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

COB-2019-0452
SKIN HEATING NUMERICAL ANALYSIS FOR BREAST TUMORS DIAGNOSES USING INFRARED THERMOGRAPHY

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Abstract. *The purpose of this study is to analyze alternatives to increase the effectiveness of thermographic images technique for the early diagnosis of breast cancer using only superficial temperatures of the breast skin. A 2D hemispherical geometry of the breast was considered to solve the bioheat transfer problem using the commercial software COMSOL. Thermal analyzes were performed considering the early stages of the disease, where cases are more difficult to diagnose. Firstly, stationary temperatures on the breast skin surface were acquired for mammary tissue with and without tumor. Then, a heating in the square wave form was applied on the skin surface, aiming to increase the thermal contrast between healthy and tumor tissue. The results obtained demostrate that heating the breast skin surface can significantly increase the thermal constrast for tumors located in deeper regions.*

Keywords: *bioheat transfer, breast cancer, thermography, numerical simulation, breast superficial temperature.*

1. INTRODUCTION

Cancer is considered a major public health problem wordwide and the second disease with the highest number of deaths in the United States, where about 1,762,450 new cases of cancers are expected and 606,880 deaths in 2019. Of all new cases of cancers, 891,480 will occur in women, and 30 % of these diagnoses correspond to breast cancers. Among the deaths caused by cancers in women, breast cancer accounts for about 15 % of cases (Siegel *et al.*, 2019).

The early diagnosis of breast cancer makes it possible to increase the efficacy of the treastment of the disease. Generally, to make the definitive diagnosis of cancer, the medical pathologist removes cells from a region that is supposed to be infected, so that it is possible to examine in the laboratory the presence of cancer cells. Aiming to early diagnose cancer, different techniques are studied and improved with the objective of assisting in the early diagnosis of breast cancer, among them are: mammography, ultrasonography, magnetic resonance, and other (Wang, 2017).

Another exam developed for the early detection of breast cancer is infrared thermography, which uses an infrared camera to measure the temperature of the breast surface (Lawson, 1956). Studies have shown that cancer cells have different blood and metabolic fluxes than healthy cells. In some situantions, the heat generated by the tumor causes alterations in the breast skin surface temperature, which can be observed by thermographic images (Lawson and Chughtai, 1963).

Breast cancer detection by thermographic images has obtained a significant space among recent searches, because the technique has potential to have a high level of sensitivity to be applied. Kennedy *et al.* (2009) presented a comparative approach about the history of the thermography being used as a medical tool. Arora *et al.* (2008) used results of a patient group to prove that the thermography can identified 58 of 60 malignancies.

Figueiredo (2018) developed therrmal correlations that may qualify infrared imaging techniques and facilitate the localization of the tumor without the need to know some properties such as blood perfusion, heat generation or thermal conductivity of the tumor. Figueiredo *et al.* (2019) used thermal correlations to locate the center of the tumor in the most common cases of breast cancer, also without the need for properties of tumor to be known, using only the surface temperature.

Aiming to improve thermography capacity for breast cancer detection, the analyzes are being directed to transient conditions of the problem, for example, by applying heating or cooling to the breast surface. Hatwar and Herman (2017) studied conditions of thermography improvement for the localization of small tumors near the breast surface, applying different types of skin cooling. Zhou and Herman (2018) demonstrated through computational studies that it is possible to achieve, with skin cooling, an increase in the thermal contrast caused by a tumor located at different depths in the breast.

Shih *et al.* (2007) studied the blood perfusion behavior in a group of people by applying a sinusoidal heat rate to the skin. The analyses show that it is possible to relate the tumors location by thermography with the skin heating, which enables to increase the thermal constrast generated by tumor on breast skin surface. Askarizadeh and Ahmadikia (2014) explored some important concepts about the skin heating applying a pulse train and a periodic heat flux, altering the skin heating with a thermal recovery, where the skin heating can penetrate more into the breast tissues, keeping the skin temperature low.

In this work, a numerical model was used to analyze the thermal response of the tumor on the skin, when applying a skin heating. The porpose of this study is that the skin surface heating induce chages in blood perfusion in tumor and in healthy tissue, causing thermal constrast more effective for thermography in the early diagnosis of breast cancer. The analyzes were performed considering initial stages of the tumor, in which the cases are more difficult to diagnose.

2. MATERIALS AND METHODS

Numerical simulations are obtained using commercial software COMSOL. The geometry of the breast used is a 2D hemispherical model, diameteer 100 mm. Only one tissue layer was considered, with properties of the gland, which fills most of the breast volume in practice. The tumor was represented with a circular domain, diameter 5 and 10 mm, and modified its position relative to the Y axis, as shown in Fig 1.

