

# Transient Bioheat Equation in Breast Tissue: Effect of Tumor Size and Location

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**Abstract:** Thermoregulation of human body maintains the body core temperature at 37°C. Body temperature rises due to the illness such as fever or heat stroke. The abnormal temperature distribution in breast tissue is caused by breast diseases like cysts, tumor, cancer etc. Most of the breast tumor, normally, develops in lobules and milk ducts at glandular layer of breasts. Medically, infrared breast imaging (thermography and mammography) is used to diagnose breast cancer, in which temperature distribution analysis plays a vital role. In this study, finite element method is used to solve one dimensional unsteady state bio-heat equation to find temperature distribution in the layers of normal and tumorous breast tissue with different size and location of tumor from areola. The results show that temperature variation of breast layers depend on size and location of tumor from areola. The temperature distribution of layers of tumorous breast tissue is higher than normal breast tissue. From the simulation results, it is observed that temperature of tumorous breast tissue achieved steady state earlier than normal breast tissue.

**Keywords:** Breast tumor; temperature distribution; FEM; bioheat equation.

## 1 Introduction

Human body is made up of 100 trillion cells [16]. Different tissues have different cells. Tumor is a mass of abnormal and uncontrolled growth of tissue caused by damage of cells. Tumor needs more nutrition for growth. So, blood perfusion and metabolic rate are high in tumor. Most of the breast tumor, normally, develops in lobules and milk ducts at glandular layer of breast. Breast cancer is the malignant tumor. It is the major health problem of women in developed and developing countries. Nowadays, it is increasing day by day. Nearly 1.7 million new cases of breast cancer and about 521,900 deaths were diagnosed among women worldwide in 2012 [5]. According to American cancer society [1], in 2017, about 252,710 new cases of breast cancer were diagnosed in women in US and in 2018, it was about 266,120. The society also estimated about 268,600 new cases of invasive breast cancer will be diagnosed among women in US in 2019 [2]. World Health Organization (WHO) [8] estimated that 627,000 women died from breast cancer in 2018, which is approximately 15 % of all cancer deaths among women. In context of Nepalese women, it is the second most common malignancy after Cervical cancer [14, 20]. About 1700 new cases of breast cancer were diagnosed in Nepal in 2012 [14]. According to WHO data published in 2017 [3], breast cancer deaths in Nepal reached 1054 or 0.65 % of total death and the age adjusted death rate is 9.21 per 100,000 of population.

Thermoregulation plays vital role to maintain temperature in human body. Temperature is a good indicator of human health. High body temperature is often caused by illness, such as fever or heat stroke [17]. The abnormal surface temperature distribution of the breast can indicate breast diseases like cysts, tumor, cancer etc [13, 28]. The existence or continue development of breast tumor causes abnormal infrared thermal imaging of the breast [19, 27]. Thermography (thermal imaging) of the breast is the recording of temperature patterns of the breast tissue to form an image (thermogram) of the temperature distribution on the surface of the breast. Breast thermography can be used for women of all ages with any breast size and density. The principle of thermography is based on the fact that the metabolism and blood perfusion in both developing breast cancer and precancerous tissue are always higher than in normal breast tissue [12, 25]. Mammogram, breast cancer screening tool, is a low-energy x-ray of the breast to detect and evaluate breast changes. It is used for early diagnose of breast cancer. The anatomical changes in breast tissue are detected by mammography but thermography detect

physiological changes in breast tissue [7]. The sensitivity of thermography is increased with tumor size and give falls positive results [29]. But the sensitivity of mammogram is higher for older women (60-69 years age group) at 85 % than younger women (age less than 50 years) at 64 % [6, 29]. Also, it is painful and its x-ray is harmful (equivalent to smoking three cigarettes) [23, 29]. The average size of tumors undetected by thermography is 1.28 cm while 1.66 cm by mammography [19].

The study of temperature distribution on breast tumor has clinical importance for medical doctors in diagnosis, treatment and cure of breast diseases like cancer. A mathematical model is better for understanding the temperature profile of the normal and tumorous breast.

