25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1626
DETECTION OF INCLUSIONS IN A BREAST MODEL USING THERMAL IMPEDANCE METHOD

Iago Smanio Saad
Gilmar Guimarães
Federal University of Uberlandia, School of Mechanical Engineering, Av. João Naves de Ávila, 2121, Campus Santa Mônica, Uberlândia, MG, Brazil.
iagosaad.is@gmail.com
gguima@ufu.br

Cleudmar Amaral Araujo
Federal University of Uberlandia, School of Mechanical Engineering, Av. João Naves de Ávila, 2121, Campus Santa Mônica, Uberlândia, MG, Brazil.
cleudmar.araujo@gmail.com

Gabriela Lima Menegaz
Federal University of Uberlandia, School of Mechanical Engineering, Av. João Naves de Ávila, 2121, Campus Santa Mônica, Uberlândia, MG, Brazil.
gabriela.menegaz@gmail.com

Abstract. *Cancer is a public health problem in several countries of the world. Among the types of cancer, breast cancer has the highest incidence and mortality in the female population worldwide. Early detection of breast cancer is essential for reducing the morbidity and mortality associated with this disease. Tumor cancer in the human body usually has a different metabolism and thermal properties from the healthy tissue, causing the region affected by cancer to have a higher temperature than the tissue surrounding. The main objective of the work was to study the detection of an inclusion, positioned in three different depths, in a breast phantom model using thermal impedance method. Heat flux and surface temperature were measured by a two HFS - 3 heat flux transducer assembly and a K-type temperature sensor to acquire temperature and heat flux data in different positions, that can be used to obtain the thermal impedance. Tests were performed with inclusion with internal heat generation, to simulate malignant abnormalities in the tissue, and the external heating of the model. These results are compared to the model without the inclusion (baseline) for analysis of this effect. The thermal impedance values were compared statically using the RMSD damage metric, which were was to show the detection of the inclusion in all the depths tested for the transducer positioned above the inclusion.*

Keywords: *thermal impedance, inclusions, detection, heat generation, breast model.*

1. INTRODUCTION

Cancer is a public health problem in several countries of the world. In Brazil, this also happens. It is estimated that in 2025, in developing countries, the impact of cancer on the population corresponds to 80% of the more than 20 million new cases, according to the World Cancer Report 2014 by the International Agency for Research on Cancer (Iarc) of the World Health Organization (WHO). It was pointed out by the Globocan/Iarc project, in 2012, that breast cancer was the second most common cancer in the world, with 1.7 million cases, second only to lung cancer, which had an occurrence of 1.8 million cases. The tumor with the highest incidence and mortality in women is breast cancer in both developing and developed countries (INCA, 2015).

Some of the methods used to characterize tissues and to enable the detection and diagnosis of abnormalities, such as tumors, are ultrasonography, magnetic resonance imaging (MRI), positron emission tomography (PET), tomosynthesis, and mammography. Mammography is the most common exam used to detect breast cancer, although it also has limitations, such as the emission of x-rays. Besides, mammography often cannot be performed on wheelchair-bound patients or women with low mobility or dwarfism because of the equipment requires the patient to stand upright (Peters and Cotton, 2016).

Carney et al. (2013) reported a sensitivity of 87% and a specificity of 96.9% for women with fatty breast tissue that did the mammography exams. However, for younger women with dense breasts, the sensitivity dropped to 62.9%, and the specificity dropped to 89.1%. Thus, new systems and studies are being developed to characterize the nature of lesions better. .

The technique proposed in this study used the temperature information measured on the surface via infrared sensors or surface thermocouples and quantitatively established an index that indicated the presence of a tumor, without requiring the knowledge of physical parameters of the tissue. This technique was based on the application of damage detection techniques in structures (Menegaz et al., 2019).

