International Journal of Heat and Mass Transfer 98 (2016) 81–95

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Estimation of growth features and thermophysical properties of melanoma within 3-D human skin using genetic algorithm and simulated annealing

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ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form 3 March 2016
Accepted 3 March 2016

Keywords:
Bioheat
Skin melanoma
Tumor growth
Thermal imaging
Inverse analysis
Genetic algorithm
Simulated annealing

ABSTRACT

A study has been performed on human skin model with the motivation to device an effective non-invasive modality to characterize the subsurface skin cancer features such as tumor diameter, penetration depth, blood perfusion and metabolic heat generation based on the thermal response of the skin surface obtained from the thermal images. The work presents the role of data mining algorithms to find the tumor features underneath the skin based on the surface temperature variations obtained from a 3-D model of human skin. The human skin is assumed to be subjected to combined radiative, convective, and evaporative heat flux boundary conditions. The study revealed that, the major variation in the thermal response of tumor is attributed to increase in the volume, blood perfusion and thermogenic capacity. The variations due to inter- and intra-patient variability of tumor properties and size are obvious, which could be explained by the retrieved multiple combinations of variables. Furthermore, the reconstructed surface thermal distributions associated with estimated variables are found to be in a good match with the actual maps. The error <10% in the measured thermal distribution tends to give accurate reconstruction. Present strategy or algorithm along with a thermal camera may prove to be a useful diagnostic tool for the characterization of subsurface skin cancer and reduce the unnecessary biopsy trials.

1. Introduction

Skin cancers are found within the epidermis or in the dermis, and are named after the type of cells. It is one of the commonly found cancers among the patients in the United States (US) and around the world [1,2]. In general, the cancer of skin is categorized into melanoma and non-melanoma. Furthermore, based on the appearance, skin lesions are also distinguished as pigmented and non-pigmented lesions. Among all types of skin cancers, the melanoma metastasizes rapidly, causes the majority of the deaths and spreads to soft tissues like lung and liver [3]. Therefore, it is important to detect and characterize the melanoma condition as early as possible.

In the present clinical settings, the traces of skin melanoma can be detected using (a) conventional approaches, viz., examining the skin morphological features using dermoscopes or by surgical excision and pathological studies [4] and using (b) newly developed microscopic and non-invasive imaging modalities [5,6]. To a certain extent, the characterization of melanoma conditions, viz., stages (tumor diameter and penetration depth) within the skin can be determined using standard biopsy procedures [4] and by imaging technique [6].

Major issues identified using these approaches are (a) some of these methods being relatively expensive and demands specialized handler, (b) relatively high cost of histologic preparation and delay in attaining relevant information, (c) possibility of multiple biopsy trails to ascertain the cause and stages, and (d) increases the patient's anxiety level. Overall, there are growing demand of methodologies which could provide first-hand information about the skin malignancy in a simple clinical setting and strengthen the confidence of medical practitioners to take a reasonable decision. Thus, prior knowledge about the various development phases of skin melanoma would lessen the unnecessary biopsy trials. Thereby, increasing the patient longevity and improves the quality of life. In view of this, the present work proposes the role of non-invasive, non-contact, quick, easy-to-handle and inexpensive thermal system along with the data-mining algorithms to measure the essential *in vivo* properties of tumor and cancer staging/growth parameters.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.020
0017-9310/

Nomenclature

B	Boltzmann probability distribution
c	specific heat (J kg^{-1} K^{-1})
d_l	tumor diameter (mm)
e_r	measurement error
Gen	generation in genetic algorithm (GA)
H	total height from datum (mm)
h_{conv}	convective heat transfer coefficient (W m^{-2} K^{-1})
h_p	tumor penetration depth (mm)
h_s	tumor depth from skin surface (mm)
$Iter$	iterations in simulated annealing (SA)
J	objective function
k	thermal conductivity (W m^{-1} K^{-1})
k_b	Boltzmann constant
N	population size in GA
P	pressure (Pa)
P_v	vapor pressure of humid air (Pa)
P_{sat}	saturated pressure of water vapor (Pa)
p_c	crossover probability
p_m	mutation probability
q''	heat flux (W m^{-2})
q_m	volumetric heat generation due to metabolism (W m^{-3})
r	position/coordinates
t	time (s)
T	temperature (°C)
T_∞	surrounding temperature (°C)

