SIMULATION OF HEAT DISTRIBUTION IN TISSUE GENERATED BY THERAPEUTIC ULTRASOUND

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SIMULATION OF HEAT DISTRIBUTION IN TISSUE GENERATED BY THERAPEUTIC ULTRASOUND

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ABSTRACT

Ultrasonic energy can stimulate the healing process of tissue by bringing the temperature to the maximal tolerated level. Because the patient's sensation of temperature is not reliable as a guide in treating deep tissue, a standard ultrasound setting must be used in routine treatment. For this study, an ANSYS 5.4 (finite element software) command log file was written to perform and analyse heat distribution in any material sonicated by therapeutic ultrasound under conditions stipulated by the user in a simulation model. Heat distributions can be displayed in two-dimensional simulation, graphic displays, etc. In this study the focus was on fat, muscle, and bone tissue. The study confirmed that the increase in temperature depends not only on ultrasonic intensity but also on physical properties of the tissue, such as thermal conductivity. With increase in depth, the temperature of fat and muscle tissue decays exponentially but bone tissue temperature decays more rapidly. A model with three layers of tissue shows that peak temperature is attained inside the bone tissue within 25-30 seconds, then inside fat tissue, and finally shifts toward muscle tissue. After 165 seconds of application of ultrasound at an intensity of 1 W/cm^2, the temperatures in the middle of muscle, fat, and bone tissue reach 43, 46.2, and 44.5° C, respectively. So, when muscle tissue temperature reaches the treatment range of 40 - 45°, pain is evoked in fat tissue. The therapist must adjust the application to obtain optimum treatment, such as by moving the sound applicator. The results obtained by using this command log file can be used to plan the appropriate procedure for various ultrasound treatments.

KEY WORDS: THERAPEUTIC ULTRASOUND / HEAT DISTRIBUTION /
COMPUTER SIMULATION / FINITE ELEMENT METHOD

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ภาพจำลองทางคอมพิวเตอร์ของการกระจายความร้อนภายในเนื้อเยื่อที่เกิดจากการรักษาด้วยอัลตร้าซาวน์ (SIMULATION OF HEAT DISTRIBUTION IN TISSUE GENERATED BY THERAPEUTIC ULTRASOUND)

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บทคัดย่อ

อัลตร้าซาวน์สามารถช่วยในการรักษาอาการบาดเจ็บของเนื้อเยื่อได้ จากการเพิ่มอุณหภูมิเนื้อเยื่อไปถึงระดับที่ผู้ป่วยสามารถทนได้ แต่เนื่องจากระบบรับความรู้สึกของผู้ป่วยที่เกี่ยวกับอุณหภูมิโดยเฉพาะในบริเวณที่อยู่ลึกลงไปมากจากผิวหนังนั้น ไม่สามารถนำมาใช้เป็นเกณฑ์ในการวางแผนการรักษาได้ ดังนั้นการรักษาจึงใช้อัลตร้าซาวน์ในระดับเดิมตามแบบที่มักใช้อยู่เป็นประจำ งานวิทยานิพนธ์นี้ได้สร้าง Command log file ในโปรแกรม ANSYS 5.4 ขึ้นมาเพื่อใช้วิเคราะห์การกระจายความร้อนในวัสดุใดๆที่เกิดจากการรักษาด้วยอัลตร้าซาวน์ โดยผู้ใช้กำหนดลักษณะแบบจำลองของวัสดุได้ตามต้องการ สามารถแสดงการกระจายความร้อนได้หลายรูปแบบ เช่น ภาพจำลองทางคอมพิวเตอร์แบบ 2 มิติและกราฟ เป็นต้น งานวิทยานิพนธ์นี้ได้วิเคราะห์ความร้อนที่เกิดขึ้นในไขมัน, กล้ามเนื้อและกระดูก พบว่าการเพิ่มขึ้นของอุณหภูมิไม่เพียงแต่ขึ้นอยู่กับความเข้มอัลตร้าซาวน์เท่านั้น แต่ยังขึ้นอยู่กับคุณสมบัติของเนื้อเยื่อด้วยเช่น ค่า thermal conductivity อุณหภูมิของไขมันและกล้ามเนื้อลดลงแบบ Exponential ตามความลึกของเนื้อเยื่อ แต่อุณหภูมิของกระดูกจะลดลงอย่างรวดเร็ว เมื่อวิเคราะห์ความร้อนในเนื้อเยื่อ 3 ชั้นพบว่า อุณหภูมิสูงสุดในช่วง 20-30 วินาทีแรกอยู่ในกระดูก หลังจากนั้นพบในไขมันแล้วเลื่อนลงไปในกล้ามเนื้อ เมื่อรักษาด้วยอัลตร้าซาวน์ 1 W/cm^2 เป็นเวลา 165 วินาทีพบว่าบริเวณกลางกล้ามเนื้อมีอุณหภูมิ 43°C ในขณะที่ไขมันและกระดูกมีอุณหภูมิ 46.2 และ 44.5°C ตามลำดับ ดังนั้นเมื่ออุณหภูมิของกล้ามเนื้อเข้าสู่ช่วงที่ให้ผลการรักษาคือ 40 - 45°C ผู้ป่วยจะรู้สึกปวดที่บริเวณชั้นไขมัน ด้วยเหตุนี้ ผู้รักษาควรต้องปรับวิธีการเพื่อให้ได้ผลการรักษาที่ดีที่สุด เช่นการเคลื่อนหัวอัลตร้าซาวน์ เป็นต้น ผลที่ได้การวิเคราะห์โดยใช้ command log file สามารถนำมาใช้วางแผนการรักษาด้วยอัลตร้าซาวน์ใน case ต่างๆที่หลากหลายได้

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CHAPTER 1
INTRODUCTION

Ultrasound is defined as a form of acoustic vibration with frequencies so high (above 17,000 Hertz (Hz)) that the human ears cannot perceive it. Ultrasonic energy for physical therapy can penetrate body tissue to a depth of about six centimeters or more and affect the tissues in three ways simultaneously: mechanically, chemically, and thermally. Mechanically it has a stirring action within the tissue that has been called “micro or intercellular” massage and chemically it increases cellular permeability and therefore the diffusion of ions into and out of the cells. Thermally the energy is transferred into heat, increasing blood flow and stimulating the healing processes. The main purpose of therapeutic ultrasound is to produce a specific temperature (by specific dosimetry) in the depth of the tissues. For vigorous effects of treatment, temperatures must be brought to the maximal tolerated level which can be done by staying just below the pain threshold. For mild therapeutic effects, one must stay significantly below that level. However, dosimetry is not available accurately, and a physiological guide of patient sensation of temperature is absent because, in most of the deep structures which ultrasound heats, temperature receptors are not present (1). The treatment should be terminated if the patient shows any sign of distress, such as pain or any uncomfortable sensation (2).

Ultrasound passes through soft tissue in the form of longitudinal waves until it strikes bone. When in the bone, some of the energy is reflected and the rest is converted into transverse waves. The propagation of ultrasonic energy depends on the frequency of the sound waves and the density of the tissues. When the ultrasound beam strikes an acoustical interface (such as different tissue layers), some of the energy is reflected or refracted. Any energy not reflected or absorbed is passed on to the underlying tissues. The intensity of ultrasonic energy decreases as the distance it travels through the tissues increases, called attenuation. This process occurs through the scattering and absorption of the waves within the tissues. Absorption of the sound waves transfers energy from the beam into the surrounding tissues through conversion of mechanical energy into thermal energy. When ultrasonic energy is absorbed by tissue, its temperature rises and we say the tissue "stores" thermal energy or heat. The amount of absorption that occurs depends on the protein content of the tissues (especially collagen). Because the amount of generated heat is different in each tissue type, '*heat transfer*' occurs underlying temperature gradient between these tissue types. Temperatures within tissue over the maximal tolerated level cause the production of irreversible structural changes (cells, macromolecules, etc.), tissue burning. Moritz and Henriques (3) found that, at skin temperatures between 44° and 51°C, the total exposure time required to destroy the epidermis is essentially identical to the total duration of steady thermal state within the epidermis, and, under this circumstance, the rate at which burning occurs is almost doubled with each degree rise in temperature. The thermal pain is also evoked at 45°C. This level of temperature is close to the therapeutic temperature level (40°-45°C) (4). Pain felt by the patient during sonication is a danger signal. It usually indicates that considerable heat generation has occurred in the periosteum, which is the interface between soft connective tissue and bone (5). Moreover, tissue cavity is produced in the fluid within tissue during the phase of rarefaction in the propagating sound waves. During the following phase of compression, cavity may again collapse creating a high-energy concentration in the form of shock waves. Nowadays, guideline for the appropriate intensity setting of therapeutic ultrasound is empirically used on the clinical experiences (6,7). Therefore, the rising of the tissue exact temperature when applying therapeutic ultrasound should be determined accurately.

Because thermotherapy remains an insufficiently defined quantitative science due, in part, to the complex interactions of diathermy energy fields with the treated tissue and to the equally significant physiological responses to changing tissue temperatures, the need for valid therapeutic thermal model development is still quite strong. Over the past several decades, the validity of the numerical solution to properly define mathematical thermal models has been demonstrated to the point where numerical thermal modeling is now used routinely to predict the behavior of non biological thermal systems (8,9,10). In physical therapy, Chan et al. (11) used a numerical approach, finite difference method, to obtaining the resultant temperature distribution in layered tissue, with thermal source and cooling inside the tissue.

For more accurate and useful predictions of heat transfer and tissue temperature relevant to ultrasound therapy, the thermal analyst must resorts numerical techniques and the digital computer. In this research, widespread numerical method, called “finite element”, is applied in calculating the temperature distribution for construct of simulation of heat distribution within tissue of ultrasonic field. Finite element method (FEM) provides a great flexibility to model complex geometries as used in solving heat transfer problem. FEM involves dividing the physical system into small sub-regions, called element, a simple unit which can be analyzed for its behavior readily. The FEM uses integral formulations to create a system of algebraic equation. An approximate continuous function is assumed to represent the solution for each element. The complete solution is then generated by connecting or assembling the individual solutions, allowing for continuity at the interelemental boundaries. The advancement in computer technology enables us to solve a large system of equations, to formulate and assemble the discrete approximation, and to display the results quickly and conveniently. This has also helped the finite element method become a powerful tool. Powerful software used in this research, which can perform all procedures, is ANSYS 5.4 finite element analysis software. The ANSYS program has a comprehensive graphical user interface that gives users easy, interactive access to program functions, commands, and documentation. A typical ANSYS analysis has three distinct steps: build the model, apply loads and obtain the solution, and finally review the results. For the building model step, user defines element types and options that are appropriate to thermal problem. Then, define element real constants, such as cross-sectional properties of element, and material properties, such as thermal conductivity, tissue density, etc. After that, finite element models are generated to adequately describe the model geometry. For meshing the object created, the ANSYS program can automatically mesh the geometry with nodes and elements. The second step after already building the tissue model is to apply loads and to obtain the solution. Users then define the analysis type and analysis options, apply loads, specify load step options, and initiate the finite element solution. Users can choose the analysis types such as static, transient, etc., based on the loading conditions and the response to calculate. The word “load” includes boundary conditions, externally and internally loads. Hence, fixed temperatures are applied at model surfaces and internal heat generation applied within model. After that, the ANSYS program takes model and loading information from the database and calculates the results. Final step, reviewing the results, ANSYS allows user to list and display results of an analysis in many ways, such as graph plotting, animation and listing results. Moreover, user can review results over time in a transient analysis at a certain point in the model. Therefore it can be used to predict how to apply ultrasound to the patients to achieve most effective treatment. This means, technician can appropriately set ultrasound modality (intensity and frequency) and treatment time duration that are consistent with tissue area. Technician can also understand the actual behavior of interaction between ultrasound and tissue even in deep and complicated layer.

CHAPTER 2

OBJECTIVES

2.1 Objectives of Study

1. Use ANSYS 5.4 finite element analysis software to construct two-dimensional simulations of heat distribution within tissue generated by therapeutic ultrasound. Obtain simulation of result temperature, create a set of personalized ANSYS command log file and use Graphical User Interface (GUI) to communicate with (control) the ANSYS program.

2. This command log file can be re-executed for analysing heat distribution of various conditions of the therapeutic ultrasound usage. User can define these conditions personally through a command log file.

3. Enable a review of the temperature results at one time step over the entire model or selected portion of the model, and at specific points in the model over all time steps.

4. In addition to display results through 2-D simulation, the results can be reviewed through other graphical displays, such as vector display, and tabular listings.

5. This command log file can be used to analyse heat distribution within individual fat, muscle, bone tissue layers, and three-layered model of idealized human thigh where the heat is generated from therapeutic ultrasound.

2.2 Scope of Study

1. A command log file can be used to construct two-dimensional simulation of rectangular flat layered model, at most three layers.

2. As user reads this command log file to ANSYS program, he is able to edit many parameters appropriately to ultrasound usages. User can change material type, its properties, model size, initial material temperature, boundary temperature, incident intensity of ultrasound, transducer’s diameter, size of element, duration of ultrasound

application, and substeps, step of time as user desires to observe result data during sonication.

3. Ultrasound reflection at tissue interface is also considered when performing two- or three-layered model analysis.

4. Assumptions are taken in the following contexts.

: Model is a homogeneous material.

: A 1 MHz continuous wave therapeutic ultrasound is applied to model by stationary technique.

: Intensity distribution is uniform in the vertical plane of ultrasound beam.

: All the ultrasound energy is converted into heat as sound wave propagates into model.

: For ultrasound attenuation, the absorption is mainly considered because it mostly affects temperature rise within tissue.

: Heat transfer within tissue is also mentioned only as heat conduction. Boundary condition is defined by applying fixed temperature at model surfaces.

: Tissue metabolism and blood flow heat-dissipation effects are considered to be negligible.

CHAPTER 3
REVIEW OF THE RELATED LITERATURES

3.1 Related Literatures

In ultrasonic diathermy, some of the beneficial results of treatment are due to mechanical effects caused directly by the vibrational energy of ultrasound, rather than by overall warming of the insonated tissues (28). But the usual treatment is to generate maximum heat in muscle tissue, especially near the bone surface, without destroying any living tissue by excessive heat. Ideally the comparatively low value of the absorption coefficient for fat should allow the sonic beam to penetrate the tissue without being unduly attenuated, and without overheating the fatty regions. The intermediate value of the absorption coefficient in muscle leads to an increased generation of heat in the muscle, and a reduction in the intensity of the beam which reaches the highly absorbing bone (12). The temperature distribution in the tissues depends on three factors (13). First, it depends on the amount of energy converted into heat at any tissue depth. This is called the pattern of relative heating. Second, it depends on the thermal properties of the tissues, such as specific heat, and, if heating continues for a relatively long term, on thermal conductivity. These factors determine the temperature rise produced by the calories absorbed. The variations in the thermal properties of tissue cause each type of tissue to differently heat by ultrasound (14). Third, it depends on the technique of application of a given modality that will modify the temperature distribution. Finally, it must be recognized that any temperature distribution thus obtained is modified by biological factors, and superimposed on the preexisting temperature distribution with its gradient from low temperatures on the outside to high temperatures at the core. Because heat distribution depends on various factors, it is therefore quite difficult to understand the temperature changing obviously when ultrasound is clinically applying to the patient. There are many studies to calculate temperature changing with various procedures. The experimental studies that were done in animals and in human are reviewed below.

Lehmann et al. (15) measured the temperature distribution in pig thigh at the bone marrow, spongy bone, cortical bone, and soft tissue level, after applying continuous wave ultrasound 1 MHz by continuous movement (head sound) technique, at the intensity is about 1.5 W/cm^2 for 5 minutes with the radiating area of the transducer at 12.5 cm^2. The mean temperature change at the spongy bone was 4.56±3.02 °C, at the bone surface was 3.57±1.92 °C, and in the soft tissue 0.4-1.0 cm. from the bone was 2.15±1.92 °C.

Draper et al. (16) investigated the temperature rise produced by 1MHz continuous wave ultrasound applied to the gastrocnemius muscles of 20 volunteers. The intensity used was 1.5 W/cm^2 with the exposure time of 10 minutes. The tissues at the depth of 3 cm. were measured. The temperature increased 4.8°C when tropical gel was used for coupling and the temperature increased only 2.1°C when using (sonicate) under water technique.

Chaipinyo K. (17) studied the temperature change in cat thigh at each tissue level produced by 1 MHz continuous wave ultrasound, using stationary technique, with various intensities. As sonicated by 0.5 W/cm^2 at 3 min., the temperature changes at subcutaneous tissue, muscle, and the tissue in front of the bone were 3.92°, 2.36°, and 2.49°C, respectively. As sonicated by 1 W/cm^2 at 1.5 min., the temperature changes at same tissue levels were 5.89°, 2.69°, and 3.88°C, respectively. For 1.5 W/cm^2, 1 min., the temperature changes at same tissue levels were 6.03°, 2.52°, and 4.19°C, respectively.

Lehmann et al. (26) applied 1 MHz continuous ultrasound with 12.5 cm^2 radiating surface, on the anterior thigh of 15 human. The average intensity of 1 W/cm2 was applied by two techniques, stroking technique, and using mineral oil as the coupling media. Ultrasonic application was discontinued when pain occurred. They were found that at degassed water temperature of 21 and 24°C, and the mineral oil at 18 and 21°C, the most increasing temperature was occurred at the tissue in front of bone. For the mineral oil at 24°C, the greatest temperature was found at the skin surface.

All of these studies investigated the temperature distribution at some points of tissue volume. The tissue properties of animal that differ from human, cause the result of temperature changing investigation error when related it to the result investigated in human tissue.

Panpitpat S. (18) mixed the tissue-equivalent phantom from various materials. Diagnostic ultrasound is applied to determine therapeutic attenuation and temperature in tissue phantom. In about the first few minutes after applying therapeutic ultrasound to the phantom, the temperature increases rapidly without the effect of heat conduction. After that, the rate of temperature rise decreases due to conduction in the tissue phantom. Therefore, the temperature slowly increases until it seems to reach a plateau at resting state.

The result data of studies done in animal or phantom indicate trend of response in human, not exact result data from the studies done in human. The experimental studies done in human always use invasive technique, which causes painful, discomfort, and may be dangerous to the volunteers. The temperature distributions in layered tissue obtained in these experimental studies accounted for only the thermal energy generated around the thermal probe (11). Therefore, the investigators choose the other way to study with harmlessness and flexibility to various cases, and to minimize error.

The quantitative analysis of tissue heating via computer (or “numerical”) modeling has been a rapidly growing field in recent years. As for the technological developments in both therapeutic heating techniques and new deep-heating devices and systems, the majority of recent thermal modeling developments have been done for applications in hyperthermia treatment of cancer rather than physical medicine (19). The studies of heat distribution within tissue of therapeutic ultrasound field using mathematical model are reviewed below.

Chan et al. (20) used a numerical approach to obtain the temperature distribution in fat-muscle-bone layers, with ultrasound as a thermal source and a cooling function inside. Calculation of the temperature distribution was based on a linear model of these three kinds of tissues separated by parallel boundaries. The mathematical prediction based on propagation and attenuation of ultrasound showed that the incident angle of 70 degrees was the critical angle which most of the acoustic energy is reflected back into the fat tissue. The angle of incident of 45-60 degrees is the angle at which maximum power loss per unit volume in the bone tissue is obtained.

Chan et al. (11) utilized a linear mathematical model of three plane-layer tissues, to calculate the pattern of selective heating of ultrasound, by finite different method. Each layer contained a thermal source function or ultrasonic power loss inside the tissue and a cooling function which is the power per unit volume carried out. The computational result showed that the highest temperature occurred at the bone tissue.

Although some finite difference techniques can solve some types of numerical problem using more nodes within a mesh than the finite element method, the restriction of having to use a uniform mesh is significant. The finite element treatment has the advantage over finite difference techniques of being able to utilize nonuniform grids, thus allowing for a high rate of spatial sampling in specific areas of interest, and using a low sampling rate in regions known to have minimal heating (21). Even mathematical model behaves the variable condition of the physical system (human tissue), and minimizes calculation error of heat distribution, it is still quite hard to understand and apply in clinical practice. So computer simulation can clearly display temperature distribution in tissue model of interest with the changing observed at any step of time. Finite element method and computer simulation used in some medical studies are reviewed below.

G. Wojcik et al. (22) used finite element modeling of tissue ablation by focused ultrasound. Focused ultrasound is used for noninvasive therapies like hyperthermia and extracorporeal shock wave lithotripsy. The numerical basis for modeling nonlinearity in this study is an incrementally linear, time-domain, finite element algorithm solving the electromechanical and bioheat equations in 2D/3D inhomogeneous elastic and acoustic media. Even a full simulation is impractical for reasons of limited memory or computer time, computer models can be localized around essential regions or structures of interest.

Paul M. Meaney et al. (21) had developed a finite element representation for modeling the thermal diffusion effects during focused ultrasound surgery exposures in clinically relevant tissue volumes. Simulations were run for focal depths of 2 and 3 cm. below the surface of pig's liver, using multiple intensity levels and exposure times. 3-D representation of the bioheat equation had been successfully employed to represent the temperature distributions.

