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Suitability of frequency modulated thermal wave imaging for skin cancer detection—A theoretical prediction

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ABSTRACT

A theoretical study on the quantification of surface thermal response of cancerous human skin using the frequency modulated thermal wave imaging (FMTWI) technique has been presented in this article. For the first time, the use of the FMTWI technique for the detection and the differentiation of skin cancer has been demonstrated in this article. A three dimensional multilayered skin has been considered with the counter-current blood vessels in individual skin layers along with different stages of cancerous lesions based on geometrical, thermal and physical parameters available in the literature. Transient surface thermal responses of melanoma during FMTWI of skin cancer have been obtained by integrating the heat transfer model for biological tissue along with the flow model for blood vessels. It has been observed from the numerical results that, flow of blood in the subsurface region leads to a substantial alteration on the surface thermal response of the human skin. The alteration due to blood flow further causes a reduction in the performance of the thermal imaging technique during the thermal evaluation of earliest melanoma stages (small volume) compared to relatively large volume. Based on theoretical study, it has been predicted that the method is suitable for detection and differentiation of melanoma with comparatively large volume than the earliest development stages (small volume). The study has also performed phase based image analysis of the raw thermograms to resolve the different stages of melanoma volume. The phase images have been found to be clearly individuate the different development stages of melanoma compared to raw thermograms.

1. Introduction

A significant number of people throughout the world are affected with skin cancers. According to World Health Organization, approximately 2–3 million cases of non-melanoma and 132,000 cases of melanoma occur every year globally (WHO, 2014). The highest rate of skin cancer is observed in Australia and New Zealand, which is four times higher than the Canada, the US and the United Kingdom. Cancer of the skin generally appears within the epidermal and dermal layers. It is often categorized into melanoma and non-melanoma. Among all types of skin cancers, the melanoma metastasizes rapidly and causes the majority of deaths. Thus, it is important that the melanoma has to be detected as early as possible before the cells start invading and spreading.

In the current clinical settings and research facilities many conventional and state-of-the-art non-invasive modalities are explored for the detection and the differentiation of skin cancer, viz., terahertz pulse imaging (Woodward et al., 2002), reflectance mode short-pulse laser detection method (Bhowmik et al., 2014a), thermal imaging (Çetingül and Herman, 2011; Bonmarin and le Gal, 2014a; Bhowmik et al., 2014b) and many more (Psaty and Halpern, 2009). In the recent years, the use of thermal imaging techniques for the detection and the differentiation of skin cancer stages have gained exceptional interest. The infrared (IR) imaging techniques are quite useful for pre- and post- clinical evaluation, since these techniques are relatively fast and can be utilized repetitively for longer span without the risk of radiation. At present, IR imaging techniques are widely used in many biomedical applications, viz., detection of early skin cancer (Bonmarin and le Gal, 2014a; Bhowmik et al., 2014b) and breast cancer (Lawson, 1956), estimation of skin temperature oscillation due to subsurface blood flow (Sagaidachnyi et al., 2014), estimation of burn injury (Cole et al., 1990), monitoring the efficacy of drugs (Hintersteiner et al., 2005) and treatment (Santa Cruz et al., 2009), vascular disorders (Bagavathiappan et al., 2009), pains (Gulevich et al., 1997),

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Nomenclature

B	modulated wave bandwidth (Hz)
c	specific heat (J kg^{-1} K^{-1})
D	diameter of lesion (mm)
f	frequency (Hz)
g	acceleration due to gravity (m s^{-2})
h	depth (mm)
k	thermal conductivity (W m^{-1} K^{-1})
P	pressure (Pa)
q''	modulated heat flux (W m^{-2})
Q'''_m	metabolic heat generation (W m^{-3})
r	vessel radius (mm)
t	time (s)
T	temperature
u, v, w	velocity (ms^{-1})
x, y, z	position/coordinates

Greek symbols

μ	viscosity of blood (Pa s)
ρ	density (kg m^{-3})
ω_b	blood perfusion within the tissue (s^{-1})
τ	duration of heating cycle (s)

Subscripts

a	arterial blood
b	blood
c	core
mel	melanoma
norm	normal
p	penetration
s	surface
t	tissue

