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# ACTIVE DYNAMIC THERMOGRAPHY IN MAMMOGRAPHY

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**Abstract:** We discuss limitations of the known methods of IR imaging in diagnostics of breast cancer. In conclusion we show that the known methods, based on simple observation of external temperature distribution, are not fully effective. Even advanced pattern recognition could not help in analysis of static images. May active dynamic thermography, known in non-destructive testing of materials, be of any help in breast cancer diagnostics? Analysis of thermal transients forced by external thermal excitation shows, even on simple models, that one may expect a visible improvement in resolution after such excitation. Applied models allow analysis of both static and active thermograms. Basing on the models one may recognise elements of the internal structure of a breast not visible in static pictures. This method, new in clinical practice, seems to be promising, but requires further studies.

**Keywords:** thermography, breast cancer, mathematical modelling

## 1. Introduction

Among malignant tumour diseases, breast cancer is the most frequent cause of death of women. Early detection is crucial for their survival.

Infrared thermography has been used clinically for over forty years. The correlation between surface skin temperature and an underlying malignant disease was first realised in the case of breast cancer [1, 2]. It was shown that the temperature difference is up to 2.5°C. A thermographic method of breast cancer diagnosis was introduced at several medical centres [3–5]. In the early publications, the obtained results were very promising and detectivity (true positive) was about 94% [6]. Unfortunately, routines of physicians, poor control of environmental conditions during examinations and a lack of understanding of the basic principles of thermography were often reasons for false diagnosis in the later period. In consequence, medical practicioners rejected the thermographic method of breast cancer detection and its current opinion is very negative.

Recently, one can observe the development of new methods of medical imaging and image processing algorithms to enhance cancer detection. One of the most interesting is the IR-thermographic technique. It is connected with new generations of

digital thermographic cameras (the improved thermal and spatial resolution) [7], with new image processing algorithms [8], and the modelling of thermal processes in living tissues (basing on the bio-heat transfer equation [9, 10] and with thermal tomography concepts [11, 12]). There are even statements that thermographic methods with external heating or cooling of breast tissues are of the highest importance [13–15].

## 2. Measurement procedure

It is known that static breast thermograms provide limited information for diagnosis. Therefore, temperature stress is applied to induce a thermal response of tested object. In active dynamic thermography a target object is thermally excited for a given time period. Different methods and sources of excitation may be applied: optical devices, microwave generators, fan cooling. After the stress, a temperature transient process in the object is recorded using a thermographic system. This technology is based on the fact, that thermal properties of matter are dependent on the internal physical structure and physiological processes of tested sample. Most importantly, the physically measurable parameters are independent of external conditions, giving quite reliable quantitative data. Determination of thermal properties of the tested tissues involves a reconstruction procedure – fitting the data to a thermal model, where thermal conductivity, $k$, the specific heat, $c_w$, and density, $\rho$, of the material play a major role. Therefore, the evaluation of local thermal effusivity is giving an objective figure of merit for the characterisation of tissue quality and its internal structure. In this paper, 1- and 2-exponential models, described by Equations (1) and (2) respectively, are used to characterize thermal properties of the tested objects:

$$T(t) = T_{eq} + \Delta T_1 e^{-\frac{t}{\tau_{1c}}}, \tag{1}$$

$$T(t) = T_{eq} + \Delta T_1 e^{-\frac{t}{\tau_{1c}}} + \Delta T_2 e^{-\frac{t}{\tau_{2c}}}, \tag{2}$$

where $T_{eq}$ is a steady state temperature of tissue; $\Delta T_1$, $\Delta T_2$ – increase of temperature; $\tau_{1c}$, $\tau_{2c}$ – time constants of the model. Estimated model parameters are correlated with thermal properties of breast tissues. The most important is the thermal time constant, as this figure is independent on the level of excitation.

An Akaike information criterion (AIC) [16] is used as a model quality measure defined by Equation (3). This model better fits the observed data for which the value of AIC is smaller:

$$\mathrm{AIC} = \mathrm{FC}(\mathbf{P}_{opt}) \cdot e^{\frac{2p}{n}}, \tag{3}$$

where $p$ is a number of model parameters, $\mathbf{P}_{opt}$ – vector of the optimal model parameters, FC – a criterion function defined as: $\mathrm{FC}(\mathbf{P}_{opt}) = \frac{1}{n-p} \cdot \sum_{i=1}^{n} [y_i - f(t_i, \mathbf{P}_{opt})]^2$, $n$ – number of measurements, $y_i$ – measurement values for time $t_i$.

