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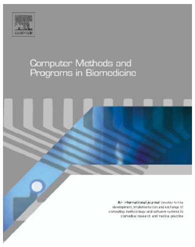

Potentialities of steady-state and transient thermography in breast tumour depth detection: A numerical study

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ABSTRACT

Breast thermography still has inherent limitations that prevent it from being fully accepted as a breast screening modality in medicine. The main challenges of breast thermography are to reduce false positive results and to increase the sensitivity of a thermogram. Further, it is still difficult to obtain information about tumour parameters such as metabolic heat, tumour depth and diameter from a thermogram. However, infrared technology and image processing have advanced significantly and recent clinical studies have shown increased sensitivity of thermography in cancer diagnosis. The aim of this paper is to study numerically the possibilities of extracting information about the tumour depth from steady state thermography and transient thermography after cold stress with no need to use any specific inversion technique. Both methods are based on the numerical solution of Pennes bioheat equation for a simple three-dimensional breast model. The effectiveness of two approaches used for depth detection from steady state thermography is assessed. The effect of breast density on the steady state thermal contrast has also been studied. The use of a cold stress test and the recording of transient contrasts during rewarming were found to be potentially suitable for tumour depth detection during the rewarming process. Sensitivity to parameters such as cold stress temperature and cooling time is investigated using the numerical model and simulation results reveal two prominent depth-related characteristic times which do not strongly depend on the temperature of the cold stress or on the cooling period.

1. Introduction

Breast thermography is an adjunct diagnostic tool to mammography for breast cancer screening. It is a non-invasive, painless and relatively inexpensive procedure for early detection of breast cancer since it does not involve compression of the breast or exposure to radiation. It was first introduced into medicine after the observation that the skin temperature over a malignant tumour in the breast is frequently between 1

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and 3 °C hotter than the surrounding skin [1]. However, there are temperature variations of similar magnitude over a surface of a normal breast due to the disposition of subcutaneous veins [2]. Because of the complex vascular patterns in a breast, thermography images were subject to widely variable and subjective interpretations among image readers and this led to unacceptable rates of false positive and false negative results.

In order to increase the sensitivity of thermograms and to reduce false positive and false negative diagnosis results, transient thermography was introduced. A clinical report by Nagasawa and Okada [3] stated that in order to differentiate breast cancer from benign breast disease, static thermography images should be captured during thermal recovery after applying cold stress. The recovery process can be visualised by sequential thermography or by digital subtraction thermography. Usuki et al. [4] subjected the breast to cold stress by using an alcohol mist and monitored the subsequent rewarming of the breast using a sequence of thermography images captured at different times. These thermography images were then compared for changes in temperature distribution patterns in order to pinpoint accurately the presence of a tumour and thereby reduce false positive results. Because of the large amount of temperature information that can be obtained from a single thermogram, computer analysis of thermography images has been undertaken. Based on theoretical models developed by Steketee [5] to describe thermal recovery of skin after cold stress, Ohashi and Ushida [6] used a digital subtraction technique referred to as μ-thermography to process a sequence of thermograms obtained every 15 s in an attempt to visualise the thermal signature of cold tumours. Results of the clinical experiment showed that diagnostic accuracy improved from 54% in steady state thermography to 82% in dynamic thermography. However, due to the inherent difficulty in applying an even air flow distribution to a curved surface such as the breast, air flow produced thermal artefacts. Recently, Arora et al. [7] conducted a clinical study on the effectiveness of thermography in the detection of cancer in 92 women with dense breasts. Cool air flow was used during thermal imaging and results showed that digital thermal imaging can be useful in detecting breast cancer with 97% sensitivity. Previous clinical studies reported enhanced image thermal contrast of the breast after applying direct thermoconductive cooling methods to the breast. However, other clinical studies that have used ice water immersion of the extremities (hands or feet) as a neurovascular stimulus to identify non-responding blood vessels of a tumour, reported low rates of correlation between the results of cold tests and case histories and the growing evidence of false positives and false negatives [8].

At the present, mammography is the gold standard technique for breast screening. However, it is not as effective for women with dense or surgically altered breasts, or women aged 40 and younger [9]. In the light of recent advance in infrared (IR) camera technology and image processing, there has been a resurgence of biomedical research interest in breast thermography [9–16]: currently, digital cameras with uncooled thermal detectors have a thermal sensitivity of 0.05 °C compared to 0.01 °C of those using cooled thermal detectors [15]. In addition to the increased thermal sensitivity and resolution of modern digital infrared, sophisticated image processing software using artificial neural network and bio-statistical analytical methods are being incorporated to help the clinician in the interpretation of thermograms, thus reducing the high incidence of false-positive results [17–20]. However, breast thermography is still limited by the false positive findings in cases of infection or inflammation of breast parenchyma. Further, thermography is technically limited for morbidly obese patients that preclude accurate recording of temperature from the interior of the breast [7]. Among other challenges of breast thermography are enhancing the thermal signature of small and deep seated tumours and predicting the diameter and the position of a tumour from the surface thermal map.

Numerical simulations, based on Pennes bioheat equation, have been used to evaluate the temperature distributions over a breast with and without a tumour and to calculate the tumour induced thermal contrast. Numerical results have provided valuable information as to whether an abnormal area is present underneath the breast skin. It was also found that the steady state thermal contrast depends on both tumour depth and diameter but was too small to be measured for deep seated tumours [21–29].

To assess the effectiveness of a cold stress test in breast thermography, Ng and Sudharsan [26] simulate the rewarming phase of a tumourous breast after using a lumped system analysis to calculate the depth of the cold layer induced by a step change in environmental temperature. The temperature pattern obtained after 60 min of rewarming was almost comparable with the steady state temperature distribution. Further, subtraction of thermal profiles obtained after three time intervals of rewarming did not provide any additional information with respect to the steady state thermogram. On the other hand, Hu et al. [30] examined the influence of the airflow on the surface thermal signature of a breast cancer using a numerical model. It was found that the presence of tumour may not be clearly shown due to the irregularities of the skin temperature distribution induced by the air flow. Nevertheless, image subtraction techniques could be employed to eliminate the effects of the flow field and thermal noise and significantly improve the thermal signature of the tumour on the skin surface. In order to differentiate tumour-induced from the gravity induced surface thermal contrast, Jiang et al. [28] compared dynamic thermography responses after changing the ambient temperature from 25 °C to 20, 15 and 10 °C during cooling and switching back the ambient temperature to 25 °C during rewarming. Results showed that tumour induced and deformation induced thermal contrasts have different transient time courses during cold stress and thermal recovery procedure. Unfortunately, none of the aforementioned numerical simulations has investigated the possibility of extracting information about the diameter or depth of a tumour from a thermogram at steady state or during recovery from cold stress.

The characterisation of tumours based on the surface temperature profile over the malignant breast represents an ill-posed inverse heat conduction problem. In the late 70s, Chen et al. [31] studied the feasibility and limitations of determining interior information from surface temperature measurements. Earlier work of Feasey et al. [32], using a simple theoretical heat transfer analysis showed that, since the tumour has a higher metabolic rate than normal tissue, it