For the interaction between ultrasound and tissue, many recent studies involve ultrasound diagnosis and hyperthermia as in the study above. Therefore, this research will use a basic trend for the study of temperature distribution within tissue caused by therapeutic ultrasound in physiotherapy field, by using finite element method and displaying the result with computer simulation.

3.2 Basic Equation for Calculating Heat Distribution within Tissues under Ultrasonic Field (29)

To design a model of an actual physical system for heat distribution within tissue of ultrasonic field, the problem to be solved is transferred into the mathematical model.

As sound is propagated through the tissue, it is gradually absorbed and converted into heat. The sound intensity is gradually attenuated and therefore decays exponentially, according to the following formula:

$$I = I_0 e^{-2\alpha x} \qquad (1)$$

where I is the acoustic intensity in the tissue at the depth x, I_0 is the intensity at $x = 0$, α is the amplitude attenuation coefficient, and e is the base of the natural logarithm. Moreover, in the three-layer tissue simulation, the reflection and transmission of acoustic wave at tissue interface influence ultrasound intensity changing. The reflection and transmission can be determined by the acoustic velocities C, and tissue densities ρ, of the respective layer. This directly involves acoustic impedance Z of tissue as in the relationship below:

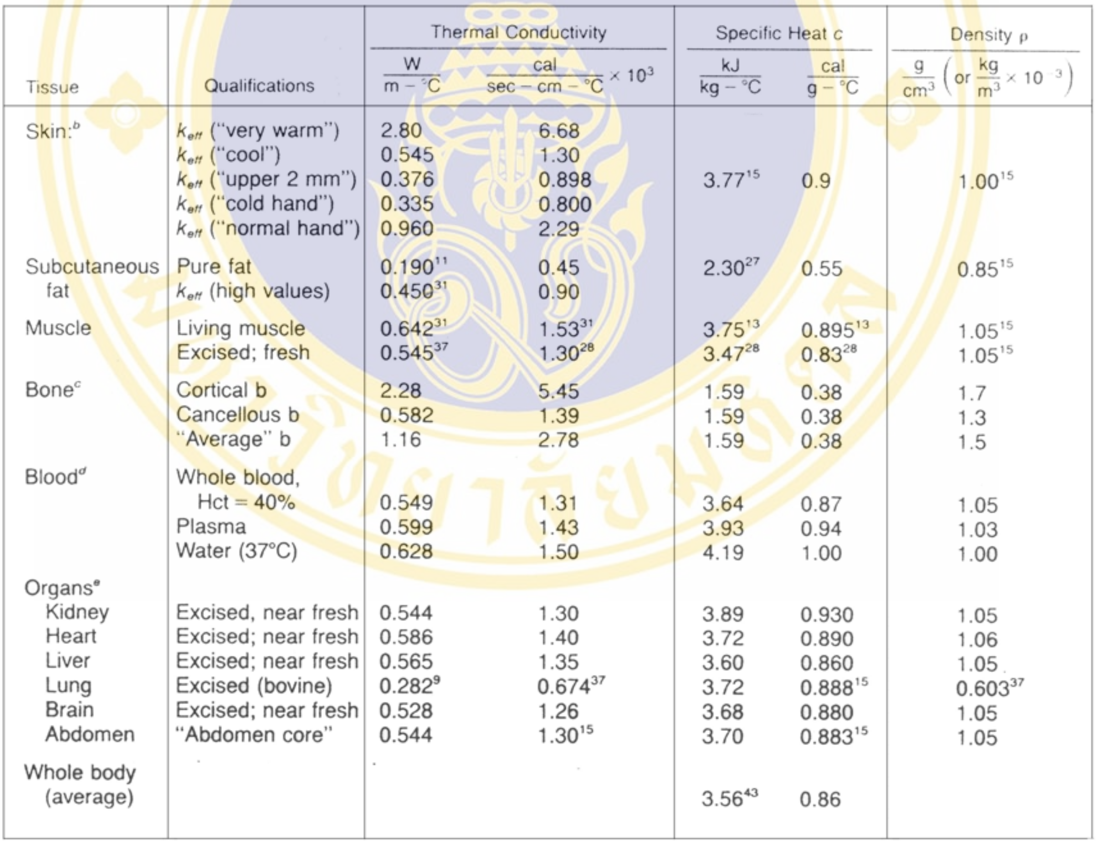
$$Z = \rho C \qquad (2)$$

Therefore, the ultrasound intensity variation, caused by normal reflection in the tissue layer of incident, can be represented as

$$\frac{I_R}{I_o} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad (3)$$

where I_0 is the incident intensity, I_R is the reflected intensity, Z_1 and Z_2 are the acoustic impedances of two different tissues (layer1 and 2, respectively). Therefore, Equation 3 indicates that the reflection at the fat-muscle interface is lower than at the muscle-bone interface. The transmitted intensity I_T in the respective tissue, layer 2, can also be expressed as

$$\frac{I_T}{I_o} = \frac{4Z_1Z_2}{(Z_2+Z_1)^2} \qquad (4)$$



Tissue	Qualifications	Thermal Conductivity		Specific Heat c		Density ρ
		$\frac{W}{m-°C}$	$\frac{cal}{sec-cm-°C} \times 10^3$	$\frac{kJ}{kg-°C}$	$\frac{cal}{g-°C}$	$\frac{g}{cm^3}\left(\text{or } \frac{kg}{m^3} \times 10^{-3}\right)$
Skin:[b]	k_{eff} ("very warm")	2.80	6.68	3.77[15]	0.9	1.00[15]
	k_{eff} ("cool")	0.545	1.30			
	k_{eff} ("upper 2 mm")	0.376	0.898			
	k_{eff} ("cold hand")	0.335	0.800			
	k_{eff} ("normal hand")	0.960	2.29			
Subcutaneous fat	Pure fat	0.190[11]	0.45	2.30[27]	0.55	0.85[15]
	k_{eff} (high values)	0.450[31]	0.90			
Muscle	Living muscle	0.642[31]	1.53[31]	3.75[13]	0.895[13]	1.05[15]
	Excised; fresh	0.545[37]	1.30[28]	3.47[28]	0.83[28]	1.05[15]
Bone[c]	Cortical b	2.28	5.45	1.59	0.38	1.7
	Cancellous b	0.582	1.39	1.59	0.38	1.3
	"Average" b	1.16	2.78	1.59	0.38	1.5
Blood[d]	Whole blood, Hct = 40%	0.549	1.31	3.64	0.87	1.05
	Plasma	0.599	1.43	3.93	0.94	1.03
	Water (37°C)	0.628	1.50	4.19	1.00	1.00
Organs[e]						
Kidney	Excised, near fresh	0.544	1.30	3.89	0.930	1.05
Heart	Excised; near fresh	0.586	1.40	3.72	0.890	1.06
Liver	Excised; near fresh	0.565	1.35	3.60	0.860	1.05
Lung	Excised (bovine)	0.282[9]	0.674[37]	3.72	0.888[15]	0.603[37]
Brain	Excised; near fresh	0.528	1.26	3.68	0.880	1.05
Abdomen	"Abdomen core"	0.544	1.30[15]	3.70	0.883[15]	1.05
Whole body (average)				3.56[43]	0.86	

Table 3.1 Thermophysical properties of human tissues and organs (23).

Thermophysical properties of human tissue are shown in Table 3.1. From Equation 1, because α represents the portion of attenuation ascribed to absorption processes, energy irreversibly converted to heat in the body of the propagating medium. Therefore, the rate of acoustic energy transfer per unit volume from the sound field is

$$-\frac{dI}{dx} = 2\alpha I \qquad (5)$$

As thermal energy transferred to produce temperature change for a mass (m), amount of heat dQ required producing temperature rise dT in the medium in the time dt is

$$\frac{dQ}{dt} = m\,c\frac{dT}{dt} \qquad (6)$$

Then, the rate of heat transfer per unit volume is

$$\frac{1}{V}\frac{dQ}{dt} = \rho\,c\frac{dT}{dt} \qquad (7)$$

where $\rho\,c$ is the heat capacity per unit volume V of the tissue (ρ is the tissue density and c is the heat capacity per unit mass per °C). As we consider Equation 5, dI/dx resembles the rate of heat transfer per unit volume, so one has:

$$\rho\,c\frac{dT}{dt} = 2\alpha I \qquad (8)$$

The rate of heat production per unit volume that results in the time rate of temperature increase in the tissue, where heat is not transported away by conduction or convection, is given by:

$$\frac{dT}{dt} = \frac{2\alpha I}{\rho\,c} \qquad (9)$$

In the actual situation, heat flows through thermally conductive materials by a process generally known as 'gradient transport'. Gradient heat transport depends on three quantities: the conductivity of the material, the cross-sectional area of the material, and the spatial gradient of temperature. The larger the conductivity, gradient, and/or cross-section, the faster the heat flows. For steady-state conduction (q_x), the rate of heat transmission in the *x*-direction per unit cross-sectional area *A* is proportional to the temperature gradient existing in the same direction, thus

$$q_x = -kA\,\frac{dT}{dx} \tag{10}$$

where *k* is the thermal conductivity of tissue. Then, the rate of heat transfer by heat conduction per unit volume in the *x*-direction is:

$$\frac{d(q_x/A)}{dx} = -k\,\frac{d^2T}{dx^2} \tag{11}$$

Where heat conduction has a significant role by work with the surrounding tissue, Equation 9 becomes:

$$\rho c\,\frac{dT}{dt} = 2\alpha I - k\,\frac{d^2T}{dx^2} \tag{12}$$

3.3 Basic Steps in The Finite Element Method (24)

Preprocessing Phase

Step 1. Create and discretize the solution domain into finite elements; that is, subdivide the problem into nodes and elements.

Step 2. Assume a shape function to represent the physical behavior of an element; that is, an approximate continuous function is assumed to represent the solution of an element.

Step 3. Develop equations for an element.

Step 4. Assemble the elements to present the entire problem. Construct the global stiffness matrix.

Step 5. Apply boundary conditions, initial conditions, and loading.

Solution Phase

Step 6. Solve a set of linear or nonlinear algebraic equations simultaneously to obtain nodal results, such as displacement values at different nodes or temperature values at different nodes in a heat transfer problem.

Postprocessing Phase

Step 7. Obtain other important information. At this point, one may be interested in values of principal stresses, heat fluxes, etc.

In general, there are several approaches to formulate finite element problems: (1) Direct Formulation, (2) The Minimum Total Potential Energy Formulation, and (3) Weighted Residual Formulations.

3.4 ANSYS 5.4 Finite Element Analysis Program

The ANSYS program is organized into two basic levels: the Begin level and the Processor level. The Begin level acts as a gateway into and out of the ANSYS program. It is also used for certain global program controls such as changing the jobname, clearing the database, and copying binary files. From the Begin level, user can enter one of the ANSYS processors. A processor is a collection of functions and routines to serve specific purposes. There are three processors that are most frequently used: 1. The preprocessor (PREP7), 2. The processor (SOLUTION), and 3. The general postprocessor (POST1). The preprocessor (PREP7) contains the commands needed to build a model. The solution processor (SOLUTION) has the commands that allow user to apply boundary conditions and loads, and obtain the solution. The general postprocessor (POST1) contains the commands that allow user to list and display results of an analysis. There are other processors that allow user to perform additional tasks. For example, the time-history postprocessor (POST26) contains the commands that allow user to review results over time in a transient analysis at a certain point in the model. For more information about ANSYS 5.4 program, see Appendix A.

3.5 Typical ANSYS Finite Element Analysis

3.5.1 Build the Model

3.5.1.1 Specifying a Jobname and Analysis Title

The *jobname* is a name that identifies the ANSYS job. The jobname is the first part of the name of all files the analysis creates. (The extension for these file names is a file identifier such as .DB).

3.5.1.2 Defining Element Types

Each element type has a unique number and a prefix that identifies the element category. The element type determines, among other things:

- The degree-of-freedom (DOF) set.
- Whether the element lies in two-dimensional or three-dimensional space.

User must be in PREP7, the general preprocessor, to define element types.

3.5.1.3 Defining Material Properties

This research assumes each model layer has isotropic material properties. As with element types, each set of tissue properties has a material reference number. While defining the elements, point them to the appropriate material reference number. The ANSYS program enables user to store a material property set in an archival material library file, then retrieve the set and reuse it in multiple analyses. The material library files also enable several ANSYS users to share commonly used material property data. Moreover, these can be used to define other, similar material property sets quickly and with fewer errors.

3.5.1.4 Creating the Model Geometry

Generating a finite element model, nodes and elements adequately describe the tissue model geometry. In ANSYS, a working plane (WP) is used to create and orient the geometry of the object as planned to model. The working plane is basically an infinite plane with a two-dimensional coordinate system. The dimensions of the geometric shapes are defined with respect to the WP. By default, the working plane is a Cartesian plane. Other attributes of the working plane may be set by the WP settings dialog submenu.

There are two methods to create the finite element model: 1. *solid modeling*, user describes the geometric shape of model and then instructs the ANSYS program to automatically *mesh* the geometry with nodes and elements. User can control the size and shape of the elements that the program creates. 2. *direct generation*, user "manually" defines the location of each node and the connectivity of each element.

3.5.2 Apply Loads and Obtain the Solution

3.5.2.1 Defining the Analysis Type and Analysis Options

Choosing the analysis type based on the loading conditions and the response wishing to calculate.

3.5.2.2 Applying Loads

The word *loads* includes boundary conditions, and externally and internally applied loads. Boundary conditions are applied by defining fixed temperature at model surfaces. For internal load in this study, *body load* is used to apply internal heat generation (transferred from ultrasonic energy) within tissue. A *load step* is simply a configuration of loads for which user obtains a solution. Load steps are also useful in dividing a transient load history curve into several segments. *Substeps* are incremental steps taken within a load step used mainly for accuracy and convergence purposes in transient analyses. Substeps are also known as *time steps* taken over a period of time. ANSYS program allows user to apply load *ramped* or *stepped*. If a load is ramped, its value increases gradually at each substep, with the full value occurring at the end of the load step. For this research, body load is stepped, internal heat generation value is applied at the first substep and stays constant for the rest of the load step.

3.5.2.3 Initiating the Solution

ANSYS program takes model and loading information from the database and calculates the results. Results are written to the results file and the database.

3.5.3 Review the Results

The solution phase calculates two types of result data: 1. *Primary data* consist of the DOF solution calculated at each node, temperatures in thermal analysis. This is known as nodal solution data. 2. *Derived data* are results calculated from the primary data, such as thermal gradients and fluxes. Derived data are also known as element solution data.

3.5.3.1 The general postprocessor, POST1, enable user to review results at one substep (time step) over the entire model or selected portion of the model. Result can be displayed by many types of graphics that are, contour displays, vector displays, etc.

3.5.3.2 The time history postprocessor, POST26, is used in reviewing results at specific points in the model over all time steps. It has many capabilities, ranging from simple graphics displays and tabular listings to more complex operations such as differential calculus. A typical usage of POST26 is to graph result items versus time in a transient analysis. All POST26 operations refer to *Variables*, which are simply tables of result item versus time.

3.5.3.3 Animation. To create animated displays, use the functions available under Utility Menu. The “one-step” animation macro, used in this research, produces an animated sequence of a contoured deformed shape varying over time in POST1.

CHAPTER 4

MATERIALS AND METHODS

4.1 Materials

4.1.1 Hardwares

All the steps of construction of simulation use ANSYS 5.4 program for finite element analysis. Minimum hardwares required for ANSYS 5.4 software, as used in this research are as follows:

1. Computer: Pentium 100.
2. Main memory (RAM): 64+ MB.
3. Hard disk: 500MB minimum free disk space.
4. Removable Media: Double speed CD-ROM drive.
5. Operating System: Microsoft Windows 95 or Microsoft Windows NT 4.0.
6. Graphics: A Windows 95 or Windows NT supported Graphics Card, capable of 1024x768 in 256 colors.
7. A 17 inch monitor (or larger) compatible with the above mentioned card is recommended.
8. Other Requirements: Microsoft Mouse or mouse 100% compatible with Win NT.

4.1.2 Software

The ANSYS 5.4 program has many finite element analysis capabilities ranging from a simple to complex analysis. The typical steps of ANSYS analysis as discussed earlier are inadequate to perform some complicated analysis. Heat generated within tissue by ultrasonic energy needs additional ANSYS procedures to accomplish the analysis and construct simulation.

4.1.2.1 *ANSYS Parametric Design Language (APDL)* is a language that allows user to build user's model in terms of parameters (variables), which in turn allows user to make design changes easily and conveniently. The basic features of

APDL used in this research consisted of looping, repeating, scalar and array parameters.

(i) *The repeating, and looping* features allow user to change the following:

- Repeating: *REPEAT command allows user to repeat the previous command several times, incrementing any field on that command by a constant value.
- Looping: allows user to loop through a sequence of commands several times. Only one block of commands within an if-then-else construct is processed. The conditions are sequentially evaluated until a true condition is found. If a condition is true, the block of commands following the condition statement is executed, and the processing is redirected to the next command after the *ENDIF.

(ii) *A do-loop* allows user to loop through a series of commands. The *DO and *ENDDO commands are used for this purpose.

(iii) *Scalar parameters* are user-named variables to which user can assign either numeric or alphanumeric values. When user use a parameter in an ANSYS command field, the value of that parameter will be substituted. To assign values to parameters, using "=" the format of this command is *Name=Value,* where *Name* is the name assigned to the parameter and *Value* is the numeric or character value of the parameter. Parametric expressions involve operations among parameters and numbers such as addition and division. A parametric function is a programmed sequence of mathematical operations which returns a single value, such as exponential and logarithm. User can use currently defined parameters later by write them out to a file.

(iv) The ANSYS 5.4 allows user to define *array parameters* (multiple valued). It has *m* rows long and *n* columns wide. Three types of array parameters are *ARRAY, CHAR*, and *TABLE.* Type *ARRAY* consists of discrete numbers that are arranged in a tabular fashion for convenience. Type *CHAR*, the tabular values are alphanumeric character strings. Type *TABLE* consists of numbers arranged in a tabular fashion, but the difference is that it allows *"in-between"* values of array elements to be calculated by linear interpolation. Another difference is the j=0 column, which consists of row index numbers, and the i=0 row, which consists of column index numbers.

For the operations among array parameters, two classes of operations can be identified: operations on column vectors, known as *vector operations*, and operations on entire matrices, known as *matrix operations.* Vector operations are simply a set of operations such as addition, sine, etc., repeated over a sequence of array elements. Matrix operations are mathematical operations between numerical array parameter matrices, such as matrix multiplication and solving simultaneous equations. To reviews more information about array parameter operations, see Appendix B.

4.1.2.2 *Animation* is a valuable tool for graphically interpreting many analytical results, including nonlinear or time-dependent behavior. User can display several frames in rapid succession to achieve an animation effect. The ANSYS and DISPLAY programs on Windows platforms use the Microsoft standard AVI file format to store animation frames (video only) of ANSYS graphics.

4.2 Methods

The task of executing simulations provides insight and a deep understanding of physical processes that are being modeled. Therefore, the steps of executing simulation are consisted of designing a mathematical model of an actual physical system, executing the model on a digital computer, and analyzing the execution output, respectively (25). For this research, using APDL is used to calculate internal heat generation within the material under ultrasonic field. Then, heat generated values are used as body loads that influence thermal change inside model, and temperature distribution is finally obtained.

4.2.1 Construction of An ANSYS 5.4 Command Log File

First step in the construction of command log file is to create a series of ANSYS command. This flexible command can be used to analyse thermal problem in various condition of ultrasound usage. Array parameters are used to calculate intensity decay within model that also includes reflected and transmitted intensity at material interface. Then, vector operations are used to calculate rate of acoustic energy transferred into heat. An array parameter of internal heat generation value is applied to the identical position of model. Next, ANSYS program uses heat generation rate as body loads that introduce heat transfer within model. When ANSYS Solution is achieved, user obtains temperature distribution within model. The procedure of thermal analysis for various ultrasound usages by ANSYS commands and GUI are explained as follows:

Step 1. ANSYS program offers a variety of derived products with features tailored for specific FEM disciplines. Choosing **ANSYS/Thermal** product is selected to perform thermal problem. Then, the jobname is defined by **/FILNAME** or **Utility Menu>File>Change Jobname**.

Step 2. Enter preprocessor through **/PREP7** command.

Step 3. Define the element type by command: **ET** or GUI: **Main Menu > Preprocessor > Element type > Add/Edit/Delete**. Then, click 'Add/Edit/Delete…' to select element type.

Step 4. Define scalar parameters of ultrasound incident intensity and fat, muscle and bone properties according to clinical ultrasound application (Table 2), which consists of incident intensity ($i0 = 1$ W/cm^2), specific heat (c), density (ρ), absorption coefficient (α), thermal conductivity (k), and acoustic impedance (z). After that, save these parameters to a file (**PARSAV** command or menu path **Utility Menu>Parameters>Save Parameters**) for another analysis (using **PARRES** command to restore parameter file).