## 3. Numerical modelling

To test the usefulness of active dynamic thermography in breast cancer diagnostics, a numerical simulation (Finite Elements Method) is carried out. Simulated thermographic experiments are obtained by numerical computation using the geometry and boundary condition of numerical models such as that presented in Figure 1. Hemispheric geometry is assumed to reduce the problem to 2D.

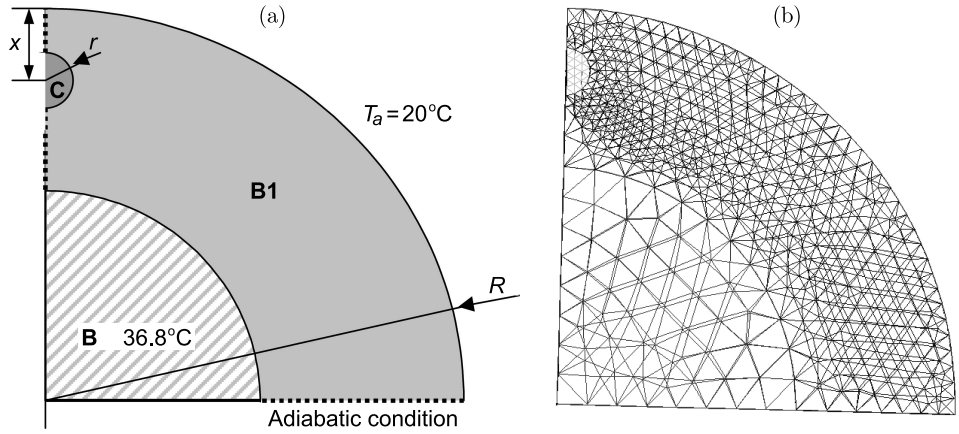


**Figure 1.** Numerical model of a breast with tumour inside:
(a) geometry and boundary conditions; (b) FEM mesh of the model

Assuming a symmetry of the breast, the model is further simplified to $1/4^{\text{th}}$ of a circle. Indications: **B** – healthy breast tissue (temperature 36.8°C and set of parameters: $k_b$, $\rho_b$, $c_{wb}$); **B1** – healthy tissue (parameters like **B**, without simulation of metabolic processes); **C** – cancer tissue ($k_c$, $\rho_c$, $c_{wc}$), $x$ – position of the cancer inside the breast; $r$, $R$ – radiuses of the cancer and the breast.

Taking into account the available procedures of thermographic inspection, two kinds of computations have been performed:

- steady state for parameters given in Table 1 (temperature distribution on the model surface is regarded as the figure of merit);
- transient analysis after thermal stimulation by heat flux $\phi = 4800\,\text{W/m}^2$, lasting 30 seconds (thermal time constants are of major importance).

**Table 1.** Parameters of the numerical model of a breast; ambient temperature $T_a = 20^\circ\text{C}$

| $r = 3\,\text{mm}$<br>$R = 70\,\text{mm}$ | specific heat<br>$c_w$ [J/(kg K)] | density<br>$\rho$ [kg/m$^3$] | conductivity<br>$k_{eff}$ [W/(m K)] | tissue temperature<br>$T$ [°C] |
|---|---|---|---|---|
| Breast tissue | 2303 | 971 | 0.36 | 36.8 |
| Tumour tissue 1 | 2303 | 1200 | 0.60 | 38.8 |
| Tumour tissue 2 | 2303 | 1200 | 0.60 | 37.8 |

Other assumptions have included an adiabatic condition at the internal boundary (there is no heat flow at the dotted lines), an ambient temperature of $T_a = 20^\circ\text{C}$, heat exchange forced at the breast surface by external excitation or by radiation and conduction at rates known for the steady state. Thermal parameters used for modelling of breast tissue have been the same as those obtained by Henriques and Moritz for in-vitro measurements for pig's skin tissue [17]. The simplest model of isotropic material has been assumed.

