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NUMERICAL ANALYSIS OF TEMPERATURE FIELD ON A SURFACE OF A BREAST WITH A TUMOR

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Abstract. Breast cancer is the one with the highest incidence and mortality rates among women in the world. A breast tumor can be detected by techniques such as mammography, magnetic resonance imaging, ultrasound and tomography. However, none of these are capable of characterizing mammary inclusions alone, and a combination is necessary to achieve this. Improvement of equipment and software have made thermographic images increasingly used to aid in the diagnosis of breast cancer, as well as being a non-invasive procedure and giving the patient greater comfort during the examination. A disadvantage found in modeling thermographic examinations is the need to know the thermophysical properties of living tissues. Techniques based on the concept of thermal impedance are very promising since it is necessary only prior knowledge of the heat flux applied to the breast surface and the thermal behavior of this surface after the application of the heat flux. The modeling is performed through Green's Functions, and the solution of the temperature field is then analyzed in the frequency domain. In this work, the authors present a numerical analysis of the superficial thermal field of a 2D hemispherical geometry, after application of heat flow, for the cases with and without tumor in the breast. This procedure was made using COMSOL MULTIPHYSICS software. The study was carried out in two stages. In the first one, the behavior of the breast surface temperature field was evaluated through changes in the parameters: depth and tumor metabolic activity and convective heat transfer coefficient. In the second step, a factorial design was performed to evaluate the influence of depth and tumor metabolic activity on the field surface temperature domain. Results show the greater influence of the convective heat transfer coefficient, which tends to be dissipated over time, and also show that the tumor depth has a greater influence on the surface temperature than the metabolic activity.

Keywords: Breast Cancer, Bioheat Transfer, Green's Functions, Tumor Metabolic Activity, Tumor Depth.

NOMENCLATURE

c	Specific heat of human tissue, $Jkg^{-1}K^{-1}$
c_s	Specific heat of tumor, $Jkg^{-1}K^{-1}$
d	Tumor diameter, mm
$h, h_{1\ldots3}$	Convective heat transfer coefficient, $Wm^{-2}K^{-1}$
$H_{1\ldots3}$	Transfer functions
k	Thermal conductivity, $Wm^{-1}K^{-1}$
Q_m	Human tissue metabolic activity, kWm^{-3}
Q_p	Tumor Metabolic activity, kWm^{-3}
r	Breast radius, mm
t, t^*	Time, s
T_a	Temperature of the physical domain, ºC

T_∞ Temperature of ambient, ºC

x, y, z   Cartesian coordinates

Y   Tumor depth, mm

Greek symbols

α Thermal diffusivity, m^2s^{-1}

γ Arc length of prescribed heat flux, $rads^{-1}$

θ Temperature, ºC

ρ Density of human tissue, kgm^{-3}

ρ_s Density of tumor, kgm^{-3}

τ Time, s

1. INTRODUCTION

Cancer is a term used for a group of disorders associated with abnormal cell growth. These abnormal cells have the potential to spread to other parts of the body (Gonzalez-Hernandez et al., 2019). Breast cancer is the type of cancer that has the highest frequency of diagnoses among women in the vast majority of countries and is also the main reason for cancer death among women (Bray et al., 2018). According to Kandlikar et al. (2017), breast cancer can originate anywhere in the breast, where more than 20 types of cancer can be identified, with ductal carcinoma and lobular carcinoma being the most common types.

Figueiredo et al. (2018) developed a new technique capable of identifying the coordinates of the geometric center of a tumor present internally in a breast using only surface temperature measurements acquired by an infrared camera. The technique is based on the use of correlations, dimensionless solutions of the temperature field in the breast and definitions of variables that do not require knowledge of the thermal properties and the metabolism of the tissue.

There are a variety of techniques available to detect breast cancer such as mammography, MRI and ultrasound. However, the sensitivities and specificities of these techniques are not so high, especially in breasts with dense tissue. Breast infrared thermography is an adjunct screening technique that has been associated with the detection of early signs of breast cancer. However, their success was limited. In this context, Gonzalez-Hernandez et al. (2019) comment on the importance of Dynamic Infrared Thermography, as it is a technique capable of improving the detection of breast cancer and reduce false positive and false negative rates.