Materials	**c** (J/g.°C)	**ρ** (g/cm^3)	**α** (Np/cm/MHz)	**k** (W/cm.°C)	**z** (g/cm^2.s)
Fat	2.30	0.85	0.07	0.0019	134000
Muscle	3.75	1.05	0.12	0.00642	171000
Bone	1.59	1.50	1.52	0.0116	780000

Table 4.1 Thermophysical and acoustic properties of fat, muscle and bone.

Parameters of the tissue properties and incident intensity as saved to a file are shown below:

```
PARAMETER STATUS-          ( 16 PARAMETERS DEFINED)
 NAME           VALUE                  TYPE       DIMENSIONS
 AB             1.52000000             SCALAR                      !  α of bone
 AF             7.000000000E-02        SCALAR                      !  α of fat
```

```
AM        .120000000          SCALAR      ! α of muscle
DENB      1.50000000          SCALAR      ! ρ of bone
DENF      .850000000          SCALAR      ! ρ of fat
DENM      1.05000000          SCALAR      ! ρ of muscle
 i0       1.00000000          SCALAR      ! Incident intensity
KB        1.160000000E-02     SCALAR      ! k of bone
KF        .001900000          SCALAR      ! k of fat
KM        6.420000000E-03     SCALAR      ! k of muscle
SPECB     1.59000000          SCALAR      ! c of bone
SPECF     2.30000000          SCALAR      ! c of fat
SPECM     3.75000000          SCALAR      ! c of muscle
ZB        780000.000          SCALAR      ! z of bone
ZF        134000.000          SCALAR      ! z of fat
ZM        171000.000          SCALAR      ! z of muscle
```

Step 5. Construct if-then-else looping for users to assign parameters of incident intensity and material properties by themselves, or to read parameters from a file saved earlier. For three-layered analysis (fat, muscle and bone), such tissue properties and intensity are saved in a parameter file as above. The if-then-else looping will execute **PARRES** command. If user wants to input personalize value, ***ASK** command will ask the user for the parameter value. The prompt (query) that asks for the parameter is included on the ***ASK** command. A default value, which will be assigned to the parameter if the response is a blank, can also be specified on the command. Model in this research is based on three-layered rectangular geometry. Therefore, specify same properties to two or three (all) layers for thermal analysis of the entire model.

Step 6. Use parameters of material properties above to define tissue density, thermal conductivity and specific heat through **UIMP** command. Then, use **SAVE** to save all information to database.

Step 7. User can set working plane by opening the WP settings dialog submenu by issuing the following commands:

Utility Menu>Workplane>WP Settings...

To display the working plane, one needs to issue the following command:

Utility Menu>Workplane>Display Working Plane.

Bring the workplane to view by using the following sequence:

Utility Menu>Workplane>Pan,Zoom, Rotate…

Step 8. For the first step of building model, ***ASK** command is used again to input thickness of model and each layer, diameter of head sound and width of surrounding material (outside ultrasound field), and assign these values to parameters.

Step 9. Create keypoints to define the vertices of an object by **K** command. Parameters from **Step 6** are substituted in **K** command to indicate location of keypoints. If parameter of surrounding material width equal to 0, if-then-else will not execute **K** outside ultrasound beam.

Step 10. Create rectangular areas from keypoints by using ***REPEAT** command to repeat the construction for several areas. Then, connect all areas together by **AGLUE** command. The **PlotCtrls** menu contains a useful graphics option that allows user to turn on keypoint numbers, line numbers, area numbers, and so on, to check the model. To access this option, use the command: **Utility Menu>PlotCtrls>Numbering ...**. Then, save all data to database by **SAVE**.

Step 11. Assign the element attributes, including element type number, material number of each layer. This step is done by selecting each area through **ASEL**, and then **AATT** command or **Main Menu>Preprocessor>-Attributes-Define>Picked Area+**. Then choose **SAVE** again. **ASEL** will be used only within ultrasound field when the model has no surrounding material in the analysis. The if-then-else is used to skip or execute **ASEL** and **AATT** command to any model.

Step 12. For meshing the model, the ANSYS program can automatically generate the nodes and elements. User defines meshing controls by defining the element size. To specify an element edge length, use command: **ESIZE** or GUI: **Main Menu>Preprocessor>-Meshing-Size Cntrls>-Global –Size**. Then, input value of the element edge length. ANSYS will generate a mesh in which no element edge is larger than the input value. For meshing areas within ultrasound field, mesh single area from upper to lower layer, to arrange nodes number from less to more. User can define element edge length of surrounding material rougher (larger) than materials within ultrasound field, to decrease calculation time and memory. Then, **SAVE**.

Step 13. Enter Solution processor through **/SOLU**, and define the analysis type by:

Command: **ANTYPE**

GUI: **Main Menu>Solution>-Analysis Type->New Analysis>...**

Step 14. To specify initial condition, or initial material temperature, by **IC** command, use ***ASK** for user to input this value. ***IF** looping command is used to choose default data (37°C) and assign it to all nodes, or user may input data that assign initial temperature to identical nodes of material.

Step 15. Construct table array parameters of heat generation rate by the following operation:

(1) Because parametric expression can not be done through GUI, *2α* and *-2α* can be calculated as follows:

```
a2f=2*af                                    ! a2f=2α   of first layer
a2m=2*am                                    ! a2m=2α   of second layer
a2b=2*ab                                    ! a2b=2α   of third layer
a_2f=-2*af                                  ! a_2f=-2α  of first layer
a_2m=-2*am                                  ! a_2m=-2α  of second layer
a_2b=-2*ab                                  ! a_2b=-2α  of third layer
```

(2) Perform scalar parameter operation and function to calculate ultrasound decayed intensity at layer interfaces. These values are used to calculate intensity reflection and transmission at every interface, and assigned to parameters for further calculation. For some layers which have same material properties, reflected intensity will be equal to 0.

(3) Select nodes within each area of ultrasound field. Then, use ***GET** command to define parameter of maximum node number of each area.

(4) Create 3 array parameters for calculating the value of three layers materials (***DIM** command). Maximum node number of each layer indicates the number of row of each array parameter.

(5) First column of array parameter indicates node number of each material type. It is done by ***VFILL** command, using **RAMP** to fill parameter with constantly increasing values.

(6) Second column is depth of ultrasound penetration (x-direction) into each material. Use ***VGET** to define coordination of node, which exhibits depth of that node.

(7) Third column is the result from the attenuated intensity decays, $e^{-2\alpha x}$, of every node depth. Use ***VOPER** command for vector operation (**MULT**=multiplication) and ***VFUN** command for parametric function (**EXP**=exponential).

(8) Fourth column is the intensity value at all nodes, calculated by, $I = i0^{*} e^{-2\alpha x}$.

(9) Reflected intensity at first/second layers interface as calculated above is gradually attenuated within first layer. Using $I = i0^{*} e^{-2\alpha x}$ to calculate this reflected intensity decay and define it as new array parameter (***DIM**). Reflected intensity therefore includes the sound intensity (value in fourth column) which decays in x direction. Use ***VOPER** command for this addition (**ADD**) to obtain total intensity within first layer, to be assigned in fifth column.

(10) Use total intensity from fifth column to calculate heat generation rate value (Q) at every node. Use ***VOPER** command to perform parametric operation according to $Q = 2\alpha I$, and assign it to sixth column of this parameter.

(11) For the second array parameter, calculation is similar to first array parameter. Transmitted intensity from first/second layers interface is calculated as before, also incidentally attenuated within second layer in x direction according to $I = i0^{*} e^{-2\alpha x}$. Use ***VOPER** command for multiplication (**MULT**) and ***VFUN** command for exponential (**EXP**) to calculate intensity of every node location within second layer.

(12) Reflected intensity at second/third layers interface is gradually attenuated within second layer. Using $I = i0^{*} e^{-2\alpha x}$ to calculate this reflected intensity decay and define it as new array parameter (***DIM**). Reflected intensity therefore includes the sound intensity which decays in x direction. Use ***VOPER** command for this addition (**ADD**) to obtain total intensity within second layer. Then, calculate heat generation rate Q in the same way as that for the first array parameter.

(13) For the third array parameter, transmitted intensity from second/third layers interface also incidentally attenuated within third layer according to $I = i0^{*} e^{-2\alpha x}$. Use ***VOPER** command for multiplication (**MULT**) and ***VFUN** command for exponential (**EXP**) to calculate intensity in every node location within third layer. Because this layer is lower than other layers, there is no reflection at its lower surface. Then, calculate heat generation rate $Q = 2\alpha I$ and assign it to final column.

(14) Finally, create one table parameter of all heat generation rate values throughout three layers model by arranging Q values together from all array parameters. Use ***VOPER** command for addition (**ADD**) heat generation rate in order of node number.

Step 16. To apply load, use the above this table array parameter as the body load on nodes. Use ***DO** and ***ENDDO** to loop through all loading commands that coincide with all material depths. To start looping 1, heat generation rate is applied on node 1 by **BF** command. Load value is introduced to model by pointing to the value in table parameter at row 1. So, *Q* values are loaded on nodes, until complete loading throughout the number of loops. Then ***ENDDO** the looping.

Step 17. Apply boundary condition by degree of freedom constraint, or fixed temperature, at surface of model. Use **NSLL** to select all nodes on lines at each surface of model, upper, lower, left, and right side. Then apply parameters of temperature value, obtained from ***ASK**, on selected nodes by **D** command and **SAVE**.

Step 18. Set output controls by command: OUTRES or GUI: Main Menu>Solution>-Load Step Opts->Output Ctrls>DB/Results File...

Step 19. Set load step and substep by using ***ASK** to ask user to input these values personally. To specify time at the end of load step, use **TIME** command, and specify the time step sizes to be used for this load step through **DELTIM** command, or GUI: **Main Menu>Preprocessor>Loads>Time/Frequenc>Time & Time Step** or **Main Menu>Solution>Time/Frequenc>Time & Time Step**.

Step 20. ANSYS program allows user to apply load *stepped* or *ramped* by using **KBC** command. For this research, body loads are stepped, and applied on nodes.

Step 21. Initiating the solution. From this step, its command will not include a command log file. User can check all defined information and, may be, make some changes before initiating solution. Then, initiate the solution by:

Command: **SOLVE**
GUI: **Main Menu>Solution>Current LS**
Main Menu>Solution>*solution_method*

Step 22. Use postprocessors to perform the following:.

(1) Animation

To create animated displays, use the functions available under **Utility Menu>PlotCtrls>Animate**. The predefined ANSYS animation macros often are convenient for animating certain types of sequences. The “one-step” animation macro used in this research is **ANTIME**. It produces an animated sequence of a contoured deformed shape varying over time in POST1 general postprocessor. Before using this macro, user must execute a display command that contains deformation, contouring, or both, and user must have a solution containing time variance. To invoke this macro, choose **Utility Menu>PlotCtrls>Animate>Contours Over Time**. The program stores the animation frames in a file called *Jobname*.AVI, where Jobname is the jobname for the current ANSYS session.

(2) The General Postprocessor (/**POST1**)

- Contour Displays. **PLNSOL** command or GUI: **Main Menu>General Postproc>Plot Results>Nodal Solu** produces contour lines that are continuous across the entire model.
- Path Operations. Path plot shows the variation of a quantity along a predefined path throughout the model. To produce a path plot, user needs to perform these tasks:

- Define path attributes using **Main Menu>General Postproc>Path Operations>Define Path>Defined Paths>On Working Plane** or the **PATH** command.

- Map the desired quantity on to the path using **Main Menu>General Postproc>Path Operations>Map onto Path** or the **PDEF** command.

- Use **Main Menu>General Postproc>Path Operations>Plot Path Items** or the **PLPATH** and **PLPAGM** command to display the results.

Moreover, command: **PRPATH** or GUI: **Main Menu>General Postproc>List Results>Path Items** calculates results and then lists specified data along a predefined geometry path in model.

- Listing Results in Tabular Form. To list temperature data, use command: **PRNSOL** or GUI: **Main Menu>General Postproc>List Results>Nodal Solution**.
- Query results. User identifies the item of nodal data that is to be queried. As user picks any node on the model, the ANSYS program will retrieve the nodal data value from the database and will display it.

(3) The Time-History Postprocessor (/**POST26**)

Because all POST26 operations refer to variables, use command: **NSOL** or GUI: **Main Menu>TimeHist Postpro>Define Variables** to define variable of nodal solution data.

- Producing Graph Plots. Command: **PLVAR** or GUI: **Main Menu>TimeHist Postpro>Graph Variables** graphs up to nine variables on a single frame.
- Listing Results in Tabular Form. Command: **PRVAR** or GUI: **Main Menu>TimeHist Postpro>List Variables** lists up to six variables in tabular form.

Using a command log file as input

The procedure for re-executing the commands is contained in a *Jobname*.LOG file or in the database log consisting of three main steps:

(i) Establish the command log file.

Pick **Utility Menu>File>Write DB Log File**, or use the **LGWRITE** command, then specify a file name or use the default name, *Jobname*.LGW. When using **RESUME** command to load a previously saved database, the program clears the database log and replaces it with the database log that is stored on the resumed database. The **/CLEAR** command or GUI path **Utility Menu>File>Clear & Start New** clears both the ANSYS database and the database log.

(ii) Edit the command log file as desired.

Sometimes, user will need to edit command log file before using it as program input. As user edits log file, user can add comments, or indentation to improve its readability, by using comment character (!).

(iii) Read in the edited log file.

In an interactive session, pick **Utility Menu>File>Read Input from** or issue the **/INPUT** command to read in the edited command log file.

4.2.2 Temperature Distribution with Various Boundary Condition Setting

As establishing a command log file is ready, it has a capability to analyse several thermal problems of ultrasound application. The various model sizes can be specified as user desires through these commands. Boundary condition of model also can be defined variously. Therefore, this section uses a command log file to analyse models of different tissue types and boundary conditions. Boundary condition is defined by applying a degree of freedom constraint load (fixed temperature on nodes) equal to 37°C at surface of model. Each tissue type, fat, muscle or bone, has different model sizes. So, temperature changes in several model sizes, with the same fixed temperature at various surface locations, will be analysed through a command log file.

4.2.2.1 Temperature Distribution in Different Thicknesses of Fat, Muscle, and Bone

(1) Fat, Muscle, and Bone Thicknesses

For each tissue type, fat, muscle or bone, model sizes are defined by three thickness values. The first value is equal to the depth of tissue where intensity decays near to zero, about 0.001 W/cm^2. The second value is about ¾ times the first value. And the last value is equal to ½ of the first value. Therefore, thickness value of each tissue type can be calculated as follows.

Use $$I = I_0.e^{-2\alpha x}$$

Then,

$$I / I_0 = e^{-2\alpha x}$$

$$\ln I - \ln I_0 = -2\alpha x$$

and hence $$x = (\ln I_0 - \ln I)/ 2\alpha ,$$

where x is depth of ultrasound penetration, I_0 is incident intensity that is equal to 1 W/cm^2, and I equal 0.001 W/cm^2. Attenuation coefficients, α, of fat, muscle, and bone equal to 0.07, 0.12, and 1.52, respectively. Therefore, three thickness values of each tissue type are tabulated as follows:

	Thickness of first model (cm.)	**Thickness of second model (cm.)**	**Thickness of third model (cm.)**
Fat	49.4	37	24.7
Muscle	28.8	21.6	14.4
Bone	2.3	1.7	1.1

Temperature results of each tissue type are compared at same depth of three models. Fat, muscle, and bone are observed at 1, 4, and 1 cm depth, respectively.

These values equal to ideal thigh model. Even ideal bone thickness equals to 2 cm, but 1 cm depth is also observed because huge intensity is absorbed at near to the bone surface.

(2) Using A Command log file.

- Ultrasound: Intensity = 1 W/cm^2, diameter of head sound = 2.5 cm.
- Surrounding Tissue Width: 5 cm extend from ultrasound beam for every tissue model.
- Tissue Properties: Same value for entire model. Each tissue has the same property as assigned to parameter file.
- Element edge length within ultrasound field: 0.2 cm for fat and muscle to decrease memory and run time of large model. 0.1 cm for bone.
- Initial Temperature: 37°C.
- Boundary Condition: 37°C at upper, lower, left, and right surfaces.
- Load step and Substeps: 600 s. and 15 s.

(3) Reviewing Results.

- Contour Displays.
- Path Plots from upper to lower surface.
- Graph Plots and Listing Results at 1, 4, and 1 cm depth of fat, muscle, and bone, respectively.

4.2.2.2 Temperature Distribution in Different Widths of Surrounding Area Outside Ultrasound Beam of Fat, Muscle, and Bone

(1) Fat, Muscle, and Bone Surrounding Tissue Width.

For this study, model sizes are defined by various surrounding tissue widths. These values are equal to 0, 1, 2, 3, 4, and 5 cm for each tissue type, fat, muscle, and bone.

(2) Using A Command log file.

- Ultrasound: Intensity = 1 W/cm^2, diameter of head sound = 2.5 cm.
- Surrounding Tissue Width: 0, 1, 2, 3, 4, and 5 cm for each tissue type.
- Thickness: 7 cm for every tissue model.
- Tissue Properties: Same value for entire model. Each tissue has the same property as assigned to parameter file.
- Initial Temperature: 37°C.

- Boundary Condition: 37°C at upper, lower, left, and right surfaces.
- Load step and Substeps: 600 s. and 15 s.

(3) Reviewing Results.

- Contour Displays.
- Path Plots from upper to lower surface and from left to right side.
- Graph Plots and Listing Results at 1, 4, and 1 cm depth of fat, muscle, and bone, respectively.

4.2.3 Temperature Distribution within Three-Layered Model of Fat, Muscle, and Bone

After using a command log file to analyse single tissue type model, this section will be carried out with three-layer model. Fat, muscle, and bone thickness values are equal to 1, 4, and 2 cm, respectively. These values are for ideal thigh model thickness. Moreover, different acoustic impedances of each layer influence intensity reflection at tissue interface. Therefore, these factors cause this model to resemble a human tissue that is applied by ultrasound. This section is interested in effect of ultrasound in two period of treatment time. First study observes temperature distribution within short duration of treatment, 3 minutes. Time steps are equal to 1 second, to observe detailed temperature changes. Second study is to obtain steady state temperature of fat, muscle, and bone. Therefore, long duration of treatment is set by 60 minutes, and 60 seconds of time steps. Because a command log file can define incident intensity (I_0) as user desires, this study analyses two models with I_0 equal to 0.5 and 1 W/cm^2.

4.2.3.1 Temperature Distribution within Three-Layered Tissue at Clinical Therapeutic Time

From the study above, (observing) time steps are equal to 15 seconds. Setting of longer time steps can reduce memory and calculation time. But in clinical ultrasound therapy, the temperature changes quickly within tissue. Therefore, this section analyses temperature change in every 1 second, during 3 minutes of treatment time.

(1) Using A Command log file.

- Ultrasound: Intensity = 0.5 W/cm^2 and 1 W/cm^2, diameter of head sound = 2.5 cm.
- Surrounding Tissue Width: 5 cm for every tissue model.

- Thickness of fat, muscle, and bone: 1, 4, and 2 cm for every tissue model.
- Tissue Properties: Default value from parameter file.
- Initial Temperature: 37°C.
- Boundary Condition: 37°C at upper, lower, left, and right surface.
- Load step and Substeps: 180 s. and 1 s.

(2) Reviewing Results.

- Contour Displays.
- Path Plots from upper to lower surface.
- Graph Plots and Listing Results at middle portion of fat, muscle, above bone surface and inside bone.

4.2.3.2 Steady State Temperature of Three-Layered Tissue

Because user is able to define treatment time through a command log file as desired, this section attempts to find steady state temperature. Therefore, to reduce memory and calculation time, set a longer substep within a long time step. Thus, define substeps to 60 seconds, with 60 minutes treatment time.

(1) Using A Command log file.

- Ultrasound: Intensity = 0.5 W/cm^2 and 1 W/cm^2, diameter of head sound = 2.5 cm.
- Surrounding Tissue Width: 5 cm for every tissue model.
- Thickness of fat, muscle, and bone: 1, 4, and 2 cm for every tissue model.
- Tissue Properties: Default value from parameter file.
- Initial Temperature: 37°C.
- Boundary Condition: 37°C at upper, lower, left, and right surface.
- Load step and Substeps: 3,600 s. and 60 s.

(2) Reviewing Results.

- Path Plots and Listing Results from upper to lower surface.
- Graph Plots and Listing Results at middle portion of fat, muscle, above bone surface and inside bone.

