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Effects of Tumor Radius, Metabolic Heat Rate and Heat Transfer Coefficient on the Temperature Distribution of Tumor Affected Breast

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***Abstract*—Tumor is a frequent abnormality of the human breast that can transform into an incurable condition if left untreated at earlier stage. Thus, early detection of tumors is crucial for successful treatment of tumor anomalies. Due to the distinct thermal characteristics of tumor affected tissues namely heat transfer coefficient and metabolic heat generation; bio heat transfer equations can be a viable option to model the temperature profile of the affected breast in order to pinpoint the faulty tissues. This study develops a two-dimensional model of a tumor-affected breast and investigates the temperature profile of it with varied realistic values of metabolic heat generation of the tumor affected area and the heat transfer coefficient at the affected boundary along with the variation of tumors size. A finite element scheme using Pennes' bio heat transfer equation is formulated and implemented for solving the model. Firstly, the dimensional effect of tumor is observed by varying tumor radius from 0.25cm to 0.75cm within a breast section of 9cm radius. It is found that the presence of tumor of any size increases the local temperature. Secondly, it is observed that an increase in the metabolic heat generation of the tumor increases the temperature of the respective region. Furthermore, it is found that an increase in the coefficient of heat transfer at the exposed breast surface decreases the temperature at that region. The findings of this study are significant to assess patients' condition and develop thermography application scheme for the early detection of tumor.**

Keywords*— *Pennes' Bio-heat Equation, breast tumor, temperature distribution, finite element method, healthcare 4.0

I. Introduction

Breast cancer is one of the most frequently diagnosed malignancy in women. Early detection of this disease can raise the rate of survival of the patient. The currently available imaging modalities for breast cancer detection include mammography, ultrasonography, breast MRI etc. which are not always viable. For example, in case of X-ray mammography, the patient is exposed to ionizing radiation and the procedure is uncomfortable to the patient due to breast compression[1]. Besides, MRI has some drawbacks like low specificity and slow imaging time [2], etc. Considering the development of high quality infrared cameras in recent years, thermography can be deemed as a promising method for early identification of breast tumor and cyst. When compared to traditional modalities of tumor detection, thermography proves to be safer for the patient and the operator. In the presence of conductive objects in the magnetic bore, radio frequency energy can cause tissue burns to the patients during MRI procedure[3]. On the other hand, thermography is free of external radiations which makes it safer[4]. As the procedure does not require the application of external radiation and the temperature mapping is taken from the infrared radiation of the surface of the organ, this method is sustainable. Besides, breast thermography is capable of identifying breast cancer 10 years before traditional modalities like mammography[4].

For successful application of thermography, temperature profile at the onset of tumor growth and spread have to be modelled accurately. Several studies are available in the literature for temperature modelling purpose using bio heat transfer correlations. The model proposed by H.H. Pennes' using Classical Fourier's Law is among the first mathematical models of bioheat transfer for describing the thermal properties of human forearm[5], which has been widely used for analytically and numerically solving bioheat transfer problems subjected to various boundary conditions. However, this equation neglected the influence of blood vessels in tissue which limits its realistic implementation. In later works, efforts have been made to integrate heat transfer in individual blood vessels. Deng and Liu adopted Green's function to formulate the bio heat equation with transient heating on biological tissue [6]. Yue et al proposed a solution of a 1D model of cylindrical tissue in the steady state based on Pennes' equation. They expressed the solution by Bessel's function which can be used to find temperature changes with radial variation[7]. In some of the studies, attempts were made to solve the heat transfer problem for biological tissue subjected to external heating sources. Talaee and Kabiri applied Eigenvalue method for solving the hyperbolic Pennes' bio heat equation for modelling radio frequency heating process. Further, they analytically assessed the solution's ability to evaluate the effects of different parameters of radio frequency heating on temperature dissemination[8]. Ghanmi and Abbas derived the fractional derivatives of Pennes' bio heat equation and found that Pennes' bioheat equation shows greater increase in temperature than the fractional Pennes' bioheat model[9].

