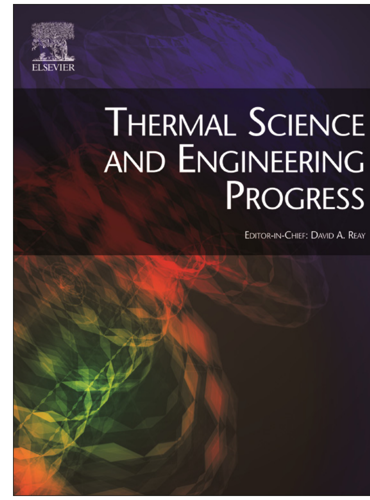

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Finite difference method based analysis of bio-heat transfer in human breast cyst

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ABSTRACT

Bio-heat transfer is a branch of bio-medical engineering which has its foundation linked to engineering disciplines of heat transfer. The thermal properties and behaviour of various malfunctioning tissues in human body varies as compared with normal tissues. Among various cancer tissues one which is commonly diagnosed in women is breast cyst (cancer causing fluid). The aim of present work is to develop one, two and three-dimensional computational models to study bio-heat transfer problems using finite difference method. First of all, a numerical model based on finite difference method is developed to solve Pennes's bio-heat transfer equation in one-dimension to get temperature profiles normal to skin surface and validated with existing analytical solutions. Secondly, the numerical model is extended to study the thermal behaviour of human breast section embedded with cyst using two-dimensional cylindrical coordinate systems and validated with previous researcher's results. The effect of size, location and presence of multiple cysts on surface temperature is studied. Lastly, the work is extended for the case of three-dimensional breast section with cyst located at the centre. The numerical results obtained using one, two and three-dimensional computational models will be highly helpful in the early detection of breast cancer tissues and also the location of it inside the body.

Keyword: Penne's bio-heat transfer equation; breast cyst; finite difference method; temperature profile

1. INTRODUCTION

Knowledge on heat transfer in biological bodies has many therapeutic applications, it involves either raising or lowering of temperature and often requires precise monitoring of the spatial distribution of thermal histories that are produced during treatment. Modern clinical treatments such as cryosurgery, cryopreservation, cancer hyperthermia, skin burn injuries etc. require thermal behaviour of a tissue or temperature distribution around tissue. Among various cancers, breast cancer is most commonly diagnosed in women. Many women feel presence of unusual lump called cyst in breast, which is a benign mass of fluid having different thermal properties than normal breast tissue. Early diagnosis of such cysts can increase the chances of survival. So there is necessity of having non-invasive methods to diagnose cancer in early stages. This could be possible by analysing thermal behaviour of body.

Numerical research and study on bio-heat transfer problems began with Pennes's bio-heat transfer equation which was defined by Pennes [1]. He obtained temperature distribution in human forearm from experiments and then developed a mathematical model. Pennes's equation was solved using Green's function and an analytical solution was obtained by Deng and Liu [2]. Further, various boundary conditions were applied with different heat input methods and the temperature behaviour along skin was observed. Monte Carlo method was used to get numerical solution for three-dimensional bio-heat problems assuming adiabatic conditions [3-4]. Karaa et al. [5] obtained temperature profiles with Krylov subspace method. Shih et al. [6] developed analytical solution based on Laplace transform method and got more accurate initial temperature distribution. Kushwaha and Ghoshdastidar [7] obtained temperature distribution in human eye during surgery using finite difference method. Sharma et al. [8] and Ahmadikia et al. [9] used thermal wave model considering relaxation time factor over Pennes's model and observed more precise temperature profile. Few porous media models are reported showing variation in temperature profiles [10]. He et al. [11] used alternating direction implicit finite difference method to get temperature plot for irregular tissue geometry. Ciesielski and Mochnacki [12] obtained temperature fields using finite volume approach. Few models represent the thermal field for cancer treatments like radiofrequency ablation, magnetic fluid hyperthermia treatment and laser irradiation [13-14]. Kengne et al. [15] considered the blood perfusion as function of temperature to get accurate temperature profile. Breast is a simple homogenous organ without major blood vessels. Various models have been developed to get breast surface temperature field. Analytical

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model can be used only if it is simple in geometry with simple boundary conditions, but for complex conditions numerical methods such as Finite Difference Method, Finite Element Method and Finite Volume Method are suitable. Further for complex geometries Finite Element Method is convenient to use. Recently, Balusu et al. [16] used Finite Element Method using COMSOL software to get temperature plot for breast with cyst inside.