CHAPTER 5
RESULTS

5.1 A Command Log File for Thermal Analysis

A command log file was written for use to analyse temperature changes of materials within therapeutic ultrasound application. This compatible log file allows user to input various data personally. All commands of log file are shown below, where comment and command explanation are behind “!”.

```
/PREP7                                               ! Enter Preprocessor
ET,1,PLANE55                                         ! Define element type
*ASK,newprop,1 to change I or material property,2
*IF,newprop,EQ,1,THEN                       ! If loop for choosing a parameter file or user input personally
*ASK,i0,Incident intensity (W/cm2),1
*ASK,specf,Specific Heat of 1st layer (J/g-C),2.30
*ASK,specm,Specific Heat of 2nd layer (J/g-C),3.75
*ASK,specb,Specific Heat of 3rd layer (J/g-C),1.59
*ASK,denf,Density of 1st layer (g/cm3),0.85
*ASK,denm,Density of 2nd layer (g/cm3),1.05                  ! Ask user to input
*ASK,denb,Density of 3rd layer (g/cm3),1.50                  parameter values of the
*ASK,af,Atten. Coef. of 1st layer (Np/cm),0.07               material properties and
*ASK,am,Atten. Coef. of 2nd layer (Np/cm),0.12               incident intensity
*ASK,ab,Atten. Coef. of 3rd layer (Np/cm),1.52
*ASK,kf,Thermal Conductivity of 1st layer (W/cm-C),0.0019
*ASK,km,Thermal Conductivity of 2nd layer (W/cm-C),0.00642
*ASK,kb,Thermal Conductivity of 3rd layer (W/cm-C),0.0116
*ASK,zf,Acoustic Impedance of 1st layer (g/cm2.s),134000
*ASK,zm,Acoustic Impedance of 2nd layer (g/cm2.s),171000
*ASK,zb,Acoustic Impedance of 3rd layer (g/cm2.s),780000
PARSAV,ALL                                           ! Save parameters
```

```
*ELSE
PARRES,NEW,allprop                               ! Restore parameters from a file
*ENDIF
UIMP,1,DENS,KXX,C,denf,kf,specf
UIMP,2,DENS,KXX,C,denm,km,specm                  ! Defining material properties by parameters
UIMP,3,DENS,KXX,C,denb,kb,specb
SAVE
*ASK,depth,Model thickness (cm),7
*ASK,first,1st layer thickness (cm),1            ! Ask user to input thickness of model and
*ASK,secon,2nd layer thickness (cm),4            each layer, diameter of head sound and
*ASK,diam,Diameter of head sound (cm),2.5        width of surrounding material, and assign
*ASK,sur,Surrounding model width (cm),5          to parameters
us=sur+diam
wide=(2*sur)+diam
d1=depth-first
d2=depth-first-secon
K,1,sur,depth
K,2, sur,d1
K,3, sur,d2
K,4, sur,0                   ! Creating keypoints within ultrasonic field
K,5, us,depth
K,6, us,d1
K,7, us,d2
K,8, us,0
*IF,sur,EQ,0,THEN            ! If loop for choosing between include/exclude surrounding material.
A,1,2,6,5                    ! Creating first area by keypoints (exclude surrounding material).
*REPEAT,3,1,1,1,1            ! Repeating create areas within ultrasound (US) field.
*ELSE
K,9,0,depth
K,10,0,d1
K,11,0,d2                    ! Creating keypoints of surrounding material.
K,12,0,0
K,13,wide,depth
K,14,wide,d1
```

```
K,15,wide,d2                 ! Creating keypoints of surrounding material.
K,16,wide,0
A,1,2,6,5
*REPEAT,3,1,1,1,1
A,9,10,2,1                   ! Creating areas of surrounding material
*REPEAT,3,1,1,1,1
A,5,6,14,13
*REPEAT,3,1,1,1,1
*ENDIF
ASEL,ALL
AGLUE,ALL                    ! connecting all areas together
SAVE
ASEL,S,AREA,,1
AATT,1,,1,0
ASEL,S,AREA,,2               ! Selecting each area within US field, and assign
AATT,2,,1,0                  the element attributes (element type number,
ASEL,S,AREA,,3               material number of each layer).
AATT,3,,1,0
ASEL,ALL
*ASK,ein,Element size within US field(cm),0.1      ! Ask to input element (E) edge length within US field.
*ASK,eout,Element size outside US field(cm),0.25       ! Ask to input E. edge length outside US field.
*IF,sur,EQ,0,THEN            ! If loop for choosing between include/exclude surrounding material
MSHAPE,0,2D
MSHKEY,0                     ! Exclude surrounding material. Defining element
ESIZE,ein                    shape, free meshing and element edge length.
AMESH,1                      Meshing areas under US field.
AMESH,2
AMESH,3
*ELSE
ASEL,S,AREA,,4               ! Include surrounding material. Selecting areas of
ASEL,A,AREA,,7               surrounding material, and assign the element attributes.
AATT,1,,1,0
ASEL,S,AREA,,5
ASEL,A,AREA,,8
```

```
AATT,2,,1,0
ASEL,S,AREA,,6
ASEL,A,AREA,,9                  ! Include surrounding material. Selecting areas of
AATT,3,,1,0                     surrounding material, and assign the element attributes.
ASEL,ALL
MSHAPE,0,2D
MSHKEY,0
ESIZE,ein                       ! Include surrounding material. Defining element
AMESH,1                         shape, free meshing and element edge length.
AMESH,2                         Meshing areas under US field.
AMESH,3
ESIZE,eout                      ! Defining element shape, free meshing and element edge
AMESH,4,9                       length. Meshing areas of surrounding material.
*ENDIF
SAVE
/SOLU                           ! Enter solution processor
ANTYPE,TRANS,NEW                ! Defining transient analysis
ALLSEL,ALL
*ASK,body,1 to change initial temp,37
*IF,body,NE,37,THEN             ! If loop for choosing material temp=37 or user input personally
*ASK,ftemp,1st layer temperature,37
*ASK,mtemp,2nd layer temperature,37     ! Ask user to input initial temperature of each layer.
*ASK,btemp,3rd layer temperature,37
ASEL,S,MAT,,1,,,1
NSLA,S,1
IC,ALL,TEMP,ftemp
ASEL,S,MAT,,2,,,1
NSLA,S,1                        ! Selecting nodes within areas of each
IC,ALL,TEMP,mtemp               material type. Apply parameters of initial
ASEL,S,MAT,,3,,,1               temperature to those nodes
NSLA,S,1
IC,ALL,TEMP,btemp
*ELSE
IC,ALL,TEMP,body                ! If entire model has initial temperature=37, apply 37 to all nodes
```

```
*ENDIF
ALLSEL,ALL
a2f=2*af
a2m=2*am
a2b=2*ab                                  ! Calculating 2α and -2α of all layers.
a_2f=-2*af
a_2m=-2*am
a_2b=-2*ab
lowf=i0*(EXP(a_2f*first))                ! Calculating US decayed intensity at lower surface of 1st layer.
rfm=lowf*((zm-zf)/(zm+zf))**2              ! Calculating reflected intensity at 1st/2nd layer interface.
tfm=lowf*(4*zf*zm)/((zm+zf)**2)            ! Calculating transmitted intensity at 1st/2nd layer interface.
lowm=tfm*(EXP(a_2m*secon))               ! Calculating US decayed intensity at lower surface of 2nd layer.
rmb=lowm*((zb-zm)/(zb+zm))**2              ! Calculating reflected intensity at 2nd/3rd layer interface.
tmb=lowm*(4*zm*zb)/((zb+zm)**2)            ! Calculating transmitted intensity at 2nd/3rd layer interface.
ASEL,S,AREA,,1                              ! FIRST LAYER
NSLA,S,1
*GET,nmaxf,NODE,,NUM,MAX                    ! Get maximum node number of 1st layer under US field
*DIM,xf,ARRAY,nmaxf,6                       ! Creating array parameters of 1st layer
*VFILL,xf(1,1),RAMP,1,1                     ! (1st layer) Column of node number arrangement
*VGET,xf(1,2),NODE,1,LOC,Y                 ! (1st layer) Get coordination of all node (x value)
*VOPER,xf(1,2),depth,SUB,xf(1,2)
*VOPER,xf(1,3),xf(1,2),MULT,a_2f            ! (1st layer)  -2α x
*VFUN,xf(1,3),EXP,xf(1,3)                   ! (1st layer)  Exponential of -2α x
*VOPER,xf(1,4),xf(1,3),MULT,i0              ! (1st layer)  I = i0* EXP(-2α x)
*DIM,irfm,ARRAY,nmaxf,4                     ! (1st layer) Defining new array parameter of reflection
*VFILL,irfm(1,1),RAMP,1,1                   ! (1st layer) Arrangement of node number for reflection
*VGET,irfm(1,2),NODE,1,LOC,Y               ! (1st layer) Get coordination of node for reflection
*VOPER,irfm(1,2),irfm(1,2),SUB,d1
*VOPER,irfm(1,3),irfm(1,2),MULT,a_2f        ! (1st layer)  -2α x  for reflection
*VFUN,irfm(1,3),EXP,irfm(1,3)               ! (1st layer)  Exponential of -2α x  for reflection
*VOPER,irfm(1,4),irfm(1,3),MULT,rfm         ! (1st layer)  I = (I reflection)* EXP(-2α x)
*VOPER,xf(1,5),xf(1,4),ADD,irfm(1,4)        ! (I total) = (I decayed incident)+(I decayed reflection)
*VOPER,xf(1,6),xf(1,5),MULT,a2f             ! (1st layer)  Q = 2α *(I total)
ASEL,S,AREA,,2                              ! SECOND LAYER
```

```
NSLA,S,1
*GET,nmaxm,NODE,,NUM,MAX                 ! Get maximum node number of 2nd layer under US field
mrow=nmaxm-nmaxf                         ! Parameter of number of nodes under US field
mrow1=nmaxf+1                            ! Parameter of first node number under US field
*DIM,xm,ARRAY,mrow,6                     ! Creating array parameters of 2nd layer
*VFILL,xm(1,1),RAMP,mrow1,1              ! (2nd layer) Column of node number arrangement
*VGET,xm(1,2),NODE,mrow1,LOC,Y          }
                                         }  ! (2nd layer) Get coordination of all node (x value)
*VOPER,xm(1,2),d1,SUB,xm(1,2)           }
*VOPER,xm(1,3),xm(1,2),MULT,a_2m         ! (2nd layer)  -2α x
*VFUN,xm(1,3),EXP,xm(1,3)                ! (2nd layer)  Exponential of -2α x
*VOPER,xm(1,4),xm(1,3),MULT,tfm          ! (2nd layer)  I = i0* EXP(-2α x)
*DIM,irmb,ARRAY,mrow,4                   ! (2nd layer) Defining new array parameter of reflection
*VFILL,irmb(1,1),RAMP,mrow1,1            ! (2nd layer) Arrangement of node number for reflection
*VGET,irmb(1,2),NODE,mrow1,LOC,Y        }
                                         }  ! (2nd layer) Get coordination of node for reflection
*VOPER,irmb(1,2),irmb(1,2),SUB,d2       }
*VOPER,irmb(1,3),irmb(1,2),MULT,a_2m     ! (2nd layer)  -2α x  for reflection
*VFUN,irmb(1,3),EXP,irmb(1,3)            ! (2nd layer)  Exponential of -2α x  for reflection
*VOPER,irmb(1,4),irmb(1,3),MULT,rmb      ! (2nd layer)  I = (I reflection)* EXP(-2α x)
*VOPER,xm(1,5),xm(1,4),ADD,irmb(1,4)     ! (I total) = (I decayed incident)+(I decayed reflection)
*VOPER,xm(1,6),xm(1,5),MULT,a2m          ! (2nd layer)  Q = 2α *(I total)
ASEL,S,AREA,,3                           ! THIRD LAYER
NSLA,S,1
*GET,nmaxb,NODE,,NUM,MAX                 ! Get maximum node number of 3rd layer under US field
brow=nmaxb-nmaxm                         ! Parameter of number of nodes under US field
brow1=nmaxm+1                            ! Parameter of first node number under US field
*DIM,xb,ARRAY,brow,5                     ! Creating array parameters of 3rd layer
*VFILL,xb(1,1),RAMP,brow1,1              ! (3rd layer) Column of node number arrangement
*VGET,xb(1,2),NODE,brow1,LOC,Y          }
                                         } ! (3rd layer) Get coordination of node for reflection
*VOPER,xb(1,2),d2,SUB,xb(1,2)           }
*VOPER,xb(1,3),xb(1,2),MULT,a_2b         ! (3rd layer)  -2α x
*VFUN,xb(1,3),EXP,xb(1,3)                ! (3rd layer)  Exponential of -2α x
*VOPER,xb(1,4),xb(1,3),MULT,tmb          ! (3rd layer)  I = i0* EXP(-2α x)
*VOPER,xb(1,5),xb(1,4),MULT,a2b          ! (3rd layer)  Q = 2α *(I total)
```

```
*DIM,qall,TABLE,nmaxb                           ! Defining table parameter of all heat generation value
*VFILL,qall(1,0),RAMP,1,1                       ! Column of all node number under US field
*VOPER,qall(1),qall(1),ADD,xf(1,6)              ! Add all Q value of 1st layer to parameter
*VOPER,qall(mrow1,1),qall(mrow1,1),ADD,xm(1,6)     ! Add all Q value of 2nd layer to parameter
*VOPER,qall(brow1,1),qall(brow1,1),ADD,xb(1,5)     ! Add all Q value of 3rd layer to parameter
qall(0,1)=1
ALLSEL,ALL
*DO,g,1,nmaxb                                   ! Do loop through loading on all nodes under US field
BF,g,HGEN,qall(g)                               ! Using table parameter to load Q on nodes
*ENDDO
*ASK,tup,Temp on upper surface,37                ! Ask user to input boundary condition (BC) or
*ASK,tlow,Temp on lower surface,37               fixed temperature at upper, lower, left and right
*ASK,tsur,Temp on both side,37                   surface of model
*IF,sur,EQ,0,THEN                         ! If loop for choosing between include/exclude surrounding material.
KSEL,S,KP,,1
KSEL,A,KP,,5                                   ! Selecting all nodes on line at upper
LSLK,S,1                                       surface of model under US field
NSLL,S,1
D,ALL,TEMP,tup                           ! Applying parameter of BC temperature on upper surface
KSEL,S,KP,,4
KSEL,A,KP,,8                                   ! Selecting all nodes on line at lower
LSLK,S,1                                       surface of model under US field
NSLL,S,1
D,ALL,TEMP,tlow                          ! Applying parameter of BC temperature on lower surface
KSEL,S,KP,,1,4                                 ! Selecting lines at left side of model under US field
LSLK,S,1
NSLL,S,1                                 ! Selecting all nodes on selected lines
D,ALL,TEMP,tsur                          ! Applying parameter of BC temperature on selected nodes
KSEL,S,KP,,5,8
LSLK,S,1                                       ! Selecting all nodes on lines at right side of
NSLL,S,1                                       model under US field
D,ALL,TEMP,tsur                          ! Applying parameter of BC temperature on right side
*ELSE
KSEL,S,KP,,1
```

```
KSEL,A,KP,,5
KSEL,A,KP,,9                              ! (Include surrounding material) Selecting all nodes
KSEL,A,KP,,13                             on line at upper surface of entire model.
LSLK,S,1
NSLL,S,1
D,ALL,TEMP,tup                      ! Applying parameter of BC temperature on upper surface
KSEL,S,KP,,4
KSEL,A,KP,,8
KSEL,A,KP,,12                             ! (Include surrounding material) Selecting all nodes
KSEL,A,KP,,16                             on line at lower surface of entire model.
LSLK,S,1
NSLL,S,1
D,ALL,TEMP,tlow                     ! Applying parameter of BC temperature on lower surface
KSEL,S,KP,,9,16
LSLK,S,1                                  ! (Include surrounding material) Selecting all nodes
NSLL,S,1                                  on line at left and right side of entire model.
D,ALL,TEMP,tsur                     ! Applying parameter of BC temperature on left and right side
*ENDIF
ALLSEL,ALL
SAVE
OUTRES,ALL,ALL                            ! Setting output control, save result to file and database
*ASK,allt,US application time(sec),180    ! Ask user to input load step time
TIME,allt                                 ! Specify load step time by parameter
AUTOTS,0                                  ! Off automatic time stepping
*ASK,step,Measured time step(sec),1       ! Ask user to input substeps
DELTIM,step,0,0,0                         ! Specify substeps by parameter
KBC,1                                     ! Setting Stepped load type
SAVE
```

! Establish the command log file from all command above by: **Utility Menu>File>Write DB Log File**

5.2 Temperature Distribution with Various Boundary Condition of Fat, Muscle, and Bone

5.2.1. Temperature Distribution in Different Thickness of Fat, Muscle, and Bone

The command log file allows user to build and analyse model variously. Thus, temperature distributions within various tissue thickness values are shown in the following sub-sections.

5.2.1.1 FAT

(1) *Contour displays.* As animation can display temperature changes continuously, contour plot is a helpful tool for user to perceive profile of temperature distribution at a specific time. Temperature distributions in various thickness values of fat at 10 minutes of ultrasound application are shown in Figures 5.1-5.3 below:

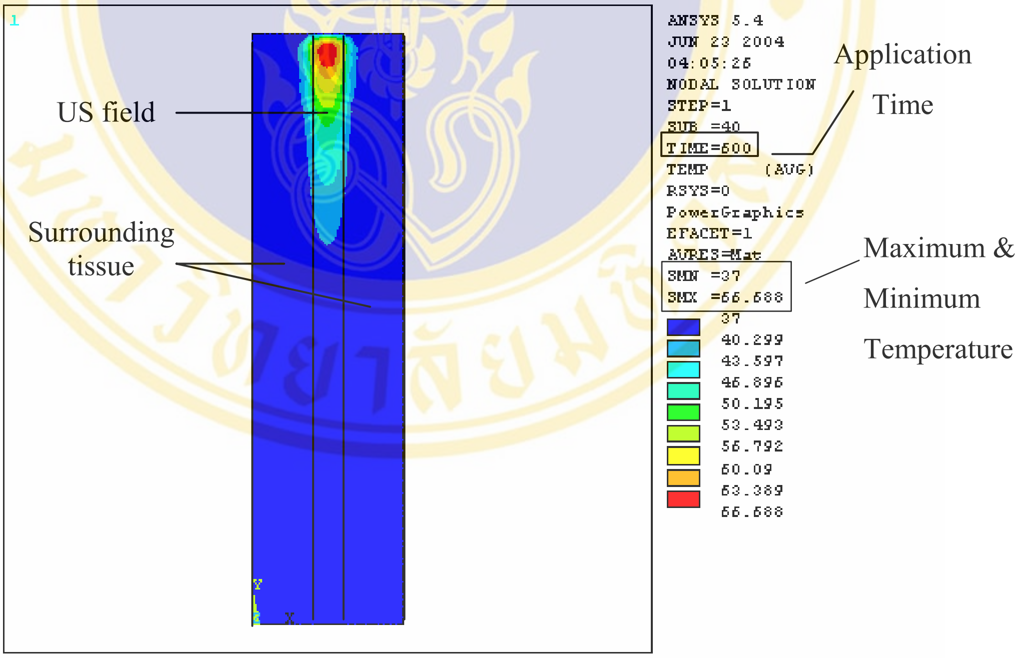


Figure 5.1 Contour display of temperature distribution at time = 600 sec. within fat, 49.4x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

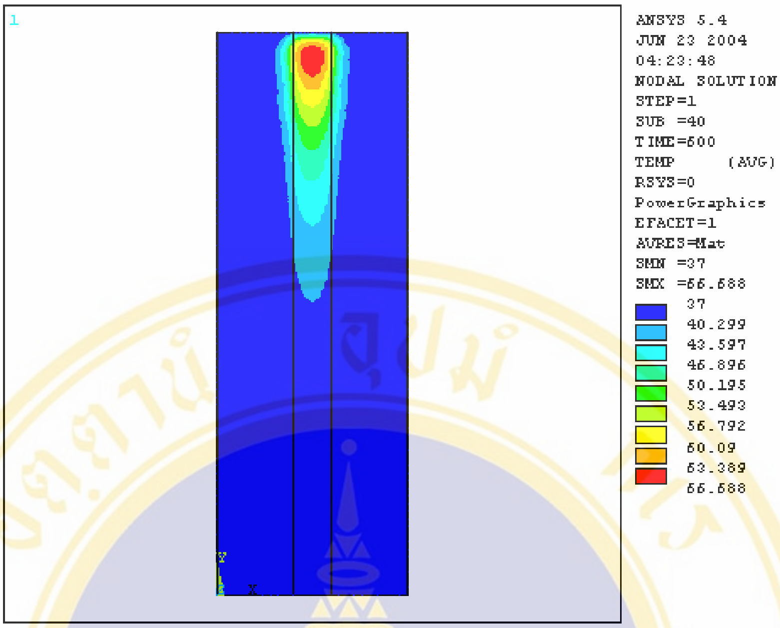


Figure 5.2 Contour display of temperature distribution at time = 600 sec. within fat, 37x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

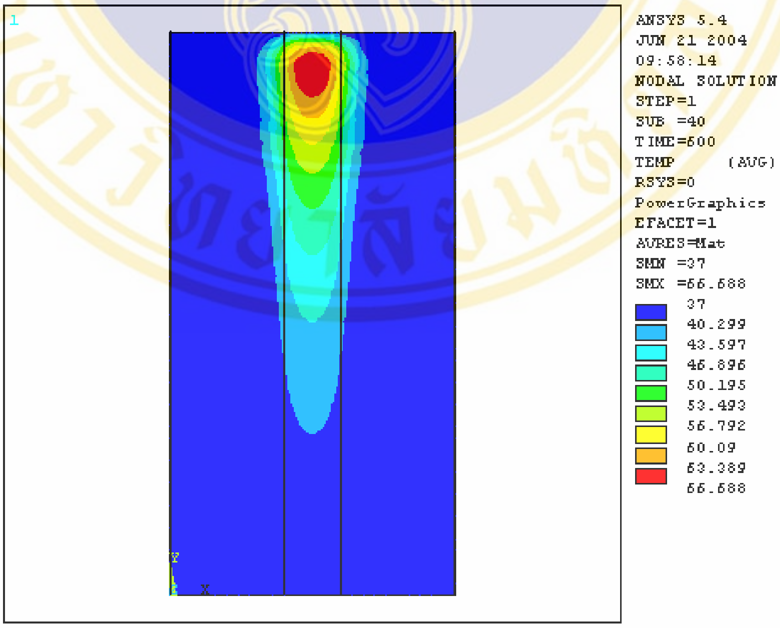


Figure 5.3 Contour display of temperature distribution at time = 600 sec. within fat, 24.7x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Path plots are defined by vertical line axis of ultrasound beam from its upper to lower surface. All path plotting and table of temperature results of fat at 10 minutes of ultrasound application are shown in Figure 5.4 and Table 5.1.