Greek symbols

α_t	thermal diffusivity (m^2 s^{-1})
ε	emissivity
ρ	density (kg m^{-3})
ϕ_a	relative humidity of air
σ	Stefan–Boltzmann constant (=5.6704 × 10^{-8} W m^{-2} K^{-4})
ω_b	blood perfusion within the tissue (m^3 s^{-1} m^{-3} tissue)
ω_{rsw}	specific humidity of skin

Subscripts

a	arterial blood
act	actual
b	blood
c	core
$cool$	cold
$conv$	convection
$evap$	evaporation
est	estimated
max	maximum
rad	radiation
s	surface
t	tissue

Inverse problems are mathematically ill-posed, which demands special algorithms for approximation. In past, various inverse algorithms were used by investigators for the estimation of thermophysical properties and dimensions of tumor within the biological bodies [7–16]. Das et al. [7–9] estimated the location, size and blood perfusion within tumor of 1-D and 2-D breast models using direct search algorithm [7], genetic algorithm (GA) [8], and curve fitting technique [9]. Recently, Das and Mishra [10] simultaneously estimated the tumor size and location by fitting the temperature profile obtained from the 3-D breast model. The study highlighted that the curve fitting method is very fast compared to the conventional inverse methods. However, the curve fitting approach [9,10] was found to be suitable only if the correlation between temperature profile and parameters are known. Similarly, Sadeghi-Goughari et al. [11] employed artificial neural network (ANN) to estimate the depth of tumor, temperature of *in vivo* tumor, and the tumor heat source based on the surface thermal response of mimicking brain tissue measured using an artificial tactile temperature sensing device. In addition, GA was used by Partridge and Wrobel [12] to estimate the size and location of tumor within 2-D model of skin. In a similar nature of studies [13,14], the conjugate gradient method (CGM) was used for the estimation of (a) external source and heat transfer coefficient at the surface of 1-D skin to attain control of temperature along the tissue during hyperthermia procedure [13], and (b) estimation of optimized thermal dose [14]. The CGM was also used for the retrieval of optimized electrode configuration, viz., position, sizes and driving voltage, used for radio frequency capacitive hyperthermia of 2-D biological body [15]. The use of Levenberg–Marquardt method was demonstrated by Huang and Huang [16] for simultaneous estimation of effective thermal conductivity and volumetric heat capacity of biological tissue.

This study pertains to an active mode of thermography, i.e., thermal mapping and screening are done during the thermal recovery of skin from the external cold stimulus [17–19]. During this method, initially the surface of skin is cooled for a certain period of time and then allowed the skin to return to its normal condition by removing the cold stress at the surface. The surface of skin is screened for cancerous lesion at the end or during thermal recovery. In this work, the forward model mimics the active mode of thermography to estimate 2-D surface thermal distribution of cancerous lesion embedded in a 3-D skin model. On the other hand, the inverse analysis demonstrates the use of two different algorithms, viz., GA and simulated annealing (SA), for simultaneous estimation of tumor growth features and thermophysical properties based on the surface thermal maps. The GA and SA does not require the gradient information, and works well for any problems. The major issue with these algorithms was the associated longer computational time. However, in the present day scenario, increasing use of parallel and high power computing mitigates such issue. The study used a 3-D model in the inverse analysis for two reasons; (a) to simultaneous estimate the unknown parameters based on the 2-D surface thermal maps and (b) to reconstruct the 2-D blood perfusion and metabolic heat generation maps/images for many important applications. The latter is not demonstrated in this work and currently under investigation.

The appearance of subsurface cancerous tumor within the skin causes a variation in surface thermal response from that of the healthy skin due to the change in tumor volume, blood perfusion and metabolic heat generation caused by tumor growth [17]. The change in surface thermal response could be measured using the present thermal imaging system in a simple clinical setting [17]. However, the associated causes, viz., tumor volume, blood perfusion and metabolic heat generation remains undetermined. These *in vivo* features reveal further information about the characteristics of cancerous tumor. Thus, the knowledge of these tumor parameters in a simple clinical setting apart from its detection would be a first-hand information for its characterization, which would reduce the time and cost of biopsy.

Therefore, the present work integrates a data-mining algorithm with the forward model (for thermal imaging system) to simultaneously estimate the various *in vivo* features using the measured skin surface thermal responses. In reality, the skin surface thermal response could be measured using a thermal camera. Then, the