Literature review infers that most of the work in bio-heat transfer problems was done using finite difference, finite volume methods in one and two dimensional cases for rectangular geometry and finite element method for cylindrical and spherical geometry, but there are not many studies which use finite difference method for complex geometry as in case of breast cyst. This paper is focused on solving bio-heat transfer in human breast embedded with cyst using finite difference method on a cylindrical and spherical co-ordinate system. The study is organized as follows. In section 2, we represent mathematical modelling of general one-dimensional bio-heat transfer problems, using Pennes' heat equation. Further study has extended for simulation of breast cyst in cylindrical and spherical coordinates. In section 3, results are discussed for above models. In section 4, we conclude summarizing all results.

2. MATHEMATICAL MODELLING AND NUMERICAL PROCEDURE

Heat transfer in biological body consists of conduction through tissues and convection due to blood flow through veins and arteries, all of which depends on blood perfusion rate with combination of internal heat generation due to metabolism. Bio-heat transfer equation is Pennes' equation [1]. It is assumed that blood and tissues are in thermal equilibrium. Term on left side of equation (1) indicates rate of energy stored in tissue. First term on right side represents conduction, while second indicates blood perfusion and third is metabolic heat generation.

$$\rho_t c_t \frac{\partial T}{\partial t} = \nabla . k_t \nabla T + \rho_b c_b \omega_b (T_a - T) + Q_m \qquad (1)$$

where, ρ_t is tissue density in $\frac{kg}{m^3}$, c_t is specific heat of tissue in $\frac{J}{Kg.℃}$, T is tissue temperature in ℃, T_a is arterial temperature in ℃, k_t is thermal conductivity of tissue, ρ_b is blood density in $\frac{kg}{m^3}$, c_b is specific heat of blood in $\frac{J}{Kg.℃}$, ω_b is blood perfusion rate in $\frac{ml/s}{ml}$, Q_m is internal heat generation in $\frac{W}{m^3}$.

2.1 Modelling for simple one dimensional problems

Equation (1) is applied with different boundary conditions and heat inputs for one-dimensional rectangular coordinate system. Additional Q_r term is added on right side of equation (1) to account for spatial heating caused during cancer treatment [2]. To get initial temperature distribution, equation (1) is solved for steady state conditions. It is given by,

$$\nabla . k_t \nabla T + \rho_b c_b \omega_b (T_a - T) + Q_m + Q_r = 0 \qquad (2)$$

Above equation is solved with boundary conditions,

$$T = T_c \text{ at } x = L \qquad (3)$$

$$-k_t \frac{dT}{dx} = h_0 [T_f - T] \text{ at } x = 0 \qquad (4)$$

where, x is distance from skin surface in m, T_c is body core temperature in ℃, L is length from surface to body core in m, h_0 is heat convection coefficient due to natural convection and radiation, T_f is surrounding fluid temperature in ℃ and $Q_r = 0$ for initial temperature distribution, as there is no spatial heating. Finite difference method is used to discretize above equation to get initial temperature distribution in the body. Further, equation (1) along with Q_r term is discretized to get temperature at any position for particular time. Time dependent boundary conditions are given by,

$$-k_t \frac{\partial T}{\partial x} = f_1(t), x = 0 \qquad (5)$$

$$-k_t \frac{\partial T}{\partial x} = h_f [f_2(t) - T], x = 0 \qquad (6)$$

where, $f_1(t)$ the time-dependent surface heat flux, $f_2(t)$ the time-dependent temperature of cooling medium and h_f the heat convection coefficient between the medium and the skin surface [2]. The body core temperature is regarded as constant assuming as biological body regulates blood flow to maintain its core at constant temperature

$$T = T_c, x = L \qquad (7)$$

In cases like tissue heating by laser, microwave or ultrasound, the spatial heating term Q_r is given by,

$$Q_r(x, t) = P_0(t)\, e^{-x} \qquad (8)$$

where, is scattering coefficient, $P_0(t)$ is time-dependent heating power on skin surface [2].