Saxena and Arya [33], Gurung et al. [15] studied temperature distribution in skin and subcutaneous tissue (SST) region under normal environmental and various physiological conditions. Saxena and Pardasani [34], Pardasani and Adlakha [31] studied the problems involving tumor in SST regions of human body. Agrawal et al. [10] studied the thermal distribution in dermal regions of human limbs with tumor. Osman and Afify [30] first used a hemispherical breast model with different tissue layers of uniform thickness. They developed a mathematical model of three dimensional temperature distribution of the normal woman's breast using the finite element method. Lawson [21] used the thermographic detection of breast cancer and observed that the local temperature of the skin over a tumor were significantly higher than normal skin temperature. Lawson and Chughtai [22] have established the regional temperature difference of breast skin surface over an embedded tumor. This difference was due to convection effect associated with increased blood perfusion and increased metabolism in tumor. Sudharsan and Ng [36] developed a two-dimensional model of surface temperature distribution of female breast with and without tumor. Makrariya and Adlakha [24] discussed the two dimensional finite element method in dermal tissues of human breast under different stages of development. It is known from the literature survey that no attempts have been made so far to study the temperature distribution in breast tissue in unsteady state case. So, one dimensional finite element model of temperature distribution in layers of breast tissue involving tumor in transient case have been developed.

## 2 Mathematical Model

The human breast is assumed to be in hemispherical in shape. In the study, breast is assumed to be divided into seven layers: epidermis, dermis, subcutaneous tissue, glandular layer, tumor, muscle and thoracic wall, as shown in Figure 1. Breast tumor can occur any layers of breast tissue but most of the breast cancer normally develops in lobules and milk ducts. So, in the study, tumor is assumed to be in glandular layer. Osman et al. [30], Sudharsan et al. [36], Mital et al. [26] and Shrestha et al. [35] have used hemispherical breast with length 72 mm from areola to body core. The same domain of breast is used in our study, in which the length of epidermis, dermis, subcutaneous tissue, glandular layer and muscle with thoracic wall are taken 1.5 mm, 3.5 mm, 5 mm, 50 mm and 72 mm from areola, respectively. As sketched on Figure 1, the thickness of epidermis, dermis, subcutaneous, glandular without tumor (before tumor region), glandular with tumor, glandular without tumor (after tumor region) and muscle with thoracic wall have been considered as  $l_1, l_2 - l_1, l_3 - l_2, l_4 - l_3, l_5 - l_4, l_6 - l_5$  and  $l_7 - l_6$ , respectively. Similarly,  $T_0, T_1, T_2, T_3, T_4, T_5, T_6, T_7 = T_b$  (body core temperature) are the nodal temperatures at a distances  $x = 0, x = l_1, x = l_2, x = l_3, x = l_4, x = l_5, x = l_6, x = l_7$ , respectively.  $T^{(i)}$  are temperature functions of sub-domain  $I^{(i)}$ ,  $i = 1, 2, 3, 4, 5, 6, 7$ , respectively.

Bioheat equation is used in the study of one dimensional model. In 1948, Harry H. Pennes [32] developed an equation for effect of blood perfusion and metabolic heat transfer within a living tissue. After Pennes, other models were developed, but due to simplicity and applicability this model has been widely used by many researchers for analysis of bioheat transfer phenomena in living tissue. This equation is written in simplified form as

$$\underbrace{\rho c \frac{\partial T}{\partial t}}_{\text{Heat storage}} = \underbrace{\text{div}(K \text{ grad } T)}_{\text{Diffusion}} + \underbrace{\omega_b \rho_b c_b (T_b - T)}_{\text{Blood Perfusion}} + \underbrace{Q_m}_{\text{Metabolism}} \quad (1)$$

where,  $\rho$  is density of tissue [ $\text{kg}/\text{m}^3$ ],  $c$  is specific heat of tissue [ $\text{J}/\text{kg } ^\circ\text{C}$ ],  $K$  is thermal conductivity of tissue [ $\text{W}/\text{m } ^\circ\text{C}$ ],  $t$  is time [s],  $\omega_b$  is volumetric blood perfusion rate per unit volume [ $1/\text{s}$ ],  $\rho_b$  is density of the blood [ $\text{kg}/\text{m}^3$ ],  $c_b$  is specific heat of the blood [ $\text{J}/\text{kg } ^\circ\text{C}$ ],  $T_b$  is arterial blood temperature [ $^\circ\text{C}$ ],  $T$  is local temperature of tissue [ $^\circ\text{C}$ ],  $Q_m$  is metabolic heat generation rate [ $\text{W}/\text{m}^3$ ].