Abbreviations

CL II	Clark level II
CL III	Clark level III
CL IV	Clark level IV
DTI	dynamic thermal imaging
ES I	early stage
FMTWI	frequency modulated thermal wave imaging

monitoring the thermal response of skin surface during photothermal ablation of subsurface tumor (Sajjadi et al., 2008; Paul et al., 2014), aftermaths of cryo-therapy (Costello et al., 2012), evaluation of the state of biological implant (Yang et al., 2009), detection and characterization of subsurface chromophores in biological materials (Milner et al., 1995; Milner et al., 1996; Telenkov et al., 2002), estimation of increasing fat thickness (Bhowmik et al., 2015), thermal tomography (Shi et al., 2014), and many more (Diakides and Bronzino, 2007). The advancement and deeper understanding of bio-optics, digital manipulation, image processing, thermal and physiological characteristics of human body made the thermography a capable technique to evaluate the subsurface changes efficiently. The advancement in IR-imaging techniques does not mean that the existing diagnostic methods lose their importance. The existing methods are equally advancing in terms of quality and effectiveness. Thermal imaging techniques have added advantages of being fast, safe and simple, and have the ability to provide thermo-physical changes at the subsurface regions which are not understood well with the other methods.

The present study evaluates the performance of newly introduced active thermal imaging method, i.e., frequency modulated thermal wave imaging (FMTWI) technique (Mulaveesala and Tuli, 2006) for the detection and the differentiation of various stages of skin melanoma with the aid of comprehensive modeling strategies. Based on the available literature on various thermal imaging techniques (di Carlo, 1995; Feasey et al., 1971; Milner et al., 1996; Telenkov et al., 2002; Deng and Liu, 2004; Çetingül and Herman, 2010, 2011; Bhowmik et al., 2013b; Bonmarin and le Gal, 2014a, 2014b; Bhowmik et al., 2014b) it can be noted that, the use of FMTWI techniques for the detection and the differentiation of skin cancer stages are limited. The thermal imaging of skin surface using FMTWI technique can be achieved by controlled heating of the surface using frequency modulated thermo-stimulation. The heating of the skin surface causes the generation of non-stationary thermal wave (i.e., frequency varies with time), which undergoes damping due to the presence of subsurface melanoma volume while diffusing within the skin. The attenuation of thermal wave due to the subsurface melanoma volume causes the appearance of identifiable temperature contour on the surface thermograms. The probing depth range of melanoma volume and the resulting resolution of the technique depend on the thermal diffusivity and band of frequencies.

It is worth noting here that, the key difference in all the earlier thermographic studies for the detection of skin cancer (Çetingül and Herman, 2010, 2011; Bonmarin and Le Gal, 2014a, 2014b; Bhowmik et al., 2014b) and for the characterization of chromophores (Milner et al., 1995; Milner et al., 1996; Telenkov et al., 2002) within the skin is the applied boundary condition on the surface of the skin. A number of investigations on skin cancer detection using dynamic thermal imaging (DTI) during thermal recovery from cold stress have been carried out by applying either the convective heat flux (Çetingül and Herman, 2010, 2011) or the combined heat flux condition (Bhowmik et al., 2014b) on the skin surface. In case of lock-in thermal (LIT) imaging of skin cancer (Bonmarin and le Gal, 2014a, 2014b), the skin surface is subjected to periodically modulated combined heat flux condition which is due to the amplitude modulation of the cold air temperature over the skin surface. The pulse photothermal radiometry (PPTR) for the detection (Telenkov et al., 2002) and the characterization of chromophores (Milner et al., 1995; Milner et al., 1996) within the skin also works on the principle similar to LIT with the difference being heating (instead of cooling) of the skin surface and the subsurface chromophores using periodically amplitude modulated (AM) radiation emitted from a CW laser. However, during FMTWI of skin melanoma, the surface of the skin is heated using frequency modulated (FM) heat flux with constant wideband amplitude for each modulation cycle. Therefore, the present method (FMTWI) is completely a different approach compared to the class of earlier thermographic approaches (viz., DTI, LIT and PPTR) employed on biological tissues. This method demonstrates (a) the utilization of frequency modulated heat flux for non-stationary thermal wave excitation compared to monofrequency excitation during LIT (Bonmarin and le Gal, 2014a, 2014b) and PPTR (Milner et al., 1995; Milner et al., 1996) and (b) the application of phase sensitive detection on each pixel to compute the images of thermal wave phase in the frequency domain compared to the raw thermal images in case of DTI (Bhowmik et al., 2014b). The FMTWI method utilizes the advantage of non-stationary thermal wave