A new method proposed by Menegaz and Guimarães (2019) consisted of an analogy between thermal systems and dynamic systems for the detection of inclusions, changing the impedance of these systems. The proposed procedure was validated experimentally in hyperplastic materials with simple geometry. The thermal impedance method showed sensitivity for small inclusion sizes, demonstrating the ability to detect early breast tumors.

This work aims at numerically analyzing the thermal behavior of a hemispherical geometry, similar to a breast, comparing the values of temperature surface for cases with and without tumor, in addition to evaluating how these parameters are affected with the position, metabolic generation and tumor blood perfusion in addition to the convection coefficient used in the simulation.

2. MATHEMATICAL MODEL

Pennes (1948) proposes a mathematical expression, as known as Bioheat Transfer Equation, which represents the energetic balance within the living biological tissues through the interaction of blood perfusion and metabolism. Menegaz and Guimarães (2019) defined thermal impedance considering an equivalent thermal system translated by the solution of thermal problem due to application of thermal (external) excitation and the mechanisms of perfusion, metabolism and diffusion present in the tissue (healthy and morbid). The problem of bioheat transfer is represented by Eq. (1), with a variable change presented by Eq. (2). Boundary and initial conditions are presented by Eq. (3) - (7).

$$k\nabla^2\theta + w_s\rho_s c_s\theta + Q_m + Q_p = \rho c\frac{\partial\theta}{\partial t} \tag{1}$$

$$\theta(x, y = 0, z, 0) = T_a - T_\infty = \theta_a \tag{2}$$

$$k\frac{\partial\theta}{\partial x}\bigg|_{x=0} = -h_1\theta; \ k\frac{\partial\theta}{\partial x}\bigg|_{x=a} = h_2\theta \tag{3}$$

$$k\frac{\partial\theta}{\partial y}\bigg|_{y=0} = q_O(t); \ k\frac{\partial\theta}{\partial y}\bigg|_{y=b} = -h_3\theta \tag{4}$$

$$-k\frac{\partial \theta}{\partial z}\bigg|_{z=0} = -h_5\theta \tag{5}$$

$$-k\frac{\partial \theta}{\partial z}\bigg|_{z=v} = -h_6\theta \tag{6}$$

$$\theta(x,y,z,0) = \theta_a \tag{7}$$

This problem can be solved in terms of Green's Functions, applying transfer functions method presented in Fernandes et al (2015). The temperature field solution of this bioheat transfer is given by Eq. (8).

$$W(x,y,z,t) = W_0 + \frac{\alpha}{k}\int_0^t \int_0^a \int_0^b \int_0^v H_1(t-\tau)[Q_m(\tau) + Q_p(\tau)] \times e^{\left(\frac{\omega_s \rho_s c_s}{k}\right)^2 \alpha\tau} dx'dy'dz'd\tau +$$

$$+\frac{\alpha}{k}\int_0^t \int_0^a \int_0^b H_2(t-\tau)q_O(\tau) \times e^{\left(\frac{\omega_s \rho_s c_s}{k}\right)^2 \alpha\tau} dx'dz'd\tau + \alpha \int_0^t \int_0^a \int_0^b H_3(t-\tau)\theta_a \times e^{\left(\frac{\omega_s \rho_s c_s}{k}\right)^2 \alpha\tau} dx'dy'dz'd\tau \tag{8}$$

3. METHODS

The geometry adopted in the numerical study was of the hemispherical type, due to the shape similar to that of a female breast. The radius adopted was d = 72 mm, according to the analysis mentioned in Gonzalez-Hernandez et al (2019). Tumor diameter was d = 10 mm, admitted as constant. This measure of d was also adopted in Menegaz and Guimarães (2019). Thermophysical properties used were those cited in Figueiredo et al (2018), except for the value of the metabolic activity rate of the tumor, whose value was used according to Gonzalez-Hernandez et al. (2019).

Numerical study of this work comprises two steps:

1) An analysis of the influence that the parameters h, Q_p, Y and *mesh refinement* exerted at a determined point of the surface of the breast, in a determined interval of time. Eleven simulations were performed, whose parameters adopted in each of them are listed in Tab. 1.

2) In the second step, a 3^n factorial design was performed, with n = 2, to evaluate which parameter, between Q_p and Y, would have the greatest influence on the temperature at a determined point on the surface of the breast. Levels adopted for each variable were Q_p = [20 45 70] kWm^{-3} and Y = [32 42 52] mm.