The objective of this work is to evaluate the functionality and application of a new method of breast cancer detection through a non-invasive technique, which consists in measuring the temperature and the heat flux to calculate the thermal impedance. In this work is used a breast phantom model, with inclusions with heat generation and sensors to measure the data needed to calculate the thermal impedance. The inclusion was positioned in three different depths inside the breast model to verify the influence of this parameter in the detection. Besides that, one sensor was positioned above the inclusion and the second one in another quadrant of the breast to study the detection using transducer in different locations.

2. THEORETICAL FOUNDATION

An inclusion, which simulates a tumor, has thermal properties and metabolism different from the healthy tissue presents in the human body. Detect this inclusion is possible by applying a non-invasive method using heat flux transducers, which are sensors with the ability to measure temperature and heat flow.

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

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

Where the parameter $q_o(\omega)$ is the thermal excitation represented by the heat flux imposed on the surface , $T(\omega)$ is the response to this flux measured at the surface temperature of the sample (system), the variable ω represents the domain of the frequency function obtained by applying the Fourier transform to the time signals of $\Delta T(t)$ and $q(t)$ is measured by the heat and temperature transducers. In the equation, $Ty=0(\omega)$ is the initial temperature, and $T\alpha(\omega)$ are the temperatures along the time, causing the impedance condition to be given as a temperature difference by the heat flow.

Since the thermal system is a function of the thermal properties, perfusion, and metabolism, the thermal impedance must also assume different values if the medium has inclusions with thermal properties or if its internal heat generation is different from its surroundings.

A reference must be established for the damage metric, corresponding to the undamaged structure, called the baseline to quantify the structural changes. Thus, it is possible to perform comparisons involving metric values for the structure considered with and without damage (Sun, et al., 1995). It is expected that these comparisons will be able to point out whether there is damage in the structure or not. The main objective of the damage metric is to quantify the difference between impedance measurements when comparing them with data obtained for the undamaged structure (reference signal, or baseline). In the decision-making process to verify if the inclusion was detected, statistical analyses are performed using damage metrics and the appropriate damage threshold. That procedure increases the reliability of the diagnosis. The thermal impedance response provides a qualitative approach for damage identification, while a scalar damage metric gives a quantitative answer. In this work, RMSD (root mean square deviation) damage metric is used and defined as shown in Eq. (2).

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

Where RMSD represents the damage metric, $Re(Z_{1,\ i})$ the electromechanical impedance measured under damaged condition, $Re(Z_{2,\ i})$ is the counterpart corresponding to the healthy condition (so-called baseline condition) at the ith frequency interval (ith frequency point), and *n* the total number of frequency points considered 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).

$$PZT_{Threshold} = \mu_{X_{max}} + 3\sigma_{X_{max}} \qquad (3)$$

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

The apparatus was assembled using a breast model of silicone, L55 3B Scientific® anatomical model, which simulates a right breast without tumors. A 10 mm diameter inclusion made of Acrylonitrile Butadiene Styrene (ABS) in the 3D printer, Fig 1 (A) simulated cancer.

The inclusion was inserted the lower part of the model, Fig. 1 (B), that corresponds to the upper outer quadrant. This region was chosen since it has the highest incidence of breast tumors (Aguillar, Bauab, And Maranhão, 2009). The diameter of the hole was 1mm. The depth was determined from a rod attached to the inclusion with three variations: 5 mm (P1), 14,5 mm (P2) e 24 mm (P3), measured from the surface of the model.

In the inclusion, an electric resistance of 4 KΩ was used to cause a temperature rise of approximately 2 ° C, which is observed in breast cancer detection studies in patients using thermography. Since the cancer cells that exist in the breast are responsible for producing nitric oxide, which changes the flow of blood vessels, as it causes vasodilation in the early stages of cancerous growth of the region of cancer cells. Because of this increased blood flow in the dilated vessels, there is a rise in temperature compared to normal breast temperature (Borchartt et al., 2013). Thus, an increase of approximately 2 ° C in the surface of the model was caused to correspond to the results observed in studies comparing the differences in superficial temperatures of healthy breasts and of breasts with tumors (Jiang, Zhan and Loew, 2011; Kandlikar et al., 2017). The generation of heat was produced within the inclusion with an electric voltage of 30 V.