### *3.1. Simulation results*

Temperature distribution at the breast surface in the steady state is shown in Figure 2 as a function of distance, $d$ [mm], from the top of the breast for various cancer positions, $x$ [mm].

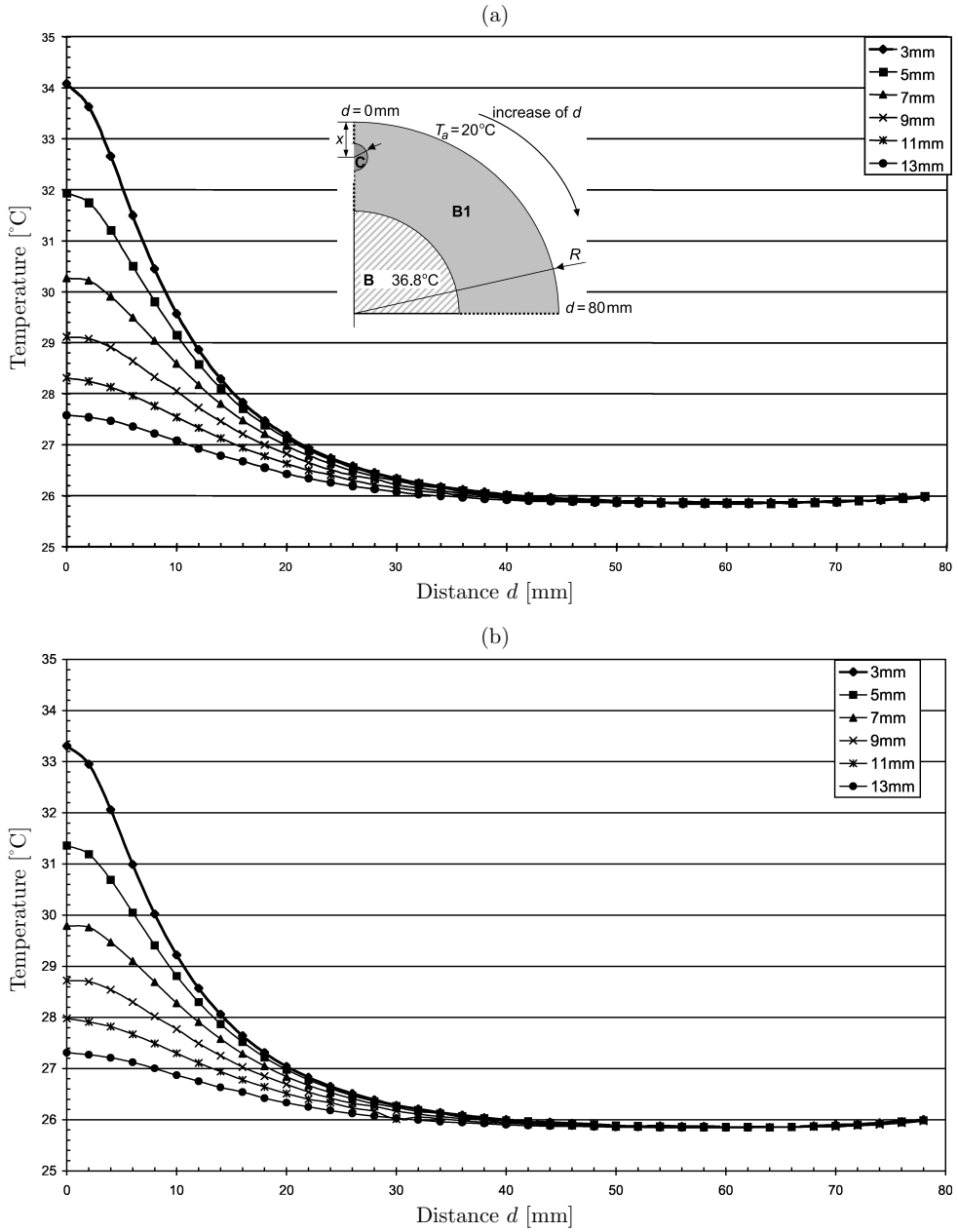


**Figure 2.** The temperature distribution on the breast surface for various cancer positions, $x$ (upper right corners). Tumour temperature: (a) $T_c = 38.8^{\circ}\mathrm{C}$, (b) $T_c = 37.8^{\circ}\mathrm{C}$

