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NUMERICAL STUDY OF THE INFLUENCE OF DEPTH IN THE DETECTION OF BREAST TUMORS BY THERMAL IMPEDANCE

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Abstract. *Cancer is the term used to describe different types of diseases in which the abnormal growth of cells with invasive potential occurs. Breast cancer is one of the main causes of death for women worldwide, being the second type that most affects women in Brazil. Early detection of breast cancer is essential for reducing mortality. In this work, the finite element method was used to study the detection of 5 and 10 mm diameter tumors in a model with equivalent geometry and properties to the human breast using the thermal impedance method. This method consists of ratio between the variation of the surface temperature according to the application of an external heat flux. The detection of inclusions becomes possible due to the calculations of the damage metrics that are statistical parameters capable of numerically represent the different measurements, without and with the presence of the tumor. Tumors of 5 mm and 10 mm in diameter were positioned at three different depths of the breast. Thermal impedances in these conditions were calculated and damage metrics were obtained. Under the conditions considered in the numerical models analyzed, tumors were detected in all depths of the cases analyzed by the thermal impedance method.*

Keywords: *Thermal impedance, Detection, Breast tumor, Finite element method*

1. INTRODUCTION

Cancer is the term used to describe more than 100 different types of diseases in which growth occurs disorder of abnormal cells with invasive potential. Several factors can act together or in sequence to promote these diseases. Considered multifactorial, breast cancer involves biological, endocrine factors, life reproductive, behavior and lifestyle (INCA, 2015). It is considered a public health problem throughout the world, being the second leading cause of death in the United States and Europe, behind only heart disease (Statisctics, 2017). The International Agency for Research on Cancer (IARC) estimated that in 2018 there were 85,620 new cases of breast cancer in Brazilian women and that over the years the number tends to increase to 90,225, and in 2040 it can reach up to 133,118 women.

There are several diagnostic techniques that are used to detect breast cancer. Mammography is seen as the main exam for early detection and diagnosis of breast cancer. Infrared thermography, capable of capturing temperature changes on the skin surface, has also been explored as a possible screening tool for the detection of breast tumors. Tumor tissue has greater vascularity and metabolic generation than tissue healthy, so the heat produced by the tumor can propagate through the tissues to the skin surface, where it generates a variation in the temperature pattern. Early detection of breast cancer can significantly reduce rates of mortality caused by the disease. Therefore, there is a need to develop new methods of detection breast cancer that make it possible to detect abnormalities in a non-invasive way, without causing discomfort to the patient and without radiation emission (Menegaz et al., 2019).

Thermal impedance has been used to identify thermal properties, such as specific heat, diffusivity and thermal conductivity. However, in the work of Menegaz and Guimarães (2019), the impedance method was proposed for the detection of inclusions in models, making an analogy to the detection of damages from the electromechanical impedance method. Computer simulations using the Finite Element Method (FEM) allow the increase of the data processing capacity and can assist in numerical modeling of geometries complex and with varied thermal and mechanical properties.

In this work, it is proposed to develop the study of thermal impedance in the detection of tumors in a tridimensional model of the breast, from simulations by the finite element method. External heating will be applied to the surface of the model and the tumor will be positioned at three different depths, varying the tumor diameter from 5 mm to 10 mm, enabling the assessment of the influence of these parameters on detection. The thermal impedance values are calculated from the external fluxes and temperatures obtained in the surface of the models. Thermal impedance signatures are plotted and the quantitative analysis of the detection is given by the statistical calculation made by the damage metrics.

2. THEORETICAL FOUNDATION

Human tissue cells, healthy or unhealthy, are physical structures with mass, stiffness and damping, thus can be represented as a dynamic system. Therefore, it is possible to establish an equivalent thermal system of the tissue. Heat transfer occurs in tissues through the generation of metabolic heat, perfusion, diffusion of heat and heat exchange with the environment. Thus, an analogy between thermal, electrical and mechanical systems can be established. The thermal impedance can be expressed as shown in Eq. (1) (Menegaz and Guimarães, 2019, Menegaz et al., 2019).

$$z_t = \frac{\Delta V(\omega)}{I(\omega)} = \frac{\Delta T(\omega)}{q_0(\omega)} = \frac{T_{y=0}(\omega) - T_a(\omega)}{q_0(\omega)} \tag{1}$$

The parameter $q_0(\omega)$ is the thermal excitation represented by the heat flux imposed on the surface, $T(\omega)$ is the response to this flow measured at the system surface temperature, the variable ω represents the domain of the frequency function obtained in the application of the Fourier transform to the time signals of $\Delta T(t)$ and $q(t)$ is measured by heat and temperature transducers. Since the thermal system is a function of thermal properties, perfusion and metabolism, the thermal impedance must also assume different values if the medium has inclusions with thermal properties or if the internal heat generation is the different from the environment.