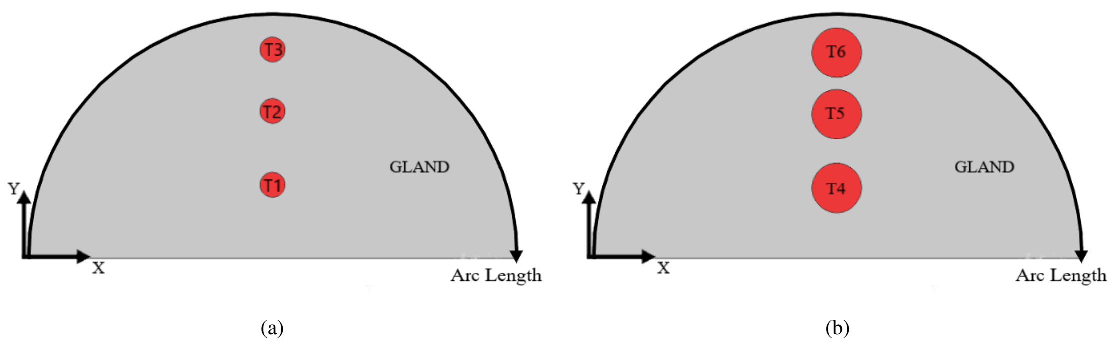


Figure 1: Schematic breast model used in simulation with all different kinds of tumor (a) diameter 5 mm, (b) diameter 10 mm.

Table 1 shows the parameters of the 3 differents types of tumors analyzed, where were positioned to cause different thermal responses in the breast skin.

Table 1: Position and diameter of the tumors.

Tumor	Size	Position (axis Y)
1		15 mm
2	5 mm	30 mm
3		42.5 mm
4		15 mm
5	10 mm	30 mm
6		42.5 mm

Thermal behavior on the skin and other human tissues can be modeled by Eq 1, named bioheat equation, which proposed by Pennes (1948).

$$k\nabla^2 T + w_b \rho_b c_b (T_b - T) + Q = \rho c \frac{\partial T}{\partial t} \tag{1}$$

where the properties k, c, w e ρ represent the thermal conductivity, specific heat, blood perfusion and density of breast tissue. Q and T represents the metabolic heat generation rate and the temperature, of the tissue. When used subscript b represent blood properties.

Figure 2 shows the mesh used in computational simulations in COMSOL, which performs the solution of the Equation 1 through the finite element method. The mesh has 12,332 triangular elements in its domain.

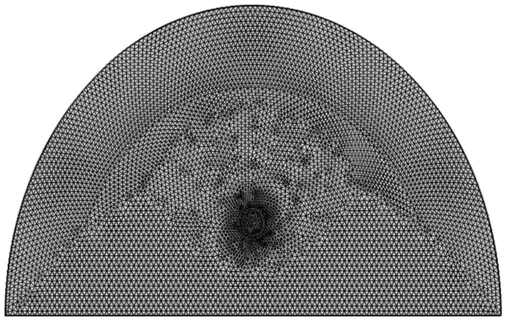


Figure 2: Mesh used in computational simulations.

American Cancer Society (2018) classifies breast cancer according to stages related to the severity of the disease, these stages range from 0 to 4. In stage 0, the tumor can not be measured. In stage 1, the tumor can have up to 2 cm of diameter. In stage 2, the tumor is considered to be invasive (it begins to affect more than one breast tissue) and the diameter is between 2 and 5 cm. In stage 4, the tumor completely extrapolates the dimensions of the breast and can reach the nearest organs. In this work all the tumors are in stage 1.

Table 2 shows the thermophisical properties and parameters of the gland and the tumor used in computational simulations. The ambient temperature, T_∞ was 22 °C, the heat convection coefficient was 10 $Wm^{-2}K^{-1}$ and the blood temperature was 37 °C.

Table 2: Thermophisical properties of the tissues. (Zhou and Herman (2018), Cheng and Herman (2014) and Figueiredo (2018)).

Properties	Tissue	
	Gland	Tumor
Thermal conductivity, k ($Wm^{-1}K^{-1}$)	0.45	0.50
Blood perfusion, ω_b (s^{-1})	0.00008	0.00630
Density, ρ (kgm^{-3})	1000	1000
Specific heat, c ($Jkg^{-1}K^{-1}$)	3600	3770
Volumetric heat generation, Q_m (Wm^{-3})	700	5000

For analyzes of the thermal response of the tumor to the skin, the temperature profile of the breast without tumor was subtracted from that of the breast with tumor, obtaining as thermal contrast on the surface of the breast caused by the tumor.

