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PARAMETRIC ANALYSIS OF HUMAN BREAST THERMAL RESPONSE AS AN AID FOR EARLY CANCER DIAGNOSIS

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Abstract. Breast cancer's lethality is associated with its stage. Early diagnosis is, therefore, essential to increase the chances of cure. One way to assess the tumors' existence and location, using a non-invasive and non-radioactive method, is by detecting metabolic alterations through thermography. A pre-existing study presents a simplified mathematical model to predict the human breast thermal response and a parametric analysis considering the aggressiveness, location and the amount of tumors. Infrared images are transformed into a 3D model of a breast, then smoothed and discretized using a cubic mash by the method of volume element model, which divides the domain to be studied into control volumes. Each element is represented by a system of equations, indicating the heat exchange by each unity. That way, it's possible to simulate the internal and the surface temperature distribution of the breast in order to locate precisely the tumor. The objective of this paper was the analysis of the mathematical model and software simulation aiming to find the model's possible limits, varying the location and size of the tumor. The model responded positively to the size variation, but not to the coordinate variation when simulated close to the chest wall.

Keywords: breast cancer,, thermography, three-dimensional modeling, Volume Element Method (VEM), model analysis.

1. INTRODUCTION

Analyzing the frequency of cancer among women, breast cancer is observed as the main one that leads to the large number of deaths among the female group. Since cancer is related to the abnormal development of breast cells that multiply repeatedly aggravating the individual's situation, it is important to emphasize that early diagnosis is essential, as is the use of screening methods that aim to reduce the large number of mortality among women.

One of these screening methods used today is thermography. It enables the temperature mapping of the surface of the breast. This mapping provides biological information, in a way that the warmest spots represent highly metabolic

tissues, thereby, showing lesions such as cancer and spots where angiogenesis is happening by observing through this method. Its efficiency is noted in cases of tumors in early stages. (ETEHADTAVAKOL et al.*,* 2013)

Among its benefits, it is notable that infrared medical thermography is a non-invasive and non-radioactive analysis instrument. Its functioning works by detecting the infrared light emitted by the body, making it possible to visualize changes in body temperature related to alterations in the blood flow. (CORTÊ et al., 2016).

A study by Dalmaso et al. (2021) presented a mathematical model capable of predicting the thermal response of a breast tumor based on physical laws and making use of mass, heat, and fluid flow empirical and theoretical correlations. Based on it, the current study aims to find the model's possible limits, simulating different size and location of the tumor in the breast.

2.   THEORETICAL BACKGROUND

2.1   Volume Elements Model

On the base mathematical model, the volume elements method was used, which consists in dividing a three dimensional model of the breast into cubic cells of finite volume, named control volumes (CV), that contain solid, fluid or both in their interior, considering the mixtures homogeneous.

To calculate the temperature of each element, it starts with obtaining the velocity field of the domain system through algebraic equations. Then, an ordinary differential equation (ODE) is derived with respect to time. In the temperature's case, the first law of thermodynamics (principle of conservation of energy) is used.   (DILAY et al., 2015).

A general volume element is represented in the figure 1 below. The transfer rates related to the time of heat or mass that it performs with neighboring elements are represented by $\dot{G}_{e},\ \dot{G}_{w},\ \dot{G}_{t},\ \dot{G}_{b},\ \dot{G}_{n},\ \dot{G}_{s}$, analyzed on the east, west, superior, inferior, north and south faces, respectively.
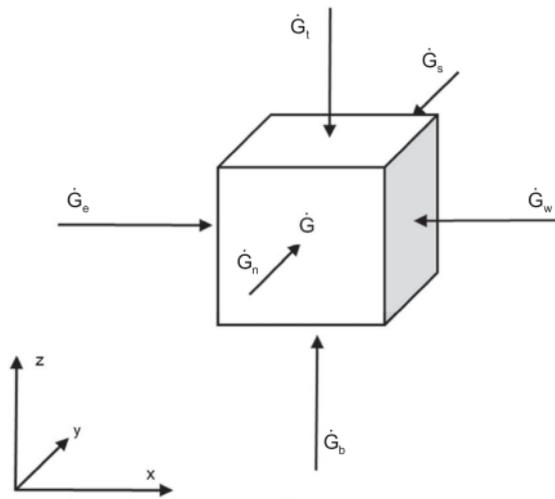

Figure 1. Representation of a generic volume element unit and its interactions.
From: Dilay et al., 2015.