Results of the simulation have shown that it is possible to detect tumour tissue characterised by increased temperature using static thermography. A temperature difference about $1^{\circ}\mathrm{C}$ between healthy and pathological tissue gives a higher temperature on the surface over the cancer's location, even for cancers lying 14mm under the surface. Unfortunately, for cancers with normal temperature it is impossible. The slicing method developed in the USA [10] allows one to estimate the depth of cancer basing

on the measurement of the surface temperature distribution. For a 2-dimensional, rectangular model of a breast with a cancer point inside, the depth of the tumour is equal to a distance to the surface for which temperature is decreased by $0.707T_{\max}$. The numerical simulation performed in this paper shows that a distance for which temperature is decreased by $0.9T_{\max}$ better describes the depth of the tumour. Temperature distribution in a cross-section of the breast is shown in Figure 3.

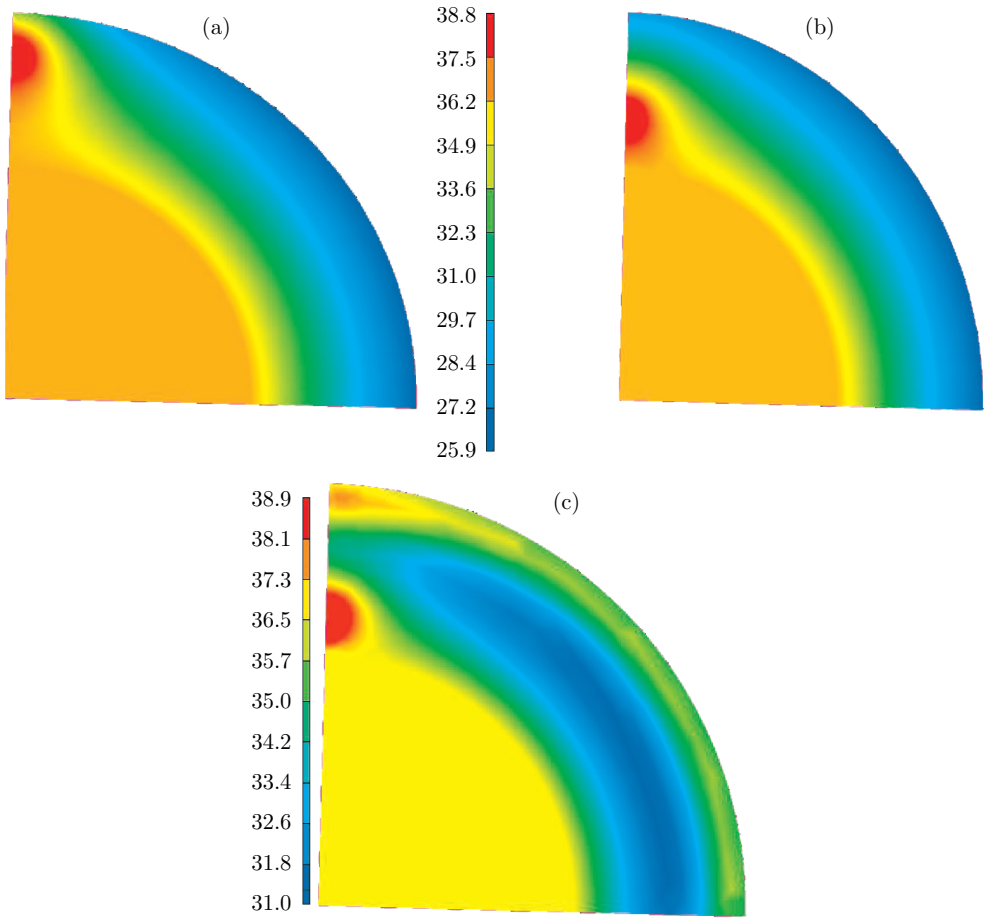


**Figure 3.** Temperature distributions: (a) steady-state breast model with cancer 6mm under the surface, (b) steady-state cancer 14mm under the surface, (c) 30 seconds following an external stimulation. Cancer temperature $T_c = 38.8^{\circ}$C in all cases

Unfortunately, not always tumours are characterised by increased temperatures. In such cases, it is impossible to detect the cancer using static thermograms. However, active dynamic thermography methods can improve the effectiveness of tests [18, 19]. Results of the FEM simulations and the fitting procedure are shown in Figure 4(a)–(c) and in Tables 2 and 3.