Table 1. Parameters and thermophysical properties for numerical analysis (step 1).

Simulation	h (Wm^{-2}K^{-1})	Q_p (kWm^{-3})	Y (mm)	Number of elements in the mesh
1	5	70	-	856
2	10	70	-	856
3	5	70	32	856
4	10	70	32	856
5	10	70	42	856
6	10	70	52	856
7	10	45	32	856
8	10	20	32	856
9	10	70	32	1302
10	10	70	32	11084

The physical system is depicted in Fig. 1a. At t = 0 s, the breast temperature is 37° C. Throughout the hemispherical curvature a type 3 boundary condition was considered, with h = 10 Wm^{-2}K^{-1} and T_∞ = 20 °C. At the base of the geometry, a temperature of 37 °C was imposed. Time variable t* is then defined. The instant t* = 0 s is adopted as the instant at which the physical system reaches the permanent regime. At this time, a periodic heat flux (Fig. 1b) is imposed for a time of 1023 s in the region indicated in Fig. 1a, whose arc length is $\gamma = \pi/3$ rad. In this region, therefore, from t* = 0 s, we have a type 2 boundary condition.
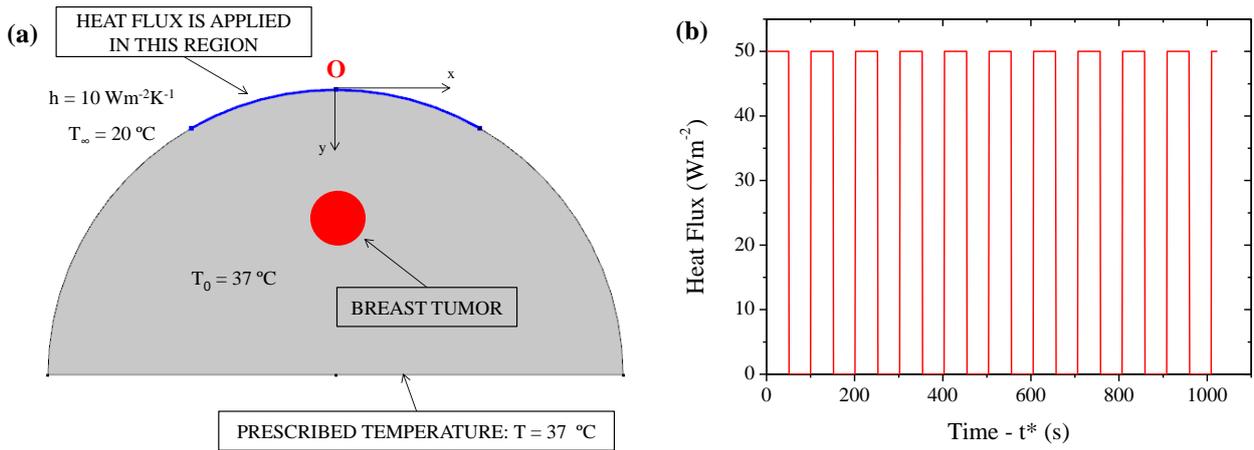
Figure 1. (a) Physical System; (b) Heat Flow.