The external heat flux was generated by an infrared lamp of 60 W positioned 17.5 cm high and parallel to the breast model. The measurement of the heat flux and the temperature at the surface of the model were made using two HFS - 3 heat flux transducer assembly and a K-type temperature sensor (Omega®), Fig. 2 (A). One of the transducers were positioned in the upper outer quadrant of the model, above of the inclusion, called TR1. While a second transducer (TR3) was positioned between the lower outer and inner quadrants, as shown in Fig. 2 (B).

For the system to enter a steady state was waited 1h before the baseline testing began and 2h before the tests with the inclusion. The experimental apparatus was mounted inside a laboratory, which maintained an air conditioner at 25 ºC, to maintain the same temperature for the tests, to avoid interferences of the external environment.

(A) (B) (C)

Figure 1. (A) Inclusion of 10 mm with the resistance used in the tests; (B) Hole for insertion of inclusions; (C) HFS - 3 heat flux transducer and a K-type temperature sensor (Omega®).

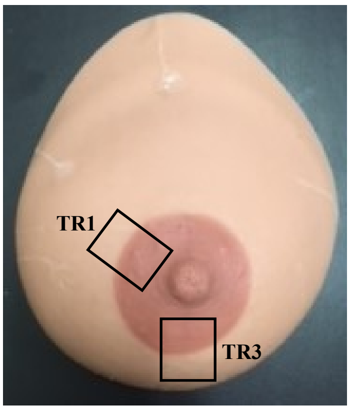

Figure 2. Breast model with the representative position of the thermal transducers.

For each configuration of the model, ten tests were performed, in which temperature and heat flux measurements were taken every second for 9 minutes. The external heating starts to be applied after the first minute. Then, was used 1 minute of heating and 1 minute without heat , until the end of the experiment. After this step, MATLAB® software was used to obtained the values of thermal impedance and damage metric. The configurations tested in the experiments and compared were:

- Baseline: model without inclusion;
- I10 – P1: model with inclusion of 10 mm at 5 mm;
- I10 – P2: model with inclusion of 10 mm at 14.5 mm;
- I10 – P3: model with inclusion of 10 mm at 24 mm.

Averages were performed in all tests and configurations. Inclusion test with 10 mm of diameter was then compared with baseline measurements.
The thermal impedance curves indicate the behavior of the presence of inclusion, and the damage metrics show if it could be detected.
The threshold value was presented, guaranteeing 95% confidence in the probability of detection of this inclusion. The results above the threshold indicate that the inclusion was detected. In cases where box plots intersect the limit, the results were considered inconclusive.

4. RESULTS

A thermal impedance signature was analyzed considering the ten tests of each model. The statistical results were calculated using the RMSD damage meter. The data for each thermal transducer was analysed separately. Figure 3 and Figure 4 show the curves of heat flux and temperature difference, respectively, measured using the sensor positioned in upper outer quadrant (TR1) for all the configurations. The curves of heat flux and temperature difference measured using the transducer placed between the lower outer and inner quadrants (TR3) were shown in the Figs. 5 and 6, for all the configurations. Then, those values were used to calculate the thermal impedance. Figure 7 shows the thermal impedance curve of the baseline test of the transducer TR1. In Figure 8, can be seen the thermal impedance curve of the test with the inclusion in the second position P2