In each volume control, conservation equations can be written for a generic field ϕ :

$$\frac{d(\rho V \phi)_i}{dt} = \sum_{j=e,\,w,\,t,\,b,\,n,\,s} \dot{G}_{j,i} + \dot{G}_i \tag{1}$$

where t = time; ρ = VC density, V = VC volume and $\dot{G}_{j,i}$ is divided into two contributions.

$$\dot{G}_{j,i} = \dot{G}_{adv,j,i} + \dot{G}_{dif,j,i} \tag{2}$$

With $\dot{G}_{adv,j,i}$ representing advective terms and $\dot{G}_{dif,j,i}$ representing diffusive terms, radiation included.

In the case of the human breast, constant volume and incompressible flow are assumed:

$$\frac{d(\rho V)_i}{dt} = 0 \tag{3}$$

Considering $\dot{m}_{e,j}$ e $\dot{m}_{s,j}$ the inlet and outlet mass flows respectively at wall j, the next relation is obtained:

$$0 = \sum_{j=e,\, w,\, t,\, b,\, n,\, s} \dot{m}_{e,j} - \dot{m}_{s,j} \tag{4}$$

The relation between the inflow and outflow, considering blood perfusion, is given by:

$$\dot{m}_{e,j} = \dot{m}_{s,j} = p_{ar}\, u_j A_j/2 \tag{5}$$

where p_{ar} = specific mass of the air, u_j = fluid velocity; A_j = the area of face j. This means that the mass flow inlet is considered, as well as the outlet, in half of the face.

As already mentioned, the phenomenon depends on the nature of the cell studied. In healthy cells, the mass flux is represented by $\dot{m}$. In the case of cancer cells, the mass flux is represented by $\dot{m}_t$.

The conservation law of energy for an element of any volume is given by:

$$\frac{dT_i}{dt} = \frac{1}{(\rho V c)_i} \sum_{j=e,\, w,\, t,\, b,\, n,\, s} (\dot{G}_j + \dot{G}_{ger}) \tag{6}$$

where T_i = VE temperature; c_j = heat transfer coefficient; $\dot{G}_j$ = heat transfer rate through the face j; $\dot{G}_{ger}$ = rate of heat generation in the EV.

From the heat released by ATP hydrolysis ($\Delta H = 47.32\ kJ/kg$), a relation is formed to calculate the rate of heat generation per unit volume, represented by $\dot{g}_{ger}$:

$$\dot{g}_{ger} = (K_{atp} \Delta H\, V) \tag{7}$$

The K_{atp} constant represents the mass consumption rate of ATP per unit volume, in $kg/s/m^3$ and can be calculated through the equation (7) above, using some initial parameters already known in the literature.

2.2 Breast properties

Lozano et al. (2020) quantified blood perfusion and the volume of distribution of healthy and for cancerous breast cells, as shown below in TABLE 1.

Table 1. Blood perfusion and distribution volume of healthy and carcinogenic breast cells.

Cell	Blood Perfusion [ml. g^{-1}.min^{-1}]	Distribution Volume [ml.g^{-1}]
Healthy	0.06	0.18
Carcinogenic	0.32	0.58

To represent the heat exchanges between the six walls of the volume element and the breast, the situation of the phenomenon must be considered, for example, if it occurs internally or externally and if it's being considered a healthy element or a tumoral one.

External interaction is considered when it happens between the Volume Element and the breast surface. On the other hand, the internal one refers to exchanges between the Volume Elements on their own. After classification, it's possible to obtain the correct thermic balance with the correspondent convection relations (external and internal), conduction (internal) and radiation (external).