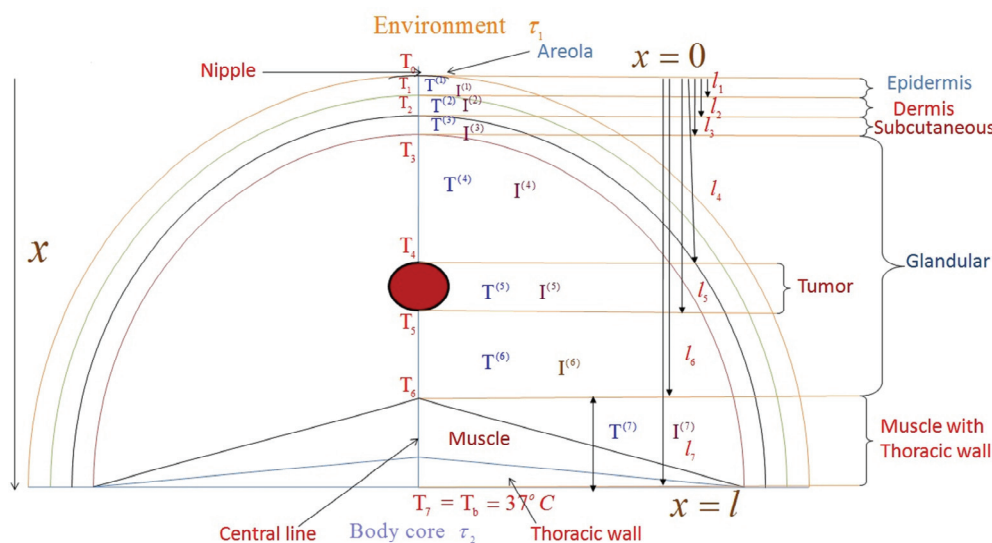


Figure 1. Schematic diagram of layers of breast tissue.

In the study, the length of the breast tissue measured from the areola to thoracic wall is assumed to be  $l$  as shown in Figure 1. Thus,  $\Omega = [0, l]$  is domain of the study.

Skin, outer surface of the breast, is exposed to the environment from where heat loss takes place by convection, radiation and sweat evaporation. So the mixed boundary condition [18, 35] is

$$\tau_1 : K \frac{\partial T}{\partial x} \Big|_{x=0} = \underbrace{h_\infty (T - T_\infty)}_{\text{Convection term}} + \underbrace{\sigma \varepsilon (T^4 - T_\infty^4)}_{\text{Radiation term}} + \underbrace{\frac{LE}{\rho}}_{\text{Sweat Evaporation}} \tag{2}$$

where,  $h_\infty$  is convection heat transfer coefficient between skin and subcutaneous tissue (SST) and ambient environment  $[W/m^2 \text{ } ^\circ C]$ ,  $T_\infty$  is Ambient room temperature  $[^\circ C]$ ,  $\sigma$  is Stefan Boltzmann constant  $(5.67 \times 10^{-8}) [W/m^2 \text{ } ^\circ C^4]$ ,  $\varepsilon$  is emissivity of the SST  $[W/m^2]$ ,  $L$  is Latent heat of evaporation  $[J/kg]$ ,  $E$  is sweat evaporation rate  $[kg/m^2 \text{ sec}]$ .

Relation (2) can be written as

$$\begin{aligned} K \frac{\partial T}{\partial x} \Big|_{x=0} &= h_\infty (T - T_\infty) + \sigma \varepsilon (T - T_\infty)(T + T_\infty)(T^2 + T_\infty^2) + LE \\ &= [h_\infty + \sigma \varepsilon (T + T_\infty)(T^2 + T_\infty^2)](T - T_\infty) + LE \\ &= (h_\infty + h_{\text{radiation}})(T - T_\infty) + LE \\ &= h_{cr} (T - T_\infty) + LE \end{aligned}$$

where,  $h_{cr} = h_\infty + h_{\text{radiation}}$

Thus,

$$\tau_1 : K \frac{\partial T}{\partial x} \Big|_{x=0} = h_{cr} (T - T_\infty) + LE \tag{3}$$

The intersection between the breast base and breast is maintained at  $37^\circ C$ . Thoracic wall is attached with body core. So the Dirichlet boundary condition in this part is

$$\tau_2 : T_7 = T_b = 37^\circ C \tag{4}$$

The variational form of the partial differential Equation (1) together with its boundary condition (3) is given by

$$I[T(x, t)] = \frac{1}{2} \int_{\Omega} \left[ K \left( \frac{\partial T}{\partial x} \right)^2 + \omega_b \rho_b c_b (T_b - T)^2 - 2Q_m T + 2\rho c T \frac{\partial T}{\partial t} \right] dx + \frac{1}{2} h_{cr} (T - T_\infty)^2 + LET \tag{5}$$