Changes in breast contour conditions (such as skin heating or cooling) cause changes in the thermal responses of tissues (Cheng and Herman, 2014), which causes changes in thermal contrast that may help in the early localization of the tumor through thermal imaging.

One of the most important stages of cancer treatment involves tumor hyperthermia, where a heat flux is applied to the breast in an attempt to cause the destruction of cancer cells by increasing the temperature in the region in a range of 40 to 44 °C (Lagendijk, 2000). In this work, conditions were studied so that the hyperthermia of the tumor caused the greatest thermal contrast possible on the surface of the skin, improving the sensitivity of the technique to the localization of tumors without damaging the mammary tissue.

Figure 3 shows the heating applied, in square wave form, on breast skin. Heating was applied at time intervals interspersed with thermal recovery. The wave period is divided into two equal parts, the first of the heating and the second of thermal rest.

With the purpose of performing a parametric analysis of the heat rate wave that generates better results for the thermal contrast of the tumor, three different situations were considered. Altering, 1. Rate intensity, 2. Wave period and 3. Duration of heating applicaiton.

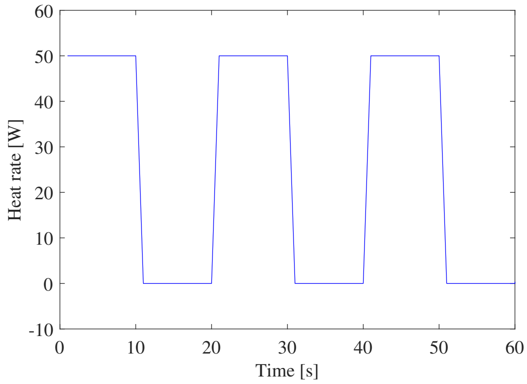


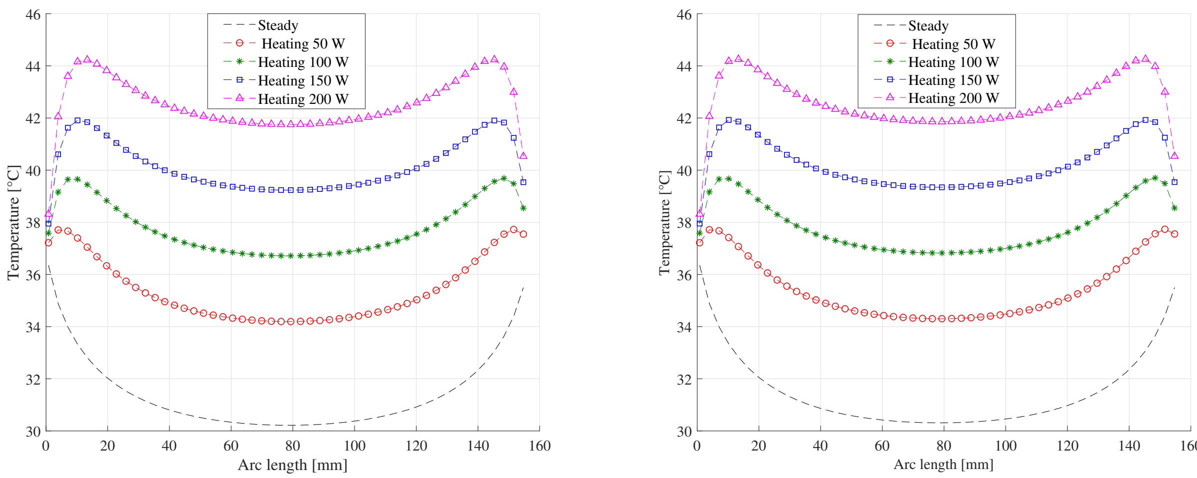
Figure 3: Heat rate used for breast skin heating.

3. RESULTS AND DISCUSSIONS

3.1 Parametric analysis of the heat rate on the bresta skin.

Figures 4a and 4b shows the superficial temperatures of the breast without and wiht tumor, respectively, related to arc length, which is the superficial length of skin of the 2D breast model. Besides the stationary regime, heating was applied using different intensities. This heat rate in the square wave format has a period of 20 s and total application time of 6 min. In the breast with tumor, Tumor 1 was inserted, as characterized in the Table 1, this tumor was used in all parametric analyzes of the heat rate.

