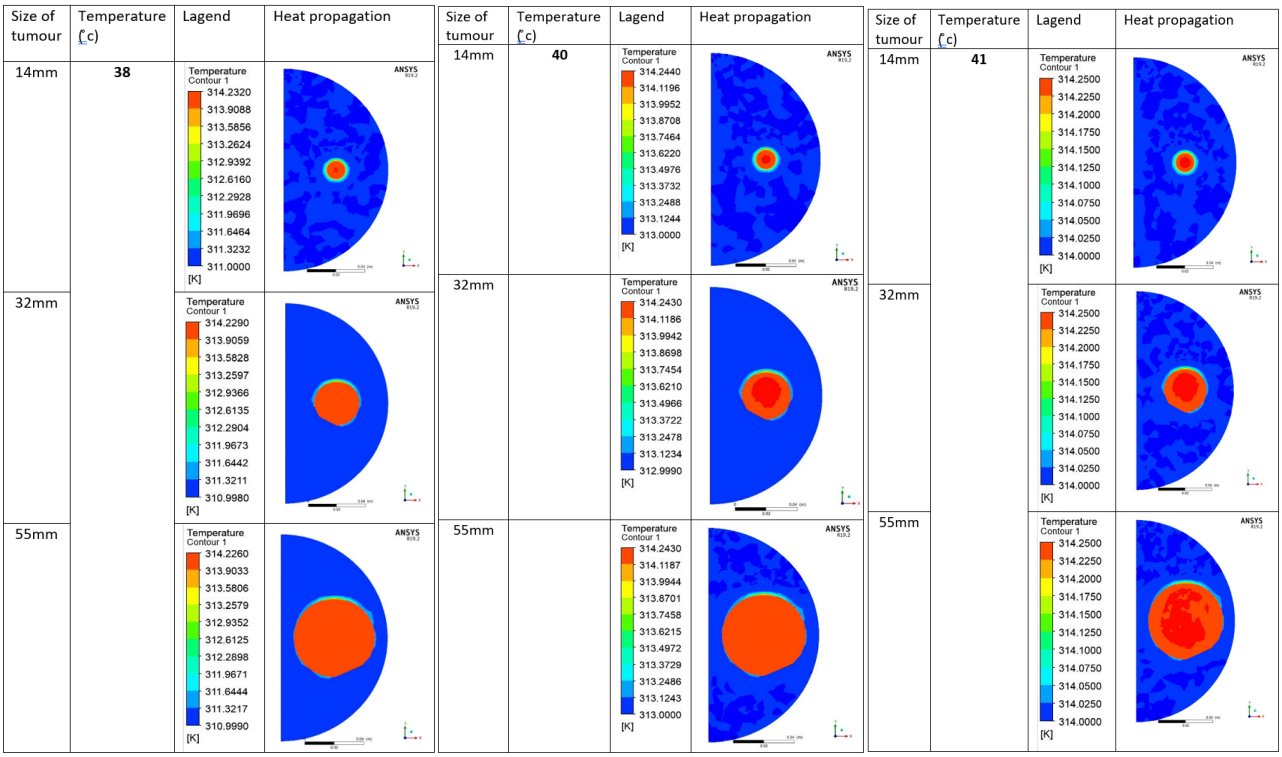

Fig. 4. The infrared heat source at the tumours 14mm, 32mm and 55mm location at the breast model

4. Discussions

Based on the result obtained, the temperature of the tumour was rising along with the rise in tissue temperature for the thermocouple heat source [13]. For an infrared heat source, the decreasing value of SAR with rising temperature resulted in lower temperature gain by the tumour. For the infrared heat source, the value of SAR also affected the result of the tumour temperature. The value of SAR is dependent on the infrared heat source and for this research, the value of SAR is followed based on previous research [14]. Based on researchers McPherson *et al*., [15], the value of SAR is decreasing due increasing value of frequency. The temperature distribution of the tumour is also affected by the SAR of the tumour. Based on the temperature distribution value of the simulation, the temperature at the tumour is decreased due to the smallest value of the SAR value. McPherson *et al*., [15] stated that the SAR decreased as the distance increased from the radiating source. A suitable distance from the heat source is needed to produce suitable SAR tissue to kill the tumour.

Based on the simulation, the bigger tumour produced less temperature distribution because the bigger tumour characteristic tends to produce more cancer cells and spread to other parts of the body [16]. In stage 1 and 2 tumours, the cells were intensely producing heat propagation to surrounding tissue [17]. These stages were associated with the smaller size of the tumour, which in turn helped generate higher heat propagation to the tissue surrounding the tumour. Increasing the temperature from the heat source would increase the overall tumour temperature. When the external heat was applied to the tissue, the tumour would counter-reacted the heat with its intrinsic heat generation. The heat from the tumour went through the surrounding tissues and the heat generation of the tumour also affected the heat propagation produced by the tumour to the surrounding tissue [18]. Based on these studies, heat generation of the tumour altered the temperature distribution because the tumour temperature was increasing linearly due to the

temperature applied from the heat source. This case, however, did not account for the tissue burn if the temperature exceeded the tolerance limit of the tissue [19].

Based on the medical study, hyperthermia treatment typically started with a comprehensive medical consultation together with previous medical-imaging reports such as X-rays, CTs, MRIs, and nuclear medical images [20]. When doing treatment, the temperature sensors were affixed to the skin above the tumour or inserted into the tissue depending on the method chosen [20]. The number of temperature sensors used depends on the size of the tumour. When doing hyperthermia treatment, the main body temperature was kept constant at a pre-determined suitable temperature. Moreover, based on Sardari and Verg, [21], clinical hyperthermia treatment systems could be exposed to a target volume of tissue from electromagnetic or ultrasound waves. Better response and survival rates were detected in patients treated with hyperthermia treatment and radiotherapy compared to radiotherapy alone in several stage 3 trials, with a higher survival rate and minimal damage to normal tissues in the patient treated with hyperthermia treatment.

Hence, these studies also conclude that infrared is suggested to be a suitable heat source because it triggered less temperature from the tumour. Tumour temperature reaction when the heat was applied should be taken into account as the tumour was often placed in the surrounding tissue which can affect the normal tissue cells. Higher temperature gain from the tumour would affect the surrounding tissue cells and might give harmful side effects to the human body. Increasing SAR value may produce suitable heat generation for the tumour and the tumour will produce a great temperature distribution because the tissue can withstand uniformly distributed heat at a certain temperature without resulting in detrimental effects on the surrounding tissues.

4. Conclusions

In conclusion, the first objective of the study would be to forecast the spread of heat by malignant breast tumours in response to exposure to various temperatures. The heat propagation from the tumour, because of the simulation, is affected by the tumour size. The thermal propagation to the side tissue was shown to be greatest in smaller tumour sizes. The heat distribution often depends on the tumour and the tissue's heat generation. Then, the second objective is to compare the heat propagation of breast tumour staging for different temperatures. In this study, the size of the tumour is affected by the temperature contour and the bigger size of the tumour is come out with less heat propagation. The smaller size of the tumour shows the heat propagates properly to the tissue. The heat generated by the tumour also affected the temperature of the tumour the tissue surrounding the tumour is applied heat.

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