Values of the Akaike criterion (AIC) show that the 2-exponential model better describes the thermal processes in multi-layer structures.

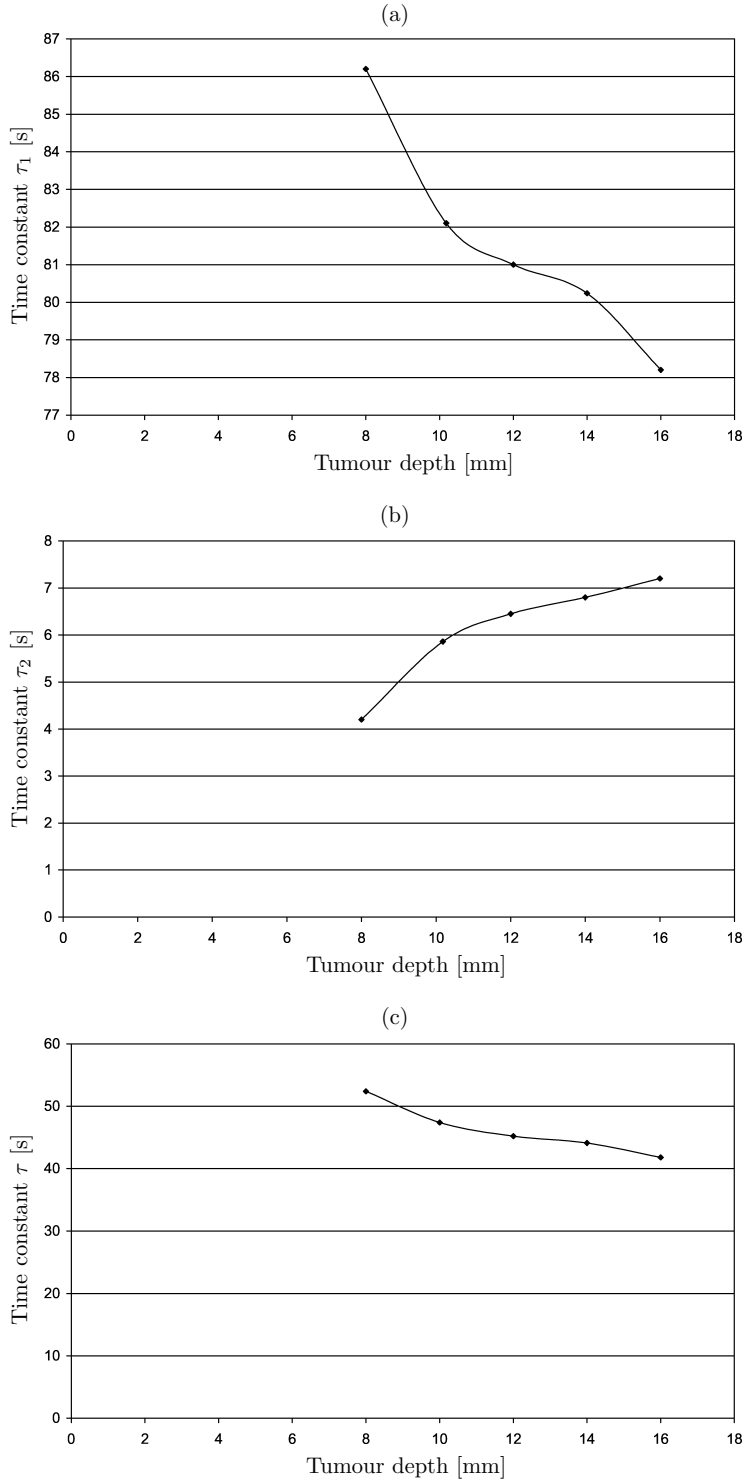


**Figure 4.** Estimated time constants of the 2-exponential model: (a) $\tau_1$, (b) $\tau_2$; and for the 1-exponential model: (c) $\tau$