4. RESULTS

Figures 2a - 2b shows 2D temperature field of the breast at time t* = 0 s, and Figs. 2c - 2d shows 2D temperature field of the breast at time t* = 1023 s. These simulations were performed in COMSOL MULTIPHYSICS software.
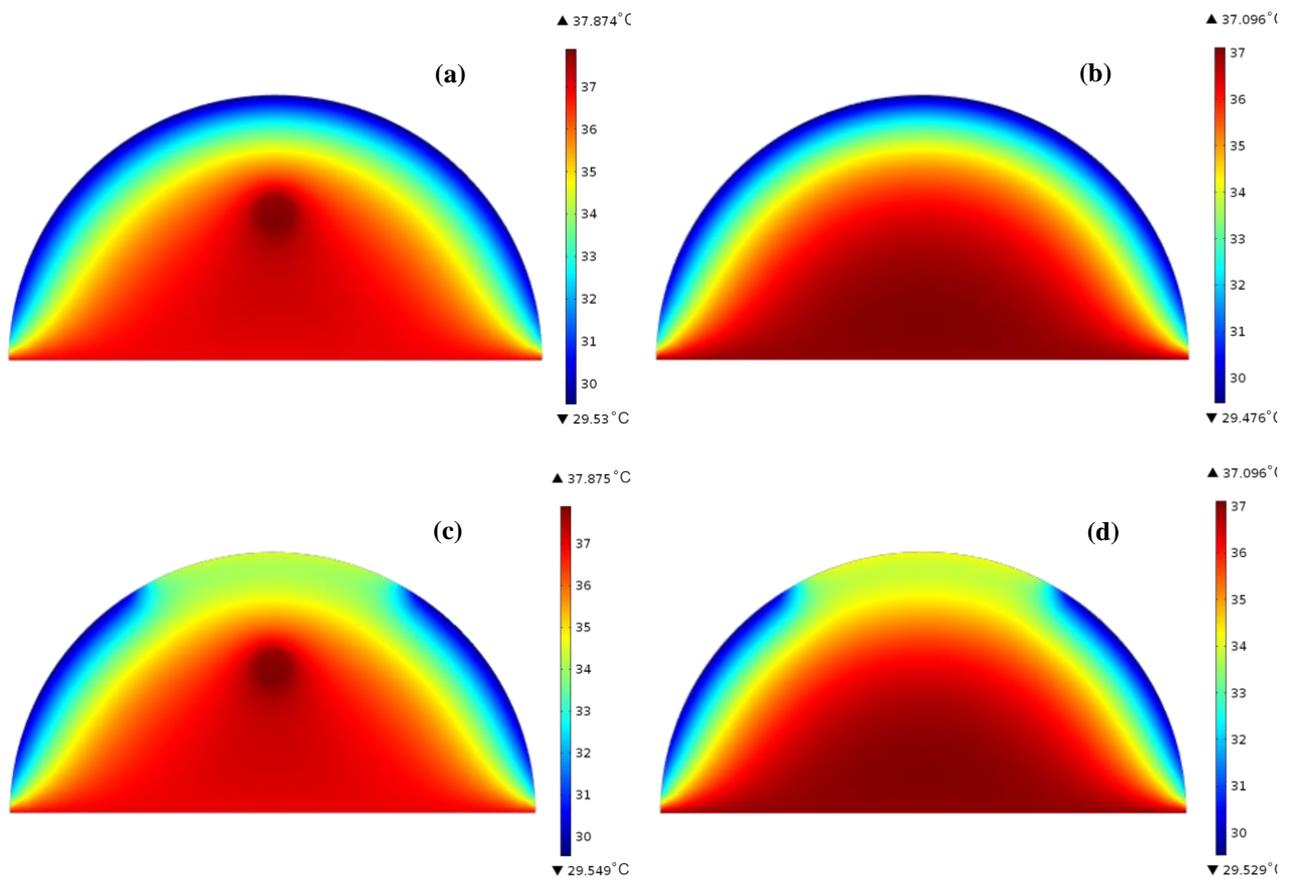

Figure 2. Steady-state - (a) With and (b) without a tumor; Breast after heat flow - (c) with and (d) without a tumor.

Figure 3 shows the temperature evolution at O point for 3 distinct values of tumor metabolic activity, in addition to the case without tumor. The following were considered: h = 10 Wm^{-2}K^{-1} and Y = 32 mm. It can be seen that the case with the highest value of Q_p has the highest temperature value at t* = 1023 s. However, there is only a slight percentage difference in temperature between this case and the others, including the case where there is no tumor, whose difference was 0.53 %.