Writing  $I$  separately for each layer as:  $I = \sum_{i=1}^7 I_i$ , where,

$$I_i = \frac{1}{2} \int_{l_{i-1}}^{l_i} \left[ K^{(i)} \left( \frac{\partial T^{(i)}}{\partial x} \right)^2 + \omega_b \rho_b c_b (T_b - T^{(i)})^2 - 2Q_m^{(i)} T^{(i)} + 2\rho c T^{(i)} \frac{\partial T^{(i)}}{\partial t} \right] dx + \frac{1}{2} h_{cr} (T_0 - T_\infty)^2 + LET_0 \quad (6)$$

For minimization of  $I$ ,

$$\frac{dI}{dT_i} = 0, \quad i = 0, 1, 2, 3, 4, 5, 6. \quad (7)$$

Then system of equation (7) can be written in matrix form

$$C \dot{T} + KT = R \quad (8)$$

where,  $\dot{T} = \left[ \frac{\partial T_1}{\partial t}, \frac{\partial T_2}{\partial t}, \frac{\partial T_3}{\partial t}, \frac{\partial T_4}{\partial t}, \frac{\partial T_5}{\partial t}, \frac{\partial T_6}{\partial t} \right]^T$ ,  $T = [T_1, T_2, T_3, T_4, T_5, T_6]^T$  and  $C$ ,  $K$ ,  $R$  are Capacitance, Conductance, Load vector matrices with dimension  $7 \times 7$ ,  $7 \times 7$ ,  $7 \times 1$ , respectively. Applying the Crank Nicolson method to solve the time derivative system (8) with respect to time and get the following relation

$$\left( C + \frac{\Delta t}{2} K \right) T^{i+1} = \left( C - \frac{\Delta t}{2} K \right) T^i + \Delta t R \quad (9)$$

where,  $\Delta t$  is time interval.

The temperature increases from outer surface of breast towards thoracic wall when ambient temperature is less than  $37^\circ\text{C}$  and vice versa. Hence, we consider the temperature increases/decreases in linear order towards body core with regard to thickness. For initial nodal temperatures  $T_0$  at time  $t = 0$ , we assume the following initial condition

$$T(x = l_i, t = 0) = T(0, 0) + \alpha l_i, \quad i = 1, 2, 3, 4, 5, 6, 7.$$

where,  $T(0, 0) = 22^\circ\text{C}$  (It is because average normal skin surface temperature is assumed  $22^\circ\text{C}$ ) and  $\alpha$  is constant to be determined. The relation (9) is repeatedly solved to get the required nodal temperatures.

### 3 Numerical Results and Discussion

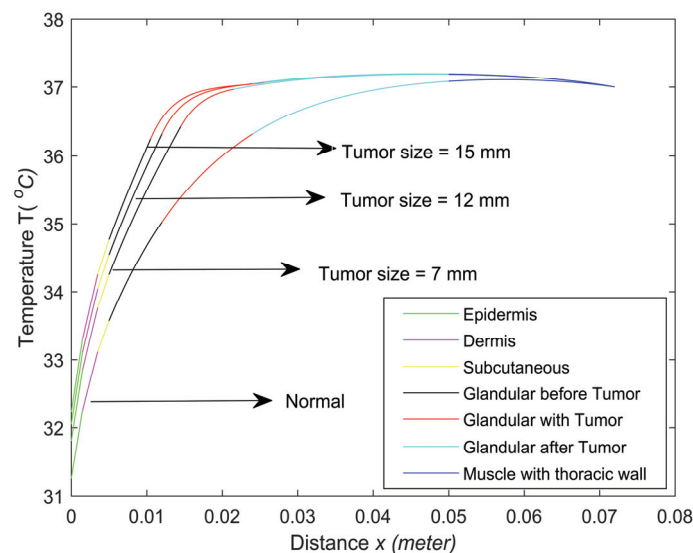
**Table 1.** Parameter values used in model [9, 35, 36]

Parameter	Values	Units
$K^{(1)}$	0.20934	W/m $^\circ\text{C}$
$K^{(2)}$	0.31401	W/m $^\circ\text{C}$
$K^{(3)}$	0.41868	W/m $^\circ\text{C}$
$K^{(i)}, i=4,5,6,7$	0.48	W/m $^\circ\text{C}$
$\omega_b \rho_b c_b$	2400	W/m $^3^\circ\text{C}$
$Q_m$	700	W/m $^3$
$\rho$	1050	kg/m $^3$
$C$	3475.044	J/kg $^\circ\text{C}$
$h_{cr}$	13.5	W/m $^2^\circ\text{C}$
$L$	$2.4 \times 10^6$	J/kg
$T_b$	37	$^\circ\text{C}$
$T_\infty$	21	$^\circ\text{C}$
$E$	0	kg/m $^2\text{sec}$

Sudharsan et al. [36], Mital et al. [26], and Shrestha et al. [35] considered the tumor as a highly perfused tissue like liver and thyroid gland. They have considered the value of perfusion and metabolism rates for tumor respectively as 20 and 2 times of muscle, skin respectively as 1/3 and 4/7 times of muscle, and glandular has the same value as muscle. The same values are considered in the study. In clinical environment, the thermographic measurement is set at the environmental temperature normally equal to  $21^\circ\text{C}$  [21, 26, 35, 36]. The same value for environment is used in this study. The other parameter values are taken as in Table 1.