The impedance signatures provide only qualitative information about the structural integrity and, to quantify the difference between one reference signal and another, the so-called damaged metrics are used (Raju, 1997). In this work, the damage metric is known as RMSD (Mean Square Root Deviation), described by Eq. (2), was used.

$$RMSD = \sqrt{\sum_{i=1}^{n} \frac{[\mathrm{Re}(Z_{1,i}) - \mathrm{Re}(Z_{2,i})]}{n}} \tag{2}$$

Where, $\mathrm{Re}(Z_1,i)$ is the real part of the impedance of the undamaged measurement at a frequency i; $\mathrm{Re}(Z_2,i)$ is the real part of the impedance at a frequency i for a new configuration of the structure and n is the total number of frequency points used in the measurement. A reliable threshold level is determined based on the information obtained for the healthy condition of the structure, using the calculated value of damage metrics. The threshold was determined according to Eq. (3).

$$Z_{t\,Thereshold} = \mu_{Xmax} + 3\sigma_{Xmax} \tag{3}$$

Where μ_{Xmax} is the upper limit for the population mean and σ_{Xmax} is the upper limit for the population standard deviation, both obtained choosing a significance level α= 5%.

3. MATERIALS AND METHODS

3.1 Geometry of the numerical model

The three-dimensional geometry was composed of a model with similar geometry to the human right breast. This geometry was obtained by scanning, using the 3D laser scanner Picza® LPX-600RE, from a breast phantom (3B Scientific®), shown in Fig.1. The malignant tumor was simulated by a sphere, initially 5 mm and after 10 mm positioned in the upper right quadrant of the breast. That quadrant chosen was based on the statistics of the occurrence of breast cancer found in the literature, which points to the highest incidence of tumors in this quadrant, Fig. 2 (Aguillar et al., 2009). Figure 3 showsthe breast geometry in COMSOL® (finite element analysis software).

Thus, a simulation of a model without tumor was performed, simulating a healthy tissue, called baseline. The numerical simulation of a breast with a tumor was made in models with tumor of 5 mm and 10 mm of diameter, varying the depth. The tumor position varied in three depths measured from the model's surface: P1 - 30 mm, away from the surface; P2 - 20 mm, intermediate depth; and P3 - 10 mm, close to the model's surface.

Figure 1. Right breast phantom (3B Scientific®).

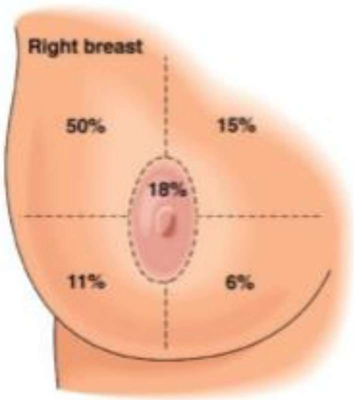


Figure 2. Breast quadrants with breast cancer occurrence percentage (Byer et al., 2002).

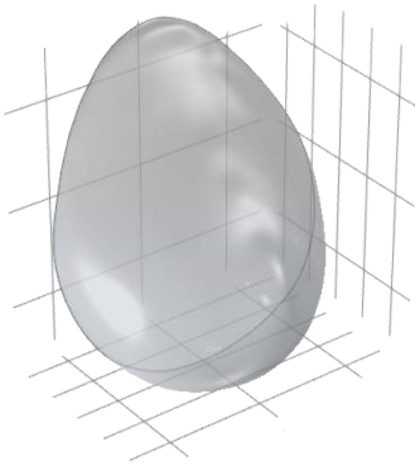
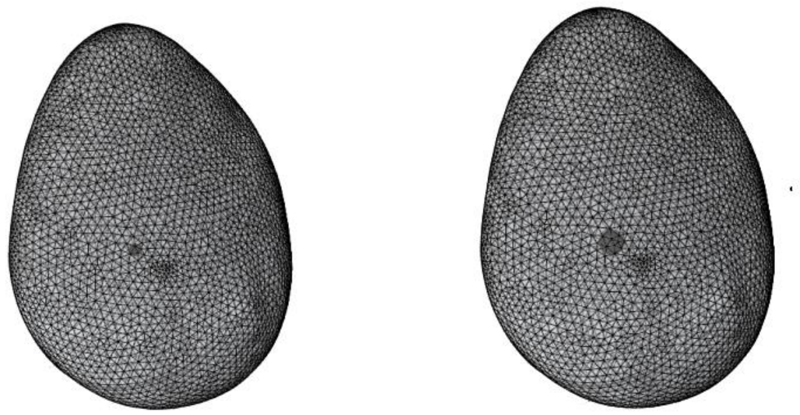