At the end of the heating, it was observed that with the increase of the intensity of the heat rate, the surface temperatures of the breast increase, as expected. It is noted that the heat rate of 150 e 200 W increase the temperature to higher values inclusive of those that are used to cause tumor deterioration in (Lagendijk, 2000). In this study, temperature incrise should not damage any breast tissue.



(a) (b)

Figure 4: Surface temperatures in breast skin, altering the heating intesity: (a) Breast without tumor, (b) Breast with tumor.

The presence of the tumor can generate changes in the breast skin temperature, which is characterized as thermal contrast, which is the difference between Figs 4a and 4b, which visually does not seem to have any difference, but can be seen in Fig 5. Thermal contrast can be noticed for most tumors even in the situation where the breast is in a steady state. However, breast heating causes an increase in temperature variations, which may provide an easier localization of tumors by infrared images. These analyzes allow to affirm that the increase of the heat rate used in the skin heating does not imply the increase of the thermal contrast.

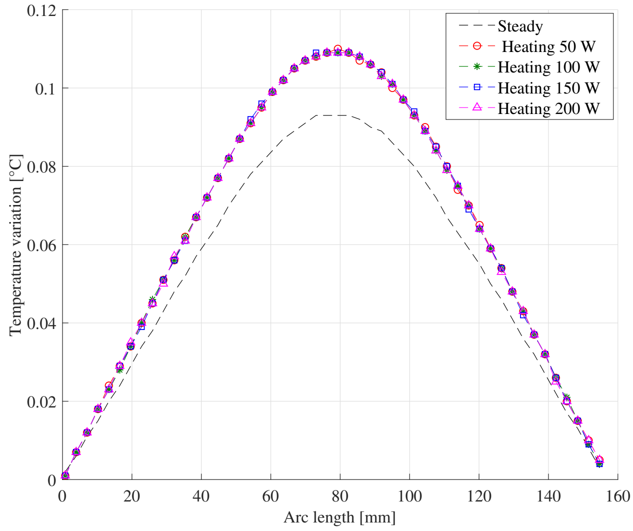


Figure 5: Thermal contrast in the breast skin with different heating intensities.

Therefore, was selected the heat rate of 50 W to breast skin heating, being that this causes lower elevation in surface temperatures, which offers more thermal comfort for the patient in clinical exams, besides ensuring the same thermal contrast as the other analyzed heat rates.

In the second moment, the analyzes were performed using three distinct values of the square wave period, 20, 100 and 200 s, applied for 10 min. Figure 6 shows the thermal constrast in this case, where very small changes occur when the wave period changes, so the modification of the period does not reflect an increase in efficacy of the tumor location.

However, in addition to thermal contrast, it is important to understand the temperature distribution on breast surface over the time of application of heating. Increasing the time interval of the wave period, at the same time increases the skin heating and thermal rest time of the skin.

In the way, it is not sufficient to analyze the temperature in the final time of application of heating, as done in the previous situation, it is importante to verify how the maximum temperature in the skin behaves throughout the procedure. The maximum temperature is reached at different time intervals for each different heating intensities, but always appears instantly after the heating range.

The period wave 200 s presents maximum temperatures at the end of each heating hegher than the other wave periods adopted, on the other side the wave period of 20 s causes the lowest maximum temperatures. Adopting a choice that offers the lowest possible maximum temperature conditions, the most appropriate wave period to be used is the 20 s.

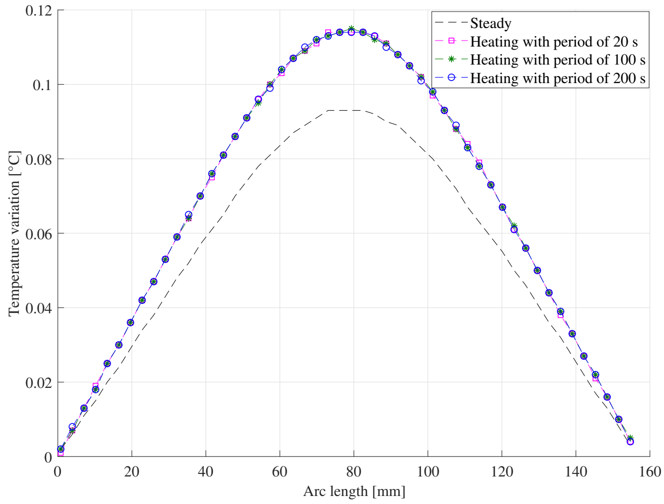


Figure 6: Thermal contrast in the breast skin with different wave period on skin heating.