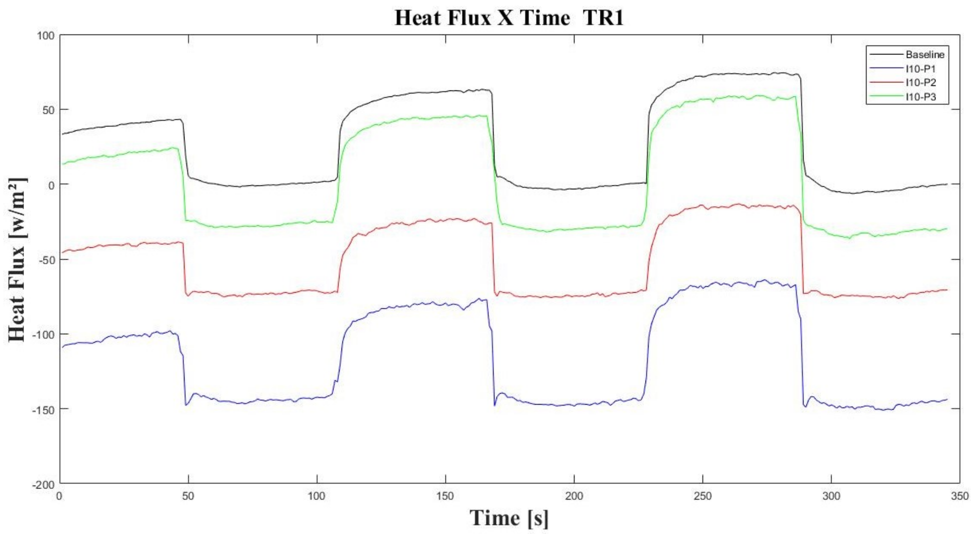

Figure 3. Heat flux evolution from TR1 sensor.

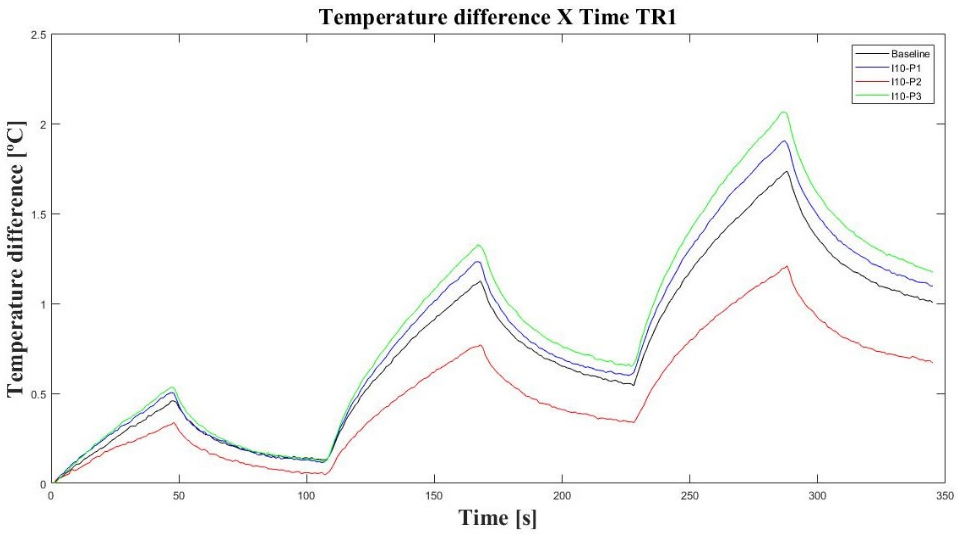

Figure 4. Temperature evolution from T1 thermocouple.

