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REVIEW ARTICLE

Numerical study of the effect of non-uniformly perfused tumor on heat transfer in women's breast during menstrual cycle under cold environment

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Abstract
In this paper, a model is proposed for heat transfer in women's breast with and without non-uniformly perfused tumour during menstrual cycle under cold environment. The important biophysical parameters like blood flow, metabolic activity and thermal conduction have been incorporated in the model. The physical condition of heat loss from outer surface of women's breast exposed to environment has been used to frame boundary conditions. The model is proposed for a two-dimensional hemi-spherical shaped women's breast. The triangular ring elements have been employed to discretize the region. The numerical solution is obtained for a steady-state case by finite element method. The effect of non-uniformly perfused tumor in women's breast during different phases of menstrual cycle has been studied with the help of numerical results. It is concluded that the thermal stress due to malignant tumor in woman's breast gets enhanced due to different phases of menstrual cycle and this information will be useful for developing more effective protocols of thermography for detection of tumors. Such models can be developed further to study the heat transfer processes in the women's breast due to various malignant and benign changes.

Keywords Cold environment · Menstrual cycle · Perfused tumor

Mathematical subject classification 92B05 · 62P10

1 Introduction

The heat transfer processes like heat conduction and heat convection due to blood flow in tissues play an important role in thermoregulation of human body organs by maintaining balance between heat generation and heat loss from the body. The various environmental and physiological conditions affect these heat transfer processes. The present study is confined to estimation of thermal stress in women's breast due to a non-uniformly perfused tumor (Saraswati et al. 2014). The mechanism of thermal interaction of arterial and venous blood plays an important role in thermal balance of women's breast. The arterial and venous blood temperature varies along flow direction with the angular position in the breast.

In general, Pennes' bio-heat equation is used to model the temperature distribution in the human body tissues. Various other models suggested have been reported as an improvement to Pennes' model that includes continuum models given by Wulf et al. (1975), and Chen and Holmes et al. (1972). Earlier Patterson (Osman and Afify 1988) made experimental investigations to obtain temperature profiles in the human body tissues. Some theoretical work is reported during the last few decades by Pennes (1984), Chao and Yang (1975), Saraswati et al. (2014), Pardasani and Adlakha (1993), Pardasani and Saxena (1989), Perl (1963) and Cooper and Trezek (1972), Gurung (2009), to study the temperature distribution in the human peripheral region under normal environmental and physiological conditions. Saxena and Pardasani (1994), Pardasani and Adlakha (1991) and Saxena and Arya (1981) made attempts to study problems of temperature distribution in the dermal regions of the

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human body involving abnormalities like tumors. Pennes (1948), Patterson (1976), Pardasani and Saxena (1990), Saxena (1983) and Saxena and Bindra (1984) developed thermal models of human limbs for one- and two-dimensional steady-state cases under normal physiological and environmental conditions. Agrawal et al. (2010, 2011, 2014, 2015) and Pardasani et al. (2010) developed one-, two- and three-dimensional finite element models to study thermal patterns in the dermal layers of human limbs with and without tumors. Naik et al. (2016), Naik and Pardasani (2018) used finite element analysis in the problems of calcium diffusion in oocytes. Khanday et al. (2000), Khanday and Saxena (2009), Khanday and Rafiq (2014), Khanday and Hussain (2014), and Khanday et al. (2015) studied thermoregulation in human head and other organs under cold environment. Mittal et al. (2015), Makrariya and Adlakha (2013, 2015), Akshara and Neeru (2017), Saxena and Pardasani (1987), Khanday and Khalid (2017), and Mittal and Ramana (2008) proposed thermal models of the normal and malignant tissues in woman's breast under various conditions. Gonzalez (2011) investigated the metabolic heat generation in breast tumors using infrared images and numerically simulating a simplified breast model and a cancerous tumor. Gonzalez (2016) has presented an overview of theoretical and clinical aspects of thermography emphasizing the need for development of standard procedure to obtain and analyze the thermograms. The lack of these standard procedures is one of the bottlenecks that is making thermography a commonly used technique. Gonzalez (2007) performed thermal simulation of breast tumors of various sizes to determine the range of size and depth of tumor in breast which can be detected with the available thermographic technology.