The length of tissue is taken as 3 cm as it is assumed that beyond this depth body core has same thermal behaviour under any circumstances. $\rho = \rho_b = 1000\frac{kg}{m^3}, c = c_b = 4200\frac{J}{kg}, T_c = T_a = 37℃, k = 0.5\frac{W}{mK}, \omega_b = 0.0005\frac{1}{s}, Q_m = 33800\frac{W}{m^3}$, forced heat convection coefficient $h_f = 100\frac{W}{m^3}$ with surrounding temperature $T_f = 25℃$ [2].

2.2 Modelling breast Cyst using Cylindrical Coordinates

Equation (9) is Pennes' bio-heat equation in cylindrical coordinates which is discretised using finite difference method in radial (r) and angular (∅) direction. Under steady state, left side of equation (9) becomes zero. Blood density ρ_b taken as $920\frac{kg}{m^3}$, specific heat capacity of the blood $c_b = 3000\frac{J}{kg}$ and arterial temperature is $310.15°K$ [16]. The thermal properties like conductivity and blood perfusion rate vary for normal tissue and cyst [16].

$$\rho_b C_b \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_t r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \emptyset}\left(k_t \frac{\partial T}{\partial \emptyset}\right) + \frac{\partial}{\partial z}\left(k_t \frac{\partial T}{\partial z}\right) + \rho_b C_b \omega_b (T_a - T) + Q_m \quad (9)$$

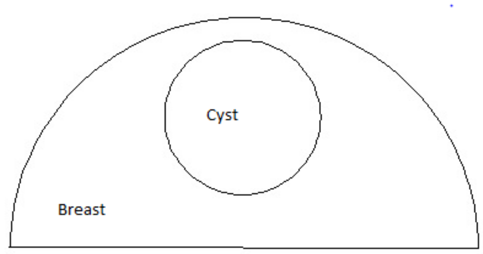

Fig. 1. Schematic of 2D breast slice with cyst embedded inside

Two-dimensional cross section of breast slice with cyst embedded in it is shown in Fig. 1. Breast section is assumed to be semi-circular, axisymmetric and homogenous, whereas cyst is in circular shape located symmetrically along breast axis. Breast slice is considered as 9 cm in radius with cyst of 3 cm radius located at a depth of 4.5 cm. The size of the cyst is modelled by varying the radius from 0.5 cm to 3 cm. The location of cyst is varied from a depth of 3 cm to 5.5 cm [16]. Base of the breast is assumed to be at body core temperature 37℃, so boundary condition for bottom surface is constant temperature of 37℃. Curved surface is having coefficient of heat transfer (h) =20 $\frac{W}{m^2K}$ [16] with boundary condition of it is given by equation (10),

$$-k_t \frac{\partial T}{\partial r} = h(T - T_s) \tag{10}$$

For both rectangular and cylindrical coordinate system the computational domain is divided into 50×50 and 100×100 nodes and discretization is done using finite difference method.

2.3 Modelling breast cyst using spherical coordinates

In this section, finite difference method is used to simulate three dimensional breast section with cyst inside it at centre. Breast resembles to half sphere in shape and cyst is of spherical shape located at the centre of breast. Also cyst is assumed to locate at the centre of breast so that entire domain is axisymmetric. Hence it is divided into four equal parts symmetric about breast axis. Figure 2 shows meshing for breast section embedded with cyst. Surface '1' in fig. 2 is maintained at constant temperature of 37℃ because this part of breast is attached to body core. As breast is divided into four parts, adiabatic boundary condition is applied to surfaces '2' and '3'. Surface '4' is exposed to surroundings so convection boundary condition is applied at this surface. Object '5' in fig. 2 represents location of cyst inside breast.

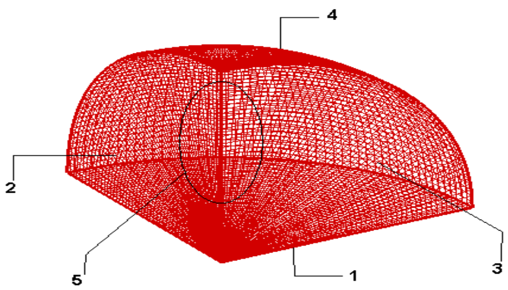

Fig. 2. Meshing for three-dimensional breast section.