Figure 3. Three-dimensional breast geometry used in the simulations.

3.2 Mesh of the model

The mesh assigned to the model was obtained using the used-controlled mesh option, with the maximum element size 4 mm, minimum 3.07 E-5, maximum element growth rate of 1.3, curvature factor 0.2 and resolution of narrow regions equal to 1. The complete mesh for the 5 mm tumor test presented 167,315 domain elements, as shown in Fig. 4

(A). For the 10 mm tumor, the mesh showed 161,349 elements as shown in Fig. 4 (B). The number of elements and figures were obtained with the tumor in position 2 of the experiment.



(A) (B)

Figure 4. Finite element mesh model: (A) Tumor of 5 mm; (B) Tumor of 10 mm.

3.3 Thermal properties of the materials

Table 1 shows the thermal properties used in the numerical simulation.

Table 1. Material properties (Gautherie, 1980; Hossain and Mohammadi, 2016, Figueiredo, 2018).

Material properties	Healthy Tissue	Tumor
Thermal conductivity, k (W/mK)	0.21	0.62
Blood perfusion, ω [1/s]	0.00022	0.016
Specific heat, c [J/kgK]	3,000	3,000
Volumetric metabolic heat generation, Q_m [W/m³]	420	100,000
Specific mass, ρ [kg/m³]	920	920

3.4 Boundary Conditions

Boundary conditions vary in two stages. Initially, the steady state was simulated and then the transient state. In the steady state, four boundary conditions were considered. The first condition applied was the natural convection on the model's surface, considering the convection coefficient of 5 W/m²K and the temperature 25°C, representing the contact of the breast with the environment. The second condition considered was the temperature constant 37 °C applied to the bottom of the model, simulating the temperature of the human body. The third condition is an internal heat generation of 100,000 W/m³ applied to the tumor and a second heat generation of the breast tissue of 420 W/m³, representing tissue metabolism. This heat generation value is based on the thermophysical properties of biological tissues (Gautherie, 1980; Hossain and Mohammadi, 2016; Figueiredo, 2018).

The results of the simulation of the model in the steady state were used as initial conditions of the transient state. In addition to the boundary conditions previously considered in the steady state, a periodic heat flux was applied on the breast surface. The periodic heat flux consisted of applying 2 W every 60 s for 8 cycles. During the initial minute, the heat flux was not applied. Thus, the test was simulated with a total time of 540 s, alternating between cooling and heating. This test was performed with the 0.5 s step due to the complexity of the simulation. All models with the tumor were compared with the reference model, baseline, that simulates healthy breast, that is, without tumor.

In tests, the temperature and heat flux values were obtained at a point on the breast surface in the same quadrant where the tumor was positioned, as shown in Fig. 5.

