Computer Simulation of Ultrasound Heating for Tissue Tightening with a Three-Layer Subcutaneous Structure

Huang-Wen Huang [#1]

[#]*Department of Innovative Information and Technology, Langyang Campus, Tamkang University, No.180, Linwei Rd., Jiaoxi Township, Yilan County 26247, Taiwan*

[1]hhw402@mail.tku.edu.tw

***Abstract*—To simulate tissue-tightening and/or fat reduction with ultrasound energy, a planar circular ultrasound transducer is placed on the skin surface and then transmits the acoustic power vertically into a three-layer subcutaneous structure modelling skin, fat and muscle. Two interfaces (skin-fat and fat-muscle) need to be paid special attention when the interface is set as one node connecting two tissue layers with different thermal and acoustic properties during simulation study. Temperature anomalies exist in heat flux across two layers of different tissues when executing simulation for the heating process of tissue-tightening. With accumulation of thermal energy, hot spots may occur near the interfaces. The simulation results show that an abrupt thermal gradient appears near the interfaces due to different properties such as thermal conductivity, ultrasonic attenuation coefficient, blood flow, etc.**

***Keywords*— Computer simulation, ultrasound heating, bio-heat transfer, numerical anomalies and neocollagenesis.**

1. INTRODUCTION

It is an precise heating technology to use thermal energy as a means of shrinking redundant or lax connective tissues through the well-established mechanism of collagen denaturation [1] which is followed by neocollagenesis [2]. The demand for non-invasive skin tightening and fat reduction procedures is increasing as patients seek safe and effective alternatives to aesthetic surgical procedures of the face, neck, and body. It is an application aim of thermal engineering to raise the temperature of target area up to therapeutic levels without significantly damaging other normal tissues. The threshold for collagen denaturation is approximately 60℃ [3]. During the delivery of controlled heating for the superficial body tissues, it needs to take account of tissue physiology, structure and blood supply [4]. For considering tissue tightening and fat reduction processes, the heat transfer mechanism for the analysis of superficial tissues is important.

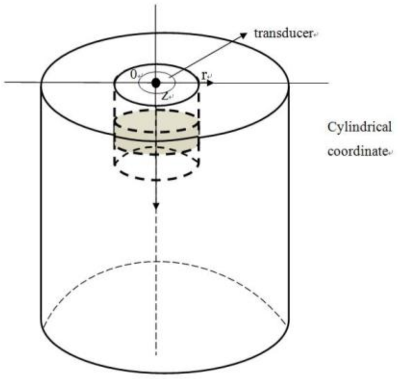
Laser, ultrasound and radiofrequency are the three major energy sources used for skin tightening, toning or lifting. Traditionally, ultrasound is in favor of deep-tissue energy delivery. In this study, we used a circular, planar ultrasound transducer and the acoustic power exponentially decays with depth and different attenuation coefficients for different tissues [5,6] during mathematical analysis. The analysis presented by Wilson and Spence [4] was based on a one-dimensional finite difference version of the bio-heat equation applied to a multi-layered model for a 10-mm superficial body tissue. However, their results were inappropriate to describe the temperatures in deep-tissue region and unable to describe the horizontal tissue temperature. In this study, we address 3-D transient temperature simulation analysis with an axis-symmetric mathematical assumption. The simulation results show that temperature anomalies exist near the interface of two different tissues and they are associated with different tissue and acoustic properties in different layers.

TABLE 1. THERMAL, ACOUSTIC AND PHYSIOLOGICAL PROPERTIES OF SKIN, FAT AND MUSCLE [7-10]

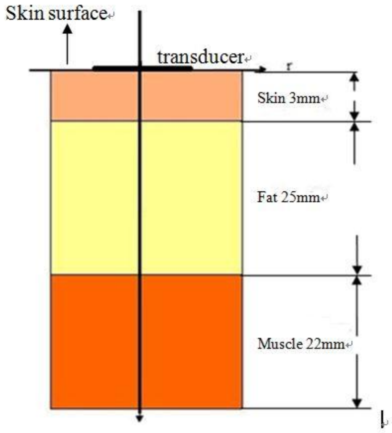
	Blood perfusion rate($kg\,m^{-3}s^{-}$)	Thermal conductivity ($W(m\,°C)$)	Specific heat ($J\,kg^{-1}°C$)	Tissue density ($kg\,m^{-3}$)	Acoustic attenuation coeff. ($Np\,m^{-1}\,MHz^{-1}$)
Skin	2.0	0.53	3800	1200	15
Fat	0.6	0.16	2300	850	5
Muscle	0.5	0.53	3800	1270	3