Equation (11) is Pennes' bio-heat equation in spherical coordinates. Equation is discretized using finite difference method in radial (r), angular ($\emptyset$) and (θ) direction.

$$\rho_b C_b \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(k_t r^2 \frac{\partial T}{\partial r}\right) + \frac{1}{r^2\,(\sin(\theta))^2}\frac{\partial}{\partial \emptyset}\left(k_t \frac{\partial T}{\partial \emptyset}\right) + \frac{1}{r^2 \sin(\theta)}\frac{\partial}{\partial \theta}\left(k_t \sin(\theta)\frac{\partial T}{\partial \theta}\right) + \rho_b C_b \omega_b (T_a - T) + Q_m \tag{11}$$

As it is a steady state case, left side of equation will become zero. As convection heat exchange at outer surface takes place primarily in 'r' direction, boundary condition is given by,

$$-k_t \frac{\partial T}{\partial r} = h(T - T_s) \qquad (12)$$

$$-k_t \frac{\partial T}{\partial \emptyset} = 0 \qquad (13)$$

$$-k_t \frac{\partial T}{\partial \theta} = 0 \qquad (14)$$

Equation (11) is discretized in 'r', 'θ' and '$\emptyset$' directions having step size of $\Delta r, \Delta\theta$ and $\Delta\emptyset$ respectively using central difference scheme. System of linear equations obtained from discretization is solved iteratively over the domain to get stable temperature distribution. Breast is considered as 9 cm in radius with cyst of 3 cm radius located at a depth of 4.5 cm. The surface joining the organ to the body is assumed to be maintained at 310 K i.e. the body core temperature, while the curved surface has a coefficient of heat transfer h= 20 $\frac{W}{m^2K}$ [16] with boundary conditions given by equation (12). Equations (13) and (14) represent the boundary conditions for surfaces '2' and '3' in fig.2.

3. RESULTS AND DISCUSSIONS

Unsteady state Pennes's bio-heat transfer equation is discretized for simple one-dimensional problem using finite difference method with Crank Nicolson scheme. Steady state Pennes's equation is discretized for breast section and cyst in cylindrical and spherical coordinates using central difference scheme. Various stability criteria have been taken into consideration for discretized equations. Number of nodes is decided as per required accuracy. It is comprehended that about 500 nodes for one-dimensional unsteady state problems as discussed in section (2.1) gives agreeable results. Also it is found that for two and three dimensional cyst problems results with 50 or 100 nodes in each direction gives satisfactory results. Numerical code is developed in MATLAB for various boundary conditions and heat inputs for all the models discussed. Solutions obtained with present finite difference method are compared and validated with existing analytical and finite element method based results.

3.1 Simple one-dimensional bio-heat transfer problem

In this section, result for simple one-dimensional problems for convection boundary conditions and heat inputs is discussed. Temperature variation at various locations is plotted along the domain at different time steps and temperature behaviour is observed. Also, deviation in location of maximum temperature is observed for each time step. Convective heat transfer condition is applied on skin surface, which is the most realistic boundary condition imposed on skin surface. We assumed $h_f = 100\ \frac{W}{m^2 °C}$ and f_2 (t) = 25°C in equation (6), and spatial heating parameters in equation (8) as P_0(t)=5000$\frac{W}{m^2}$, $\quad = 200\ m^{-1}$ [2]. Figure 3 shows the comparison between present Finite Difference Method (FDM) results and analytical results of [2]. Figure 3 depicts the temperature distribution in the tissues due to the surface cooling by the flowing medium, because of that the highest tissue temperature occurs at certain position below the skin. As time passes the position of the highest temperature move towards the body core as seen in fig.3.

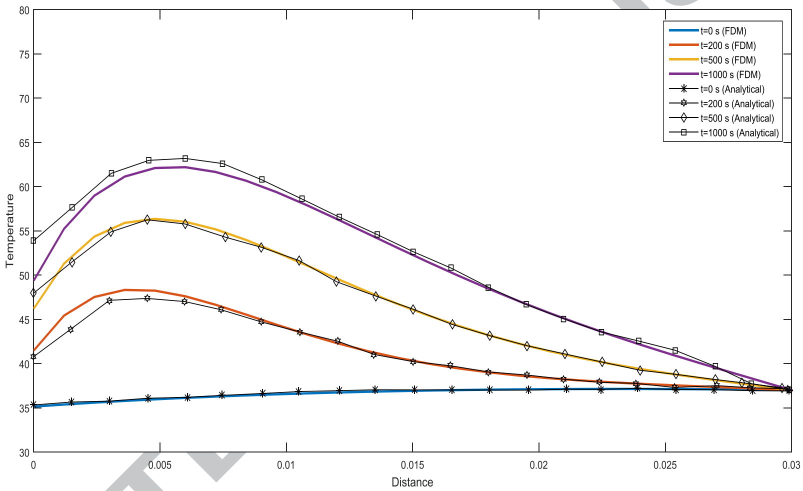

Fig. 3 Comparison between FDM results (Present) and analytical results [2]

