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Heat transfer in multi-phase porous media for intelligent cancer detection

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Micro Abstract
The underlying research project aims to improve cancer diagnosis by determining the correlation between the locally increased heat production of hyper-perfused cancerous tissue and the body surface temperature distribution, measurable using thermography. In this work, a preliminary experimental study of the detectability of an embedded heat source in a perfused solid by means of thermography is presented. Furthermore, the suitability of different mathematical modelling approaches is studied.

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Introduction

Breast cancer is the most common type of cancer in women worldwide and its incidence is continuously increasing. As early detection significantly improves survival rates, a widely available, reliable detection method is needed [3]. The current gold standard for breast cancer screening, mammography, has recently engendered controversy [3]. Hence, the underlying research project aims to develop a new detection method based on infrared imaging of the skin which is economical and non-hazardous. The significant hyper-perfusion of cancerous tissue is known to lead to a local increase in temperature. While the application of infrared thermal imaging has recently shown promising results in skin cancer diagnosis [7], the application to breast cancer detection has not yet led to satisfying results. The difficulty mainly lies in the complexity of the breast structure consisting of different tissue types and vessels with varying diameters resulting in complex heat transfer. The cancerous heat source can have a detectable influence on the surface temperature field of the breast depending on its location, size and heat generation e.g.. The challenge lies in solving the inverse problem and determining the location and intensity of the source from measured infrared radiation of the breast surface. While most research in this field concentrates on image processing, the approach of this project is to subsequently develop a porous media model for heat transfer in the female breast for improved thermographic breast cancer detection. Energy transport in biological tissue has been investigated for decades but until today the pioneering Pennes's bioheat equation (1948) has been popular among scientist, mainly due to its simplicity. While Pennes's bioheat equation is appropriate for various medical applications, it is known to have several shortcomings. Current research can be divided into three groups: a) improvement of Pennes's model by correction factors e.g., b) porous media models with thermal non-equilibrium and c) discontinuous models using exact vessel geometry [2, 4, 5]. In this work a preliminary study of the detectability of an embedded heat source in a perfused solid is presented. The suitability of different modelling approaches for the intended application is studied.

1 Method

The main initial objective is to assess the feasibility of the envisaged approach for breast cancer detection. A preliminary experimental study to determine the limitations of the proposed method regarding cancer properties such as heating power and distance from the surface is executed. Simultaneously, a FEM study is conducted to determine the most suitable mathematical modelling approach.

1.1 Experiments

As a clinical study is difficult to conduct for this purpose, simplified specimens are manufactured to resemble the female breast and cancerous tissue regarding the properties of interest. Cubes with side lengths of $w = h = l = 30\,\mathrm{mm}$ incorporating evenly distributed channels of $\varnothing = 1\,\mathrm{mm}$ are manufactured using a 3D FDM printing device which allows for a resistance to be inserted into the material without causing any material discontinuities. A cylindrical resistance ($l_c = 8\,\mathrm{mm}$, $\varnothing_c = 2\,\mathrm{mm}$) of $10\,\Omega$ is intended to act as a modulatable heat source in analogy to cancerous heat sources of different stages. It is assumed that the heating power generated by the resistance is equivalent to the electrical power. The power is set to 0.4 W, 0.9 W and 1.6 W respectively. Specimens with different source positions and channel patterns are manufactured. The channel pattern consists either of 6x6 horizontal channels ($a = 5\,\mathrm{mm}$) or 6x6 horizontal and 6x6 connected vertical channels. The closest distance of the heat source to the measured surface was set to $s = 5.5\,\mathrm{mm}$ and $s = 11\,\mathrm{mm}$, respectively. The channels were either air-filled or flown-through by water (5 ml/s, right to left). Water temperature was set to approximately 24.5 °C, ambient temperature was 23 °C. Figure 1 schematically shows the setup. The thermal radiation of the front surface was measured by an infrared camera (Infratec IR 5300) and converted to temperature images.