In recent decades, various numerical solutions have also been proposed that account for complex boundaries or shapes, especially problems containing a range of time or space-dependent boundary constraints. The steady state temperature distribution of a two dimensional human eye model was determined using the boundary element method by Ang and Ng. They demonstrated that for determining normal flow of heat on the surface of the cornea, the boundary element approach yielded better results than the finite element method [10]. Other bioheat models, such as the "thermal wave model of bioheat transfer (TWMBT)" and "Pennes' Bioheat transfer model", were compared in some of the research. Blood perfusion rate and relaxation time significantly affected their results. Some of the works focused on finding temperature plots for irregular domains. Attempts were also made to implement hybrid approaches by incorporating more than one method. Using the Laplace transform method, Liu and Tu developed a numerical methodology for analyzing the bio - heat problem with transient blood temperature [11]. Balusu et al. observed decrease of local temperature of a human breast in presence of a cyst[12]. Patil and Maniyeri used finite difference method to find the temperature profile of a three dimensional human breast with embedded cyst[13].

The driving factors of local temperature variation in case of tumor disease can be attributed to the size of the tumor as well as to the thermodynamic properties of the affected tissues, so for successful thermography detection of the tumor these parameters need to be addressed. This study investigates the factors that influence the temperature of a human breast if a tumor is implanted. The correlation with both metabolic heat generation and tumor radius has been explored. The heat transfer coefficient's role in temperature change at the breast-ambient air interface has also been investigated.

II. Methodology

A. Mathematical Model

"Pennes' bioheat equation" is used in this study to model the temperature profile (T) of a healthy breast and tumor affected breast. Thermal equilibrium between the tissue and the blood is assumed. The rate of blood perfusion (ω_b) is accounted for convection heat transfer along with metabolic heat production (Q_m). Combining the convection and generation term with traditional conduction part, the equation in 2D Cartesian coordinates is given as:

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

where, the density of tissue and blood are denoted by ρ_t and ρ_b , specific heat of tissue and blood are denoted by c_t and c_b , thermal conductivity of the tissue is denoted by k_t , and T_a indicates arterial blood temperature in the pulmonary vein.

B. Numerical Modelling

To solve (1) under stationary conditions, a Finite Element Method (FEM) is used. The breast is approximated as a 2D semicircle with a radius of 9cm. The radius of the tumor is varied from 0.25cm to 0.75cm at a depth of 5cm. The blood density ρ_b is approximated as 920 $\frac{kg}{m^3}$, the specific heat capacity of the blood c_b is taken as 3000 $\frac{J}{kg.K}$, and the arterial blood temperature is considered as 310.15K. Thermal conductivity, blood perfusion rate, and metabolic heat generation change across the breast and tumor domains [12]. A room temperature of 293.15K is maintained as the initial value for the simulation. No thermal insulation is considered between the biological tissue domains or at the breast-air boundary. The temperature of the surface connecting the breast to the body will be the body core temperature. So the flat part of the semicircle has been maintained at 310K. The semicircle's curving side is exposed to the outside environment, which consists of ambient air. Heat transfer through radiation is assumed to occur at the exposed breast surface. At the curved surface, the three modes of heat transfer are evaluated using the following boundary condition.,

$$q_0 = h(T_{ext} - T) \qquad (2)$$

Where h denotes the heat transfer coefficient which is varied from 10.8 $\frac{W}{m^2\,K}$ to 16.2 $\frac{W}{m^2\,K}$. T_{ext} is external temperature taken as 298K.

III. Results and Discussion

The model is solved in COMSOL Multiphysics which is a general purpose simulation software based on complex numerical method [14]. The thermal characteristics of the breast tissue and the tumor tissue are collected from previous studies [12], [15], [16] which are listed in TABLE I. The model is solved using the finite element method. In solving the model, a user controlled mesh is employed which is demonstrated in Fig. 2. The entire mesh has 16388 domain elements and 560 boundary elements. There are 8 vertex elements and 560 boundary elements with a minimum element quality of 0.5876.