No theoretical study of effect of non-uniformly perfused tumors on temperature in women's breast during various phases of the menstrual cycle is reported till date. Here a finite element model is proposed to study thermal stress in peripheral layers of women's breast involving non-uniformly perfused tumor in presence and absence of menstrual cycle.

2 Mathematical models

It is assumed that the properties are most variable along the radial r and angular θ direction, but almost uniform along azimuthal angle φ. The biophysical properties vary mostly along the radial direction and less along the angular direction. But this variation is almost negligible along the azimuthal angle φ as compared to other directions. Thus 3D problem can be modeled as 2D problem assuming that the heat flow and temperature distribution along φ direction is almost uniform. But this temperature distribution varies along radial and angular direction θ. This model assumption is also based on our focus of study which is aimed to analyze the temperature distribution along radial and angular direction as the variation in temperature distribution along radial and angular direction are more significant as compared to azimuthal angle φ.

The partial differential equation for heat flow in peripheral tissues of women's breast for a two-dimensional steady-state case is given by Jas and Pardasani (2000):

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(Kr^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(K\sin\theta\frac{\partial T}{\partial \theta}\right) + m_b c_b\left(T_b - T\right) + S + W = 0. \tag{1}$$

Here, K, m_b, c_b, T_b, T, S and W are the coefficients of thermal conductivity of tissue, blood mass flow rate, specific heat of blood, blood temperature, tissue temperature at position r, rate of controlled and uncontrolled metabolic heat generation, respectively. The heat loss due to conduction, convection, radiation, and evaporation at the outer surface of women's breast exposed to the environment is expressed as the following boundary condition:

$$-K\frac{\partial T}{\partial r} = h\left(T - T_a\right) + LE \text{ at } r = r_n\ \theta \in (0,\pi), \tag{2}$$

where h, T_a, L and E are the coefficients of heat transfer, atmospheric temperature, latent heat and rate of sweat evaporation, respectively. The tissue temperature varies along radial and angular direction. The tissue temperature is higher near the core of the breast and lower at the surface of the breast. So the gradient between arterial blood temperature will be less near the core of the breast and higher near the surface of the breast. The tissue temperature in the region of the breast having arteries is at the higher temperature while the tissue temperatures in the region of breast having veins will be at the slightly low temperature. Therefore, the geometry has effect on heat transfer due to blood tissues interfaces. During low environmental temperature, the temperature of inner shell of women's breast varies along angular direction θ and can be expressed as following boundary condition:

$$T\left(r_0,\theta\right) = F(\theta),\ F(\theta) = a_1 + a_2\theta + a_3\theta^2. \tag{3}$$

The other form of expression in terms of exponential, trigonometric, and transcendental functions can also be constructed in place of Eq. (3). However, there the focus is on using simplest mathematical expressions to represent the physical phenomenon.

The value of constants a_1, a_2, and a_3 are found by using the conditions:

$$T\left(r_0,\theta\right) = \alpha \text{ at } \theta = 0,\ T\left(r_0,\theta\right) = \beta \text{ at } \theta = \pi/2,$$
$$T\left(r_0,\theta\right) = \gamma \text{ at } \theta = \pi,$$

where α and γ represents the temperatures of location of shell from where the arteries are passing and therefore taken to be equal to the body core temperature. β is found to be lower than α, and γ during low atmospheric temperatures.

The variational form of Eq. (1) with the boundary conditions is given by:

$$I^{(e)} = \frac{1}{2} \iint \left[K^{(e)} r^2 \left(\frac{\partial T^{(e)}}{\partial r} \right)^2 + K^{(e)} \left(\frac{\partial T^{(e)}}{\partial \theta} \right)^2 + \left\{ M^{(e)} \left(T_A^e - T^{(e)} \right)^2 - \bar{S}^{(e)} \right\} r^2 dr d\theta \right], + \frac{\lambda^{(e)}}{2} \int_{\theta i}^{\theta_k} \left\{ h \left(T^{(e)} - T_a \right)^2 + 2LET^{(e)} \right\} r^2 d\theta : \ e = 1(1)416, \tag{4}$$

where e tends to no. of element and is defined element 1–416 starting with node 1.