Figure 3 clearly depicts that finite difference method based results are in good agreement with analytical results of Deng and Liu [2], and hence it concludes that finite difference method is simple and comparable to exact method. Though, there are few methods to solve Pennes's equation analytically, they are restricted to one-dimension and also it is impossible to incorporate all boundary conditions. Therefore in those cases finite difference scheme can be effective.

3.2 Simulation of two-dimensional breast cyst in cylindrical coordinates

The two-dimensional breast model is solved using finite difference method in cylindrical coordinates. Code is developed for this model using MATLAB. Thermal parameters for healthy tissue and cyst are taken from previous work as listed in Table 1 [16], also thermal properties at cyst boundary are assumed to be same as cyst properties.

Table 1. Simulation Parameters

	Tissue	Thermal conductivity $\frac{W}{mK}$	Blood perfusion $\frac{1}{s}$	Metabolic heat generation rate. $\frac{W}{m^3}$
1	Normal Breast	0.42	0.00018	450
2	Cyst	0.56	0	0

In this section, results of simulation for two-dimensional breast section in cylindrical coordinates are discussed and compared with previous researcher's results. Temperature contour over domain of breast section embedded with cyst is observed for condition of varying cyst location. Effect of presence of multiple cysts on surface temperature is studied.

3.2.1 Breast section embedded with single cyst

Figure 4 shows simulation of healthy breast section by considering semi-circular geometry. Colour coded contour are plotted for temperature distribution over breast section without and with cyst as shown in fig.4 and fig.5 respectively. Red colour indicates maximum temperature at the core of body while minimum temperature is at surface filled with blue colour. It is observed that, presence of the cyst affects the temperature distribution over surface. In fig.5, circle inside the contour indicates the location and size of the cyst. It can be compared from fig.4 and fig.5 that temperature is disturbed in the region of the circle. Temperature is decreased in this region as cyst has zero heat generation. These results are in good agreement with that of [16], where similar simulation has performed using finite element method.

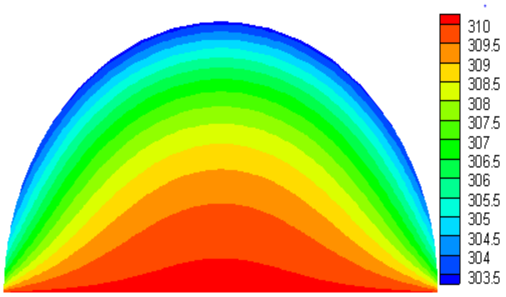

Fig. 4. Representative temperature distribution in healthy breast using FDM

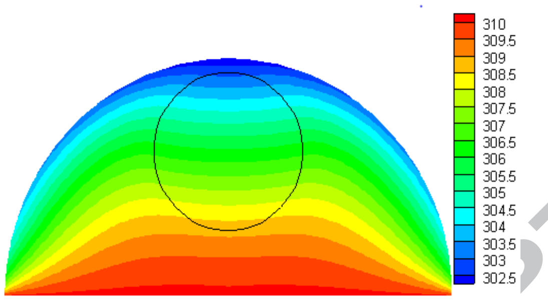

Fig. 5. Representative surface temperature distribution in the breast with cyst of radius 3 cm and depth of 3.5 cm using FDM