Finally, the total heating time was analyzed for 10, 20, 30 and 40 min using the 20 s period selected above. The Figures 7a and 7b present the temperature distribution on the surface of the breast without and with tumor, respectively, in the final time of application of the heating. After heating the breast at different times, it is observed that by increasing the duration of the heating, the temperatures reach values that extrapolate the limits studied by Lagendijk (2000) where 40 °C can begin to damage the tissues.

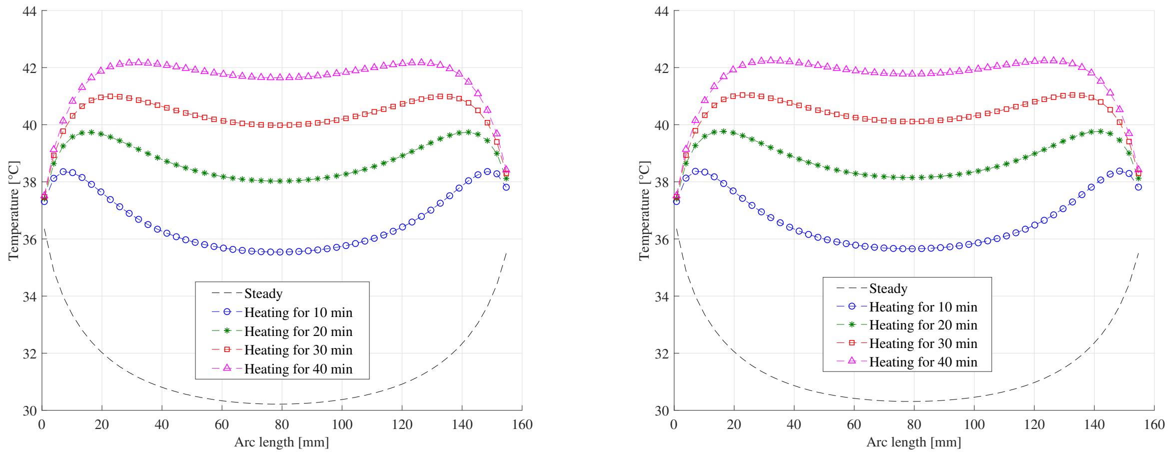


Figure 7: Surface temperatures in breast skin, altering the duration of application of skin heating: (a) Breast without tumor, (b) Breast with tumor.

Figure 8 shows the thermal constrast, which is the difference between Figs 7a and 7b, generated in the different cases where the skin heating time is increased. A longer time of application of the heat rate offers a higher thermal contrast, however this increase in temperature variation is no t significant, when compared for example with the increase in temperature in the skin, which can even damage the breast tissue. Another important aspect is that the thermal contrast, when passing from 10 to 20 min, only increases 0.009 °C, which is a small increase compared to the rise in skin temperature that is 2 °C, that can be seen in the Figs 7a and 7b. Therefore, the time of 10 min was selected for the heating, which ensures a significant thermal contrast in relation to the other intervals of duration and lower temperatures.