Here r_i and r_j are radii of the eth element. $K^{(e)}, M^{(e)}, \overline{S^{(e)}}, T_A^{(e)}$ and $T^{(e)}$ denote the values of $K, M, \overline{S}, T_A$ and T, respectively, in eth layer. $\lambda^{(e)}$ is 1 for elements along the surface and $\lambda^{(e)}=0$ otherwise. The peripheral region of the women's breast is divided into the epidermis, dermis and subcutaneous tissues. The epidermis and subcutaneous tissues are divided in one layer each, whereas the dermis is divided into 11 layers due to non-homogeneity (Table 1). The region is discretized into 416 triangular ring elements (as shown in Fig. 1).

The following bilinear shape function is assumed for variation of temperature within each element:

$$T^{(e)} = c_1^{(e)} + c_2^{(e)} r + c_3^{(e)} \theta, \tag{5}$$

where $c_1^{(e)}$, $c_2^{(e)}$, and $c_3^{(e)}$ are constants for the eth element, here

$$T^{(e)} = T_p, \ p = i, j, k. \tag{6}$$

The integral $I^{(e)}$ in expression (4) are evaluated for each element using expression (6) and assembled as given below:

$$I = \sum_{e=1}^{N} I^{(e)}. \tag{7}$$

The integral I is extremized with respect to each nodal temperature T_i. $i = 1, 2, 3 \ldots n$ as given in (1) and it leads to a system of linear algebraic equations as given below:

$$[X]_{n \times n} \left[\overline{T_{n \times 1}} \right] = [Y]_{n \times 1} \tag{8}$$

Table 1 Triangular ring element information

Element	i	j	k	Type	Element	i	j	k	Type
1	1	16	15	1	27	15	16	29	1
2	1	2	16	1	28	29	16	30	2
3	2	3	16	1	29	16	31	30	1
4	16	3	17	2	30	16	17	31	1
5	3	18	17	1	31	17	18	31	1
6	3	4	18	1	32	31	18	32	2
7	4	5	18	1	33	18	33	32	1
8	18	5	19	2	34	18	19	33	1
9	5	20	19	1	35	19	20	33	1
10	5	6	20	1	36	33	20	34	2
11	6	7	20	1	37	20	35	34	1
12	20	7	21	2	38	20	21	35	1
13	7	22	21	1	39	21	22	35	1
14	7	8	22	1	40	35	22	36	2
15	8	9	22	1	41	22	37	36	1
16	22	9	23	2	42	22	23	37	1
17	9	24	23	1	43	23	24	37	1
18	9	10	24	1	44	37	24	38	2
19	10	11	24	1	45	24	39	38	1
20	24	11	25	2	46	24	25	39	1
21	11	26	25	1	47	25	26	39	1
22	11	12	26	1	48	39	26	40	2
23	12	13	26	1	49	26	41	40	1
24	26	13	27	2	50	26	27	41	1
25	13	28	27	1	51	27	28	41	1
26	13	14	28	1	52	41	28	42	2