2. METHODS

The computational geometry and dimensions of the model is shown in Figure 1(a), as a circular, planar ultrasound transducer is placed on the skin surface in 3-D. Figure 1(b) shows a central 2-D cross-sectional domain from Fig. 1(a) on the r-z plane and illustrated a three-layer structure (skin, fat and muscle) with transducer on the top of skin surface. The thermal, acoustic and physiological properties of skin, fat and muscle are shown in Table 1. The skin surface and the other boundaries are assumed 37 ℃. The skin thickness is 3 mm (z = 0 to 3 mm), fat thickness is 25 mm (z = 3 to 28 mm) and muscle thickness is 22 mm (z = 28 to 50 mm). The interfaces are located at z = 3 mm and 28 mm.



(a)



(b)

Figure 1. (a) Geometry and dimensions of the model used in this study: an ultrasound transducer placed on the skin surface in 3-D. (b) A central 2-D cross-sectional domain on the r-z plane. The figure illustrates a three-layer structure (skin, fat and muscle) with transducer on the top of skin surface.

2.1 Mathematical Equations

Two mathematical equations involve in the study: Pennes bio-heat transfer equation and ultrasonic power deposition as a heat generation term. Table 1 shows the thermal, acoustic and physiological properties of the three-layer subcutaneous tissues for the simulation.

2.1.1 Ultrasonic power

A circular, planar ultrasound transducer is placed on the skin surface and it emits ultrasound power penetrating into the tissues. The propagated ultrasound intensity is assumed as the following form,

$$I(z) = I_0 \bullet e^{-2\mu z} \quad (walts/m^2) \quad \text{where } \mu = \alpha f \qquad (1)$$

α is ultrasound attenuation coefficient (15, 5 and 3 Np/(m-MHz) for skin, fat and muscle, respectively), f is frequency (3.0 MHz is used in this study). I_0 is the ultrasound intensity on the skin surface (10^4 W/m^2 is used in this study). Thus, the absorbed ultrasound power density ($Q(z)$, W/m^3) is as the following and used in the Pennes bio-heat transfer equation.

$$Q(z) = 2\alpha f I(z) \qquad (2)$$

2.1.2. Pennes bio-heat transfer equation (PBHTE)

Axisymmetric is used to solve the tissue temperatures and metabolism term is negligible for a short period of heating time. Thus the transient PBHTE is reduced to,

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r}) + \frac{\partial}{\partial z}(k\frac{\partial T}{\partial z}) + q_{gen} - wc_b(T - T_a)$$
(3)

r is the radius of cylindrical coordinates and z is the vertical axis pointing downward from the skin surface as shown in Fig. 1. w is the blood perfusion term, c_b is the specific heat of blood, k is the tissue thermal conductivity, T_a is the arterial blood temperature (37 ℃ is assumed.), T is the tissue temperature and $\rho$is the tissue density, c is the tissue specific heat and t is the time. The heat generation term, q_{gen}, is the absorbed ultrasound power density from Eqn. (2).

2.2 Numerical Computation

Crank-Nicolson finite difference method is used to obtain tissue temperatures by solving transient Pennes bio-heat transfer equation and the heat generation term by ultrasound is obtained according to Eqn. (2). Axis-symmetry is assumed and a 3-D computational cylindrical domain has been reduced to a 2-D transient case. Time step side is 0.08 s and grid step size is 1 mm at the numerical computation.

The numerical approach adopted central difference in time and space with a 2nd-order accuracy. To ensure stability and accuracy, the ratio of $\dfrac{k(time\ step\ side)}{c\rho(grid\ step\ side)^2}$ is maintained to be less than 1, where k is the thermal conductivity, c is the specific heat and $\rho$is the tissue density. The different thermal, acoustic and physiological properties of skin, fat and muscle are shown in Table 1, and special numerical treatment at the layer interfaces is required.