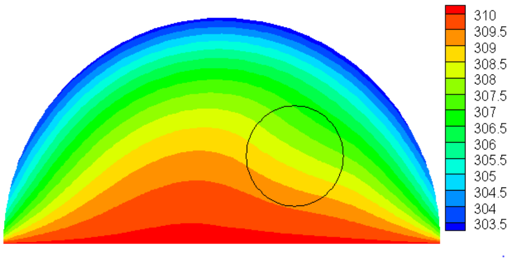

Fig. 6. Cyst of radius 2cm located at x=3cm and y=3.5cm

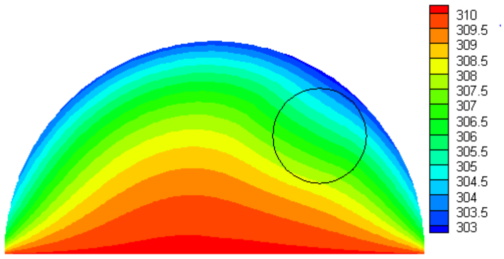

Fig. 7. Cyst of radius 2cm located at x=4.5cm and y=5cm

Figures 6 and 7 show temperature contours for breast section with changed locations of cyst. Cyst is located at right or left of the breast axis, and minimum surface temperature is observed with respect to the condition of cyst at centre and no cyst. In the case of fig.6 minimum surface temperature is 303.167 K and in case of fig.7 minimum surface temperature is 302.768 K. Hence from above it is concluded that for small temperature difference, cyst location change is substantial.

3.2.2 Breast section embedded with multiple cysts

In breast cancer there is a possibility that cyst gets split into two or more lumps. Thus, presence of many cysts gives additional temperature disturbance. Figures 8 and 9 show breast section with two and three cysts having minimum surface temperature of 303.066K and 303.019K respectively. Above study inferred that minimum surface temperature increases with decrease in size of cyst and number of cysts.

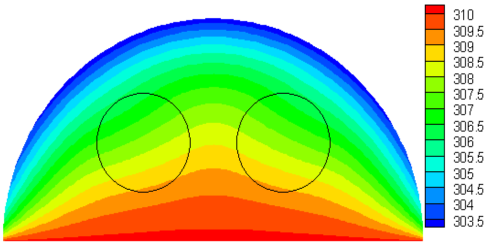

Fig. 8. Two cysts of radius 2cm with 6cm apart

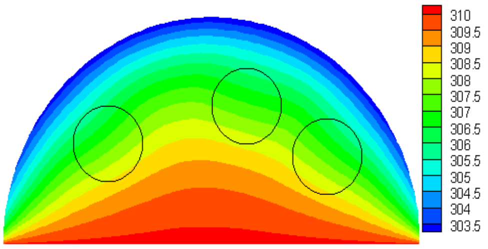

Fig. 9. Three cysts of radius 1.5cm

Size and depth of cyst is varied and minimum surface temperature is plotted which is shown in fig. 10 It can be concluded that, surface temperature decreases with increase in cyst size and also, it decreases when cyst is closer to the surface.

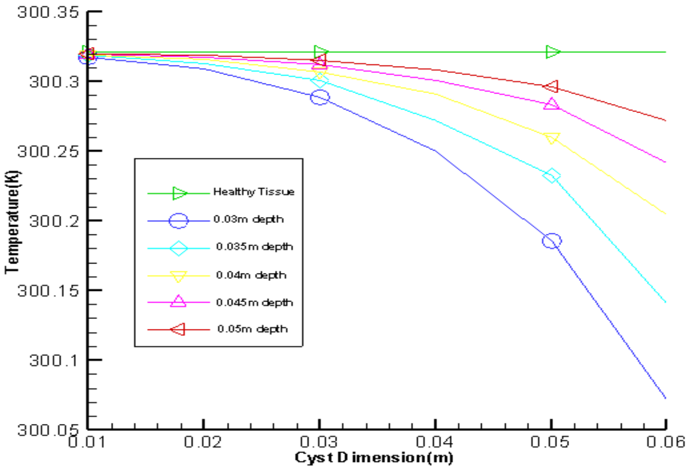

Fig. 10. Minimum surface temperatures of breast region with varied size and depth of cysts

3.3 Simulation of three-dimensional breast cyst in spherical coordinates

Simulation of three-dimensional (3D) objects for various thermal boundary conditions is complex and requires high computational effort. Generally finite element method is used to simulate such objects, as it is easy to integrate different boundary condition. In this section, finite difference method is used to simulate three-dimensional breast section with cyst inside it at centre. Breast resembles to half sphere in shape and cyst is of spherical shape located at the centre of breast. Since geometry is axisymmetric, for convenience it is divided into four equal parts.