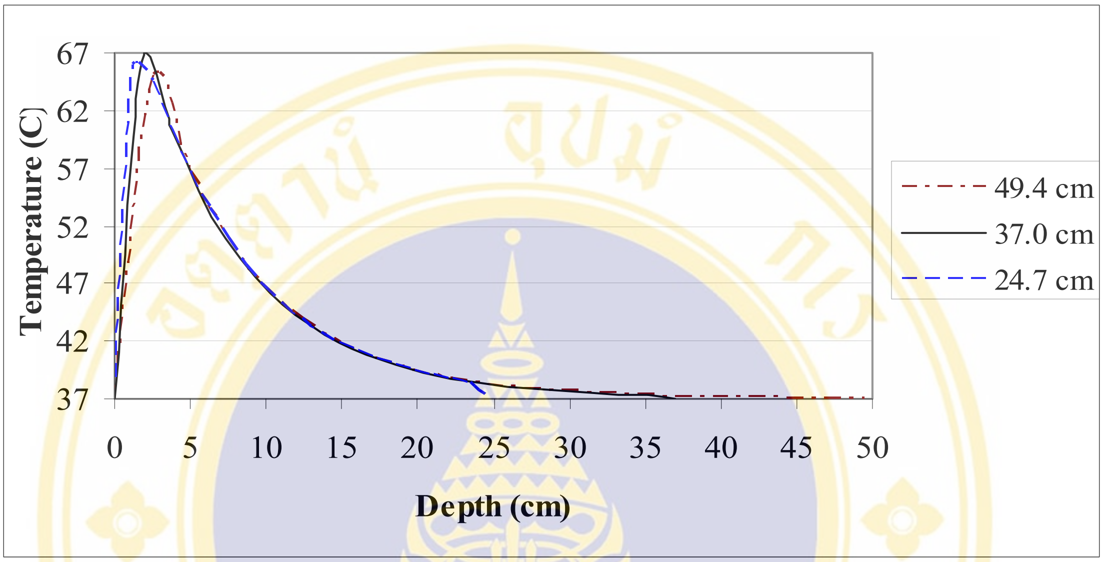


Figure 5.4 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 fat models, thickness values = 49.4, 37.0, 24.7 cm., and applied ultrasound intensity = 1 W/cm^2.

Table 5.1 List results of temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 fat models, thickness values = 49.4, 37.0, 24.7 cm., and applied ultrasound intensity = 1 W/cm^2.

Fat thickness = 49.4 cm.		Fat thickness = 37.0 cm.		Fat thickness = 24.7 cm.	
Depth (cm)	Temperature (°C)	Depth (cm)	Temperature (°C)	Depth (cm)	Temperature (°C)
0	37	0	37	0	37
2.47	64.608	1.85	66.376	1.235	66.038
4.94	56.657	3.7	60.385	2.47	64.608
7.41	50.789	5.55	55.025	3.705	60.368
9.88	46.745	7.4	50.802	4.94	56.664
12.35	43.903	9.25	47.642	6.175	53.469
14.82	41.886	11.1	45.217	7.41	50.791
17.29	40.455	12.95	43.343	8.645	48.584
19.76	39.446	14.8	41.895	9.88	46.744
22.23	38.729	16.65	40.777	11.115	45.196

Table 5.1 (Continued) List results of temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 fat models, thickness values = 49.4, 37.0, 24.7 cm., and applied ultrasound intensity = 1 W/cm^2.

Fat thickness = 49.4 cm.		Fat thickness = 37.0 cm.		Fat thickness = 24.7 cm.	
Depth (cm)	Temperature (°C)	Depth (cm)	Temperature (°C)	Depth (cm)	Temperature (°C)
24.7	38.223	18.5	39.914	12.35	43.894
27.17	37.866	20.35	39.25	13.585	42.8
29.64	37.613	22.2	38.737	14.82	41.881
32.11	37.434	24.05	38.342	16.055	41.107
34.58	37.307	25.9	38.035	17.29	40.454
37.05	37.217	27.75	37.799	18.525	39.905
39.52	37.154	29.6	37.617	19.76	39.443
41.99	37.109	31.45	37.476	20.995	39.055
44.46	37.077	33.3	37.367	22.23	38.724
46.93	37.054	35.15	37.278	23.465	38.333
49.4	37	37	37	24.7	37

(3) *Graph Plots at Specific Point in Model*. This postprocessor, POST26, displays result of temperature versus time at same depth, 1 cm., in every fat models (Figure 5.5). Their results show that they have same temperature value. For table of temperature result, see Table 1 in Appendix C.

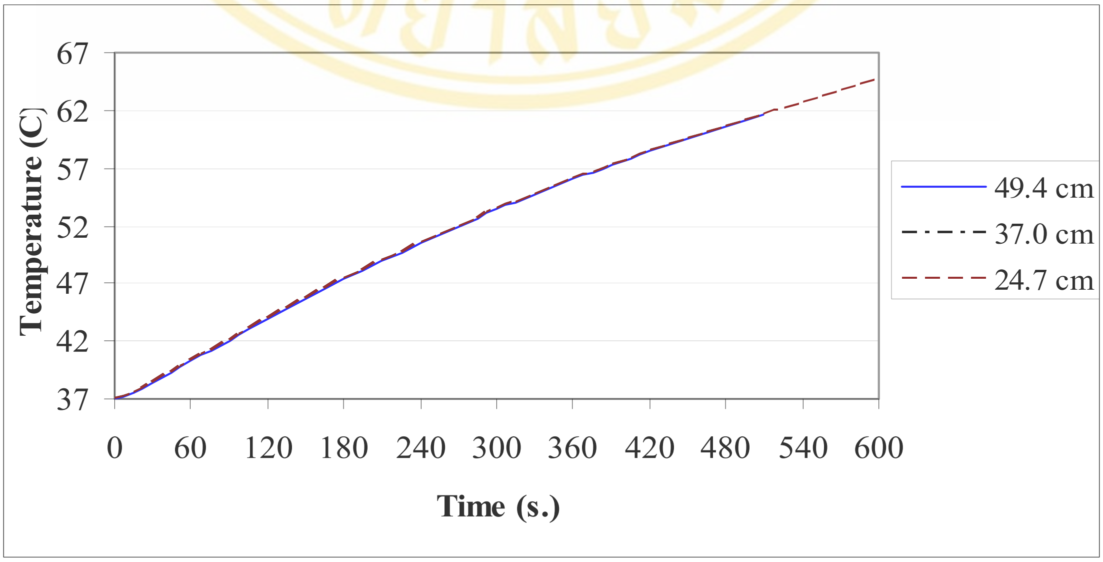


Figure 5.5 Temperature versus time at same depth 1 cm. of 3 fat models, thickness values = 49.4, 37, and 24.7 cm., and intensity = 1 W/cm^2.

5.2.1.2 MUSCLE

(1) *Contour displays*. Temperature distributions in various thickness values of muscle at 10 minutes of ultrasound application are shown in Figures 5.6-5.8 below:

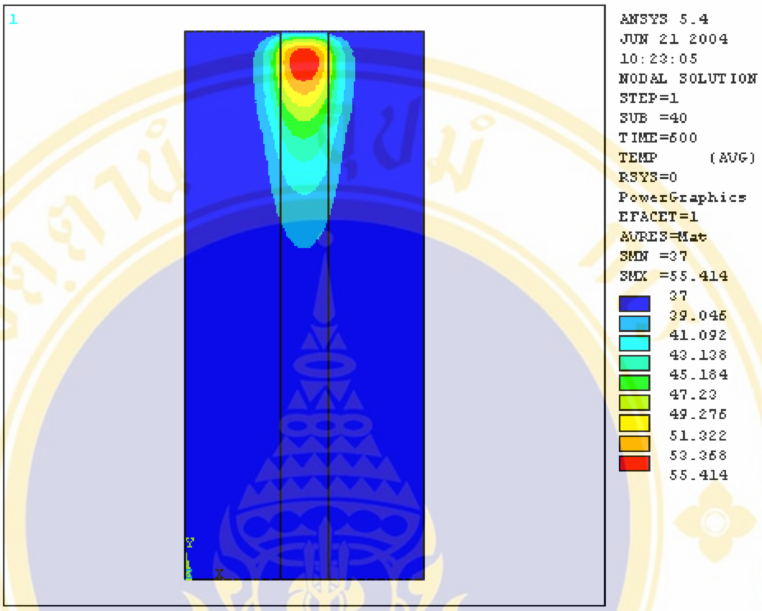


Figure 5.6 Contour display of temperature distribution at time = 600 sec. within muscle, 28.8x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

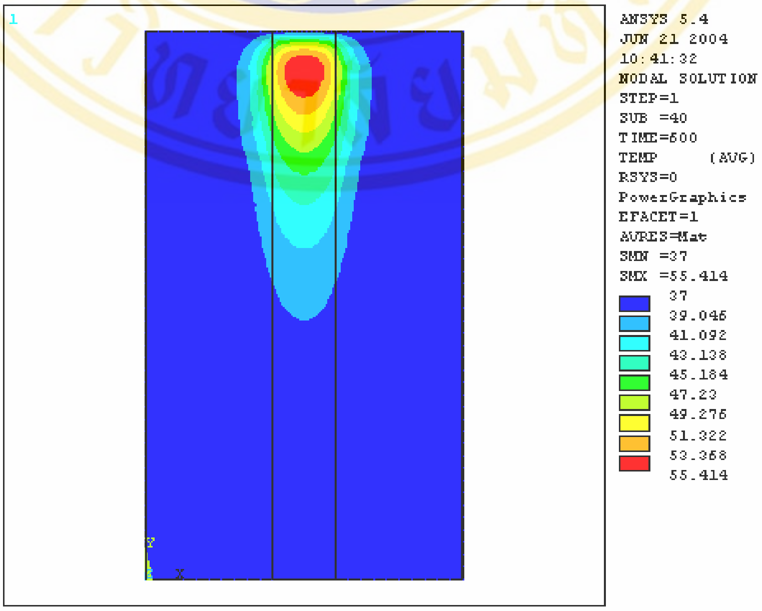


Figure 5.7 Contour display of temperature distribution at time = 600 sec. within muscle, 21.6x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

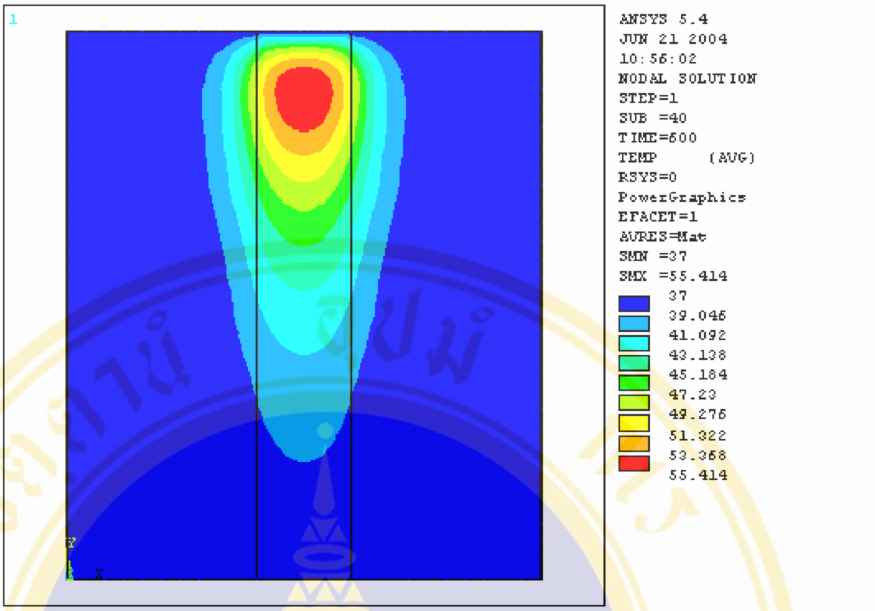


Figure 5.8 Contour display of temperature distribution at time = 600 sec. within muscle, 14.4x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Path plots are defined by vertical line axis of ultrasound beam from its upper to lower surface. All path plotting and table of temperature results of muscle at 10 minutes of ultrasound application are shown in Figure 5.9 and Table 5.2.

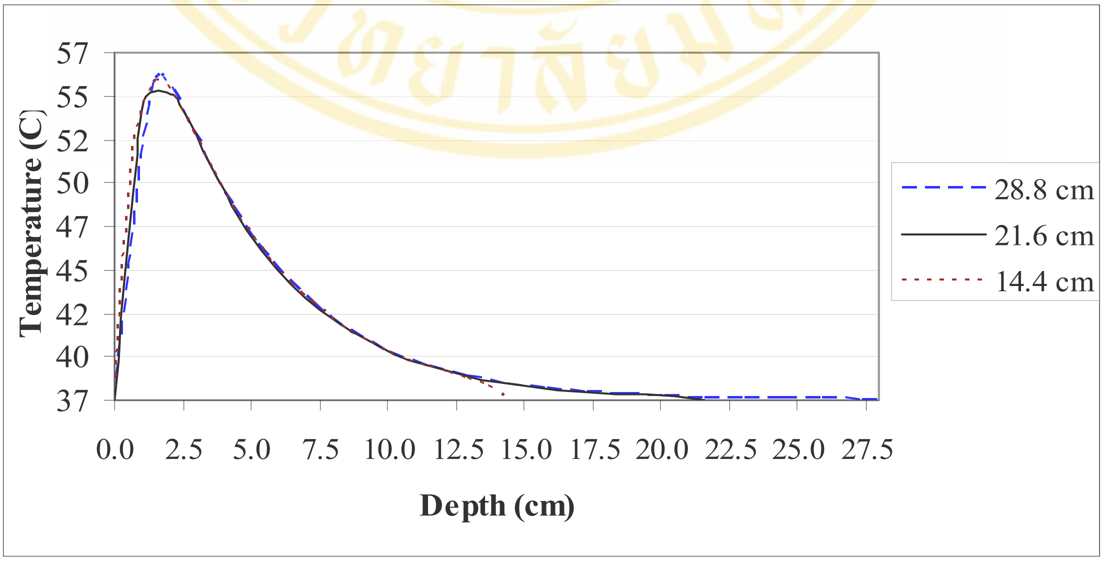


Figure 5.9 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 muscle models, thickness values = 28.8, 21.6, 14.4 cm., and applied ultrasound intensity = 1 W/cm^2.

Table 5.2 List results of temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 muscle models, thickness values = 28.8, 21.6, 14.4 cm., and applied ultrasound intensity = 1 W/cm^2.

Muscle thickness = 28.8 cm.		Muscle thickness = 21.6 cm.		Muscle thickness = 14.4 cm.	
Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)
0	37	0	37	0	37
1.44	55.296	1.08	54.191	0.72	51.352
2.88	52.52	2.16	54.627	1.44	55.296
4.32	48.188	3.24	51.369	2.16	54.627
5.76	44.905	4.32	48.188	2.88	52.52
7.2	42.602	5.4	45.623	3.6	50.245
8.64	40.98	6.48	43.65	4.32	48.188
10.08	39.809	7.56	42.143	5.04	46.409
11.52	38.973	8.64	40.975	5.76	44.904
12.96	38.384	9.72	40.057	6.48	43.645
14.4	37.971	10.8	39.342	7.2	42.589
15.84	37.685	11.88	38.795	7.92	41.698
17.28	37.485	12.96	38.378	8.64	40.938
18.72	37.343	14.04	38.062	9.36	40.297
20.16	37.243	15.12	37.819	10.08	39.762
21.6	37.172	16.2	37.632	10.8	39.316
23.04	37.122	17.28	37.489	11.52	38.941
24.48	37.087	18.36	37.378	12.24	38.605
25.92	37.062	19.44	37.288	12.96	38.258
27.36	37.04	20.52	37.189	13.68	37.788
28.8	37	21.6	37	14.4	37

(3) *Graph Plots at Specific Point in Model*. This postprocessor, POST26, displays result of temperature versus time at same depth, 4 cm., in every muscle model (Figure 5.10). Their results show that they have same temperature value. For table of temperature result, see Table 2 in Appendix C.

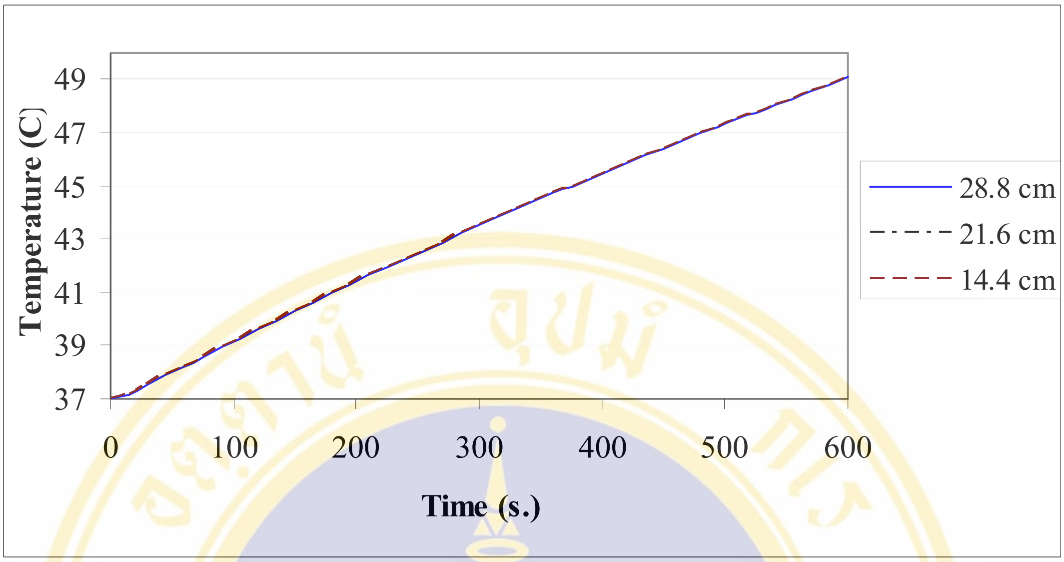


Figure 5.10 Temperature versus time at same depth 4 cm. of 3 muscle models, thickness values = 28.8, 21.6, 14.4 cm., and intensity = 1 W/cm^2.