Figure 4 shows the increase in temperature at O point with increasing t*, for three different tumor depths and the case without tumor. We considered h = 10 Wm⁻²K⁻¹ and Q_p = 70 kWm⁻³. It can be seen that the temperatures of the case with lower tumor depth are more evident. The curves of greater depth of tumor and that of the case without tumor are visually coincident, with a difference of 0.06 % for the values of temperature in t* = 1023 s.
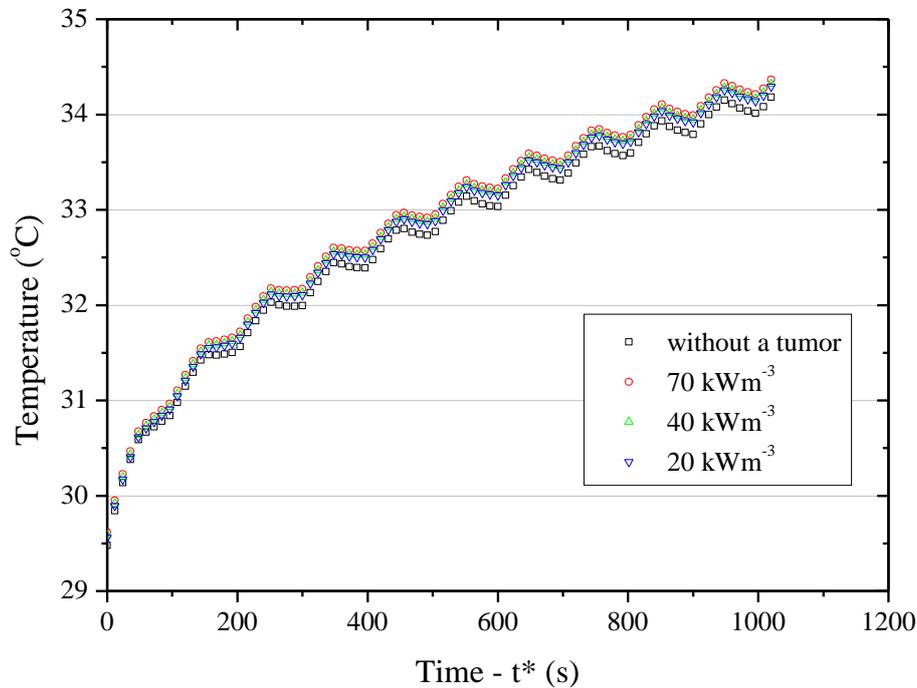

Figure 3. The temperature at O point for distinct values of tumor metabolic activity.
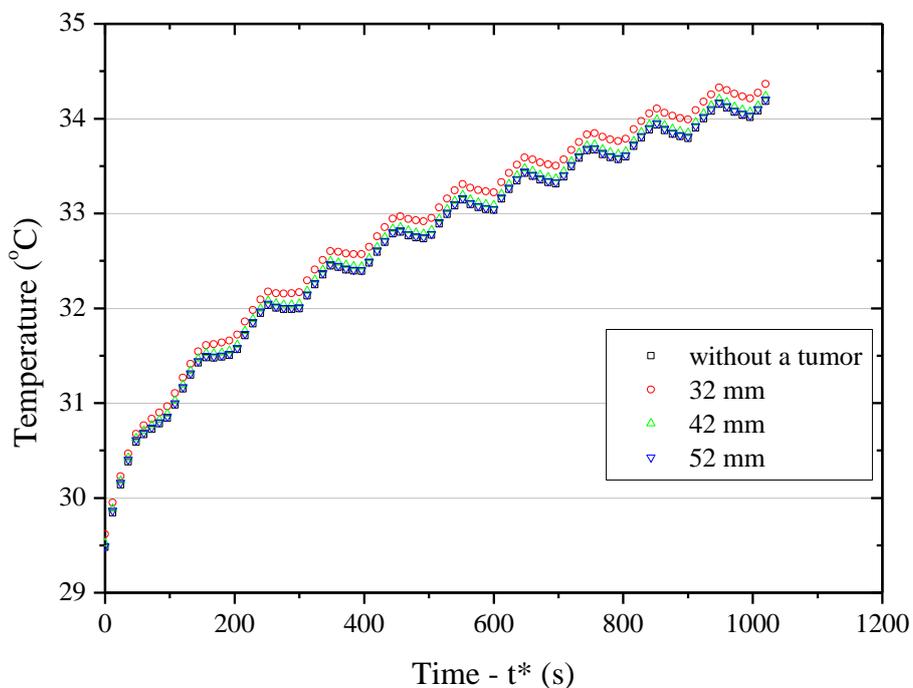

Figure 4. The temperature at O point for different tumor depths.