### 3.1 Effect of Tumor Size in Temperature of Breast Tissue

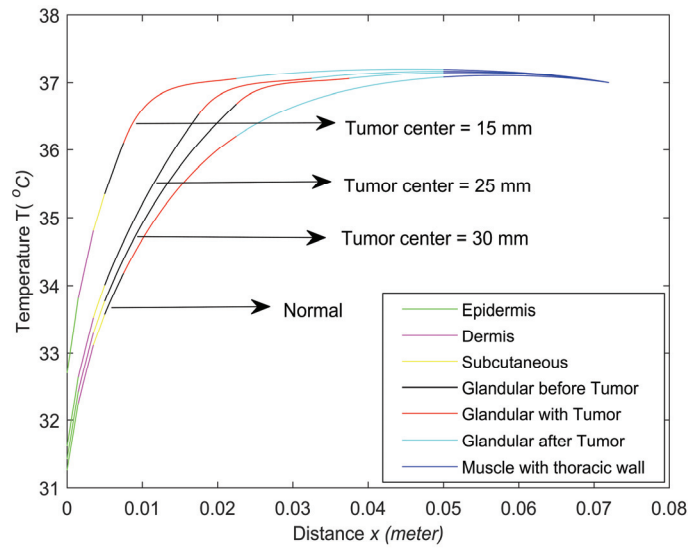
The Figure 2 presents the graphs of the temperature distribution on the layers of the breast tissue in case of normal and tumor with different tumor size having tumor center 18 mm from the areola. The result shows that temperature of each layers of tumorous breast is higher than normal and tissue temperature increases with the increase in tumor size. The graphs exhibit that the surface temperature of normal breast is  $31.27^{\circ}\text{C}$  and tumorous breast are  $31.81^{\circ}\text{C}$ ,  $32.04^{\circ}\text{C}$  and  $32.22^{\circ}\text{C}$  of tumor size 7 mm, 12 mm and 15 mm, respectively. In breast tissue, the metabolic rate and blood perfusion rate decrease from thoracic wall to areola due to the concentration of vasculature decreases from the thoracic wall towards areola [4]. It then causes the temperature rise in the in-vivo breast tissue than breast skin surface. In our study, in-vivo breast tissue temperature is obtained higher than surface temperature of breast. Sudharsan et al. [36] observed in their study that the difference between normal and tumorous skin surface temperature of breast was  $0.4^{\circ}\text{C}$ ,  $0.7^{\circ}\text{C}$  and  $0.95^{\circ}\text{C}$  in the tumor size 7 mm, 12 mm and 15 mm, respectively. In our study, we have observed that the skin surface temperatures of tumorous breast rise by  $0.54^{\circ}\text{C}$ ,  $0.78^{\circ}\text{C}$  and  $0.96^{\circ}\text{C}$  in the tumor size 7 mm, 12 mm and 15 mm, respectively than normal. The slight variation in our results may be consideration of different layers in the skin of breast.



**Figure 2.** Temperature distribution profile on breast layers with and without tumor at different size: steady state case.