5.2.1.3 BONE

(1) *Contour displays.* Temperature distributions in various thickness values of bone at 10 minutes of ultrasound application are shown in Figures 5.11-5.13 below:

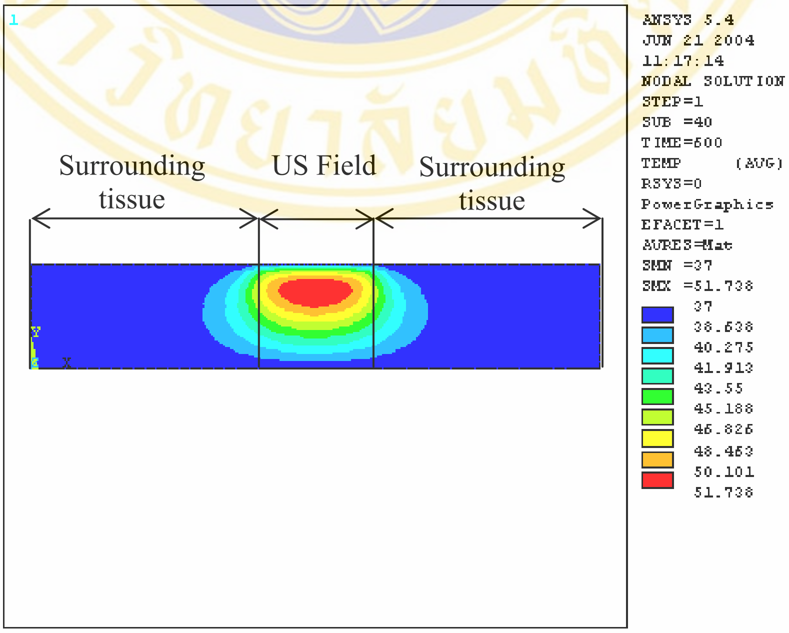


Figure 5.11 Contour display of temperature distribution at time = 600 sec. within bone, 2.3x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

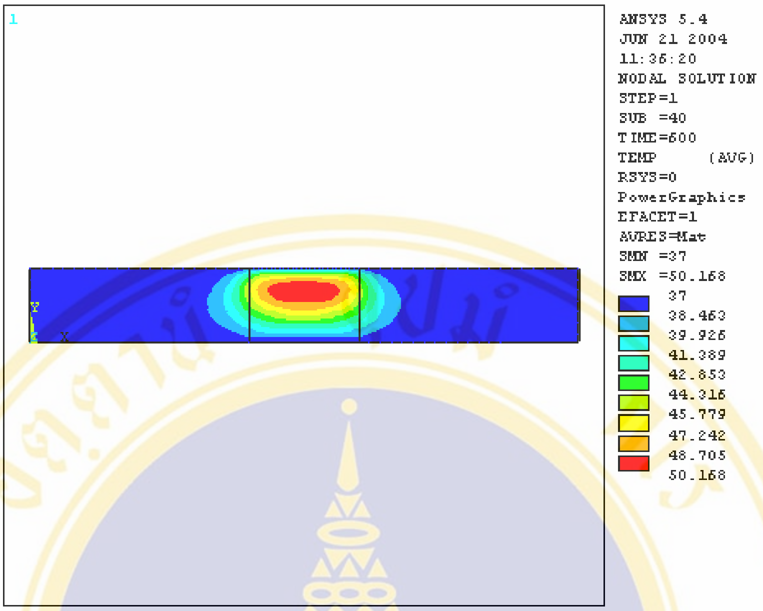


Figure 5.12 Contour display of temperature distribution at time = 600 sec. within bone, 1.7x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

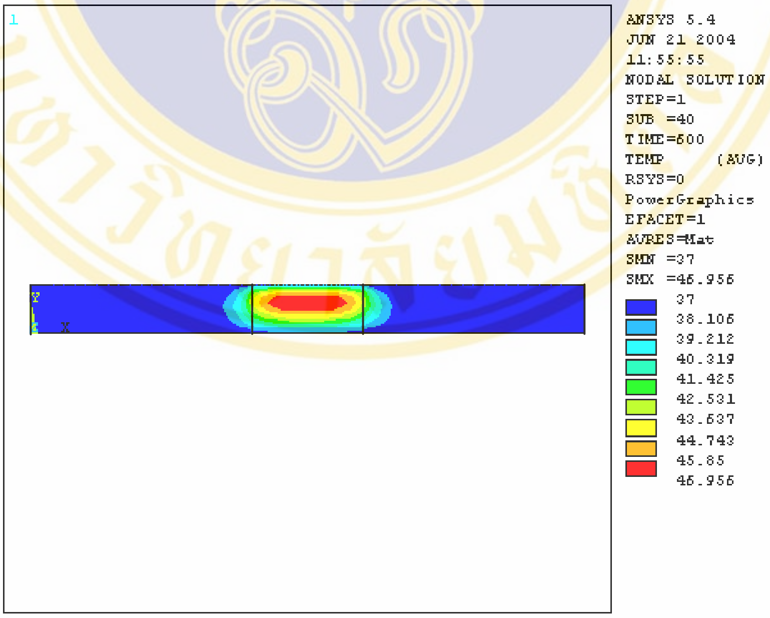


Figure 5.13 Contour display of temperature distribution at time = 600 sec. within bone, 1.1x12.5 cm. (height x width), and applied ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Path plots are defined by vertical line axis of ultrasound beam from its upper to lower surface. All path plotting and table of temperature results

of bone at 10 minutes of ultrasound application are shown in Figure 5.14 and Table 5.3.

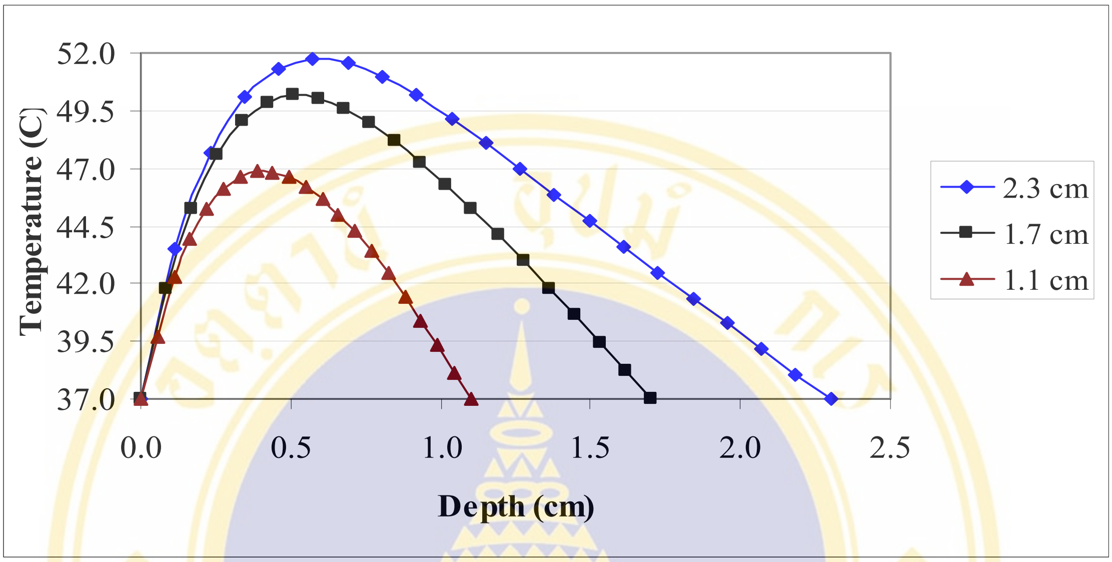


Figure 5.14 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 bone models, thickness values = 2.3, 1.7, 1.1 cm., and applied ultrasound intensity = 1 W/cm^2.

Table 5.3 List results of temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 bone models, thickness values = 2.3, 1.7, 1.1 cm., and applied ultrasound intensity = 1 W/cm^2.

Bone thickness = 2.3 cm.		Bone thickness = 1.7 cm.		Bone thickness = 1.1 cm.	
Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)
0	37	0	37	0	37
0.115	43.523	8.50E-02	41.804	5.50E-02	39.728
0.23	47.644	0.17	45.228	0.11	42.258
0.345	50.067	0.255	47.562	0.165	43.901
0.46	51.298	0.34	49.042	0.22	45.253
0.575	51.699	0.425	49.856	0.275	46.098
0.69	51.53	0.51	50.154	0.33	46.624
0.805	50.968	0.595	50.039	0.385	46.884
0.92	50.146	0.68	49.606	0.44	46.833
1.035	49.175	0.765	48.97	0.495	46.665
1.15	48.115	0.85	48.179	0.55	46.213
1.265	47.004	0.935	47.271	0.605	45.711
1.38	45.87	1.02	46.275	0.66	45.003

Table 5.3 (Continued) List results of temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 3 bone models, thickness values = 2.3, 1.7, 1.1 cm., and applied ultrasound intensity = 1 W/cm^2.

Bone thickness = 2.3 cm.		Bone thickness = 1.7 cm.		Bone thickness = 1.1 cm.	
Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)	Depth(cm)	Temp. (°C)
1.495	44.73	1.105	45.216	0.715	44.248
1.61	43.596	1.19	44.105	0.77	43.373
1.725	42.472	1.275	42.963	0.825	42.441
1.84	41.36	1.36	41.798	0.88	41.443
1.955	40.26	1.445	40.617	0.935	40.388
2.07	39.169	1.53	39.422	0.99	39.3
2.185	38.083	1.615	38.216	1.045	38.156
2.3	37	1.7	37	1.1	37

(3) *Graph Plots at Specific Point in Model*. This postprocessor, POST26, displays result of temperature versus time at same depth, 1 cm., in every bone model (Figure 5.15). For table of these temperature results, see Table 3 in Appendix C.

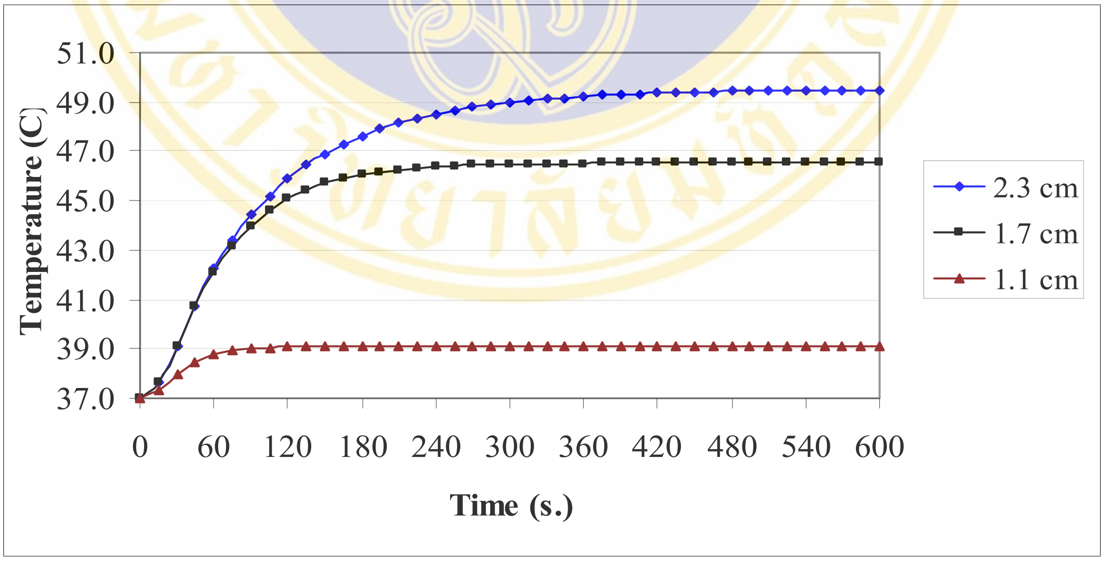


Figure 5.15 Temperature versus time at same depth 1 cm. of 3 bone models, thickness values = 2.3, 1.7, 1.1 cm., and intensity = 1 W/cm^2.

5.2.2 Temperature Distribution in Different Width of Surrounding Area Outside Ultrasound Beam of Fat, Muscle, and Bone

5.2.2.1 FAT

(1) *Contour displays.* Temperature distribution in fat with no surrounding tissue outside ultrasound beam and with surrounding tissue widths 1, 2, 3, 4, 5 cm., at 10 minutes of ultrasound application are displayed in Figures 5.16-5.21, respectively.

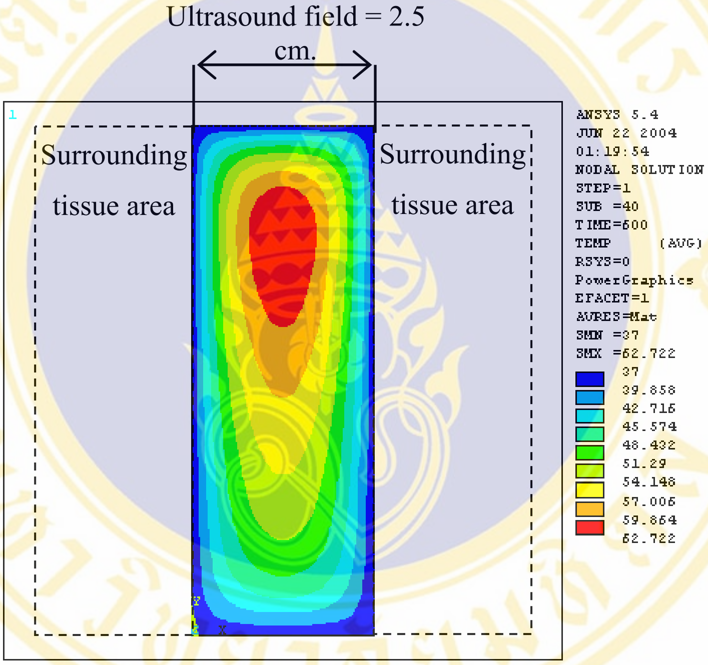


Figure 5.16 Temperature distribution at time = 600 sec. within fat, 7x2.5 cm. (height x width) with no surrounding tissue. Ultrasound intensity = 1 W/cm^2.

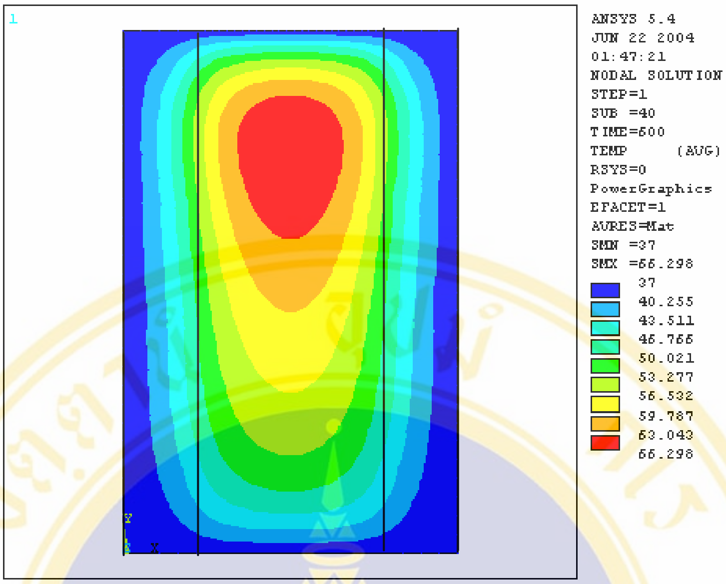


Figure 5.17 Temperature distribution at time = 600 sec. within fat 7x4.5 cm. (height x width), which has 1 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

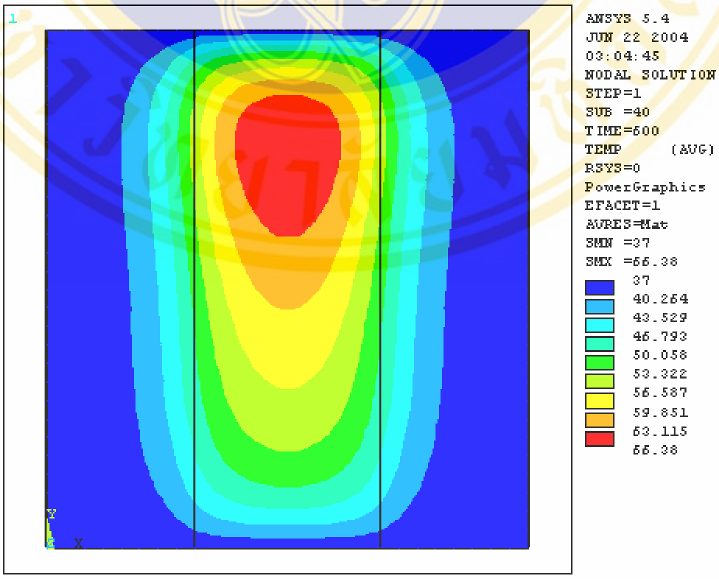


Figure 5.18 Temperature distribution at time = 600 sec. within fat 7x6.5 cm. (height x width), which has 2 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

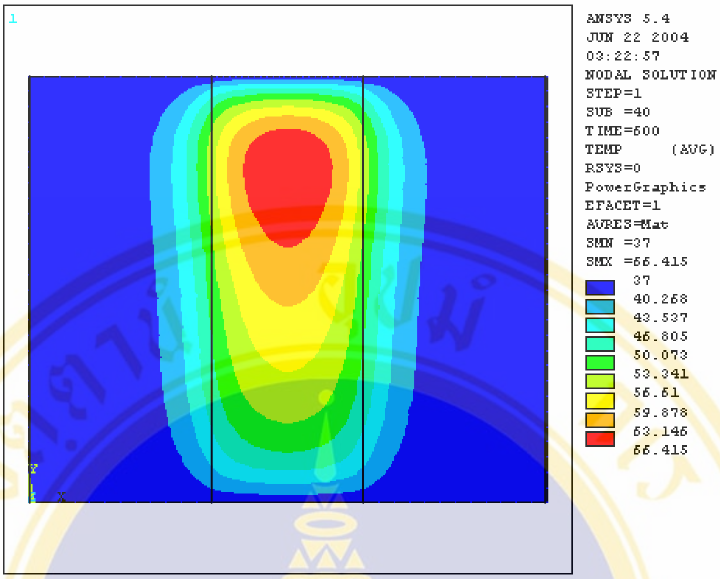


Figure 5.19 Temperature distribution at time = 600 sec. within fat 7x8.5 cm. (height x width), which has 3 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

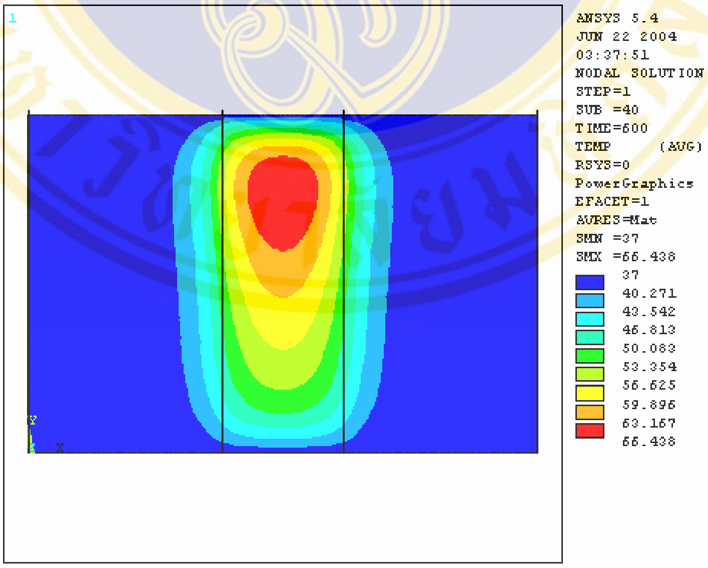


Figure 5.20 Temperature distribution at time = 600 sec. within fat 7x10.5 cm. (height x width), which has 4 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

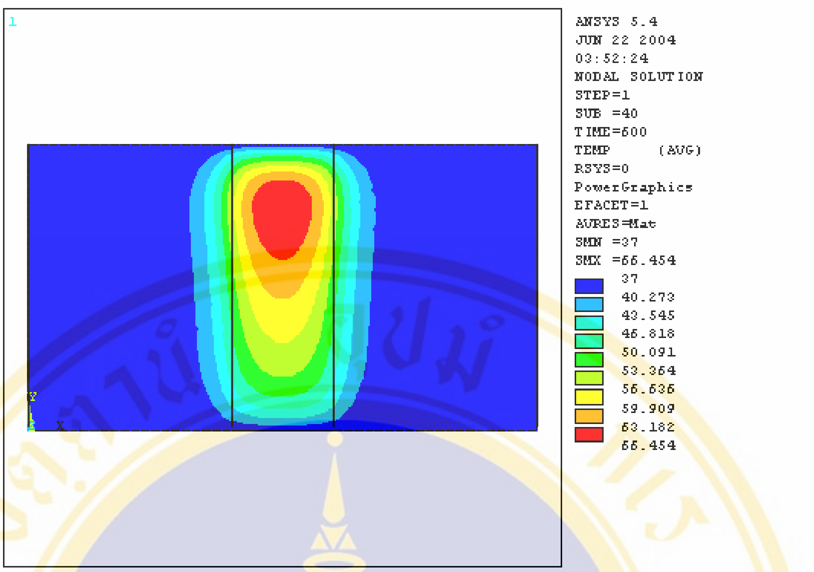


Figure 5.21 Temperature distribution at time = 600 sec. within fat 7x12.5 cm. (height x width), which has 5 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. This section performs two-path plotting, which consist of (1) vertical line axis of ultrasound beam from its upper to lower surface, and (2) cross sectional line of model from left to right side of model at a specific depth. Temperature results of vertical path plotting of fat model, with 0–5 cm. surrounding tissue width, are shown in Figure 5.22. For path plotting on cross section of models, every fat model is defined along the path at depth equal to 1 cm. Graph plotting of temperature results of this path are shown in Figure 5.23. To review these results, see Table 1 and 2 in Appendix D.