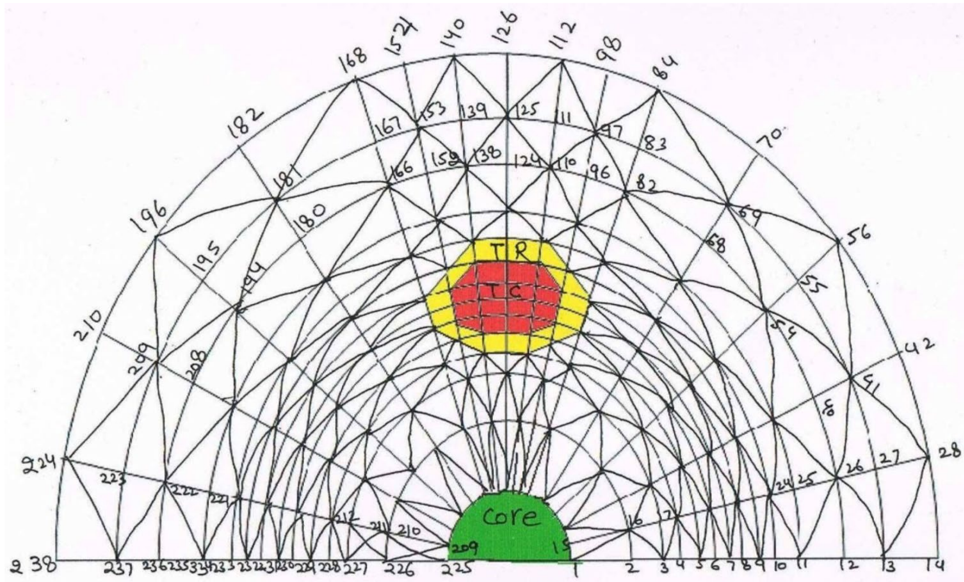

Fig. 1 Finite element discretization of breast region

X and *Y* is system of matrices of order *nx1* and *n x n*, respectively, and $\overline{T} = \left[\overline{T_1}\ \overline{T_2}\ \overline{T_3}\ ----\ \overline{T_n}\right]^T$. The Gauss elimination method has been used to obtain the solution (8).

3 Numerical results and discussion

The numerical results are obtained by Agrawal and Pardasani (2016), Acharya et al. (2016), Saxena and Pardasani (1987) and Viana et al. (2010) using the values of physical and physiological constant given in Table 2.

For a particular sample of peripheral tissue layers, r is assigned the following values: $r_1 = 8$ cm; $r_2 = 8.5$ cm; $r_3 = 8.54$ cm; $r_4 = 8.58$ cm; $r_5 = 8.62$ cm; $r_6 = 8.66$ cm; $r_7 = 8.7$ cm; $r_8 = 8.74$ cm; $r_9 = 8.78$ cm; $r_{10} = 8.82$ cm; $r_{11} = 8.86$ cm; $r_{12} = 8.9$ cm; $r_{13} = 9.0$ cm, and $r_{14} = 9.1$ cm.

Here we take $W = \eta S$, which implies that the metabolic activity in tumor is η times of that normal tissues (Table 3). The metabolic activity in tumor varies 7 times of that in normal tissues. As a particular case we take $\eta = 5.0$. We observe the effect of variable boundary condition at $r = 8$ and $\theta = 0$ to π with temperature 37 °C at $\theta = 0$ and $\theta = \pi$ and 36 °C at $\theta = \pi/2$. The temperature falls down as we move away from core to the outer skin surface in Figs. 2, 3 and 4. Also the slope of the curve changes at the nodes of epidermis, dermis and subdermal tissues in Fig. 2. This is due to the different properties of each layer. In Figs. 3, 4 the slope of curves changes at the nodes of normal tissues, tumor periphery, and tumor core. This is due to the different properties of tumor core and tumor periphery. There is elevation in temperature profiles is observed at the interface of normal tissues and tumor periphery and then fall in temperature is seen at the interface of tumor periphery and tumor core. There is elevation at the interfaces of tumor core and tumor periphery and then fall in temperature at the interface of tumor periphery and normal tissues. These changes in temperature profiles in the form of elevation and deviation downwards at the various interfaces of normal tissues and tumor give us the idea about the size and location of each layer of tumor and whole tumor. Figures 5 and 6 show temperature differences in spherical shaped woman's breast with non-uniformly perfused tumor due to absence and presence of menstrual cycle. The maximum values of temperature difference in Figs. 5, 6 are, respectively, 0.21 °C and 0.27 °C. The maximum temperature differences in women's breast with tumor

Table 2 The value for physical and physiological constants (Saxena and Pardasani 1987; Viana et al. 2010)

S. no.	Tissues	K (cal/cm min °C)	c_b (cal/g °C)	S (cal/cm^{3}min)	m_b (cal/cm^{3}min °C)
1	Bone	0.075	17	0	0
2	Muscle	0.042	3768	0.0684	0.001046
3	Fat	0.016	23	0.058	0.0001880
4	Skin	0.047	368	0.0357	0.003
5	Cysts	0.056	0	0	0

Table 3 The value for physical and physiological constants for different phases of menstrual cycle (Agrawal and Pardasani 2016; Acharya et al. 2016)