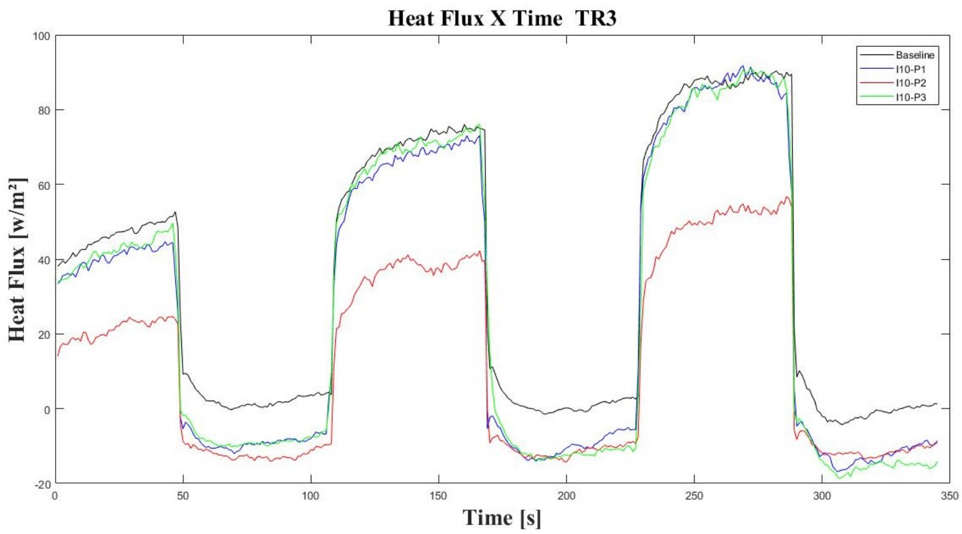

Figure 5. Heat flux evolution from TR3 sensor .

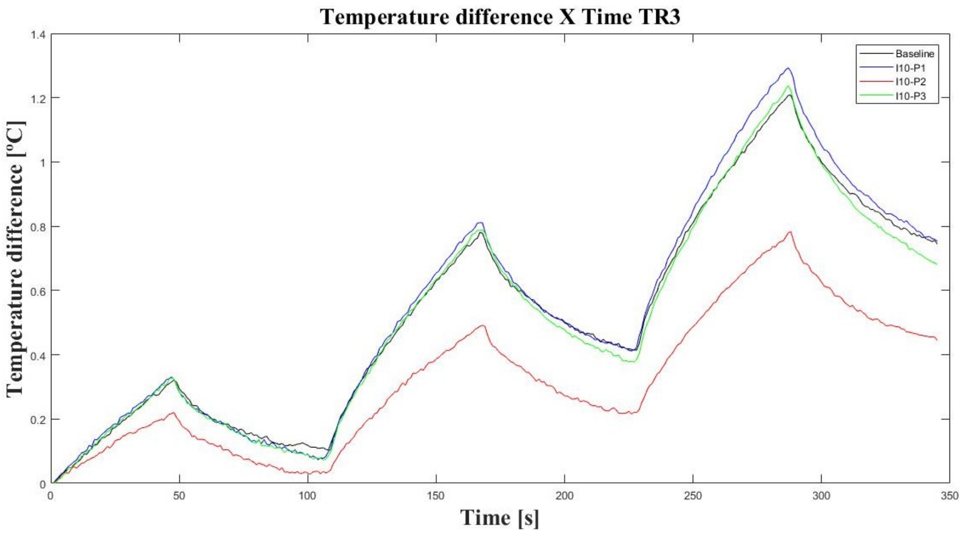

Figure 6. Temperature evolution from T3 thermocouple.