2.3 Computational Processes at interfaces

One node is present at the interface and two conditions must be met at the interfaces: continuity of temperature and identical heat flux. They are at the interfaces

$$T_i = T_j \qquad i, j \text{ are two different tissue layers.} \quad (4)$$

$$-k_i \frac{\partial T}{\partial z} = -k_j \frac{\partial T}{\partial z} \qquad k \text{ is thermal conductivity} \quad (5)$$

The identical heat flux makes thermal gradients adjusted according to thermal conductivity of two different layers near the interfaces in solving linear system of equations.

The whole domain is divided into three computational domains (skin, fat and muscle) and two interfaces. The interface temperatures are varied in the r-direction and act as connecting boundary conditions between two different tissue domains. Thus, the temperatures in skin domain with three constant boundary conditions and one variable boundary condition (the interface) are first to be solved. Fat and muscle are calculated subsequently to the skin domain. The interface represents as a variable boundary condition in calculating each domain.

.

3. RESULTS

3.1 Temperature contour in different tissue layers with assumed uniform thermal and physiological properties

To simplify engineering analysis and to compare the case with non-uniform properties later, uniform thermal and physiological properties (thermal conductivity 0.5 $W(m\,°C)^{-1}$, density 1000 $kg\,m^{-3}$, specific heat 4000 $J\,kg^{-1}°C^{-1}$ and perfusion rate 0.5 $kg\,m^{-3}s^{-1}$) are assumed in all three tissue layers. Figure 2 shows the temperature contour on the central r-z plane with a heating duration of 16 s and no pre-cooling on the skin surface (with initial temperature of 37℃ in all domain). The skin surface and the other boundaries are assumed 37 ℃. Temperatures range from 37℃ (black) to 60 ℃ (white).

The highest temperature is near z = 3 mm and lobe-like temperature contours are shown in Figure 2. Lobe-like temperature contours revealed thermal energy aggregated at the center area which ultrasound power is directly projected from the skin surface. As the absorbed ultrasound power density decreases along the z-direction, temperature decreases. The heated area penetrates into the deep-tissue region as the circular, planar ultrasound transducer emits acoustic power in the range of $-5\,mm \le r \le 5\,mm$. No abrupt temperatures are observed in this case.

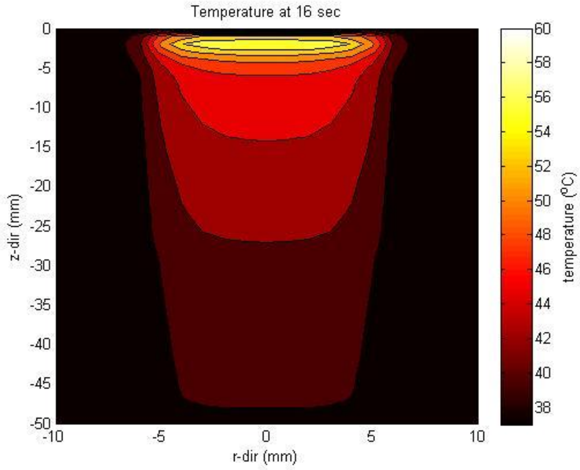


Figure 2. Temperature contour on the central r-z plane with a heating of 16 s and no pre-cooling on the skin surface (with initial temperature of 37℃ in all domain) for the case with assumed uniform thermal and physiological properties in all three layers. The skin surface and the other boundaries are assumed 37 ℃. Temperatures range from 37℃ (black) to 60 ℃ (white). The skin thickness is 3 mm (z = 0 to 3 mm), the fat thickness is 25 mm (z = 3 to 28 mm) and the muscle thickness is 22 mm (z = 28 to 50 mm). The interfaces are located at z = 3 mm and 28 mm.

3.2 Temperature contour in different tissue layers with different thermal and physiological properties

Figure 3 shows the temperature contour on the central r-z plane with a heating of 16 s and no pre-cooling on skin surface when different thermal and physiological properties (as shown in Table 1) are considered in the three-layer tissues with the same operating conditions as previous uniform property case. The skin surface and the other boundaries are assumed 37 ℃. Temperatures range from 37℃ (black) to 60 ℃ (white).

Pin-like temperature contours appear near both ends of interfaces as properties vary in the tissue layers. In addition, abrupt, higher tissue temperatures also appear near the interface regions and less thermal energy deposits in the deeper region.