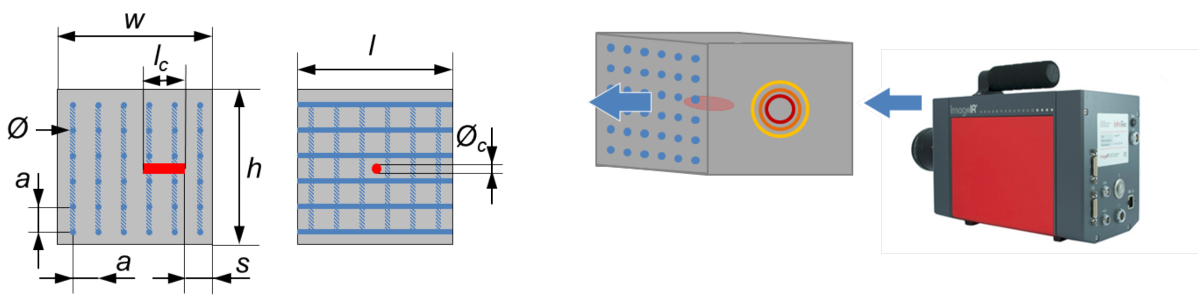


Figure 1. specimen geometry and setup

1.2 Mathematical Model

The underlying research project aims at the development of an accurate mathematical model of heat transfer in the female breast, by firstly investigating the most popular modelling techniques. A promising approach is the modelling on basis of porous media theories, which are based on volume averaging and the definition of separate temperature fields for tissue and fluid phase on the same control volume with thermal non-equilibrium between fluid and tissue e.g. [4]. However, in his work He [2] argues the exact channel geometry of thermally significant vessels should be considered. He therefore proposes a coupled continuum-discrete model. Two approaches are therefore investigated in this work. Heat transfer in a model using the exact vessel geometry was implemented using Fourier equation for heat transfer:

$$\nabla \cdot (k_s \nabla T_s) + q = 0. \tag{1}$$

Herein, T, k, q, are the temperature, thermal conductivity and heat production, respectively. Heat transfer between solid and fluid passing through the flow channels was modelled using estimated heat transfer coefficients.
Heat transfer on basis of porous media theories was modelled based on the mathematical model of Xuan and Roetzel [8] who used a thermal non-equilibrium model as described in the work of

Amiri and Vafai, among others, [1]:

$$\nabla \cdot (\mathbf{k}_s \cdot \nabla \langle T \rangle^s) + h_{fs} \left(\langle T \rangle^f - \langle T \rangle^s \right) + q\,(1-\varepsilon) = 0 \qquad \text{for } \Omega_s, \tag{2}$$

$$\nabla \cdot \left(\mathbf{k}_f \cdot \nabla \langle T \rangle^f \right) + h_{fs} \left(\langle T \rangle^s - \langle T \rangle^f \right) = \varepsilon\,(\rho c_p)_f \left(\mathbf{v}_f \cdot \nabla \langle T \rangle^f \right) \qquad \text{for } \Omega_f, \tag{3}$$

where ε, $\langle T \rangle$, $\mathbf{k}$, h_{fs}, $\mathbf{v}_f$ are the porosity, local averaged temperature, effective thermal conductivity tensor, interstitial convective heat transfer coefficient and blood velocity, respectively.

2 Results

2.1 Experimental Results

A specimen with water flow through horizontal channels and a heat source close to the surface ($s = 5.5\,\text{mm}$) was measured for different heating powers of 0 W to 1.6 W. The greater the heating power, the higher is the maximal temperature at the surface (cp. figure 2–5). The temperature without any heat source is approximately 24.5 °C. The maximal temperature increases to approximately 25.1 °C, 26.3 °C and 27.5 °C for a heating power of 0.4 W, 0.9 W and 1.6 W respectively. In figure 6–9 the surface temperature field for a constant heating power of 0.4 W is depicted. For a source close to the surface ($s = 5.5\,\text{mm}$) and air filled channels, the maximum temperature at the surface is found to be 32.2 °C. For a specimen with 2x(6x6) channels (in horizontal and vertical direction) and a source at $s = 11\,\text{mm}$, the maximum temperature at the surface decreases to 26.5 °C. Figure 8 and 9 show the surface temperature when water is flowing through the channels. The heat source close to the surface ($s = 5.5\,\text{mm}$) shows a small but detectable hotspot of 25.1 °C while the source at $s = 11\,\text{mm}$ and 2x(6x6) channels does not result in a detectable temperature difference at the surface.

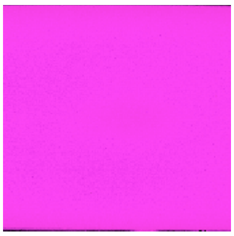


Figure 2. P=0 W, water flow, source close

Figure 3. P=0.4 W, water flow, source close

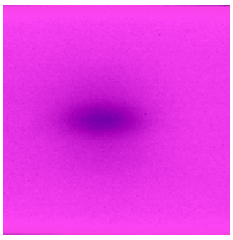


Figure 4. P=0.9 W, water flow, source close

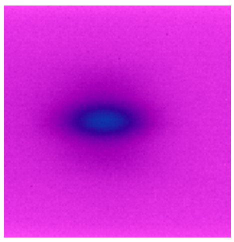
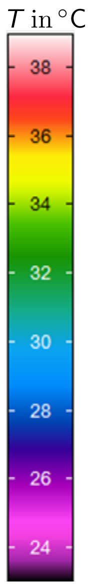