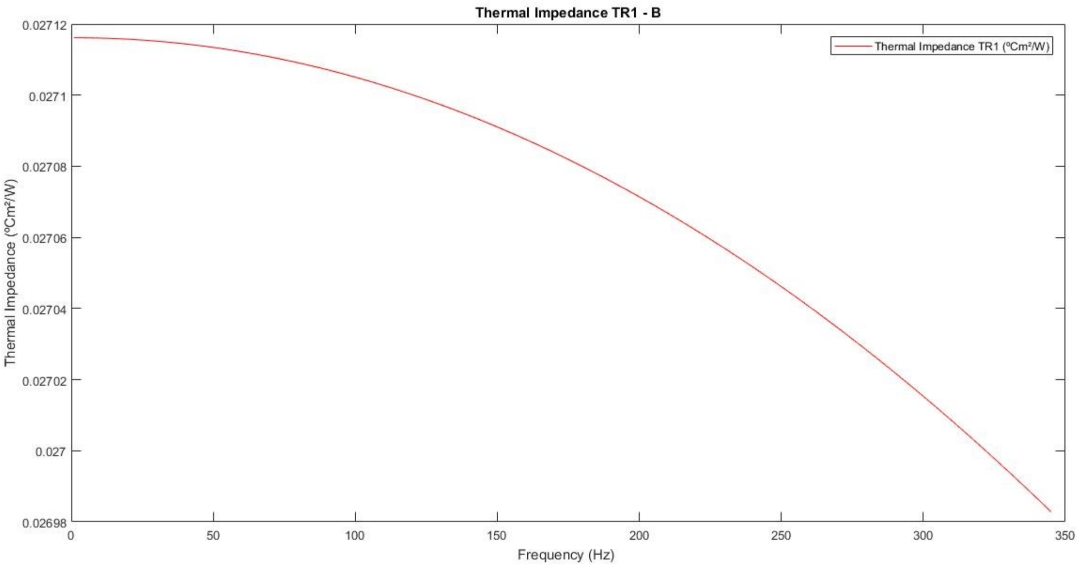

Figure 7. Impedance evolution for baseline configuration from TR1 sensor and Thermocouple T1.

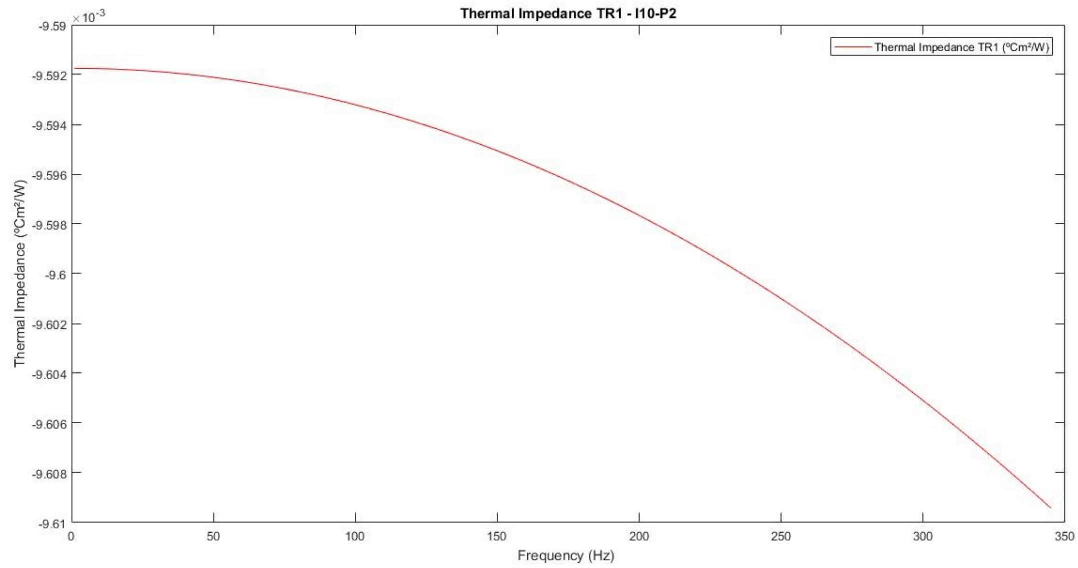

Figure 8. Impedance evolution for the inclusion of 10 mm diameter from TR1 sensor and Thermocouple T1.

Data were analysed separately for each transducer, and results are below. In the results of TR1, a statistical test of damage metric was done, and it was verified significant changes in the data. Thus, can be concluded that the inclusion was detected in all three depths because, in the statistical analysis, the data of the tests were all above of the threshold line (Fig. 9).

In the results of the TR3, a statistical test of damage metric was done. The detection of the inclusion for the positions P1 and P2 were inconclusive. The inclusion was not detected when it was in the lower position P3 by this transducer (Fig. 10).