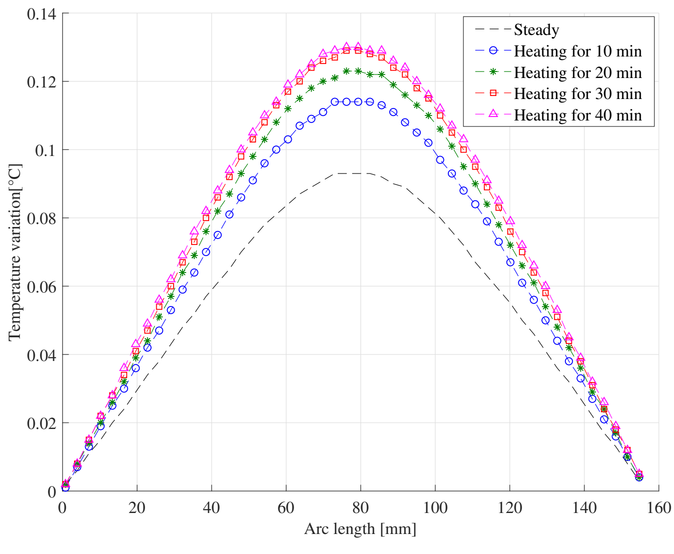


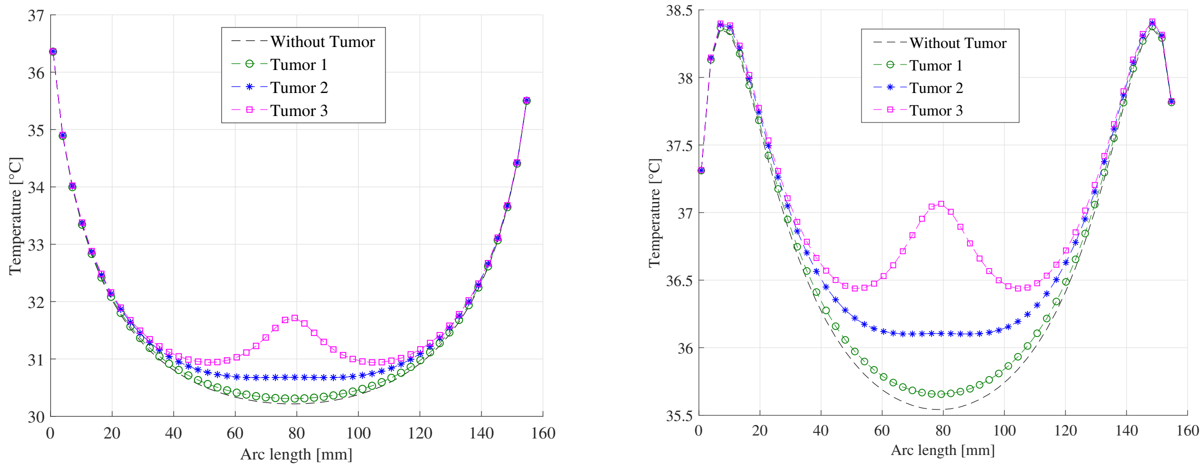
Figure 8: Thermal contrast in breast skin, altering the duration of application of skin heating.

The parameters selected for the increase of the thermal contrast in the breast skin and avoiding damages to the tissues were the intensity of the heat rate, period of the wave and total time of heating equal to 50 W, 20 s e 10 min, respectively.

3.2 Analysis of the effect of breast heating for tumors in different regions.

After selecting the parameters of the heat rate to be used in heating the skin of the breast, was analyzed the potential to increase the thermal contrast generated by tumors of different sizes and positions, as shown in the Table 1.

Figures 9a e 9b show the superficial temperatures of the breast without and with heating, respectively, for the tumors 1, 2 and 3. These graphs show that the breast with tumor 3 (closer to the skin surface) was the one who presented the greastest increase in temperature on the surface of the skin.



(a) (b)

Figure 9: Surface temperatures in breast skin, altering the position of the tumor: (a) Without heating, (b) With heating.

Figure 10 shows the thermal contrast profile for each tumor when compared to situations with heating (transient) and without heating (steady state). Tumor 2, reacts better to skin heating, this means that the difference between the thermal contrast in situations with and without heating is 0.072 °C, whereas for Tumor 1 it is only 0.021 °C (approximately 30 % of Tumor 2).

In Tumor 3, the increase in thermal contrast is as small as in Tumor 1, 0.027 °C, because this tumor is in a region of high sensitivity. For tumors in this situation conditions with few changes in surface temperature are necessary, since for most superficial tumors the thermal contrast is enough for its localization even at steady state (without heating) (Hatwar and Herman, 2017).

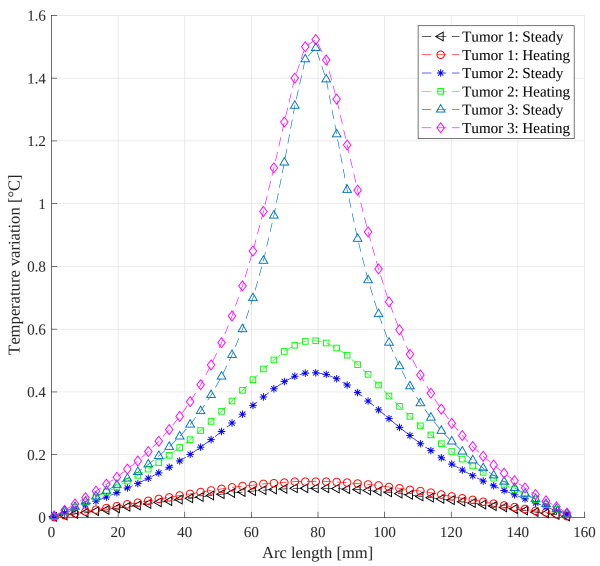
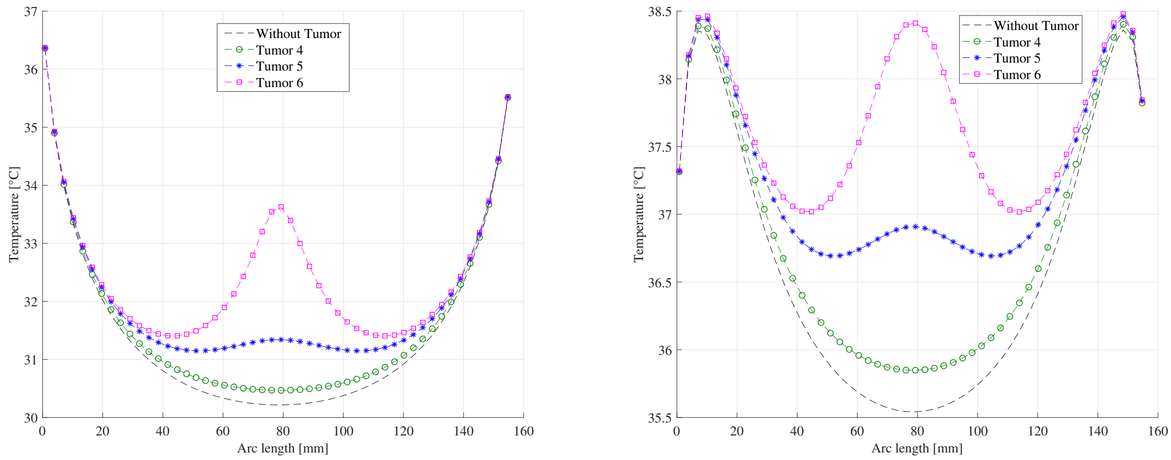