The temperature variation trend of a healthy breast without any tumor is shown in Fig. 3. The maximum temperature of 310K is observed at the surface where the breast is connected to the body. The minimum temperature of 301K is observed at the outermost part of the breast. The temperature gradually decreases from the breast-body interface to the breast-ambient boundary. This natural trend of the surface temperature distribution happens owing to the higher temperature at the body side because of the body heat generation and the lower temperature at the ambient interface from where heat is convected and radiated to the environment. This profile can be used as the normal trend for thermography apparatus.

The change of temperature profile owing to the growth of a tumor is demonstrated in Fig. 4. From this figure, it is evident that the temperature of the affected area rises when a tumor is present. The deviation can be attributed to the higher metabolic heat production rate of the tumor tissues than the breast tissue.

Along with the detection of the tumor, tumor size and thermal characteristics according to severity and age of the patients are also needed to be measured for a successful thermography implementation. The temperature distribution for tumor size and various tumor thermal properties along a

TABLE I. SIMULATION PARAMETERS

Tissue	*Thermal conductivity, k_t (W/m.K)*	*Blood perfusion rate, ω (1/s)*	*Metabolic heat generation(W/m³)*
Breast	0.42	0.00018	450
Tumor	0.48	0.016	700-65400

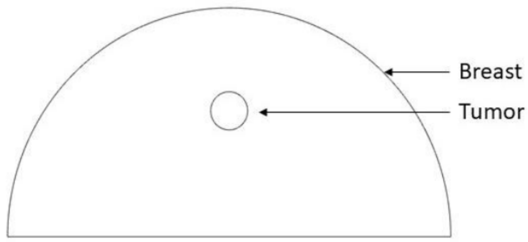

Fig. 1. 2D diagram of breast with embedded tumor.

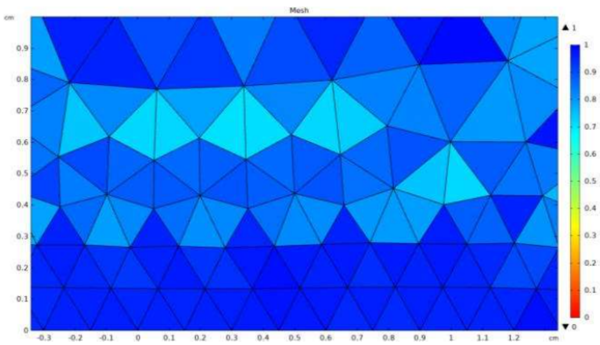

Fig. 2. Mesh Resolution.

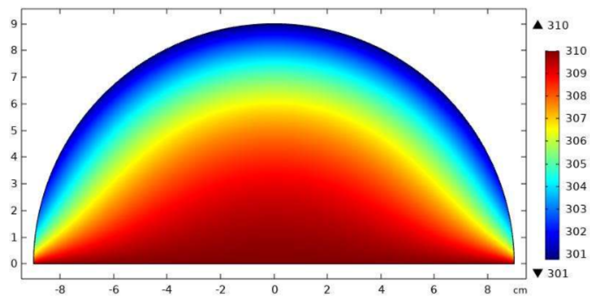

Fig. 3. Temperature distribution in healthy breast with h = 16.2 $\frac{W}{m^2\,K}$.