S. no.	Tissues	$m_{b\ follicular}$ (cal/cm^{3}min °C)	$m_{bluteal}$ (cal/cm^{3}min °C)	$S_{follicular}$ (cal/cm^{3}min)	S_{luteal} (cal/cm^{3}min)
1	Bone	0	0	0	0
2	Muscle	0.0005	0.0007	0.133	0.1415
3	Fat	0.00009	0.00012	0.0985	0.1135
4	Skin	0.01538	0.02197	0.0665	0.0707
5	Cysts	0	0	0	0

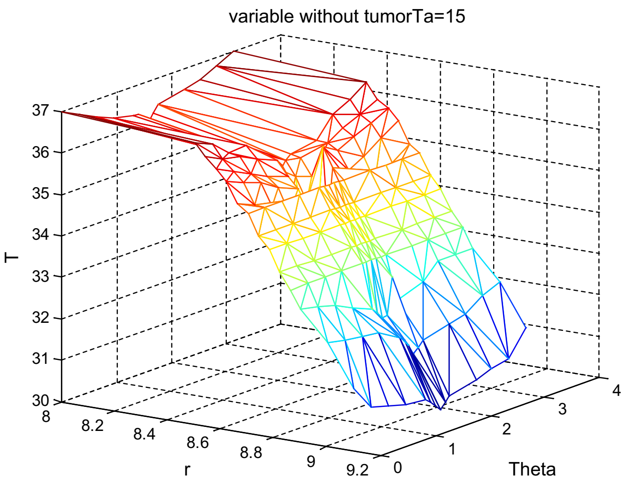

Fig. 2 Temperature distribution along r and θ direction in female breast with non-uniformly perfused tumor in absence of menstrual cycle for $T_a = 15$ °C, E = 0 gm/cm^2 min

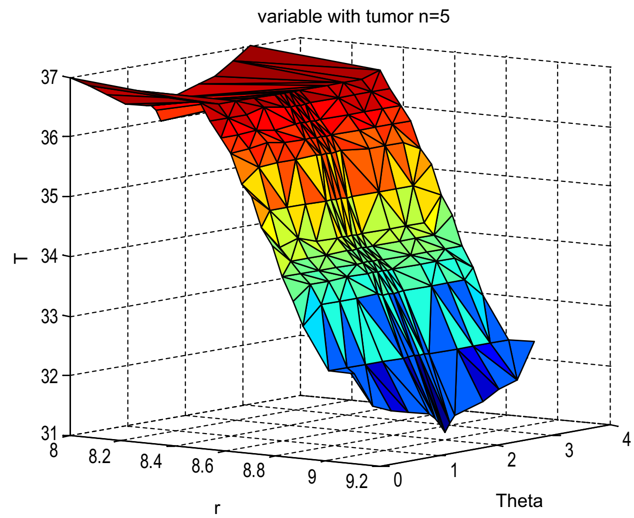

Fig. 4 Temperature distribution along r and θ direction in female breast with non-uniformly perfused tumor during follicular phase of menstrual cycle for $T_a = 15$ °C, $E = 0$ gm/cm^2 min

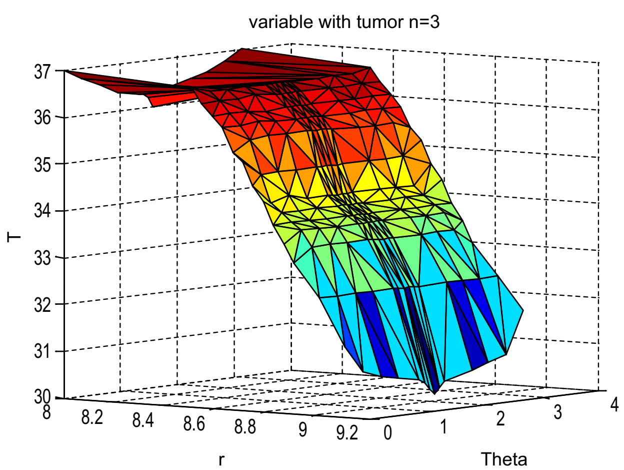

Fig. 3 Temperature distribution along r and θ direction in female breast with non-uniformly perfused tumor during follicular phase of menstrual cycle for $T_a = 15$ °C, E = 0 gm/cm^2 min