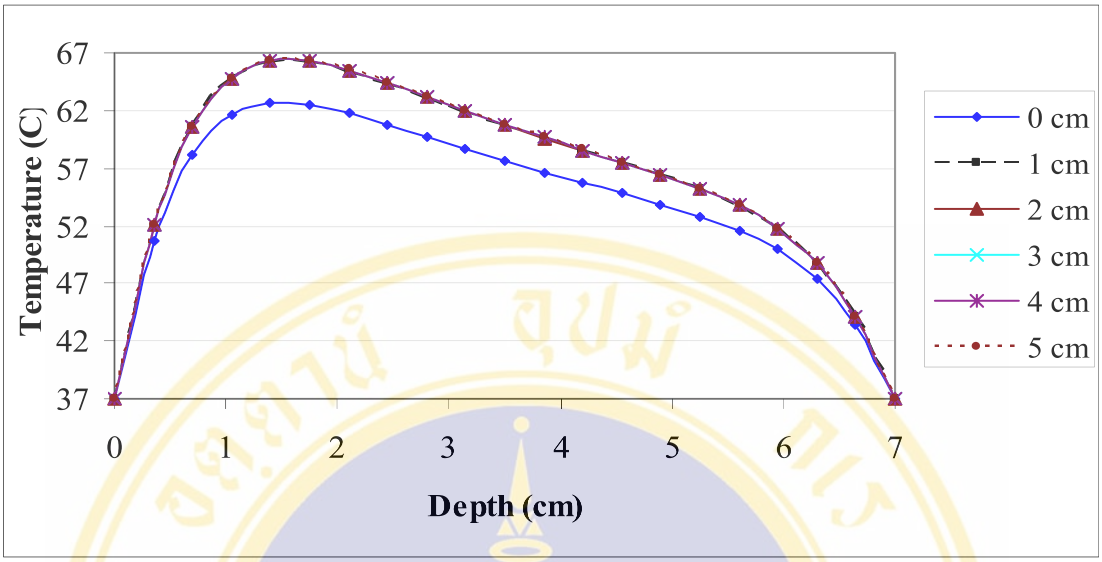


Figure 5.22 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 fat models, surrounding tissue widths of 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

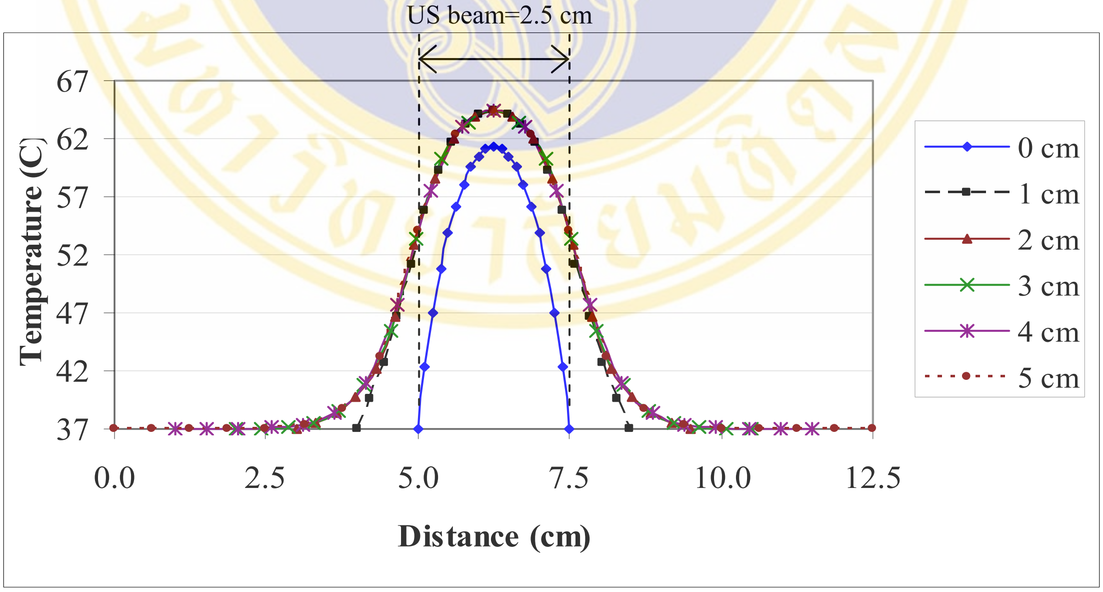


Figure 5.23 Temperature distribution at time = 600 sec. on cross section of 6 fat models at 1 cm depth, surrounding tissue widths of 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

(3) *Graph Plots at Specific Point in Model*. Figure 5.24 displays the result of temperature versus time at same depth, 1 cm., in every fat models. To review table of these temperature results see Table 3 in Appendix D.

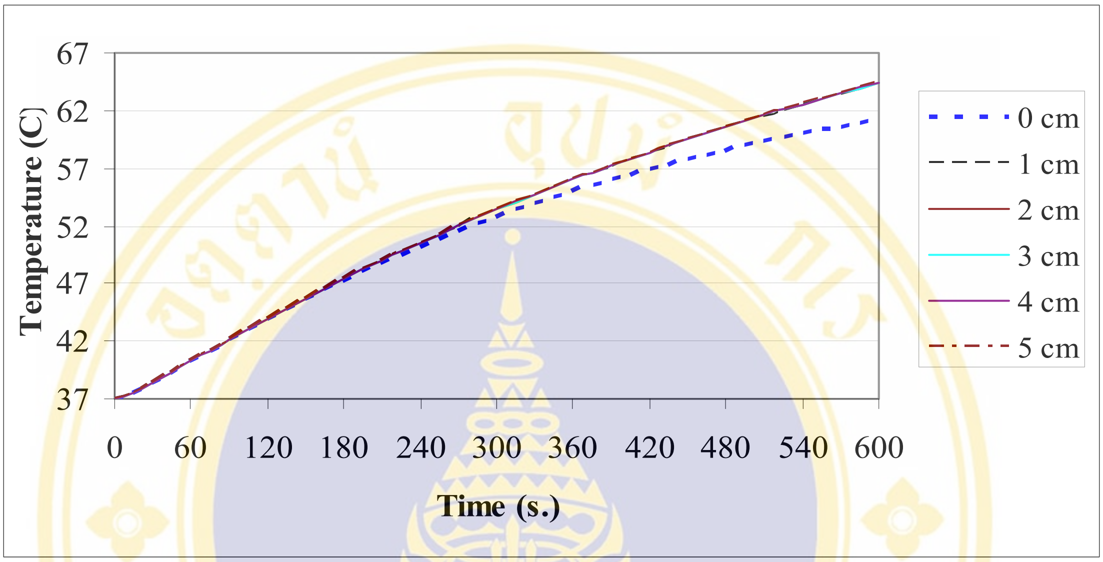


Figure 5.24 Temperature versus time at depth 1 cm. of 6 fat models, surrounding tissue widths of 0, 1, 2, 3, 4, 5 cm, and intensity = 1 W/cm^2.

5.2.2.2 MUSCLE

(1) *Contour displays.* Temperature distribution in muscle with no surrounding tissue outside ultrasound beam and with surrounding tissue widths of 1, 2, 3, 4, 5 cm., at 10 minutes of ultrasound application are displayed in Figures 5.25-5.30, respectively.

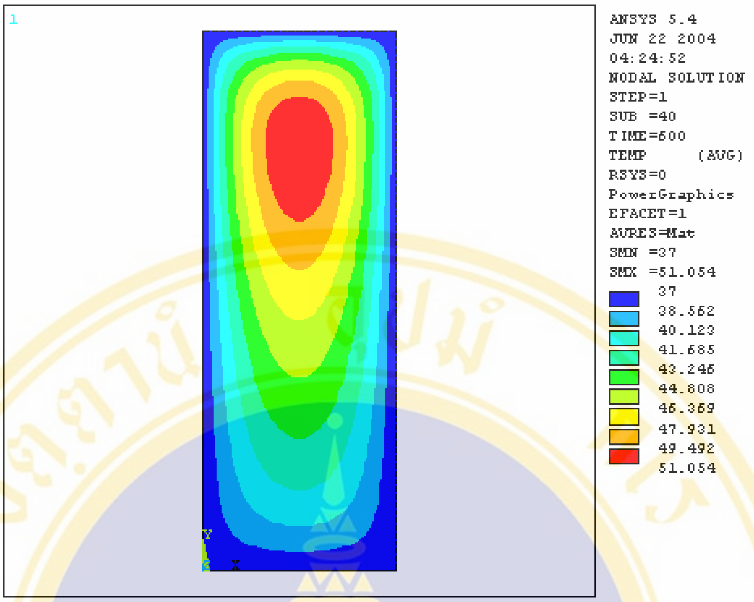


Figure 5.25 Temperature distribution at time = 600 sec. within muscle 7x2.5 cm. (height x width), with no surrounding tissue. Ultrasound intensity = 1 W/cm^2.

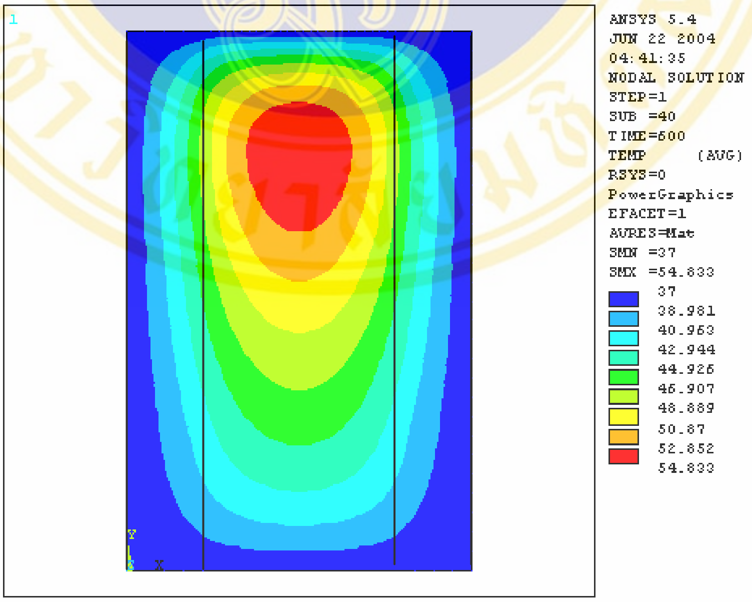


Figure 5.26 Temperature distribution at time = 600 sec. within muscle 7x4.5 cm. (height x width), which has 1 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

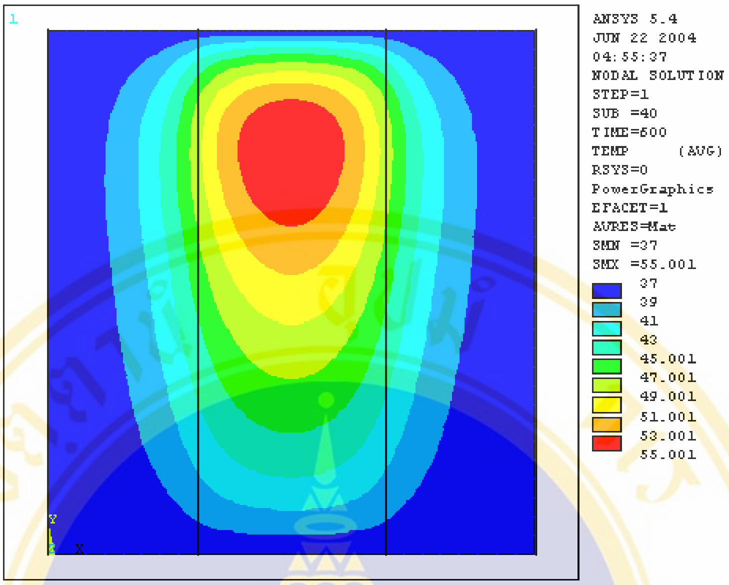


Figure 5.27 Temperature distribution at time = 600 sec. within muscle 7x6.5 cm. (height x width), which has 2 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

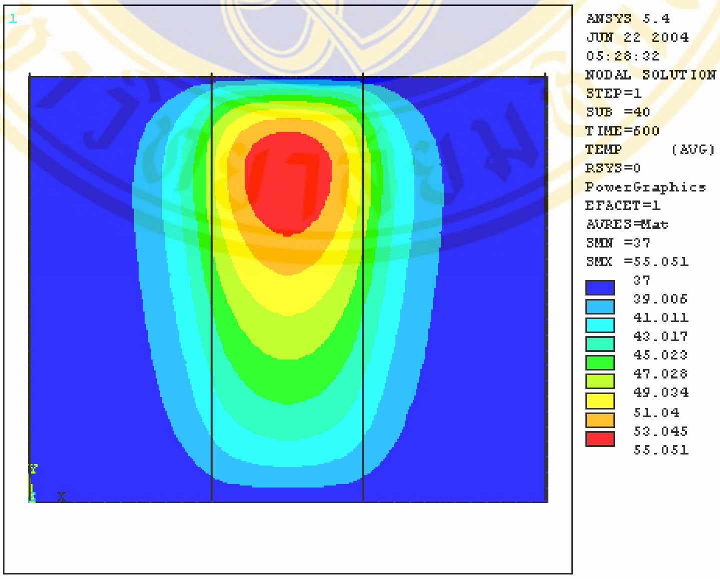


Figure 5.28 Temperature distribution at time = 600 sec. within muscle 7x8.5 cm. (height x width), which has 3 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

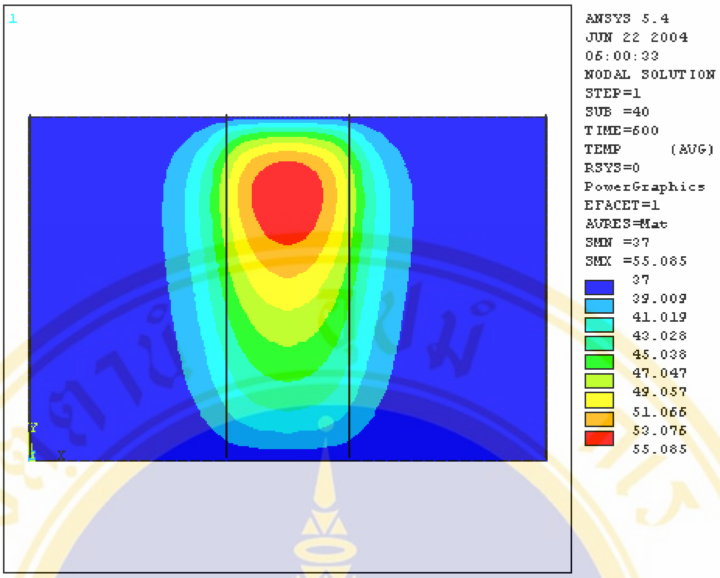


Figure 5.29 Temperature distribution at time = 600 sec. within muscle 7x10.5 cm. (height x width), which has 4 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

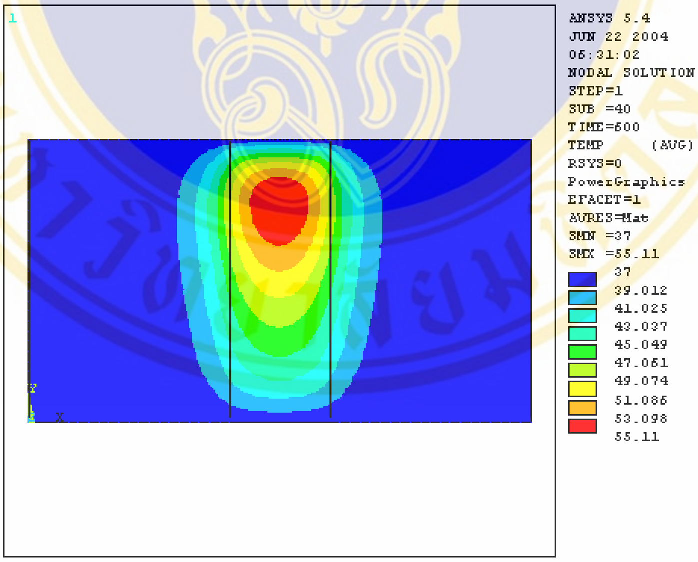


Figure 5.30 Temperature distribution at time = 600 sec. within muscle 7x12.5 cm. (height x width), which has 5 cm. width of surrounding tissue, and ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. In fat thermal analysis, two-path plotting also consists of vertical axis and cross sectional model at a specific depth. Temperature results of vertical and cross section path plotting of muscle model, with 0–5 cm. surrounding

tissue width, are shown in Figures 5.31 and 5.32, respectively. For path plotting on cross section of muscle, models are defined along the path at depth equal to 4 cm. To review these results, see Table 4 and 5 in Appendix D.

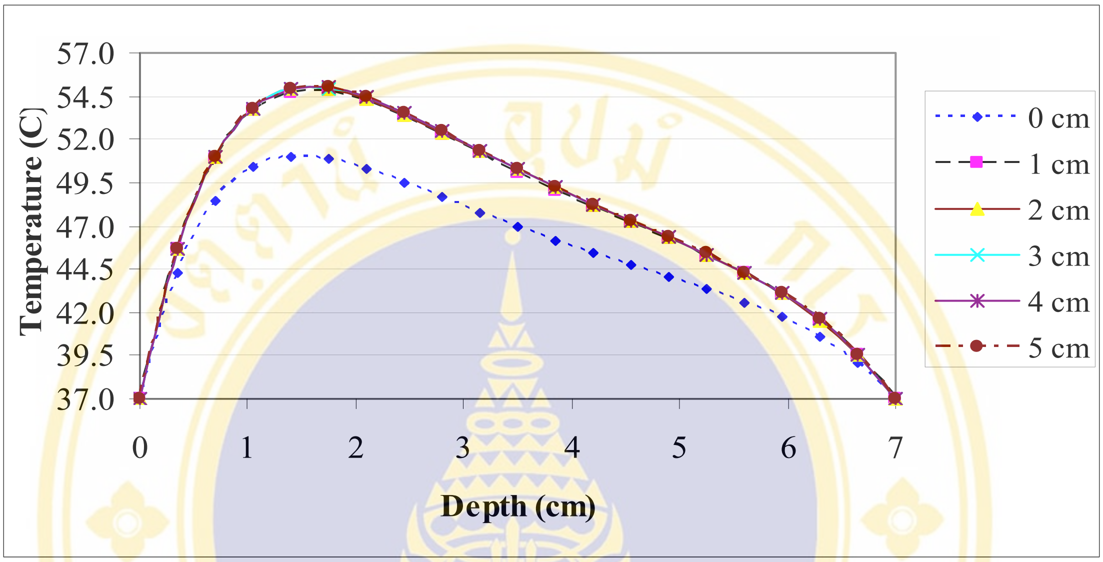


Figure 5.31 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 muscle models, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

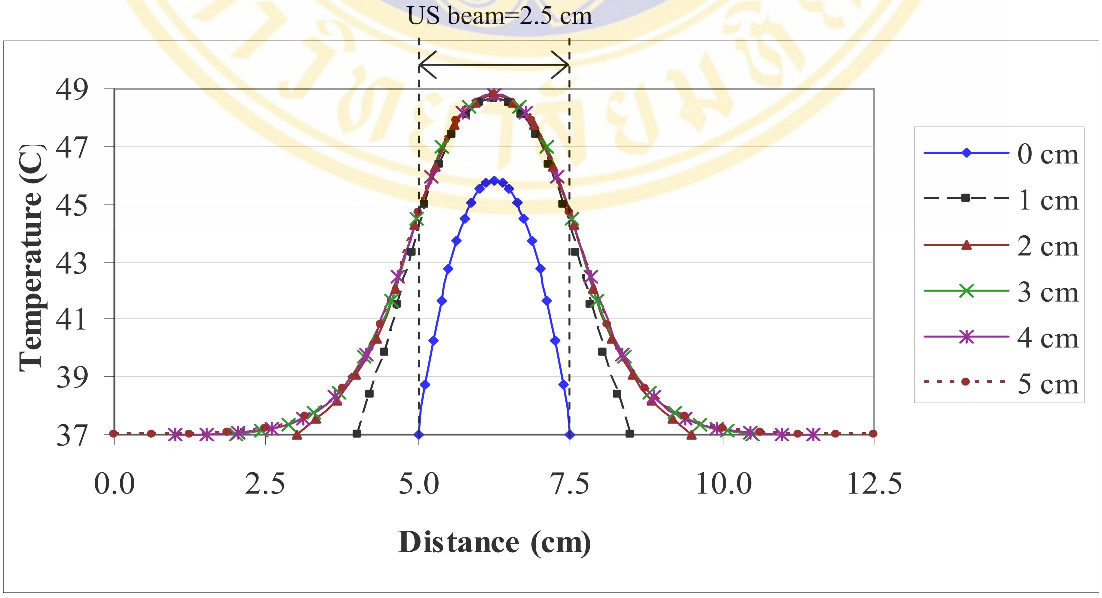


Figure 5.32 Temperature distribution at time = 600 sec. on cross section of 6 muscle models at 4 cm. depth, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

(3) *Graph Plots at Specific Point in Model*. Figure 5.33 displays the result of temperature versus time at same depth, 4 cm., in every muscle model. To review these temperature results, see Table 6 in Appendix D.