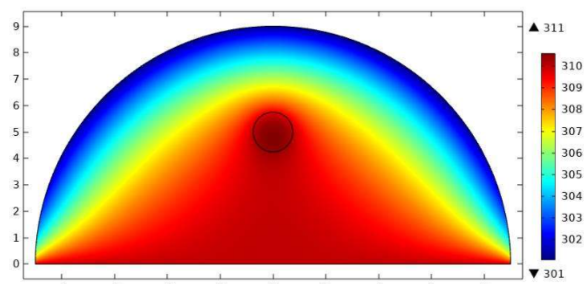

Fig. 4. Temperature distribution in breast with tumor of radius 0.75cm, depth of 5cm, h = 13.5$\frac{W}{m^2\,K}$ and tumor Q_m = 32600 $\frac{W}{m^3}$.

perpendicular line running through the center of the breast is displayed from Fig. 5 to Fig. 7. The extent of the radius of the tumor has significant effect on the temperature profile of the breast which is shown in Fig. 5. where the values of radius is varied from 0.25 cm to 0.75 cm. It is found that with the increase of the tumor radius to about four times of the beginning value, the area of high temperature region widens

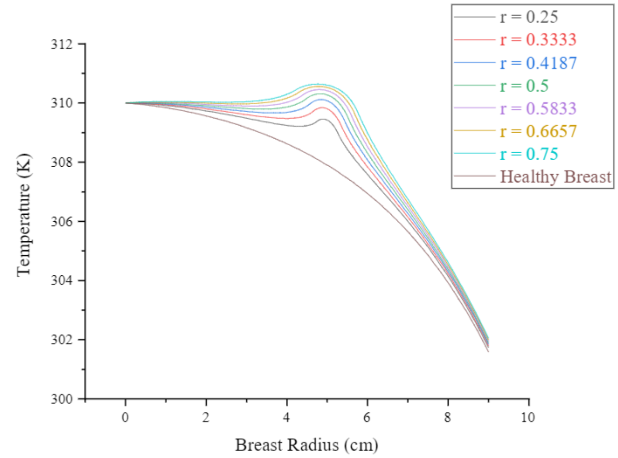

Fig. 5. Temperature distribution with varied radius of the tumor with h = 13.5 $\frac{W}{m^2\,K}$ and tumor Q_m = 32600 $\frac{W}{m^3}$.

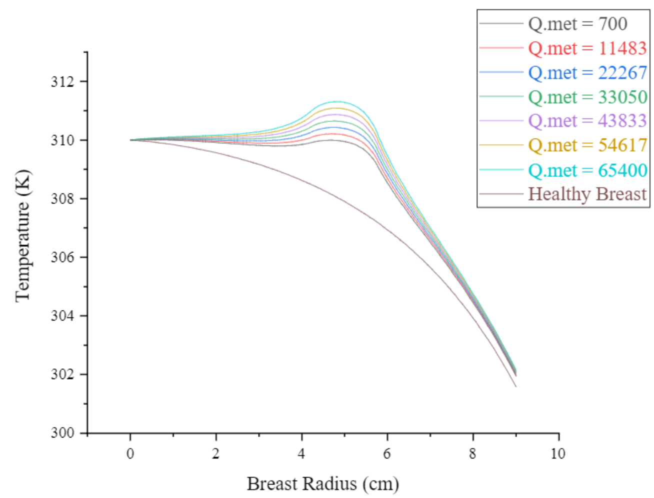

Fig. 6. Temperature distribution with varied metabolic heat generation of the tumor with tumor radius of 0.75cm and h = 13.5 $\frac{W}{m^2\,K}$.

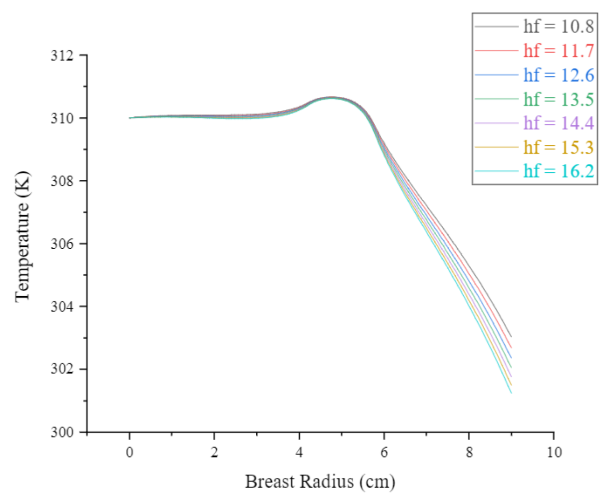

Fig. 7. Temperature distribution with varied heat transfer coefficient at the surface with tumor radius of 0.75 cm and tumor Q_m = 32600 $\frac{W}{m^3}$.

and the highest variation is about 3 K. This trend matches with the increase of higher heat generation regions owing to the growth of tumor radius. Besides, it also indicates that a moderately sensitive detector can be used to detect tumor size variation.