Figure 5 shows the influence of the convective coefficient in temperature at O point. Four cases were evaluated: a) without a tumor, h = 10Wm⁻²K⁻¹, b) Y = 32 mm, Q_p = 70 kWm⁻³ and h = 5 Wm⁻²K⁻¹; c) Y = 32 mm, Q_p = 70 kWm⁻³ and h = 10 Wm⁻²K⁻¹; d) without a tumor, h = 5 Wm⁻²K⁻¹. The strong influence that h exerts on the temperature value, especially at the initial instants, is thus perceived. However, with increasing time the influence of h tends to decrease because the

condition of imposed heat flux begins to prevail over the condition of heat convection. Moreover, the perturbation of the temperature at the O point, caused by the presence of the tumor, tends to increase with the increase of t*.

Figure 6 shows a mesh convergence analysis with three distinct quantities of elements that compose the domain of the simulation. It was considered: $h = 10$ $Wm^{-2}K^{-1}$ and $Y = 32$ mm. It can be seen that the curves are visually superimposed, justifying the use of smaller mesh refinement, aiming at a shorter computational time
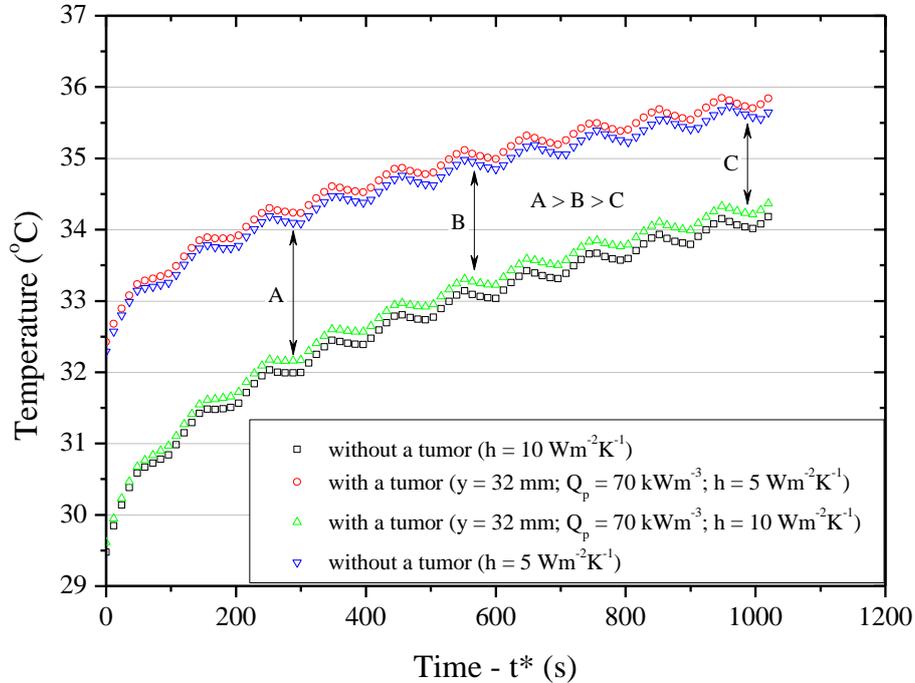

Figure 5. Influence of convective heat transfer coefficient in temperature at O point.
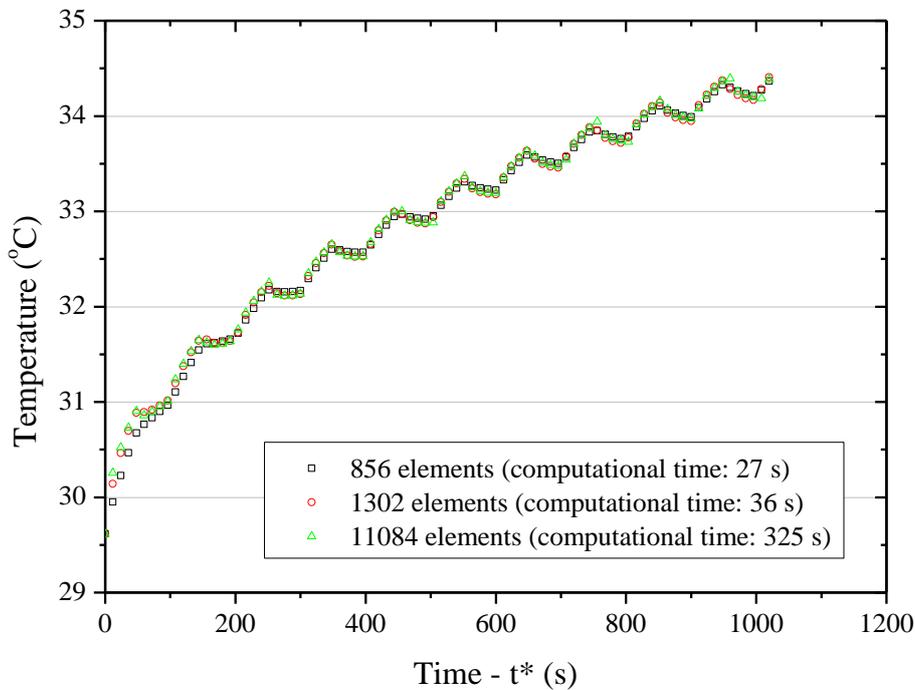