The model was then adjusted and validated.

3. SIMULATIONS

In the original simulation, Dalmaso used real magnetic resonance and tomography images to develop a three-dimensional model of the human breast, the model generated by the Invesalius software is treated and smoothed by using the Meshmixer program, thereby making possible the discretization of the model through a cubic mesh of 60000 elements, by using the ray tracing process.

According to the developed mathematical model, a computer program was written in FORTRAN in order to obtain the thermal response of tumors on the surface of the human breast. The Runge-Kutta/Felhberg method was used to integrate in time the system of equations, finding the steady state solution to obtain the stationary temperatures at the center of each VE. Then, the Newton-Raphson method was used to solve the nonlinear system, linearized with respect to the unknown value at the center of the cell. (DALMASO, 2021). The output data are opened in a program called Visit, and ultimately, visualized in the three-dimensional model developed.

The model and the thermal response of a healthy breast, without tumor, and one simulated by Dalmaso with its geometric center coordinates (0.04, 0.04, 0.04), and dimensions 0.001m are presented below in figures 2 and 3 respectively:
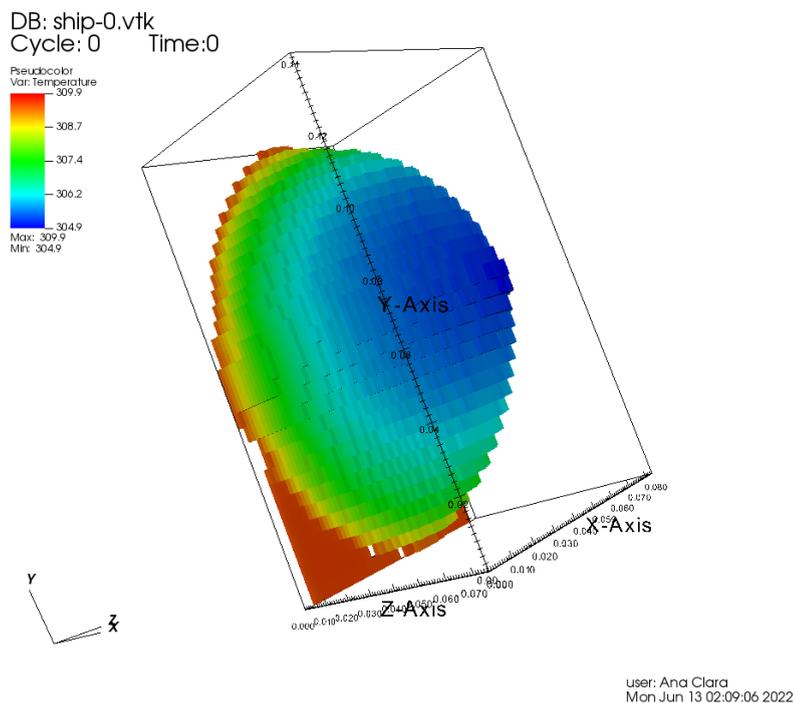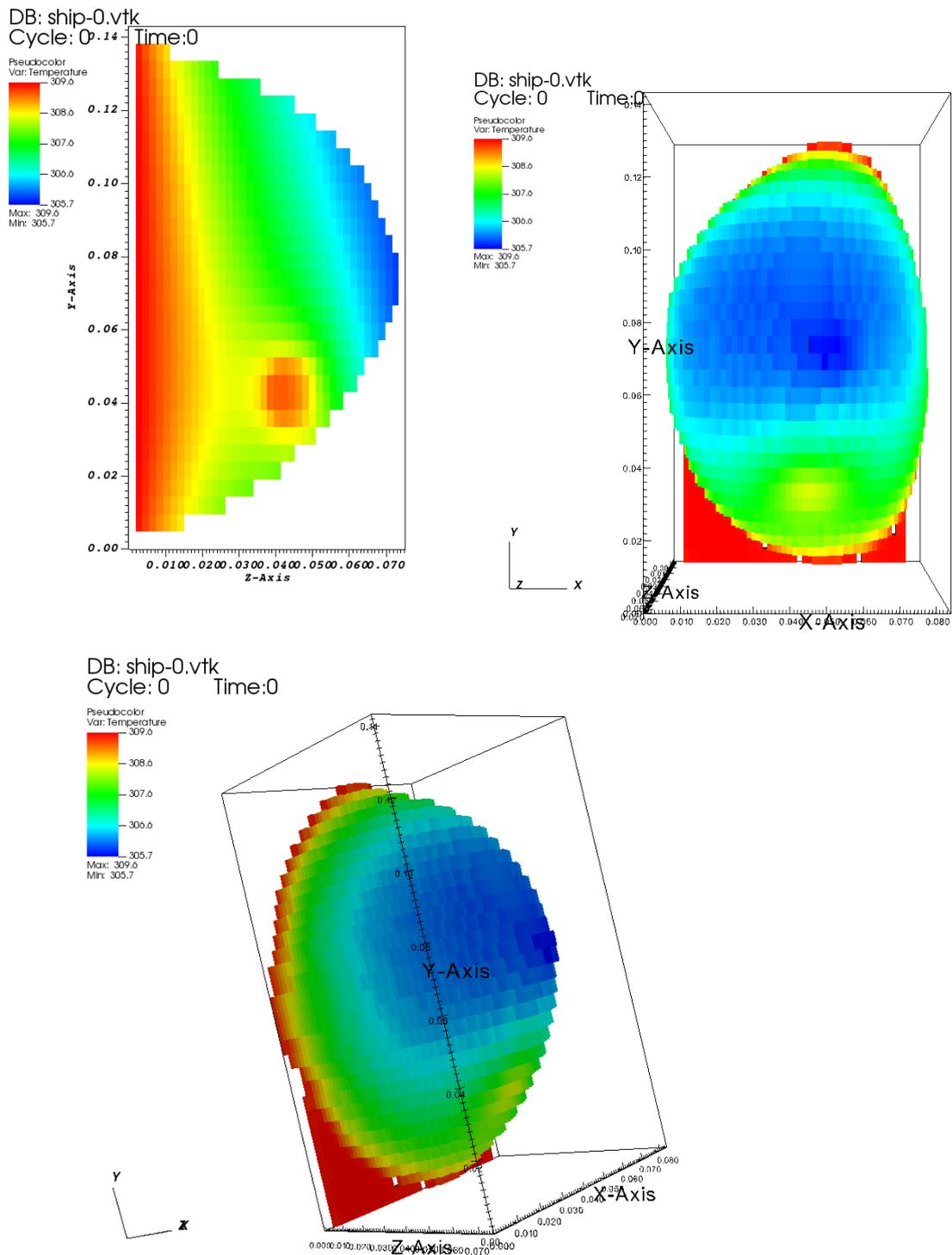