Fig. 6 demonstrates the tumor's response to the increased metabolic heat generation. The metabolic heat generation of the tumor is varied from 700 W/m^3 to 65400 W/m^3 with a step size of 16175 W/m^3. The temperature of the tumor-affected area rises as the tumor's metabolic heat output rises. This pattern can be explained by the tumor's metabolic heat generation increasing with each stage. However, for almost 93 times increase of heat generation is subjected to the highest 4 K variation of the temperature, demanding more sensitivity measure for the detector.

The effect of varied coefficient of heat transfer on the temperature profile is shown in Fig. 7. It has been shown that as the heat transfer coefficient increases, the temperature at the exposed breast surface decreases. This occurs due to loss of heat caused by increased convection and radiation to the external environment. For 2 times coefficient value increase, highest 2 K variation is found, demanding a moderate sensitive detector.

The insights from this study can be used to successfully implement thermography method for early tumor detection of people of varied age. As described in Fig. 1 and Fig. 7, this study explores the temperature profile of the affected area considering a wide range of heat transfer coefficient and heat generation values and proper correlation of these properties with patients' age and severity can be a useful way for setting guidelines for thermography method and determining the resolution of the detector. Besides, the effect of the testing room temperature on the derived result can also be understood and correlated from this study using the boundary condition of (2). Moreover, like the trend described in Fig. 5, this study is also helpful for setting multiple tumor detection scheme for thermography. Furthermore, integration of internet connectivity with the thermograph will allow remote monitoring and incorporation of thermal image processing will allow efficient and reliable detection which complies with the goals of healthcare 4.0, another aspects of industry 4.0

However, this study simplifies the heat transfer trend within the tumor tissue by some preliminary assumptions like homogenous breast tissue, thermal resistance free blood vessel, uniform density blood, etc. By suitable considerations of this criteria, this study can be implemented for a realistic 3D breast, which is the future goal of this study.

IV. Conclusion

The trend of the internal temperature profile of the human breast with the inclusion of a tumor is investigated in this study using Pennes' bio heat transfer equation for thermography application. A finite element numerical scheme is developed in COMSOL Multiphysics to solve the developed numerical model with suitable boundary conditions. The effects of tumor radius, tumor metabolic heat generation and heat transfer coefficient at the exposed breast surface are also demonstrated. It is found that the presence of a tumor raises the temperature of that region. The radius of the tumor, the internal metabolic heat production of the tumor, and the heat transfer coefficient all influence this tendency. With the increase of the radius of the tumor, the high temperature region is expanded. Furthermore, as tumor metabolic heat production rises, so does the temperature in the tumor affected area. When the heat transfer coefficient at the boundary is raised, however, the temperature at the surface drops dramatically. Variation of the temperature data can be utilized to assess patient condition and set the thermal detector resolution. With the help of the studied thermal mapping based on major thermal characteristics, this study could be useful in the early diagnosis of breast cancer and be implemented as a sustainable technology for the development of industry 4.0 in medical sector.

References

[1] N. Kosus, A. Kosus, M. Duran, S. Simavli, and N. Turhan, "Comparison of standard mammography with digital mammography and digital infrared thermal imaging for breast cancer screening," *J. Turkish Ger. Gynecol. Assoc.*, vol. 11, no. 3, pp. 152–157, 2010, doi: 10.5152/jtgga.2010.24.