Figure 10: Thermal contrast in breast skin for tumors in different regions.

The results obtained with tumors 1, 2 and 3, which have a diameter of 5 mm, it is observed that there is an increase in thermal contrast caused by skin heating, but that this increase is still small. In another case, tumors of 10 mm diameter were used according to recent researches such as (Zhou and Herman, 2018) and (Figueiredo *et al.*, 2018), these tumors are still in stage 1 of severity.

Figures 11a and 11b shown the surface temperatures considering the tumors 4, 5 and 6, all of them with 10 mm of diameter. The tumors 5 and 6 generate an increase in the temperature in the skin in it is proximity that can easily be noticed in cases with and without heating of the skin



(a) (b)

Figure 11: Surface temperatures in breast skin, altering the position of the tumor: (a) Without heating, (b) With heating.

Figure 12 shows that the difference in thermal contrast caused by the tumor when the breast is without and with heating. This alteration has the highest result for Tumor 5, 0.245 °C, which is positioned at the same region of the Tumor 2 of the Fig 10.

However, for Tumor 6, tumor in the surface region, heating does not cause the increased thermal contrast, similar phenomenon as occurs with Tumor 3, however for Tumor 6, which at steady state already has significantly high thermal contrast, skin heating impairs tumor localization.

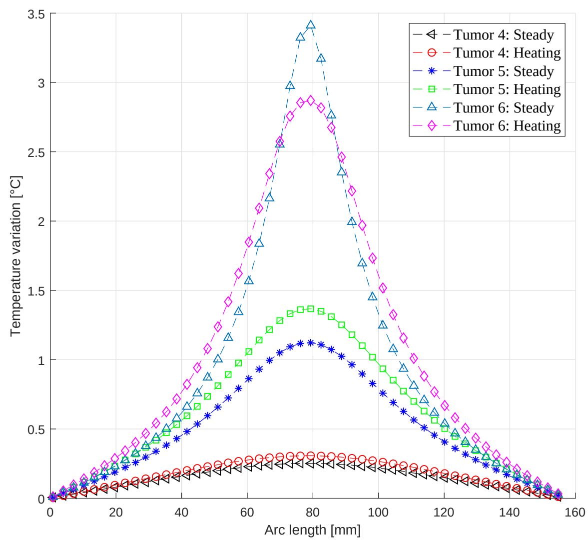


Figure 12: Thermal contrast in breast skinfor tumors in different regions.

Table 3 presents the thermal contrast found for al tumors analyzed, being in stationary (without heating) and trasient (with heating). It can be obserbed that the heating condition causes an increase in thermal contrast for most of the tumors studied, up to 0.245 °C of increase to Tumor 5, which proves the most significant efficacy for tumors in the central region of the breast. However for superficial tumors, skin heating did not produce positive results, for example for Tumor 6, where the termal contrast after skin heating is below steady state in the tumor region.

Table 3: Thermal contrast for the tumors choose for the stationary and transient analysis.

