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Implementation of a thermomechanical model to simulate laser heating in shrinkage tissue (effects of wavelength, laser irradiation intensity, and irradiation beam area)

Patcharaporn Wongchadakul[a,**], Phadungsak Rattanadecho[b,*], Teerapot Wessapan[c]

[a] Faculty of Medicine and Public Health, HRH Princess Chulabhorn College of Medical Science, Chulabhorn Royal Academy, Bangkok, 10210, Thailand
[b] Center of Excellence in Electromagnetic Energy Utilization in Engineering (C.E.E.E.), Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani, 12120, Thailand
[c] School of Aviation, Eastern Asia University, Pathumthani, 12110, Thailand

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ABSTRACT

Advancements in the use of laser technology in the medical field have motivated the widespread use of thermal energy to treat a wide variety of diseases and injuries. During laser-induced thermotherapy, the tissue gains heat from laser irradiation and its shape is deformed due to non-uniform temperature distribution. To describe the phenomenon adequately, the mathematical model that considers both heat transfer and mechanical deformation is needed. In this study, the formulation of mathematical model describing coupled heat transfer and mechanical deformation of tissue subjected to laser-induced thermotherapy is numerically implemented. The effects of laser irradiation time, wavelength, laser intensity, laser beam radius and blood perfusion rate on temperature distribution, Von Mises stress distribution, and displacement of the layered skin during laser irradiation are systematically investigated. The values obtained provide an indication of limitations that must be considered in administering laser-induced thermotherapy.

1. Introduction

Given applications ranging from surgery, treatment of skin diseases, and cosmetic dermatology, lasers have become extremely important treatment devices in the field of dermatology. Compared with traditional methods, laser irradiation is more effective and reliable for treating small wounds and for accelerating the recovery process for treating skin conditions. A laser is produced from a device that emits light in wavelength range between 150 and 11,000 nm [1] through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term laser is an acronym for Light Amplification by Stimulated Emission of Radiation [2], which was first demonstrated by Maiman [3]. Since then, possible laser applications have been investigated in many fields. Biologists and physicians have been involved in designing new methods in which this special light instrument could be efficiently used to replace conventional techniques, as well as to overcome the inherent limitations of classical medical and research techniques. One of the first laser applications is in ophthalmology, which was studied by Zaret et al. [4], just one year after the laser was invented.

In certain medical treatment applications, laser light sources are used to generate thermal effects in tissue. In these treatments, laser-induced thermotherapy can be optimized by maximizing the therapeutic effect and by minimizing unwanted side effects from the rising thermal energy. For example, high temperatures could cause undesired thermal damage in the surrounding pathology. The thermal response of the tissue exposed to laser light depends principally on a number of parameters including the thermal and optical properties of each tissue and the light source [2]. In addition, thermal denaturation of the skin tissue can lead to remarkable changes in mechanical, thermal, and optical properties [5]. In medical treatment applications with light, simulation tools can be used to predict the thermal and mechanical responses of tissue, such that an appropriate laser light dosage and irradiation time for the subject tissue can be determined.

The skin is the largest sense organ in contact with external environment and can respond to stimuli including temperature, touch, vibration, pressure, and pain. These perceptions are consequence of variable combinations of three types of sensory receptor:

* Corresponding author.
** Corresponding author.
E-mail addresses: patcharaporn.pw@gmail.com (P. Wongchadakul), ratphadu@engr.tu.ac.th (P. Rattanadecho).

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mechanoreceptors for touch, vibration, and pressure; thermal receptors for temperature; and nociceptors for pain. The International Association for the Study of Pain (IASP) defines pain as an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage [5]. All the essential functions of nociceptors, as special receptors for the sensation of pain, depend on ion channels [8,9]. These channels are generally converted from a closed to an open state or gated primarily by three types of stimulus, namely, thermal, mechanical, and chemical stimuli with a threshold of 43 °C and about 0.2 Mpa for the thermal and mechanical stimuli, respectively. The field of skin biothermomechanics is highly interdisciplinary in nature such that it involves bioheat transfer, biomechanics, burn damage, and neurophysiology - all of which are related to the sensation of thermal pain. During heating, thermally induced mechanical stress arises due to thermal denaturation of the skin, which results in shrinkage [10]. Then, mechanical and thermal energy are transduced to an ionic current that leads, in turn, to the sensation of nociceptive pain [11]. Consequently, stress, temperature, burn damage, and thermal pain are highly correlated [5]. The modeling of heat transport in skin has been investigated. Thermal modeling of skin is an important tool for investigating the effect of external heat sources and for predicting abnormalities within tissue. Due to its simplicity, the bioheat transfer model introduced by Pennes [12] was highly utilized and has been used by various researchers over the past decade as the governing equation to simulate the transient temperature distribution in tissue during laser-induced thermotherapy [13–28]. Several numerical models of skin heat transfer have been investigated to illustrate the temperature distribution in skin in different treatment conditions [13–15]. Some studies were carried out on heat transfer of the laser-ultrasonic technique in the skin based on the bioheat model [16–18]. The bioheat models of human tissue subjected to electromagnetic field are also studied [19–21]. The investigation of the temperature distribution in the skin tissue model with an embedded vascular system using the bioheat model is the focus of studies by Lee and Lu [22] and Pual et al. [23]. Dua and Chakraborty [24] presented the modeling of the multiple phase change such as on the melting of fat and the vaporization of water content in tissue. Shen and Zhang [25] presented a mathematical model describing the thermo-mechanical interactions in biological tissue at high temperatures. Recently, a numerical simulation for minimizing undesired thermal damage focusing on the surface cooling effect has been implemented [26].