### 3.2 Effect of Tumor Depth from Areola in Temperature of Breast Tissue

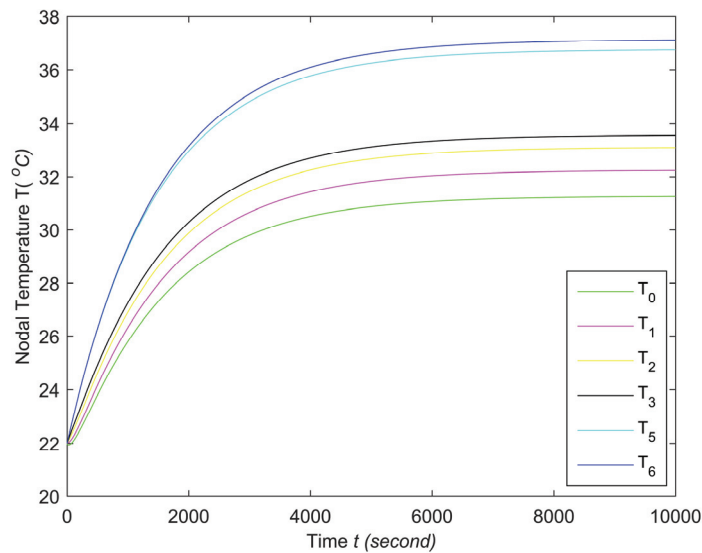
In Figure 3, we have compared the temperature distribution profile of normal breast tissue with different location of tumor having tumor size 15 mm. The graph shows that the surface temperature of normal breast is  $31.27^{\circ}\text{C}$  and tumorous breast are  $32.69^{\circ}\text{C}$ ,  $31.61^{\circ}\text{C}$  and  $31.42^{\circ}\text{C}$  of tumor center 15 mm, 25 mm and 30 mm, respectively from the areola. Skin surface temperature is higher when tumor is closer to skin surface [11, 35]. In our study, we observed the similar behavior of temperature rising in skin surface of breast. The result shows that the skin surface temperature is rising by  $1.42^{\circ}\text{C}$ ,  $0.35^{\circ}\text{C}$ ,  $0.15^{\circ}\text{C}$  than normal breast tissue with tumor center 15 mm, 25 mm and 30 mm, respectively from areola. From the temperature profile, it is observed that the breast skin surface temperature is increased when tumor is nearest to skin surface and decreased when tumor is farthest away from skin surface.



**Figure 3.** Temperature distribution profile on breast layers with and without tumor at different location: steady state case.

### 3.3 Transient Result of Normal Breast Tissue

Transient temperature distribution profile on normal breast tissue layers are shown in Figure 4. From the result, it is observed that the skin surface temperature reach steady state after 7000 seconds for the thickness 72 mm between areola and thoracic wall. Acharya et al. [9] observed in their study of human dermal part that the temperature of skin surface takes 15 seconds to reach steady state for 9 mm domain size. Similarly, KC et al. [18] observed that the surface temperature of human eye take 3600 seconds for 25 mm domain size to reach steady state. The result shows that tissue takes long time to achieved steady state temperature for larger domain size.



**Figure 4.** Temperature distribution profile on normal breast layers: transient case.

### 3.4 Transient Result of Tumorous Breast Tissue

The transient temperature distribution profile on tumorous breast layers is shown in Figure 5 with tumor size 15 mm and tumor center 25 mm from areola. In presence of tumor, metabolic heat generation and blood perfusion rates are higher than healthy tissue [11, 26, 35, 36], which causes the higher temperature in tumor. The exhibit graph shows that the anterior temperature ( $T_4$ ) and posterior temperature ( $T_5$ ) of tumor region are achieved steady state earlier than other layers of breast tissue. From the simulation result, it shows that the anterior and posterior temperature of tumor region rises rapidly than other interface temperature of breast layers due to high impact of metabolic and blood perfusion in tumor. The anterior and posterior temperature of tumor region reach steady state at  $36.53^\circ\text{C}$  and  $37.03^\circ\text{C}$  after 2000 and 2500 seconds respectively. Similarly, the skin surface temperature ( $T_0$ ) reach steady state at  $31.60^\circ\text{C}$  after 3000 seconds. Muscle layer is close to body core and far from skin surface of breast tissue. Also, it is far from tumor when tumor is closer to skin surface. So, the interface temperature of glandular and muscle layer takes more time to achieve steady state than other layers of breast tissue. From Figures 4 and 5, it is observed that each layers of tumorous breast tissue are achieved steady state earlier than normal.