Tumor	Thermal Contrast	
	Steady	Heating
1	0.093 °C	0.114 °C
2	0.491 °C	0.563 °C
3	1.496 °C	1.523 °C
4	0.251 °C	0.307 °C
5	1.122 °C	1.367 °C
6	3.411 °C	2.871 °C

4. CONCLUSION

The increase in thermal contrast provided bu the heating of breast skin was shown to be as effective as the cooling performed by (Zhou and Herman, 2018), in the situations of the Tumors 2 and 5. For Tumors 1 and 4, skin heating increases thermal contrast, but there are still difficulties in locating tumors in this region, because the thermal contrast remains small. For surface tumors, Tumors 3 and 6, the heating dos not shown be effective. However, for these tumors the contrast is high even in the stationary study.

In this work, parameters were explored that result in a greater defficulty in locating the tumors, as a small diameter and located in deeper regions in the breast. Heating does not cause skin temperature to exceed a limit of 38.5 °C, which offers thermal comfort for the patient during clinical exams. The results of this study may contribute to increase the reliability of thermographic exams and increase the sensitivity of the technique.

5. REFERENCES

American Cancer Society, 2018. “Breast cancer early detection and diagnosis”. American Cancer Society. 14 Feb. 2018 <https://www.cancer.org/cancer/breast-cancer/screening-tests-and-early-detection.html>.

Arora, N., Martins, D., Ruggerio, D., Tousimis, E., Swistel, A.J., Osborne, M.P. and Simmons, R.M., 2008. “Effectiveness of a noninvasive digital infrared thermal imaging system in the detection of breast cancer”. *The American Journal of Surgery*, Vol. 196, No. 4, pp. 523–526.

Askarizadeh, H. and Ahmadikia, H., 2014. “Analytical analysis of the dual-phase-lag model of bioheat transfer equation during transient heating of skin tissue”. *Heat and Mass Transfer*, Vol. 50, No. 12, pp. 1673–1684.

Cheng, T.Y. and Herman, C., 2014. “Analysis of skin cooling for quantitative dynamic infrared imaging of near-surface lesions”. *International Journal of Thermal Sciences*, Vol. 86, pp. 175–188.

Figueiredo, A.A.A., 2018. *Uso de correlações de temperaturas superficiais e qualificação da técnica de imagens infravermelhas para a detecção e localização de tumores de mama*. Ph.D. thesis, Universidade Federal de Uberlândia, Uberlândia, Brasil.

Figueiredo, A.A.A., do Nascimento, J.G., Malheiros, F.C., da Silva Ignacio, L.H., Fernandes, H.C. and Guimaraes, G., 2019. “Breast tumor localization using skin surface temperatures from a 2d anatomic model without knowledge of the thermophysical properties”. *Computer Methods and Programs in Biomedicine*.

Figueiredo, A.A.A., Fernandes, H.C. and Guimaraes, G., 2018. “Experimental approach for breast cancer center estimation using infrared thermography”. *Infrared Physics & Technology*, Vol. 95, pp. 100–112.

Hatwar, R. and Herman, C., 2017. “Inverse method for quantitative characterisation of breast tumours from surface temperature data”. *International Journal of Hyperthermia*, Vol. 33, No. 7, pp. 741–757.

Kennedy, D.A., Lee, T. and Seely, D., 2009. “A comparative review of thermography as a breast cancer screening technique”. *Integrative cancer therapies*, Vol. 8, No. 1, pp. 9–16.

Lagendijk, J., 2000. “Hyperthermia treatment planning”. *Physics in Medicine & Biology*, Vol. 45, No. 5, p. R61.

Lawson, R., 1956. “Implications of surface temperatures in the diagnosis of breast cancer”. *Canadian Medical Association Journal*, Vol. 75, No. 4, p. 309.

Lawson, R.N. and Chughtai, M., 1963. “Breast cancer and body temperature”. *Canadian Medical Association Journal*, Vol. 88, No. 2, p. 68.

Pennes, H.H., 1948. “Analysis of tissue and arterial blood temperatures in the resting human forearm”. *Journal of applied physiology*, Vol. 1, No. 2, pp. 93–122.

Shih, T.C., Yuan, P., Lin, W.L. and Kou, H.S., 2007. “Analytical analysis of the pennes bioheat transfer equation with sinusoidal heat flux condition on skin surface”. *Medical Engineering & Physics*, Vol. 29, No. 9, pp. 946–953.

Siegel, R.L., Miller, K.D. and Jemal, A., 2019. “Cancer statistics, 2019”. *CA: a cancer journal for clinicians*.

Wang, L., 2017. “Early diagnosis of breast cancer”. *Sensors*, Vol. 17, No. 7, p. 1572.

Zhou, Y. and Herman, C., 2018. "Optimization of skin cooling by computational modeling for early thermographic detection of breast cancer". *International Journal of Heat and Mass Transfer*, Vol. 126, pp. 864–876.

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