A model for thermal mechanical deformations of skin has also been studied. The precise heat-induced behavior of tissue and shrinkage depends on several factors, including the maximum temperature reached, the irradiation time [27], and the mechanical stress applied to the tissue during heating [28,29]. Garaizar et al. [30] presented a study of the model for deformation effects of skin induced by the thermal and working environment. The researchers used Finite Element Analysis (FEA) to analyze the simulated results. The modeling of thermal-induced mechanical behaviors of soft tissues for thermal ablation is investigated by Li et al. [31]. A method integrating the heating process with thermal-induced mechanical deformations of soft tissues for simulation is presented, and the thermal ablation process is analyzed. Bioheat transfer and constitutive elastic material law under thermal loads and under non-rigid motion dynamics are used to predict thermal-mechanical deformations through the finite difference method. In the same way, Keangin et al. [32] created a computer simulation of liver cancer treated using a microwave coaxial antenna (MCA). The mathematical models consist of a coupled electromagnetic wave equation, a bioheat equation, and a mechanical deformation equation. In numerical simulations, these coupled mathematical models are solved by using an axisymmetric finite element method (FEM) with temperature-dependent thermal and dielectric properties to describe the microwave power absorbed, the specific absorption rate (SAR) distribution, the temperature distribution, and the strain distribution in liver tissue. A three-dimensional discrete skin fibre tissue model was developed by Jor et al. [33]. The macroscopic mechanical response of the tissue is determined. The parameters are fibre density, fiber thickness, and fiber stiffness. In similar earlier work, Larrabee [34], developed a model to study the deformation and mechanical properties of skin, including its viscoelastic properties (hysteresis, creep, and stress relaxation). The mathematical model is used to simulate wound closures such as the ellipse and rectangular advancement flap. Most studies on skin exposure to laser treatment, however, focused on modeling and determining the effects of specific parameters such as wavelength. In contrast, only a few studies would investigate the effect of thermal stress on heat transfer in the layered skin, although the effect of thermal stress will directly affect the therapeutic heat transfer and pain sensation during treatment.

In present study, the deformed layered skin model exposure to laser treatment is numerically modeled. The temperature distribution, Von Mises stress distribution, and displacement are the dependent variables considered given their clinical importance. In the present study, the thermal mechanical deformation model of skin during laser-induced thermotherapy is developed based on a 3-layered skin model. The finite element method (FEM) is applied for modeling numerical simulations in order to analyze temperature changes in layers of skin tissue. The study utilized the energy absorption equation of the laser irradiation described by Beer-Lambert's law and Pennes's bioheat model for spatial transient temperature distribution. Further, the equilibrium equation is used to describe the laser-induced shrinkage phenomenon in skin. This modeling approach is used in deference to ethical considerations: that is, exposing living humans to laser irradiation for experimental purposes must be limited due to the potential risks involved in doing so. It is also more convenient to develop a biological tissue model, including transport processes, through the numerical simulation, as described above.

2. Formulation of the problem

According to the real biological structure, skin is divided into three layers: the epidermis, the dermis, and subcutaneous tissue [35]. In realistic situation, when skin tissue is exposed to laser irradiation, deformation is occurred at the heated positions due to the temperature gradient. In the present work, a 2D axisymmetric thermomechanical skin model is used to study phenomena that occur in the skin layer during subjected to laser thermography. The absorption characteristics and phenomena occurred depend on number of factors, including the optical, thermal, and mechanical properties of skin tissue, as shown in Table 1.

3. Methods and model

The study focuses attention on heat transfer characteristics and mechanical deformation induced in the skin during subjected to laser irradiation in different therapeutic situations. The FEM-based numerical simulation via COMSOL™ Multiphysics, is applied to model the temperature changes and deformation of skin layered skin. In this study, the surface spatial mode of the laser beam is assumed to be Gaussian in nature. The attenuation of laser light in the layered skin described using Beer-Lambert's law. Mechanical deformation of layered skin is described by equilibrium equations. Using this skin thermomechanical model, the temperature and stress history within layered skin tissue is obtained.

3.1. Physical model

A 2D three layer axisymmetric skin model, which is modified from Ref. [36], is employed to determine the temperature distribution and deformation within the target tissue during laser induced thermotherapy process. With this model, the deformation or thermal shrinkage can be predicted directly in term of the thermal characteristics. Fig. 1