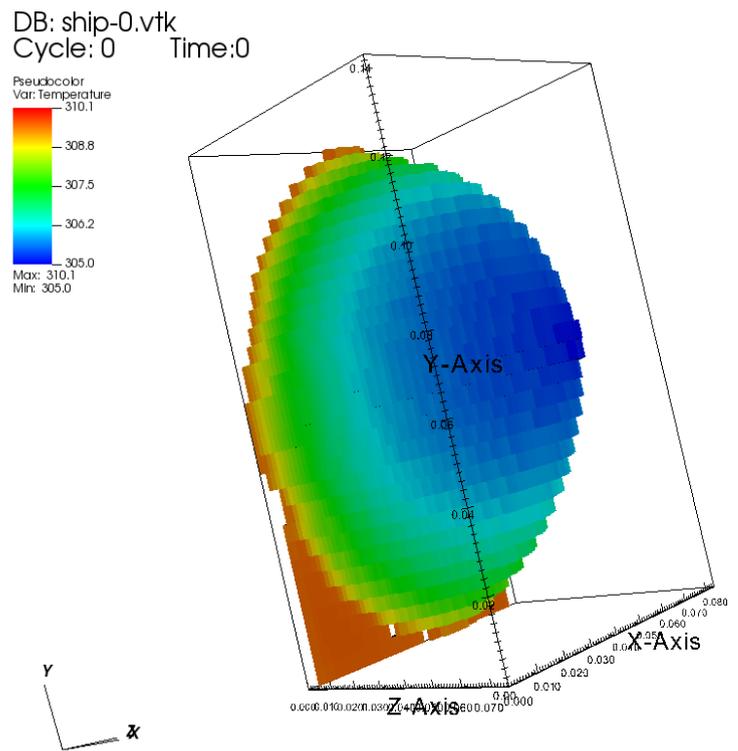Figure 2. Thermal response obtained by the first simulation (no tumor).

Figure 3. Thermal response obtained by the second simulation (0.04 0.04 0.04).

It is noted that the response on the surface indicates an abnormal situation in the breast, indicated by a yellow spot on the green surface, representing a temperature of 307.6K instead of 306.6K.

Afterwards, a tumor was simulated at different coordinates, trying to locate the farthest tumor possible from the breast surface and the thermal response is presented in the figure 4 below.

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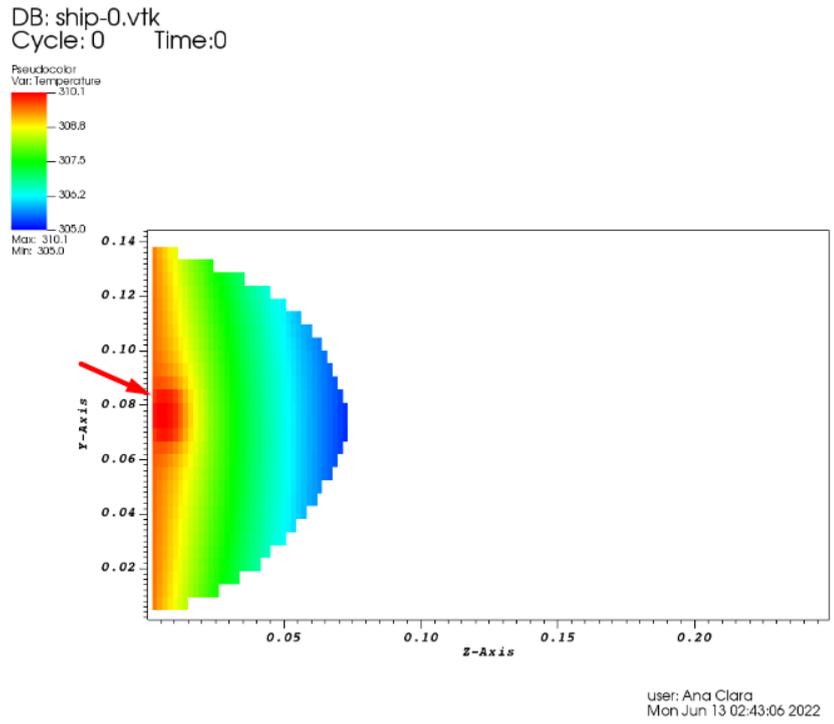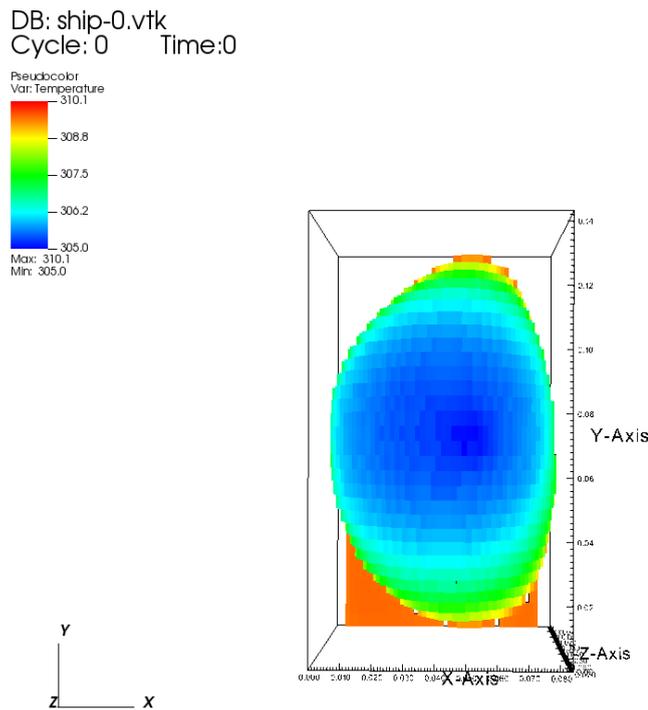
Figure 4. Thermal response obtained by the third simulation.