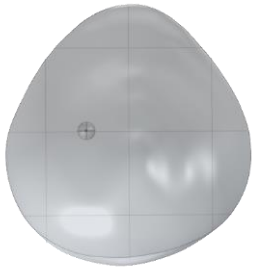
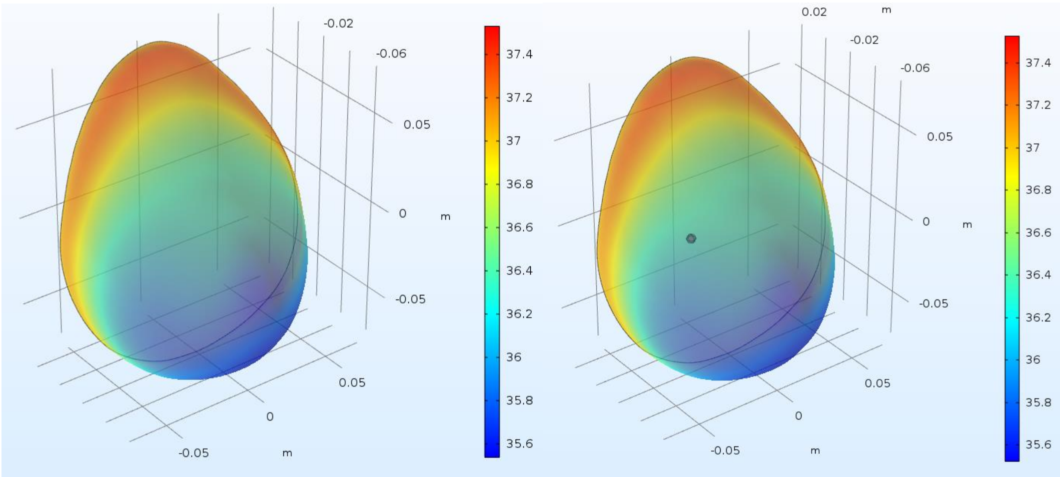


Figure 5. Point for acquiring temperature and heat flux data.

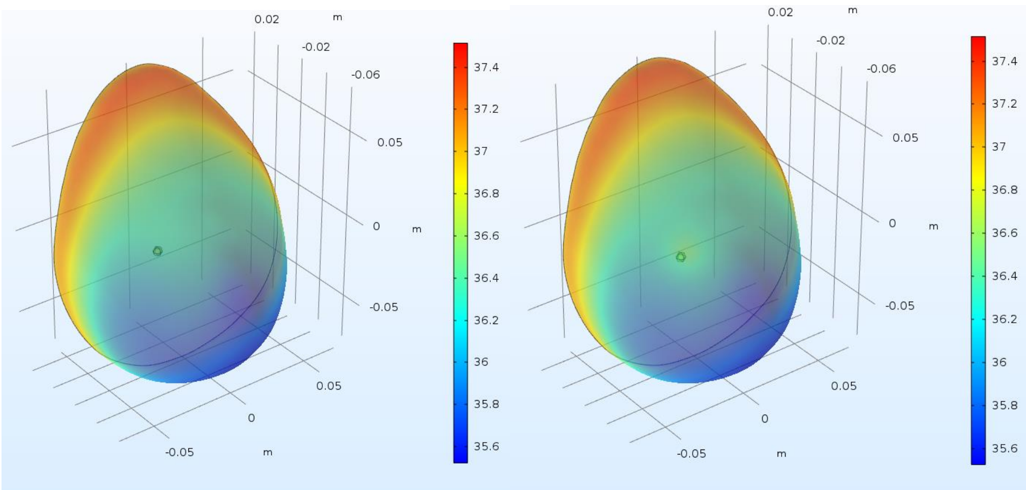
4. RESULTS

4.1 Model with 5 mm tumor

Figure 6 (A) shows the temperature distribution in the baseline model, with the highest temperatures in the region that simulates the union with the chest, which would be the bottom of the model. Figure 6 (B) shows the distribution of breast temperature with the 5 mm tumor in the first position (P1), that after the steady state had a maximum temperature of 34.25 °C and at the end of the transient regime the temperature reached 35.97 °C. Figure 6 (C) shows the temperature distribution of the model with the tumor in the second position (P2). In this case, a temperature was observed maximum of 34.28 °C after the permanent regime and 36.02 °C after the end of the simulation. Temperature distribution of the tumor with the third position (P3) is shown in Fig. 6 (D), in which the maximum temperature after the regimen temperature was 34.44 °C and in the simulation sequence a temperature of 36.21 °C was obtained.