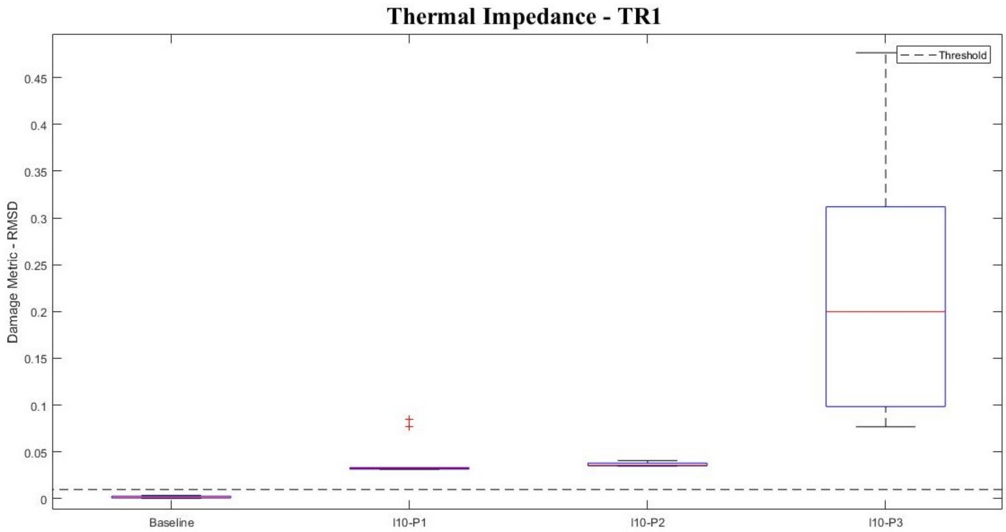

Figure 9. RMSD damage metrics for the breast model with inclusion of 10 mm in TR1.

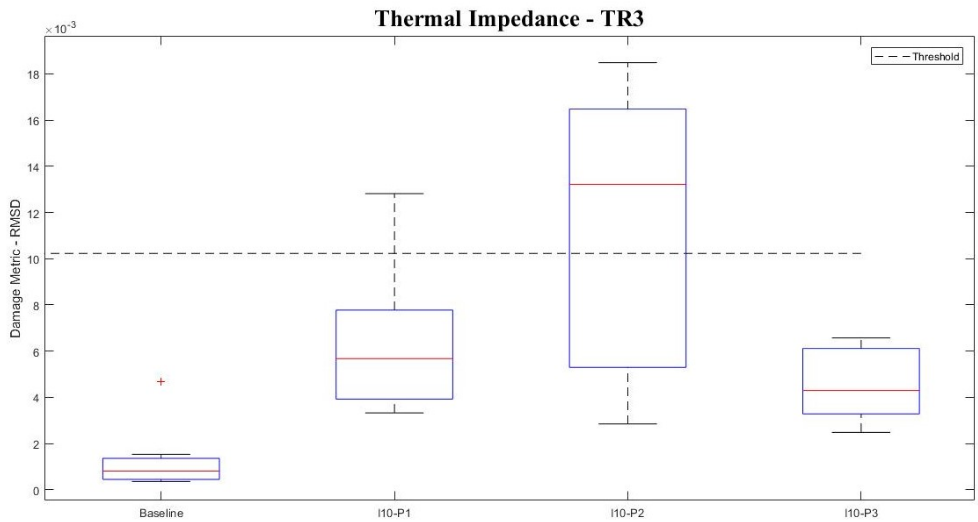

Figure 10. RMSD damage metrics for the breast model with inclusion of 10 mm in TR3.

5. CONCLUSION

In this work, the detection of inclusions in a breast model using the thermal impedance technique was evaluated. Tests were carried out with the inclusion of ABS with a diameter of 10 mm. The heat was then generated internally by the Joule effect to simulate the metabolism. An infrared lamp provided the external heating at the surface sample. The heat flux and temperature difference data were obtained in two different transducers and used to calculate the thermal impedance. Tests were made in the model without inclusion and with the inclusion for three different depths. Damage metrics were calculated to indicate the detection or not of the inclusion.