**Table 2.** Estimated model parameters for numerical simulations, cancer temperature $T_c = 38.8^{\circ}$C, region on the surface above the tumour (distance $d = 0$mm), 2-exponential model, $\pm se$ – standard error

| Tumour depth $x$ [mm] | 8mm | | 10mm | | 12mm | | 14mm | | 16mm | | healthy | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ |
| AIC | 0.054 | | 0.054 | | 0.076 | | 0.098 | | 0.087 | | 0.076 | |
| $T_{eq}$ | 32.5 | 0.0 | 31.2 | 0.0 | 30.5 | 0.0 | 30.1 | 0.0 | 29.6 | 0.0 | 28.2 | 0.0 |
| $\Delta T_1$ | 14.8 | 0.1 | 12.3 | 0.1 | 11.2 | 0.1 | 10.9 | 0.1 | 10.8 | 0.1 | 11.3 | 0.1 |
| $\tau_{1c}$ | 86.2 | 0.6 | 81.4 | 1.3 | 81.0 | 1.7 | 80.6 | 1.8 | 78.2 | 1.7 | 68.7 | 1.4 |
| $\Delta T_2$ | 11.0 | 0.2 | 12.7 | 0.2 | 13.1 | 0.2 | 12.4 | 0.2 | 12.5 | 0.2 | 12.0 | 0.2 |
| $\tau_{2c}$ | 3.7 | 0.1 | 6.7 | 0.2 | 7.2 | 0.2 | 6.6 | 0.2 | 7.2 | 0.2 | 4.9 | 0.2 |

**Table 3.** Estimated model parameters for numerical simulations, cancer temperature $T_c = 38.8^{\circ}$C, region on the surface over the tumour (distance $d = 0$mm), 1-exponential model, $\pm se$ – standard error

| Tumour depth $x$ [mm] | 8mm | | 10mm | | 12mm | | 14mm | | 16mm | | healthy | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ | Value | $\pm se$ |
| AIC | 0.515 | | 0.767 | | 0.809 | | 0.736 | | 0.694 | | 0.683 | |
| $T_{eq}$ | 32.8 | 0.1 | 31.9 | 0.1 | 31.4 | 0.1 | 30.9 | 0.1 | 30.3 | 0.1 | 28.7 | 0.1 |
| $\Delta T_1$ | 18.2 | 0.2 | 17.3 | 0.2 | 16.7 | 0.3 | 16.1 | 0.2 | 16.4 | 0.2 | 15.7 | 0.2 |
| $\tau_{1c}$ | 52.4 | 0.9 | 47.4 | 1.2 | 45.2 | 1.2 | 44.1 | 1.2 | 41.8 | 1.1 | 42.1 | 1.1 |

Numerical simulations show an evident correlation between the physical structure, the thermal properties and the estimated model parameters. Thus, basing on active dynamic thermography procedures and an estimation of thermal model parameters it is possible to detect an abnormality in a living tissue structure.

## 4. Clinical tests

Clinical tests were performed in the Oncology Surgery Clinic, Medical University of Gdansk. Three women with diagnosed breast cancer (mammography and biopsy) were examined using an active dynamic thermography procedure. Results for one of them are presented below.

A set of halogen lamps was used as an external heating source (of electrical power of 1000W), from the distance of 50cm, a pulse lasting 30seconds. Basing on sequences of thermograms recorded during the cooling phase, synthetic images, were calculated according to the thermal properties of tissue (see Figure 5).

Static thermogram analysis shows "hot spots" and significant asymmetries in temperature distribution at quadrants of the left and right breast. Active dynamic thermography detects pathological changes at the right-upper quadrant of the breast.

## 5. Conclusions

The most valuable conclusion from our numerical simulations is that the estimated time constants $\tau_1$ and $\tau_2$ of the thermal model allow the recognition of abnormal tissue placed under a layer of healthy tissue. It is especially important when the affected tissue or tumour have the same temperature as healthy tissue but