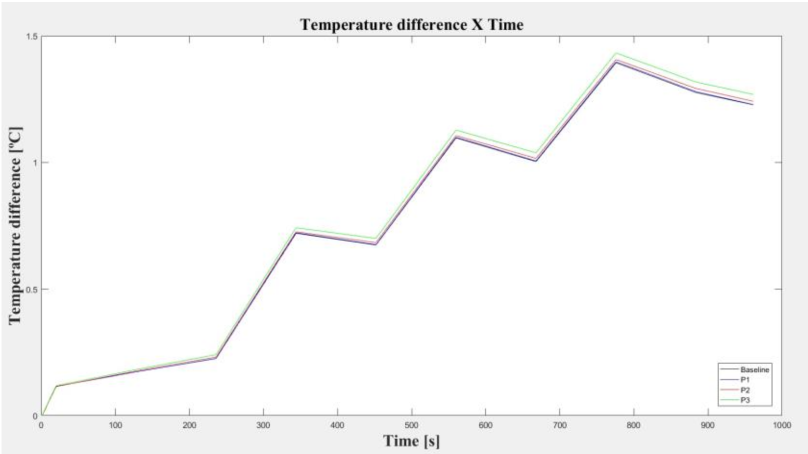
(A) (B)



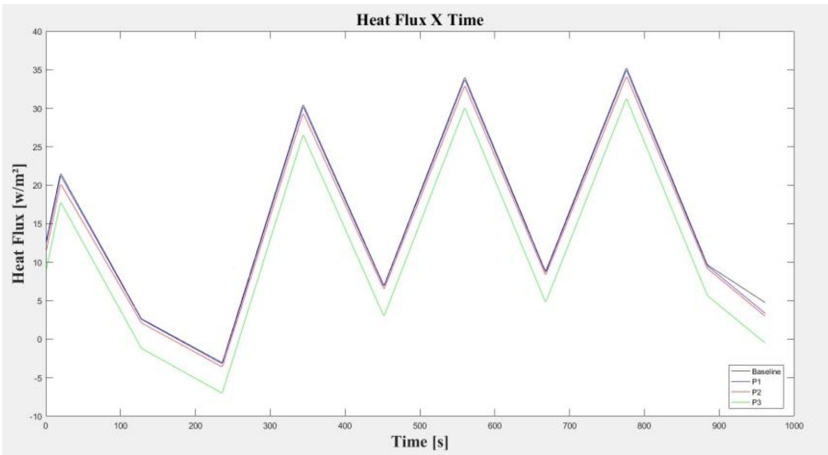
(C) (D)

Figure 6. Temperature distribution of models with a 5 mm tumor: (A) Baseline model; (B) Model with tumor in position P1; (C) Model with tumor in position P2; (D) Model with tumor in position P3.

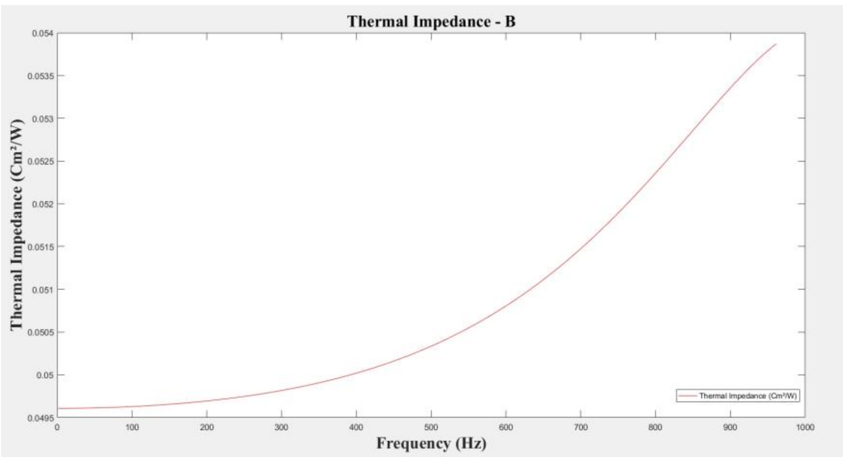
Figure 7 (A) shows the temperature difference varying over time for the four conditions. The graph of heat flux curves varying with time for each model are shown in Fig. 7 (B). After obtaining the flow of heat and temperature in each of the models the respective thermal impedances were calculated. Figure 7 (C) shows the graph of the impedance curve obtained for the model without tumor.



(A)



(B)



(C)

Figure 7. (A) Graph of temperature difference curves x time; (B) Graph of heat flow curves x time; (C) Graph of thermal impedance x frequency for the baseline model.

The thermal impedance curves qualitatively indicate variations in the system that has occurred due to presence of the tumor at different depths. However, calculating the RMSD damage metrics makes it possible to quantitative assessment of variations. Thus, it is possible to determine whether the tumor was detected for the simulated conditions using the thermal impedance technique methodology. The threshold value was presented, guaranteeing 95% of confidence in the probability of tumor detection. Results above the threshold indicate that the detection occurred with success. In cases where the results cross the threshold line, the results were considered inconclusive.