It was observed that the transducer closest to the inclusion location was able to detect it at all depths. While the most distant transducer presented inconclusive detection results. Therefore, based on the results of the tests performed with these configurations, it can be hypothesized that the transducer position will influence the detection of inclusions. Thus, the closer the transducer is to inclusion, the detection may yield more successful results. It was also observed, from the results of the TR1 sensor, that the depth of the inclusion did not significantly influence the detection since the inclusion, in this case, could be detected in the three positions tested.

This data will still be compared with other tests in other depths and with inclusions of different sizes. These results are preliminary studies on the detection of inclusions using thermal impedance and are inserted in a survey of the association of thermography and impedance techniques.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Brazilian Agencies CNPq, CAPES/PROEX, and FAPEMIG for financial support and the laboratories involved in the research: Laboratory of Mechanical Projects (LPM), Laboratory of heat transfer: Modeling and experiment (LTCME), and Laboratory of Structural Mechanics (LMEst).

7. REFERENCES

Aguillar, V. L. N., Bauab, S. P., Maranhão, N. M., 2009. *Mama: diagnóstico por imagem: mamografia, ultra-sonografia, ressonância magnética*. 1st edition. Rio de Janeiro: Revinter.

Borchartt, T. B.; Conci, A.; Lima, R. C. F.; Resmini, R.; Sanchez, A., 2013. "Breast thermography from an image processing viewpoint: A survey". *Signal Processing*, Vol. 93, pp. 2785–2803.

Carney, P.A., Miglioretti, D. L., Yankaskas, B.C., Kerlikowske, K., Rosenberg, R., Rutter, C.M., Geller, B.M., Abraham, L.A., Taplin, S.H., Dignan, M., Cutter, G., Ballard-Barbash, R., 2003. "Individual and combined effects of age, breast density, and hormone replacement therapy use on the accuracy of screening mammography". *Annals of Internal Medicine,* Vol. 138, pp. 168-175.

Gonzalez-Hernandez, J., Recinella, A.N., Kandlikar, S.G., Dabydeen, D., Medeiros L., Phatak, P. 2019. "Technology, application and potential of dynamic breast thermography for the detection os breast cancer". *International Journal of Heat and Mass Tranfer,* Vol. 139, pp. 558-573.

INCA, 2015. "Estimativa 2016, Incidência de Câncer no Brasil". Instituto Nacional de Câncer José Alencar Gomes da Silva. Coordenação de Prevenção e Vigilância, Rio de Janeiro, pp. 122.

Jiang, L., Zhan, W., Loew, M. H., 2011. "Modeling static and dynamic thermography of the human breast under elastic deformation". *Physics in Medicine and Biology*, Vol. 56, pp. 187-202.

Kandlikar, S. G., Perez-Raya, I., Raghupathi, P. A., Gonzalez-Hernandez, J.-L., Dabydeen, D., Medeiros, L., Phatak, P., 2017. "Infrared imaging technology for breast cancer detection – Current status, protocols and new directions". *International Journal of Heat and Mass Transfer*, Vol. 108, pp. 2303–2320.

Menegaz, G.L. and Guimarães, G., 2019. "Development of a new technique for breast tumor detection based on thermal impedance and a damage metric". Infrared Physics and Technology, Vol. 97, pp. 401 – 410.

Menegaz, G. L., Tsuruta, K. M., Finzi Neto, R. M., Steffen Junior, V., Araujo, C. A., Guimarães, G., 2019. "Use of the electromechanical impedance method in the detection of inclusions: application to mammary tumors". Structural Health Monitoring, pp. 1-16.

Peters, K., Cotton, A., 2016. "Environmental, structural and process barriers in breast cancer screening for women with physical disability: A qualitative study". *Radiography,* Vol. 22, pp. 184-189.

Sun, F. P., Chaudhry, Z., Liang, C. and Rogers, C. A, 1995. "Truss structure integrity identification using PZT sensor–actuator". *Journal of Intelligent Material Systems and Structures*, Vol. 6, pp. 134-139.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.