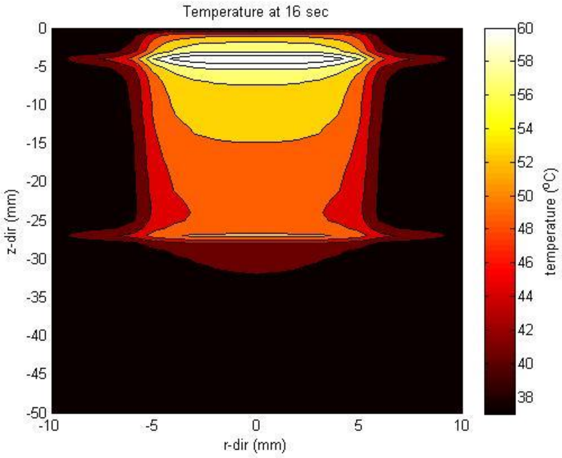


Figure 3 Temperature contour on the central r-z plane for the case with different thermal and physiological properties for the three layers of tissues as shown in Table 1. The skin surface and the other boundaries are assumed 37 ℃. Temperatures range from 37℃ (black) to 60 ℃ (white). The skin thickness is 3 mm (z = 0 to 3 mm), the fat thickness is 25 mm (z = 3 to 28 mm) and the muscle thickness is 22 mm (z = 28 to 50 mm). The interfaces are located at z = 3 mm and 28 mm.

4. CONCLUSIONS

This simulation study presents the temperature distribution during tissue-tightening or fat reduction with the application of a circular, planar ultrasound transducer on the skin surface and the considerations of a three-layer subcutaneous structure modelling skin, fat and muscle. Two conditions are required to meet at the interfaces: one is the continuity of temperature and the other is the identical heat flux. Numerical anomalies of abrupt high temperatures would appear near the interfaces between different tissue layers due to different tissue and acoustic properties of the layer tissues. This kind of temperature response is very important for tissue-tightening and/or fat reduction when using a circular, planar ultrasound transducer to produce the temperature.

ACKNOWLEDGMENT

The author would like to thank the Ministry of Science and Technology for partially supporting this research under no. MOST104-2221-E-032-015.

REFERENCES

[1] Arnoczky, S.P. and A. Aksan, *Thermal Modification of Connective Tissues: Basic Science Considerations and Clinical Implications.* J Am Acad Orthop Surg, 2000. **8**: p. 305-313.

[2] Hayashi, K., et al., *Effect of Nonablative Laser Energy on the Joint Capsule: An In Vivo Rabbit Study Using a Holmium:YAG Laser.* Lasers in Surgery and Medicine, 1997. **20**: p. 164-171.

[3] Hayashi, K., et al., *The effect of thermal heating on the length and histologic properties of the glenohumeral joint capsule.* Am J Sports Med, 1997. **25**(1): p. 107-12.

[4] Wilson, S.B. and V.A. Spence, *A tissue heat transfer model for relating dynamic skin temperature changes to physiological parameters.* Phys. Med. Biol., 1988. **33**(8): p. 895-912.

[5] LIN, W.-L., et al., *A THEORETICAL STUDY OF CYLINDRICAL ULTRASOUND TRANSDUCERS FOR INTRACAVITARY HYPERTHERMIA.* Int. J. Radiation Oncology Biol. Phys., 2000. **46**(5): p. 1329-1336.

[6] Siddiqi, T.A., et al., *In vivo ultrasonographic exposimetry: Human tissue–specific attenuation coefficients in the gynecologic examination.* Am J Obstet Gynecol, 1999. **180**(4): p. 866-874.

[7] Lin, J.C., *Microwave Thermoelastic Tomography and Imaging*, in *Advances in Electromagnetic Fields in Living Systems*, J.C. Lin, Editor. 2005. p. 41-76.

[8] Deng, Z.-S. and J. Liu, *Non-Fourier Heat Conduction Effect on Prediction of Temperature Transients and Thermal Stress in Skin Cryopreservation.* Journal of Thermal Stresses, 2003. **26**(8): p. 779-798.

[9] Pailler-Mattei, C., S. Bec, and H. Zahouani, *In vivo measurements of the elastic mechanical properties of human skin by indentation tests.* Med Eng Phys, 2008. **30**(5): p. 599-606.

[10] Franco, W., et al., *Hyperthermic injury to adipocyte cells by selective heating of subcutaneous fat with a novel radiofrequency device: feasibility studies.* Lasers Surg Med, 2010. **42**(5): p. 361-70.