Figure 8 shows the result obtained for the metric RMSD and indicates that, under the conditions tested, the 5 mm tumor simulated in the breast was successfully detected using the thermal impedance technique for all the different positions of the tumor.

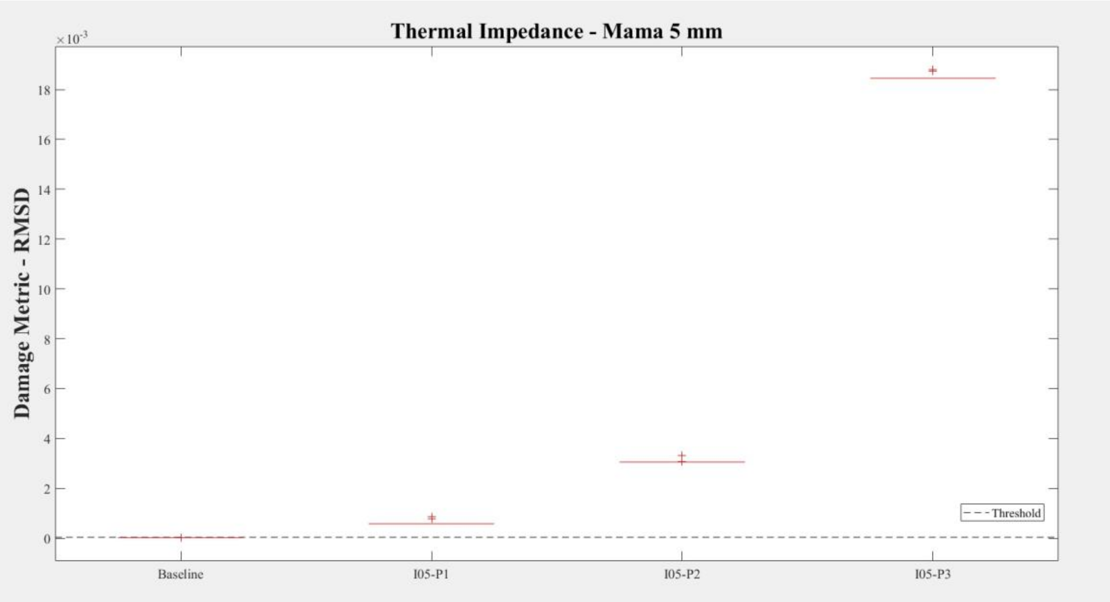
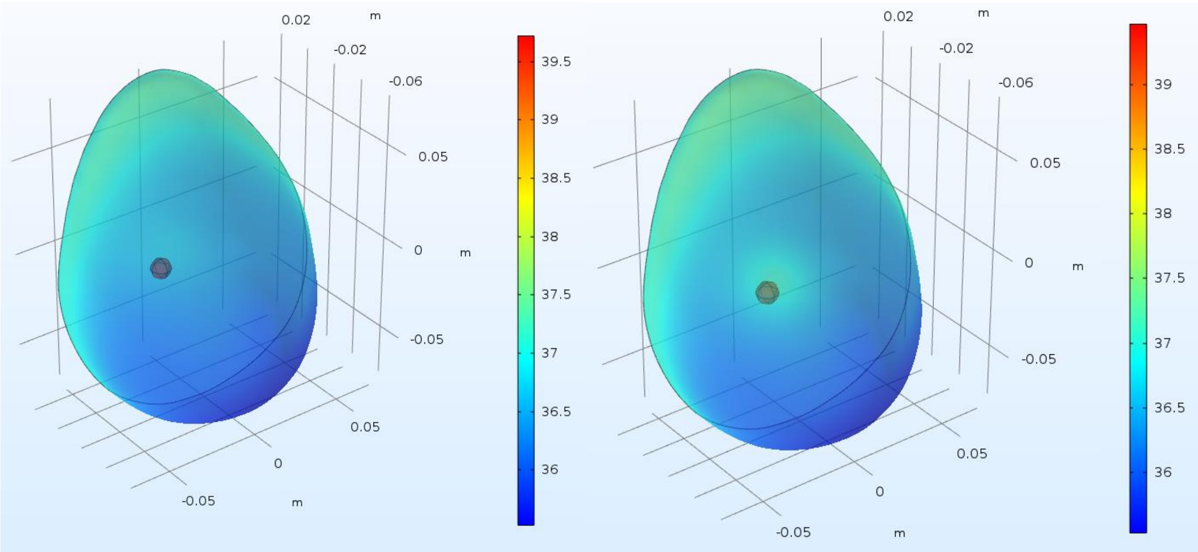