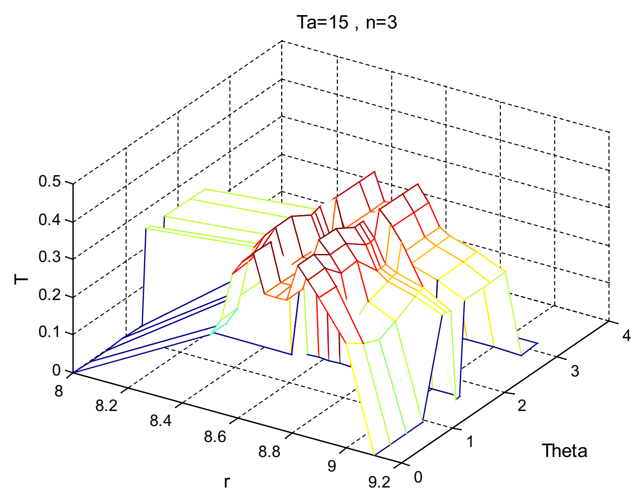

Fig. 5 Distribution of temperature differences in female breast with non-uniformly perfused tumor between normal condition and follicular phase of menstrual cycle for $T_a = 15$ °C, E = 0 gm/cm^2 min

due to presence and absence of menstrual cycle is observed in luteal phase of menstrual cycle. Thus, the thermal stress caused by malignant tumor in women's breast is more in luteal phase than in follicular phase of menstrual cycle. The information generated regarding the changes in the slopes of the curve at different junctions of tumor and normal tissues can be exploited in thermograms for identification of shape,

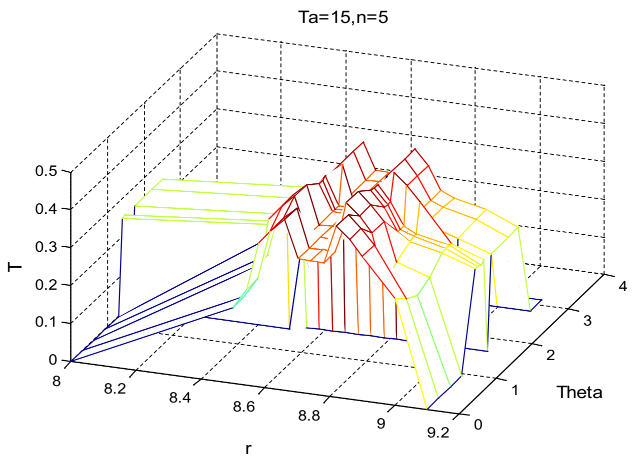

Fig. 6 Distribution of temperature differences in female breast with non-uniformly perfused tumor between normal condition and luteal phase of menstrual cycle for $T_a = 15$ °C, $E = 0$ gm/cm^2 min

size, location and boundaries of various layers of tumors and normal tissues in woman's breast. Further, the enhanced effect of tumors in woman's breast during various phases of menstrual cycle can also be useful in improving protocols for diagnosis of tumors by thermo graphic techniques.

4 Conclusions

The finite element model is proposed and employed to estimate the thermal stress due to non-uniformly perfused tumors in peripheral regions of woman's breast during different phases of menstrual cycle under cold environment. From the results it is concluded that the non-uniformly perfused malignant tumor in the woman's breast causes thermal disturbances which vary in quantity, shape of thermal patterns in women's breast and are specific to the type, size, shape and location of tumor. The thermal patterns due to malignant tumor in women's breast also vary due to benign changes caused during follicular and luteal phase of menstrual cycle. The thermal stress due to malignant tumor in women's breast gets enhanced due to benign changes caused during the follicular and luteal phase of menstrual cycle. Therefore, it is concluded that the thermography will be more effective in detection of malignant tumor in women's breast during luteal and follicular phase of menstrual cycle. The triangular ring element-based finite element approach has proved to be quite effective in incorporating the non-homogeneity of the region and variations in biophysical parameters. The proposed model is applicable for benign changes due to various phases of menstrual cycle. However, there are other benign changes occurring in woman's breast due to various causes and can influence the thermal stress in woman's breast due to malignant tumors and the authors intend to incorporate them in their future studies.

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