In this case, the tumor is visible when we slice the model using the software Visit, but the response on the surface of the breast does not indicate visually a significant change if compared to the healthy breast thermal response. It indicates the highest temperature if compared with the other simulations, but the surface temperature is about the same as the no-tumor case.

Now, simulating a smaller tumor with dimensions 0.0002m, the results obtained are represented next:
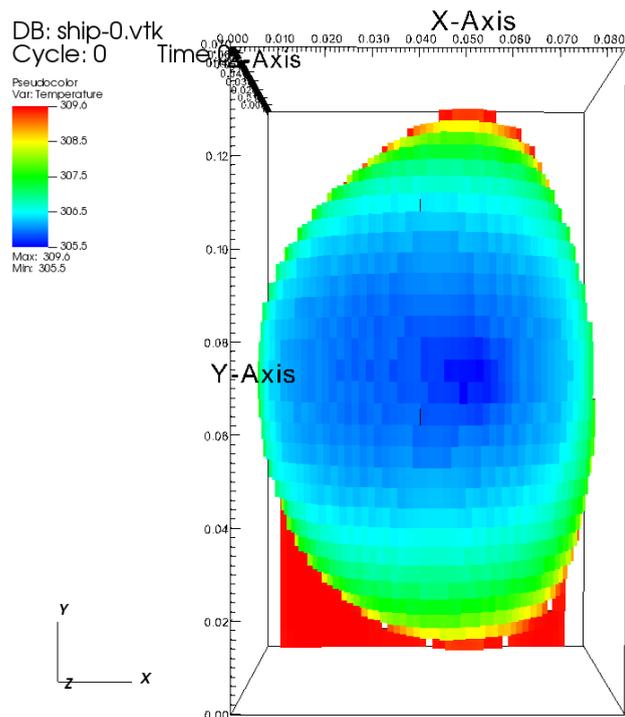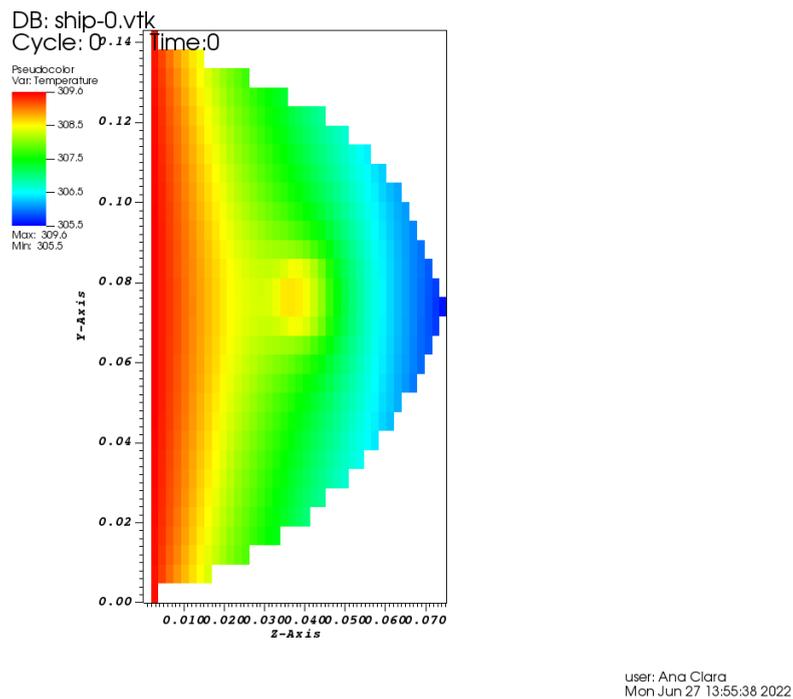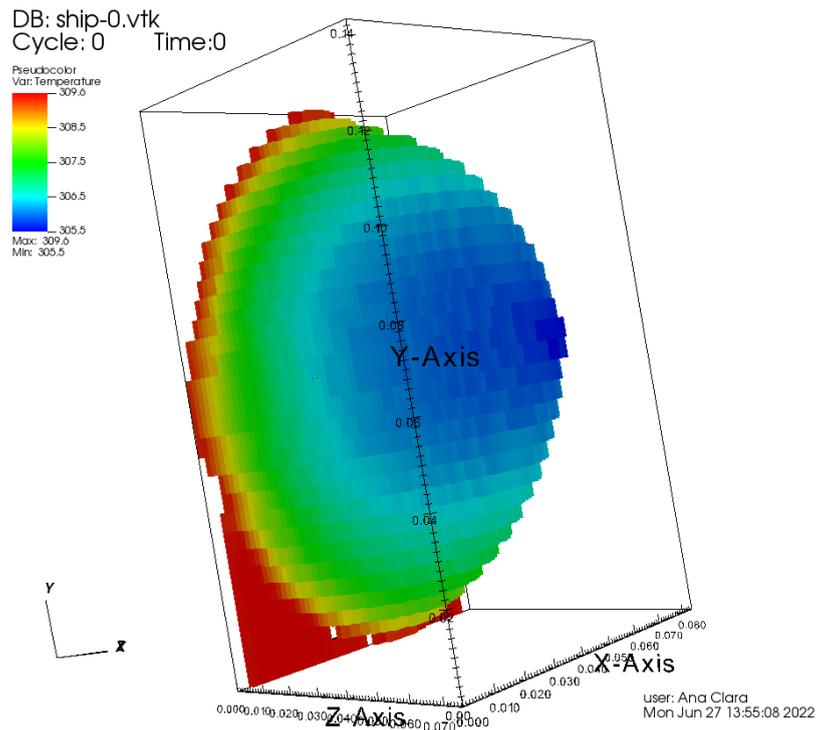
Figure 4. Thermal response obtained by the fourth simulation (smaller tumor).

Again, the smaller tumor is not clearly visible on the surface, we can visualize it only by slicing the model. But in this case, comparing the results with the no tumor simulation, the surface temperatures are higher and the results are closer with the Dalmaso's simulation.

To visualize better the results and to be easier to analyze them, the data is grouped in the following table 2.

Table 2. Results compared.

Simulation	Lowest temperature on the surface [K]	Highest temperature measured [K]	Tumor's temperature measured on the surface [K]
First	304.9	309.9	-
Second	305.7	309.6	308.6
Third	305.0	310.1	did not show
Fourth	305.5	309.6	did not show

4. CONCLUSIONS

Comparing the simulations, it is notable that, although the method is safe and reliable, there are some limits about the tumor's depth in the breast. Tumors located deeper inside the breast, close to the chest wall, may not indicate a temperature anomaly in the surface in the simulation.

On the other hand, the simulation was positive in regard to the size of the tumor. Even when dividing the original size of the tumor by 5 in each direction, the response still indicated the anomaly because the surface temperature was considerably higher than the simulation of a healthy breast. .

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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