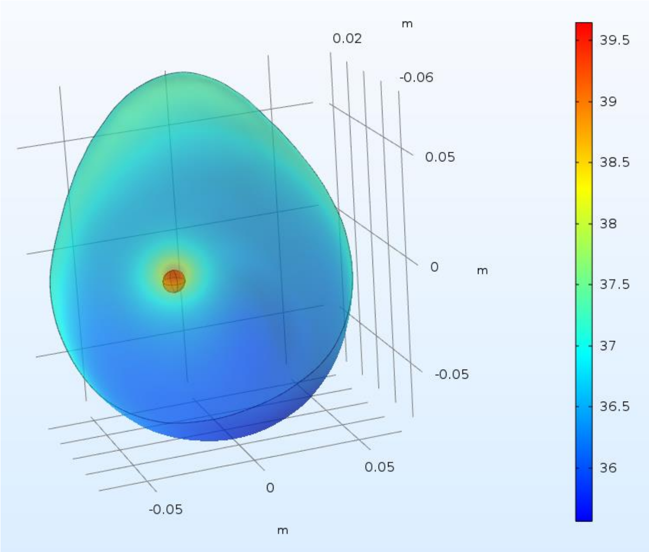
Figure 8. RMSD damage metric for the 5 mm diameter tumor model.

4.2 Model with 10 mm tumor

The baseline model used for comparison with the 10 mm tumor model is the same as the previous model. At distribution obtained with inclusion in the P1 position, temperatures vary from 34.37 °C at steady state and reach 36.13 °C at the end of the simulation, as shown in Fig. 9 (A). For the model with the inclusion in position P2 the temperature maximum of the model was 34.65 °C at the end of the first simulated stage and reached 36.51 °C, Fig. 9 (B). Figure 9 (C) shows the temperature distribution for the model with the tumor in the third position (P3), at the beginning of the transient state the temperature was 35.89 °C and at the end of the simulation 38.03 °C.



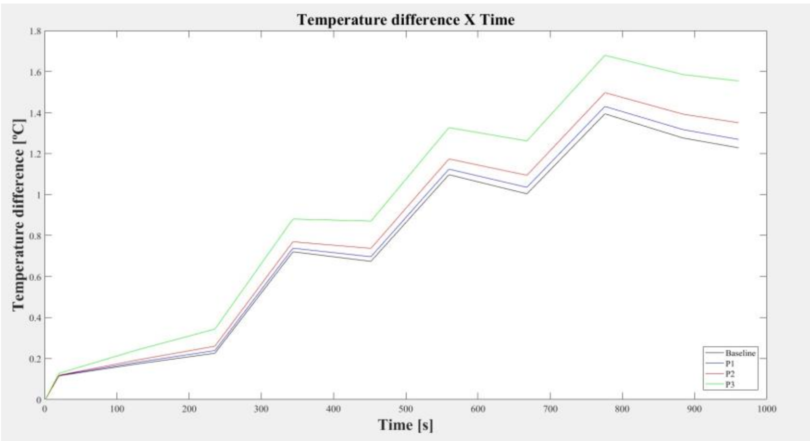
(A) (B)



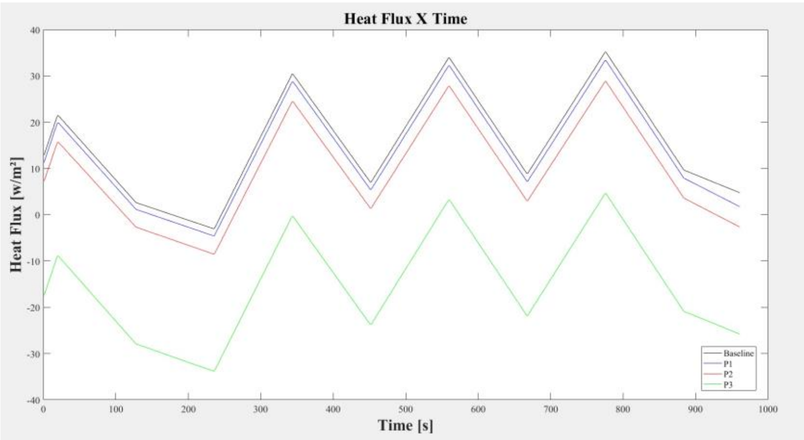
(C)

Figure 9. Temperature distribution of models with 10 mm tumor: (A) Model with tumor in position P1; (B) Model with tumor in position P2; (C) Model with tumor in position P3.