[2] C. M. Sehgal, S. P. Weinstein, P. H. Arger, and E. F. Conant, "A review of breast ultrasound," *J. Mammary Gland Biol. Neoplasia*, vol. 11, no. 2, pp. 113–123, 2006, doi: 10.1007/s10911-006-9018-0.

[3] N. Consiglio, "MRI and Patient Safety," doi: 10.1016/S0820-5930(09)60130-4.

[4] N. Dey, A. S. Ashour, and A. S. Althoupety, "Thermal imaging in medical science," *Comput. Vis. Concepts, Methodol. Tools, Appl.*, pp. 1109–1132, Jan. 2018, doi: 10.4018/978-1-5225-5204-8.CH046.

[5] H. H. Pennes, "Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm," *https://doi.org/10.1152/jappl.1948.1.2.93*, vol. 1, no. 2, pp. 93–122, Aug. 1948, doi: 10.1152/JAPPL.1948.1.2.93.

[6] Z. S. Deng and J. Liu, "Analytical study on bioheat transfer problems with spatial or transient heating on skin surface or inside biological bodies," *J. Biomech. Eng.*, vol. 124, no. 6, pp. 638–649, 2002, doi: 10.1115/1.1516810.

[7] K. Yue, X. Zhang, and F. Yu, "Analytic solution of one-dimensional steady-state Pennes' bioheat transfer equation in cylindrical coordinates," *J. Therm. Sci.*, vol. 13, no. 3, pp. 255–258, 2004, doi: 10.1007/s11630-004-0039-y.

[8] M. R. Talaee and A. Kabiri, "Analytical solution of hyperbolic bioheat equation in spherical coordinates applied in radiofrequency heating," *J. Mech. Med. Biol.*, vol. 17, no. 4, pp. 1–14, 2017, doi: 10.1142/S0219519417500725.

[9] A. Ghanmi and I. A. Abbas, "An analytical study on the fractional transient heating within the skin tissue during the thermal therapy," *J. Therm. Biol.*, vol. 82, no. December 2018, pp. 229–233, 2019, doi: 10.1016/j.jtherbio.2019.04.003.

[10] E. H. Ooi, W. T. Ang, and E. Y. K. Ng, "Bioheat transfer in the human eye: A boundary element approach," *Eng. Anal. Bound. Elem.*, vol. 31, no. 6, pp. 494–500, 2007, doi: 10.1016/j.enganabound.2006.09.011.

[11] K. C. Liu and F. J. Tu, "Numerical Solution of Bioheat Transfer Problems with Transient Blood Temperature," *Int. J. Comput. Methods*, vol. 16, no. 4, pp. 1–12, 2019, doi: 10.1142/S0219876218430016.

[12] K. Balusu, S. S. Suganthi, and S. Ramakrishnan, "Modelling Bio-heat transfer in Breast Cysts using Finite Element analysis," *2014 Int. Conf. Informatics, Electron. Vision, ICIEV 2014*, pp. 1–4, 2014, doi: 10.1109/ICIEV.2014.6850842.

[13] H. M. Patil and R. Maniyeri, "Finite difference method based analysis of bio-heat transfer in human breast cyst," *Therm. Sci. Eng. Prog.*, vol. 10, no. January, pp. 42–47, 2019, doi: 10.1016/j.tsep.2019.01.009.

[14] "COMSOL - Software for Multiphysics Simulation." .

[15] A. A. A. Figueiredo, H. C. Fernandes, F. C. Malheiros, and G. Guimaraes, "Influence analysis of thermophysical properties on temperature profiles on the breast skin surface," *Int. Commun. Heat Mass Transf.*, vol. 111, 2020, doi: 10.1016/j.icheatmasstransfer.2019.104453.

[16] N. M. Sudharsan and E. Y. K. Ng, "Parametric optimization for tumour identification: Bioheat equation using ANOVA and the Taguchi method," *Proc. Inst. Mech. Eng. Part H J. Eng. Med.*, vol. 214, no. 5, pp. 505–512, 2000, doi: 10.1243/0954411001535534.