3.3.1 3D breast section without cyst

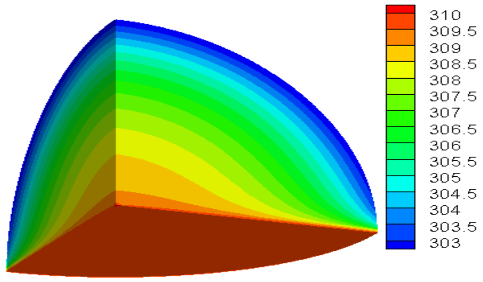

Fig. 11. Side view of 3D breast section without cyst

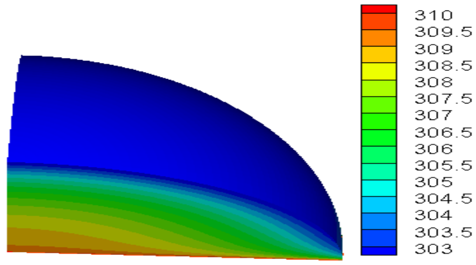

Fig. 12. Top view of 3D breast section without cyst

Figures 11 and 12 display the side and top views of three-dimensional breast section without cyst. Bottom surface with red colour represents body core temperature, as this part is attached to the core of the body. Blue curved surface represents outer surface of breast which is exposed to convection boundary condition. This surface belongs to minimum breast temperature. Reduction in minimum surface temperature is observed for three-dimensional breast section as compared to two-dimensional case. This temperature variation is about 0.3 percent so it can be inferred that we can use two-dimensional simulation for breast section since it is computationally less expensive compared to three-dimensional ones.

3.4.2 Three-dimensional breast section with cyst

Three-dimensional temperature contour for breast section with cyst of radius 3 cm and located centrally at the depth of 4.5 cm from surface is plotted as shown in fig. 13. Comparing with fig. 11, decrease in temperature in the region of cyst is observed. Also, if it is compared with two-dimensional breast section with cyst case as shown in fig. 5, change in temperature is insignificant. It is observed that minimum surface temperature for three-dimensional breast section with cyst is 301.79 K and that for two-dimensional section is 302.722 K. This temperature variation is not much significant, so it is inferred that one can use two-dimensional simulation for breast section, because it is time saving and computational efforts are also less. Figure 14 shows sectional view along ‘r- θ’ plane. It can be seen that cross section resembles to the two-dimensional breast section simulation with cyst inside it.

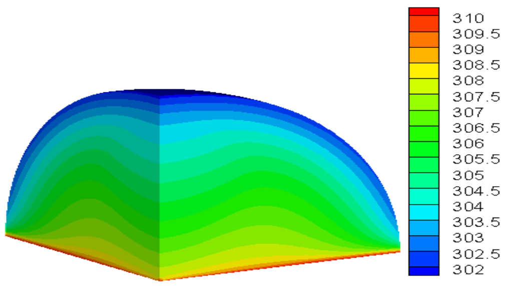

Fig. 13. Side view of 3D breast section with cyst

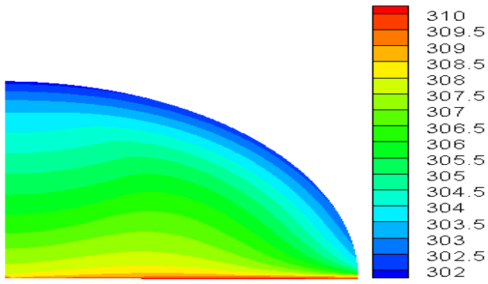

Fig. 14. Cross section of breast along 'r- θ' plane

4. CONCLUSIONS

In this paper, a one-dimensional computational model for bio-heat transfer problem is developed using finite difference method and validated with existing analytical results. Further, the model is extended to simulate the case of breast section embedded with cyst in two and three-dimensions. It is found that there is a decrease in temperature in the region of cyst as it belongs to no heat generation region. It is also observed that for minor change in temperature variation, change in location of cyst is significant. Numerical simulations are performed to study variation of temperature for multiple cysts (two and three). It is found that the temperature decreases with increase in number of cysts. With the developed model three-dimensional numerical simulations are carried out similar to the cases done in two-dimensional study. It can be inferred that the developed three-dimensional model closely mimics the actual physical problem of breast cyst. The present work can be useful in correlation studies with infrared images and design of thermal image camera for the automated diagnosis of breast cancer. Also, on replacing thermal properties of benign cyst with malignant cancer cells one can detect presence of cancer cells and that will be helpful in early detection of cancer.

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Highlights

- Numerical study on bio-heat transfer in human breast cyst using finite difference method
- One, two and three-dimensional modeling of bio-heat transfer problem.
- Effect of location of cyst and location of cyst.
- Simulation of multiple cysts.
- Results helpful for early detection of cancer.