Figure 10 (A) shows the temperature evolution for all configurations. The evolution of heat flux related image is shown in Fig. 10 (B). After obtaining the heat flow and the temperature difference, the respective thermal impedance was calculated.



(A)



(B)

Figure 10. (A) Evolution of the temperature difference; (B) Evolution of the heat flux.

The damage metrics and threshold values were presented, guaranteeing 95% confidence in the probability of tumor detection. Figure 11 shows that for the inclusion of 10 mm the tumor was detected at the three depths simulated.

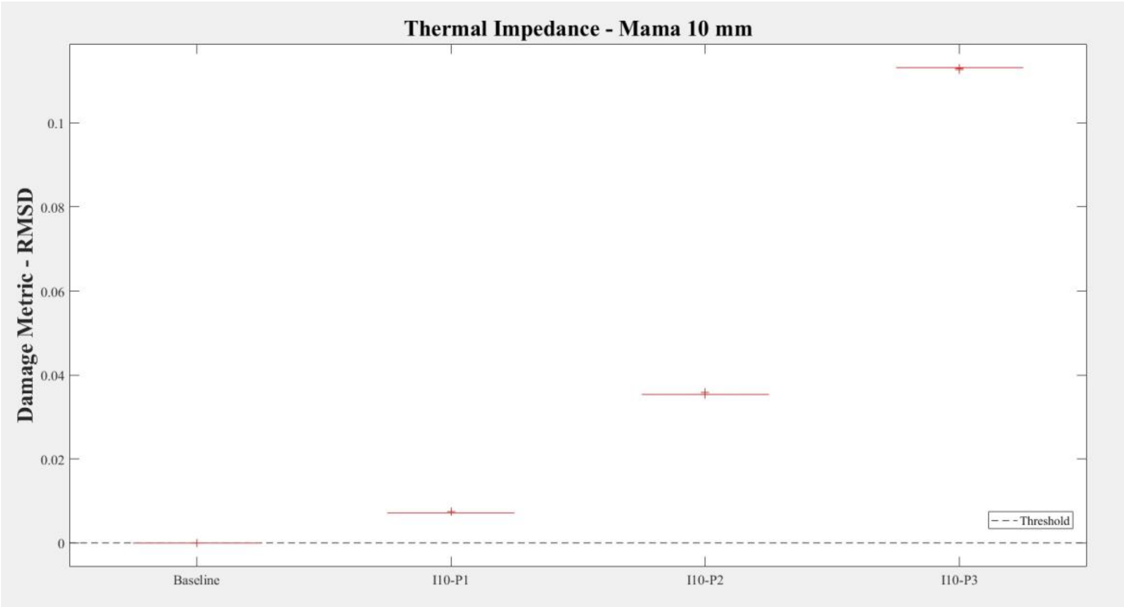


Figure 11. RMSD damage metric for the 10 mm diameter tumor model.

5. CONCLUSION

In this work, numerical simulations were made using the finite element method of healthy breast and breast models with the presence of a malignant tumor of 5 and 10 mm in diameter at different depths, in order to detect the tumor using the thermal impedance method. For this, a external heat flux was applied to the model's surface and the simulations obtained the temperature distributions and the resulting heat flux in the surface of the models, which made it possible to calculate the impedance and thereafter the damage metric.

It was observed that the models presented the expected thermal behavior and the thermal impedance signatures could be obtained. From the analysis of the damage metric, it was observed that the tumor of 5 mm and 10 mm was detected at the three depths tested, without influence of this parameter for its detection.

These results are part of studies with the finite element method to assist in the analysis involving the detection of tumors using the thermal impedance method. The research is being developed for the consolidation of the technique and its future use in living tissues, enabling the detection of tumors and other anomalies using a non-invasive technique, with no radiation emission and accessible to people with disabilities or low mobility.

6. ACKNOWLEDGEMENTS

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