Figure 6. Mesh convergence analysis.

Figure 7 presents a 3^n factorial design, result achieved in numerical analysis. Was considered $h = 10$ $Wm^{-2}K^{-1}$. It is observed that the depth of the tumor exerts a greater influence on the temperature of the O point than the metabolic activity

since small variations of Y for the same value of Q_p can cause greater percentage variations of temperature about the O point.
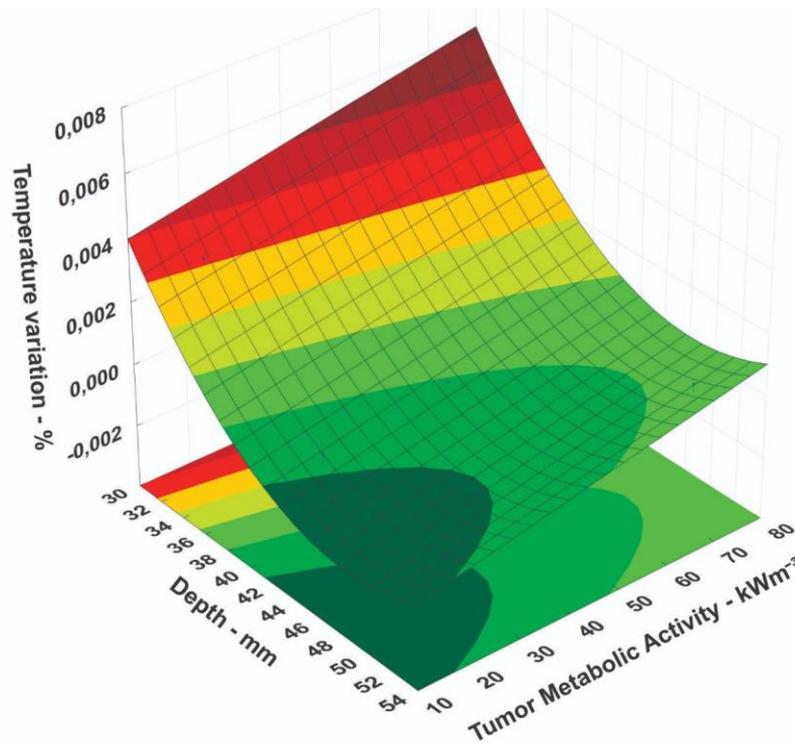

Figure 7. The influence exerted by the depth and tumor metabolic activity on the surface temperature of the breast.

5. CONCLUSIONS

This work aimed to perform a numerical study of the temperature at a certain superficial point of a breast, in cases with and without a tumor, using the COMSOL MULTIPHYSICS software. In the case with tumor, the influence of the parameters Q_p, Y and h, besides the influence of mesh refinement, was investigated in the temperature domain of the physical domain under study. The methodology used consisted of two steps: in the first step, eleven simulations were performed, with pre-determined values of the parameters; in the second step, a 3^n factorial design was carried out to evaluate which parameter, between Q_p and Y, would have a greater influence on the surface temperature field. Results showed a strong influence of h at initial instants, which tends to be dissipated over time, due to the greater influences of the prescribed flow condition and the presence of the tumor in the temperature field than the convection boundary condition. Another important result, obtained through the factorial design, is that the depth of the tumor exerts greater inflation in the surface temperature field than its metabolic activity. For future works, the authors suggest new analyzes, this time considering the tumor diameter as variable, besides the consideration of skin layers in the physical domain.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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