Figure 5. P=1.6 W, water flow, source close



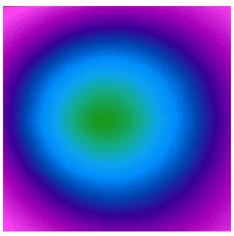


Figure 6. P=0.4 W, air-filled, source close

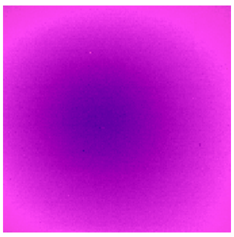


Figure 7. P=0.4 W, air-filled, 2x(6x6) channels, source far

Figure 8. P=0.4 W, water flow, source close

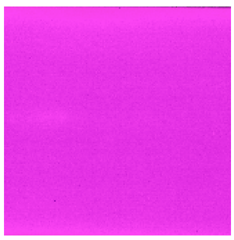


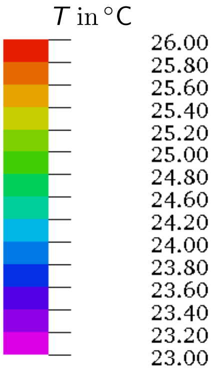
Figure 9. P=0.4 W, water flow, 2x(6x6) channels, source far

2.2 Simulation Results

The simulation results for one test case are shown in figure 10–15. Figure 10,12, 13 show the temperature field calculated with implemented channel geometry. Below, the results obtained by the porous media model are shown. The surface temperature fields as well as the internal temperature fields are qualitatively quite similar, but show discrepancies especially in the area close to the channels. In order to thoroughly compare and assess both models, further investigation is necessary to be carried out.

Figure 10. implem. geometry -surface

Figure 11. porous media- surface



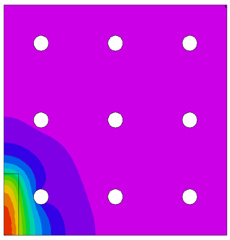


Figure 12. implem. geometry - horiz. cut

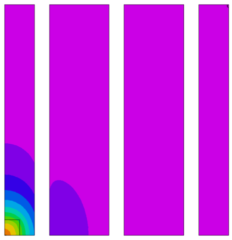


Figure 13. implem. geometry - vert. cut

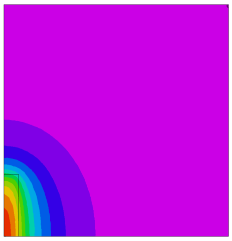


Figure 14. porous media - horiz. cut

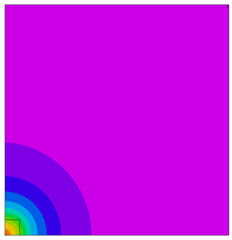
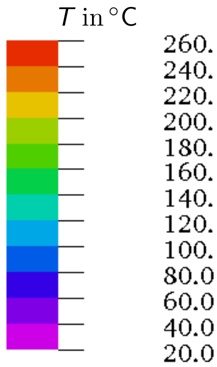


Figure 15. porous media - vert. cut



Discussion, Conclusions and Outlook

The experimental investigation has shown that an internal heat source is detectable by infrared thermal imaging in certain ranges. The visibility is strongly dependent on the heating power of the source. In the very early stage of breast cancer, detection with infrared measurements will be challenging. It needs to be further investigated which cancer stage still might be detectable. Another strong dependence is the amount of perfusion. Higher perfusion leads to a decreased temperature difference at the surface and thus decreased detectability. This can be taken advantage of when conducting measurements of breast cancer patients. The perfusion of tissue can be influenced by, for example, application of cold stress, which is known to reduce the blood perfusion of healthy tissue but not of cancerous tissue [6]. Furthermore, the experimental data can be used to improve modelling of heat transfer in the female breast. Regarding the mathematical model, it is of interest if a porous media model can be as accurate as a model with implemented vessel geometry. The later would be rather impracticable for clinical practice, as the individual vessel geometry of a patient is unknown. The discrepancy of both models to reality strongly depends on the test case parameters such as the vessel diameter. A final assessment cannot be made at this point, but will be addressed in the future. An accurate numerical model of the breast and breast cancer will facilitate an extensive study of correlations between depths, perfusion, source heating power and detectability at the skin surface.

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