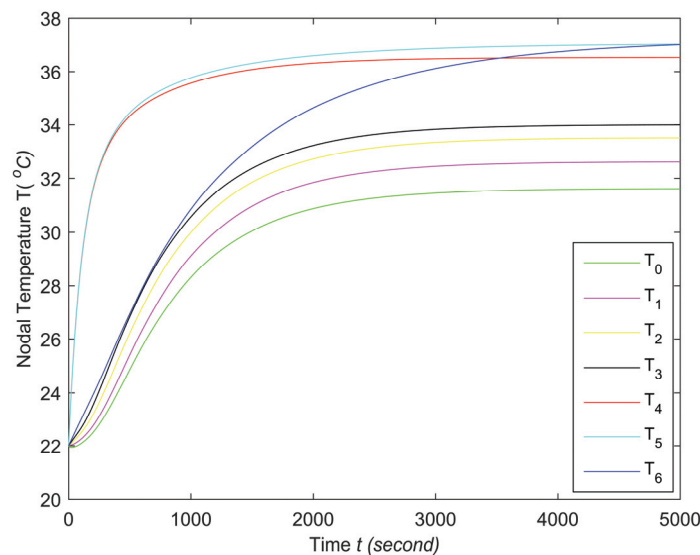
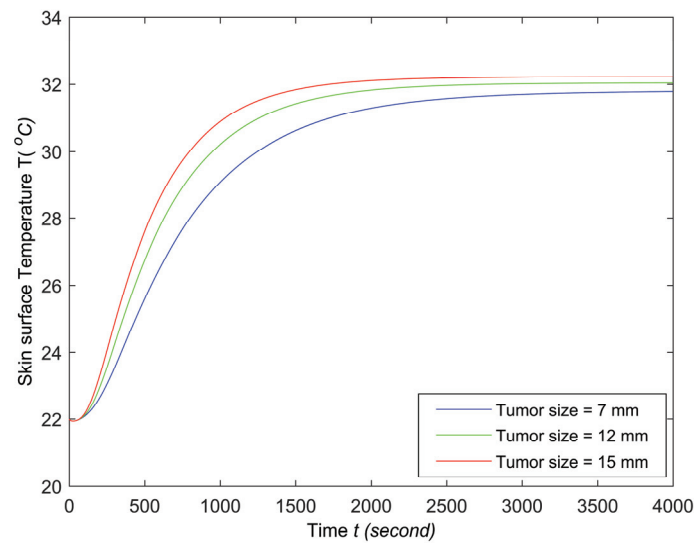


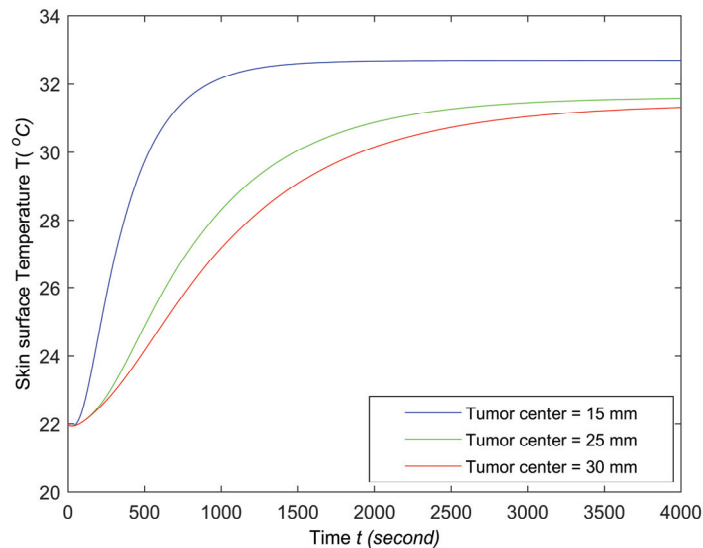
Figure 5. Temperature distribution profile on tumorous breast layers: transient case.

### 3.5 Transient Skin Surface Temperature with Different Tumor Size and Location

The surface temperature distribution profile on breast tissue with different tumor size and location are shown in Figure 6 and Figure 7, respectively. Temperature profile of tumorous breast is depended on size and location of tumor [35, 36]. In Figure 6, skin surface temperature is compared with different tumor size 7 mm, 12 mm and 15 mm having tumor center 18 mm from areola. Increase in tumor size decreases the distance between areola and tumor. From the simulation result, it is observed that the skin surface temperature goes up rapidly with increase in tumor size and achieved study state earlier than smaller size of tumor. The steady state skin surface temperature of tumor size 15 mm is rising by  $0.18^\circ\text{C}$  and  $0.45^\circ\text{C}$  than 12 mm and 7 mm tumor size. In Figure 7, skin surface temperature is compared with different tumor center 15 mm, 25 mm and 30 mm from areola at tumor size 15 mm. Tumor is closer to skin surface when tumor center is nearest from areola. From the exhibit graph, the result shows that when tumor is closed to skin surface, the skin surface temperature rises rapidly and reach steady state earlier than other location of tumor. The result shows that the skin surface temperature of tumorous breast with different tumor size and location is achieved steady state earlier when tumor is closed to skin surface of breast.