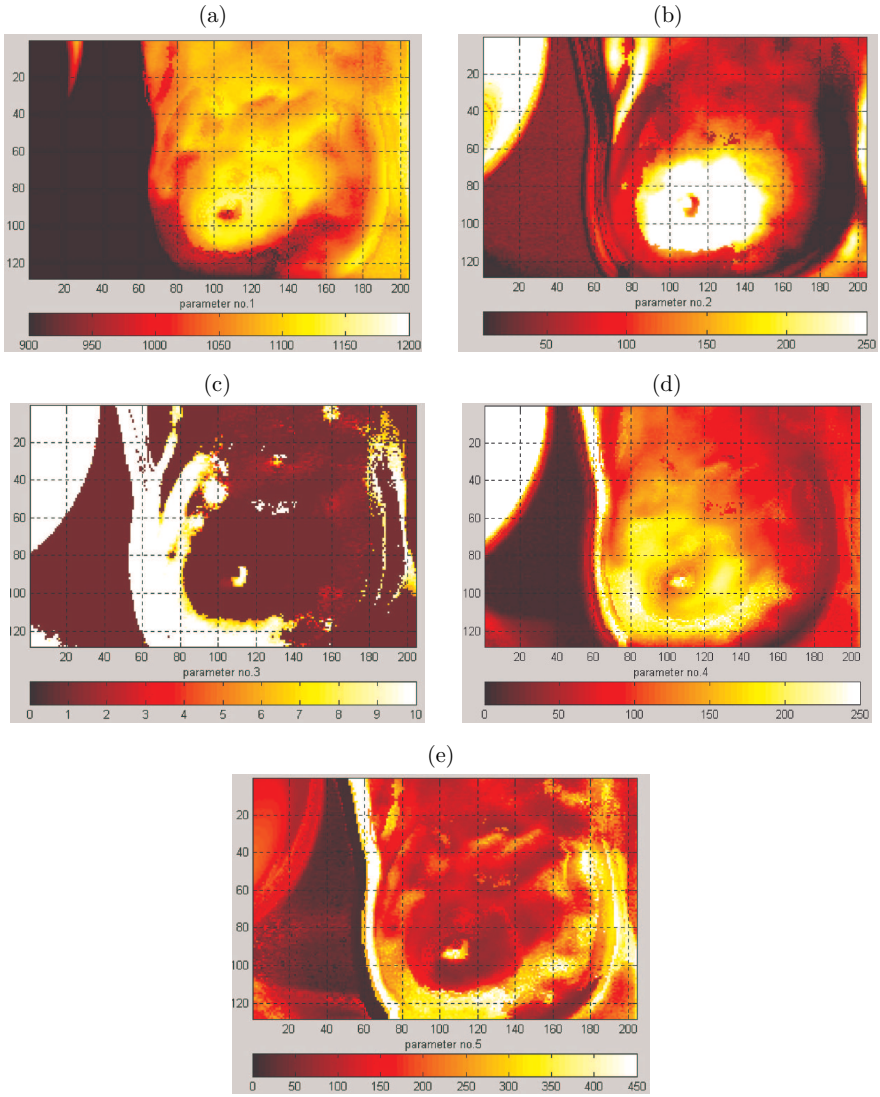


**Figure 5.** Synthetic images of thermal model parameters: (a) $T_{eq}$, (b) $\Delta T_1$, (c) time constant $\tau_1$, (d) $\Delta\ T_2$, (e) time constant $\tau_2$

different thermal properties (thermal conductivity, thermal capacity). In this case, it is impossible to detect a tumour using static thermography. Of course, one must take into account the limitations of the new technique. Due to the limited thermal resolution of the thermal camera and limited (safe for the patient) power of external excitation, the depth of detectable cancers is also limited.

Joining the thermal model with registered thermal sequences using an active dynamic thermography procedure is the first step to generate thermal tomography images showing the internal structure of the investigated object.

The presented technique involves the evolution of temperature distribution on the skin after thermal excitation. This new method has the ability to detect tumours lying deeper, smaller and even those not characterised by temperature changes. We

have proved that dynamic thermography could be applied in medical procedures for monitoring the state of the skin and subdermal tissue structure, giving objective, measurable ratings. Changes in tissue vascularisation are important for prediction of the cancer growth process. The method is non-contact, non-invasive, clean and stress-free. It allows a wide area of investigation and clear and objective documentation of diagnoses and the treatment process.

Living systems have very sophisticated tissue structures, with many interactions and non-linear processes, also multiple and cross-scattering effects between layers are unavoidable. These create difficulties in interpretation of thermograms and parametric images. Therefore, further studies based on computer simulations are necessary to understand the phenomena taking place in living organisms. Numerical simulations can help us assess the limitations and advantages of thermal tomography.

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