**Figure 6.** Skin surface temperature profile with different tumor size: transient case.



**Figure 7.** Skin surface temperature profile with different tumor location: transient case.

### 3.6 Transient Result of Tumor Region with Different Size and Location of Tumor

Figures 8 and 9 present the temperature profile of tumor region with different tumor size and location from areola. The solid curves represent the anterior temperature of tumor region and dotted curves represent the posterior temperature of tumor region. In Figure 8, anterior and posterior temperature of tumor region are compared with different tumor size 7 mm, 12 mm and 15 mm at tumor center 18 mm from areola. In Figure 9, anterior and posterior temperature of tumor region are compared with different tumor center 15 mm, 25 mm and 30 mm from areola at tumor size 15 mm. In both cases, anterior part of the tumor regions are closed to skin surface which gives the result that anterior temperature of tumor region is achieved steady state earlier than posterior temperature of tumor region.



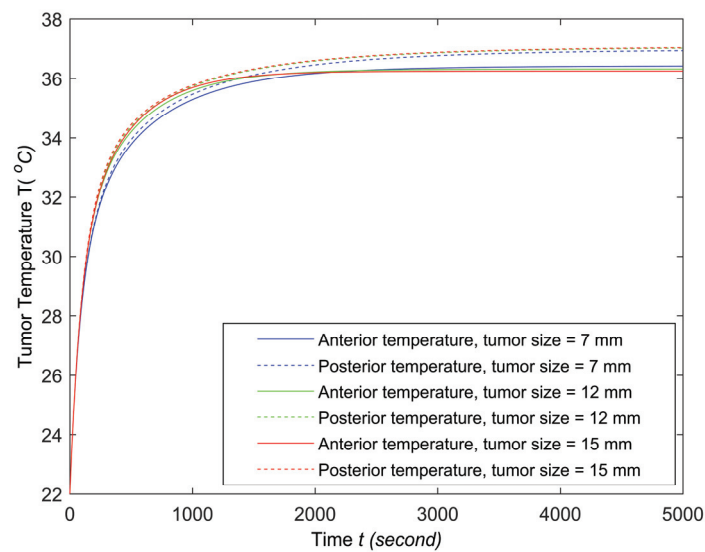


Figure 8. Temperature distribution profile of tumor on breast tissue with different tumor size.

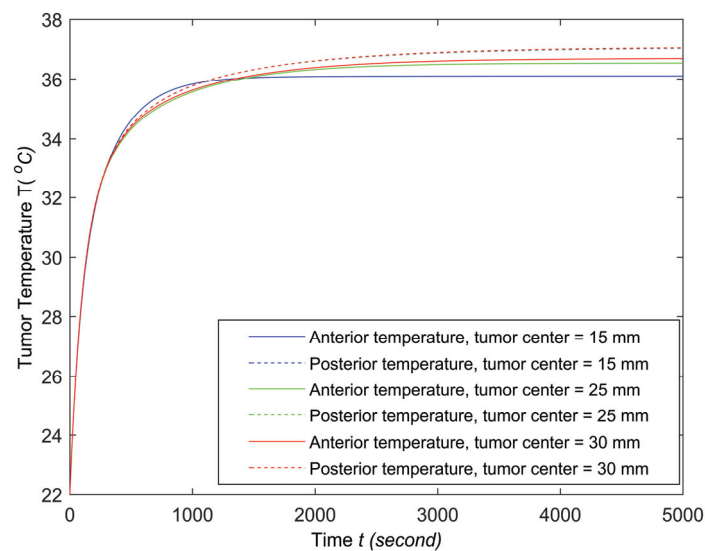


Figure 9. Temperature distribution profile of tumor on breast tissue with different tumor location.

## 4 Conclusions

In this study, steady and transient state temperature distribution of human female breast is computed using one dimensional finite element method with and without tumor. From the study, the following conclusions are made

- I. Temperature distribution in each layer of tumorous breast tissue is higher than normal.
- II. Increase in tumor size increases breast surface temperature.
- III. Increase in tumor center from areola decreases breast surface temperature.
- IV. The temperatures of tumorous breast tissue reach steady state earlier than normal breast tissue.
- V. Temperature of muscle layer of tumorous breast tissue takes more time to reach steady state if tumor is far from it and vice-versa.
- VI. The temperatures of tumor region reach steady state earlier than other layers of breast tissue.
- VII. Skin surface temperature of normal breast reaches steady state after 7000 seconds whereas tumorous breast reach after 3000 seconds. It depends on size and location of tumor.

- VIII. The interface temperature of glandular and muscle layer takes more time to achieve steady state than other layers of breast tissue.
- IX. The skin surface temperature of tumorous breast with different tumor size and location is achieved steady state earlier when tumor is closed to skin surface of breast.
- X. The anterior temperature of tumor region is achieved steady state earlier than posterior temperature of tumor region.

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