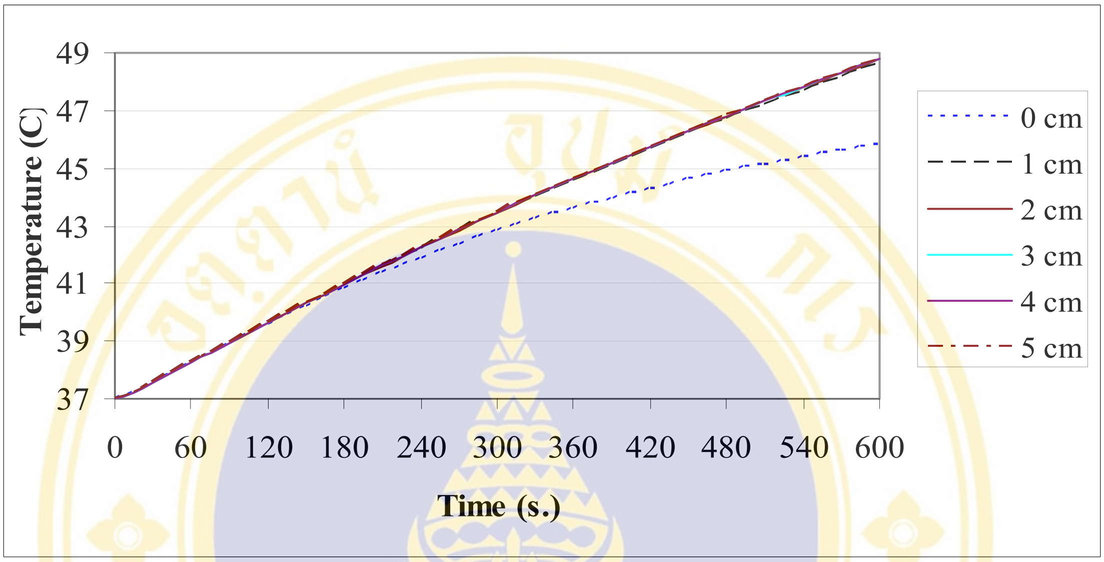


Figure 5.33 Temperature versus time at depth 1 cm. of 6 bone models, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and intensity = 1 W/cm^2.

5.2.2.3 BONE

(1) *Contour displays.* Temperature distribution in bone with no surrounding tissue outside ultrasound beam and with surrounding tissue widths of 1, 2, 3, 4, 5 cm., at 10 minutes of ultrasound application are displayed in Figures 5.34-5.39, respectively.

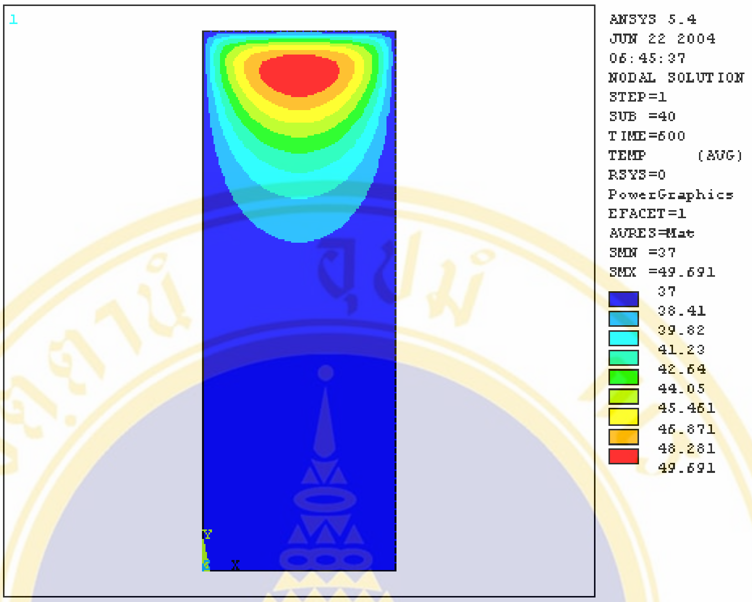


Figure 5.34 Temperature distribution at time = 600 sec. within bone, 7x2.5 cm (height x width) with no surrounding tissue. Ultrasound intensity = 1 W/cm^2.

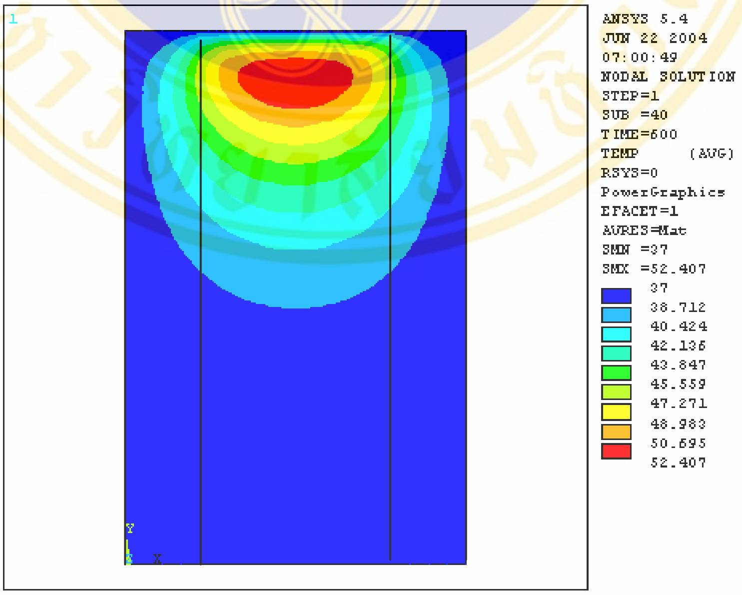


Figure 5.35 Temperature distribution at time = 600 sec. within bone 7x4.5 cm. (height x width), which has 1 cm. width of surrounding tissue. Ultrasound intensity = 1 W/cm^2.

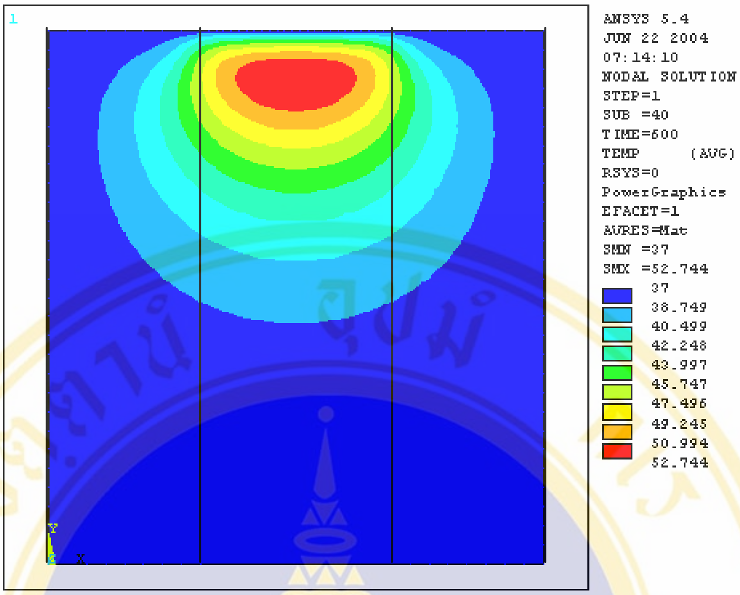


Figure 5.36 Temperature distribution at time = 600 sec. within bone 7x6.5 cm. (height x width), which has 2 cm. width of surrounding tissue. Ultrasound intensity = 1 W/cm^2.

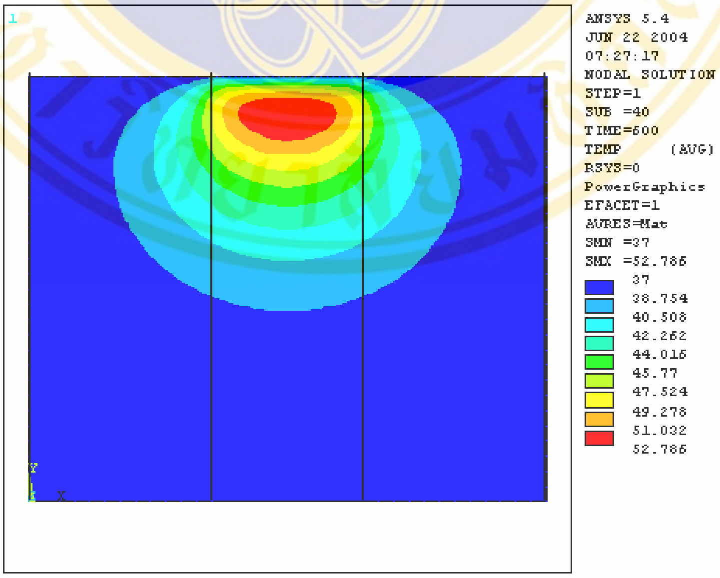


Figure 5.37 Temperature distribution at time = 600 sec. within bone 7x8.5 cm. (height x width), which has 3 cm. width of surrounding tissue. Ultrasound intensity = 1 W/cm^2.

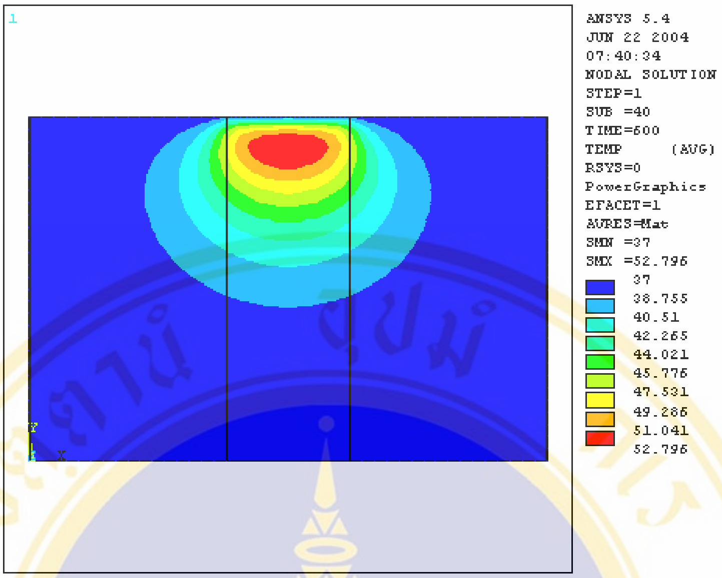


Figure 5.38 Temperature distribution at time = 600 sec. within bone 7x10.5 cm. (height x width), which has 4 cm. width of surrounding tissue. Ultrasound intensity = 1 W/cm^2.

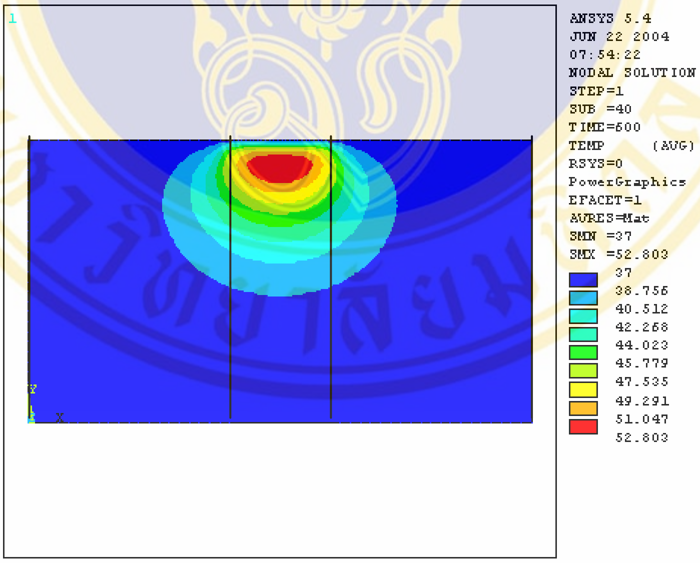


Figure 5.39 Temperature distribution at time = 600 sec. within bone 7x12.5 cm. (height x width), which has 5 cm. width of surrounding tissue. Ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Temperature results of vertical and cross section path plotting of bone model, with 0–5 cm. surrounding tissue width, are shown in Figures 5.40 and 5.41, respectively. For path plotting on cross section of bone, models are

defined along the path at depth equal to 1 cm. To review these results, see Table 7 and 8 in Appendix D.

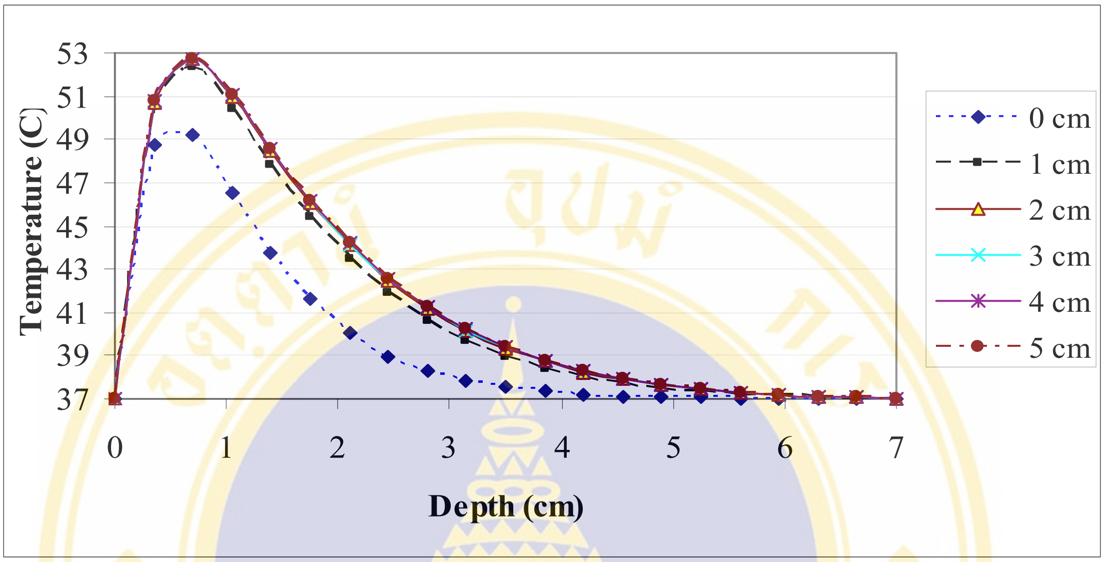


Figure 5.40 Temperature distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 bone models, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

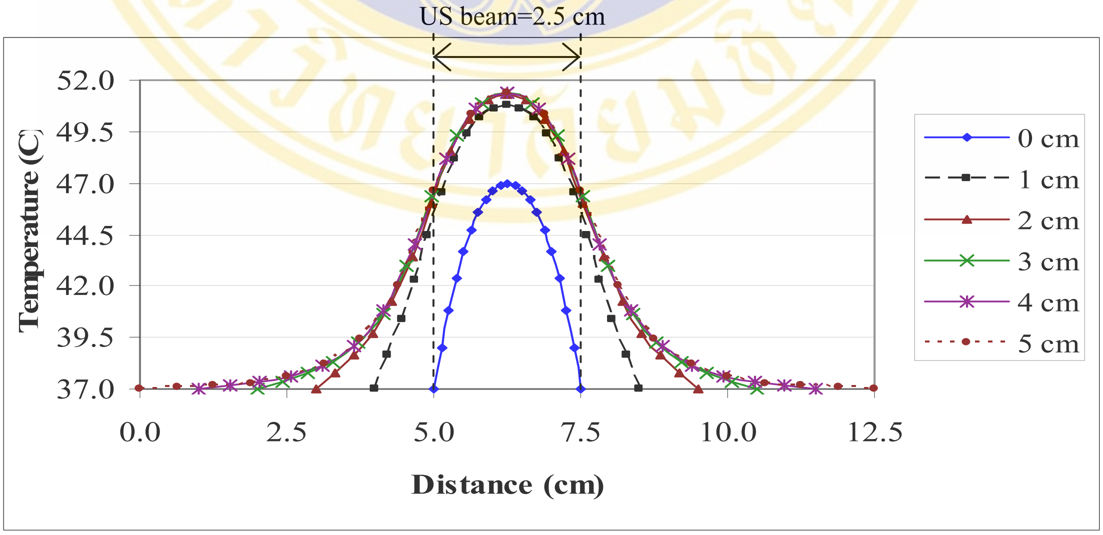


Figure 5.41 Temperature distribution at time = 600 sec. on cross section of 6 bone models at 4 cm. depth, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

(3) *Graph Plots at Specific Point in Model*. Figure 5.42 displays the result of temperature versus time at same depth, 1 cm., in every bone model. To review these temperature results, see Table 9 in Appendix D.

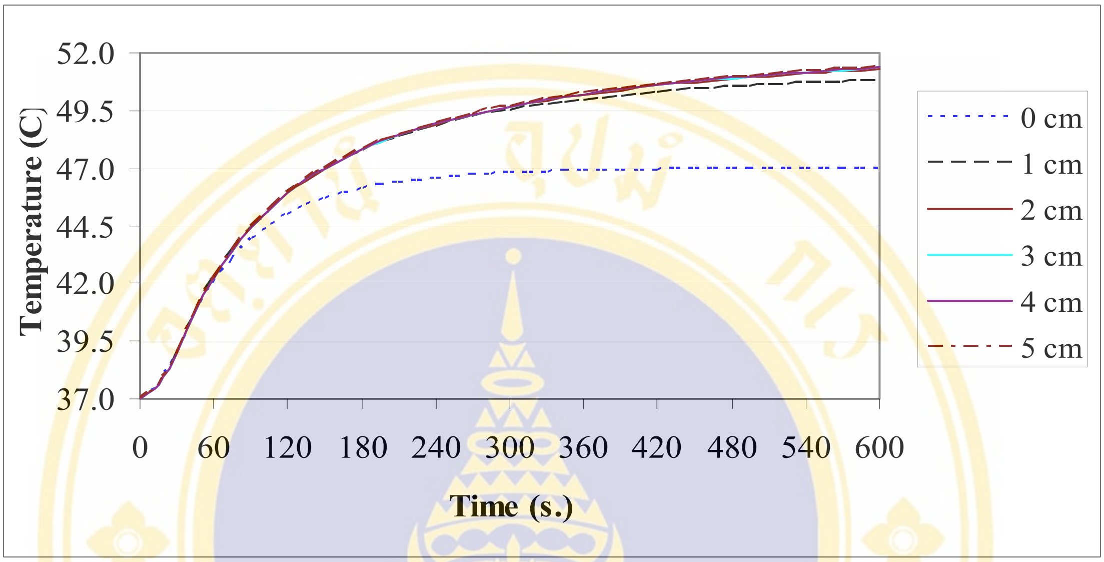


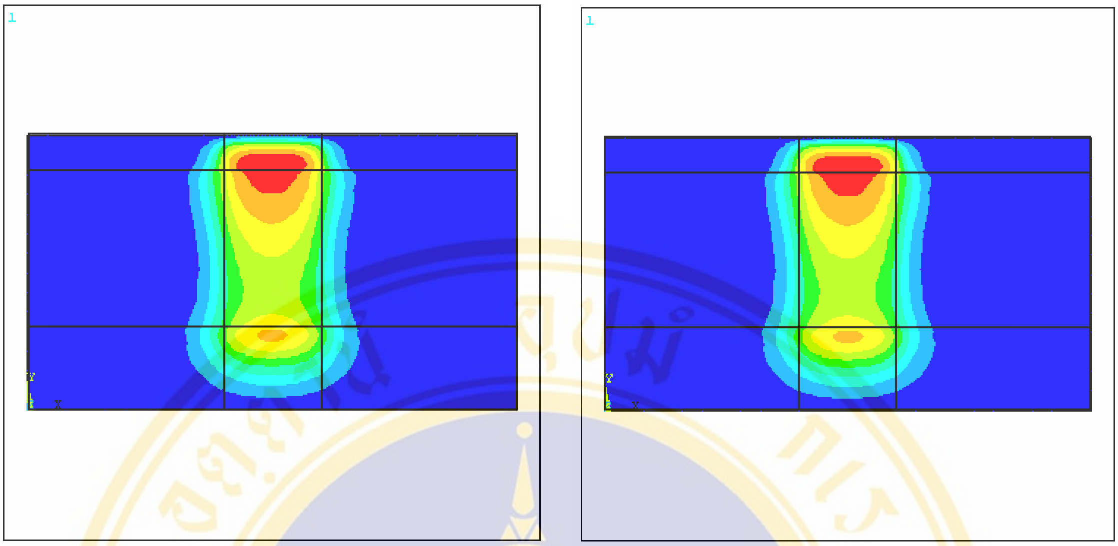
Figure 5.42 Temperature versus time at depth 1 cm. of 6 bone models, surrounding tissue widths = 0, 1, 2, 3, 4, 5 cm., and intensity = 1 W/cm^2.

5.3 Temperature Distribution within Three-Layered Model of Fat, Muscle, and Bone

5.3.1 Temperature Distribution within Three-Layered Tissue at Clinical Therapeutic Time

This study analyses two models that are applied ultrasound intensity equal to 0.5 and 1 W/cm^2. Thus, temperature results of these models are shown in the following sub-sections.

(1) *Contour displays.* Temperature distribution in three-layered tissue, at 3 minutes of ultrasound application, using intensity equal to 0.5 and 1 W/cm^2, are displayed in Figure 5.43 below:



(A) Incident intensity = 0.5 W/cm^2.

Maximum temperature = 41.884°C.

(B) Incident intensity = 1 W/cm^2.

Maximum temperature = 46.769°C.

Figure 5.43 Temperature distribution at time = 180 sec. within three-layered tissue. **(A)** Ultrasound intensity = 0.5 W/cm^2. **(B)** Ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Temperature results of vertical path plotting of three-layered models that are applied by 0.5 and 1 W/cm^2, are shown in Figures 5.44 and 5.45, respectively. Temperature results are plotted at every 30 seconds. To review these results, see Tables 1 and 2 in Appendix E.

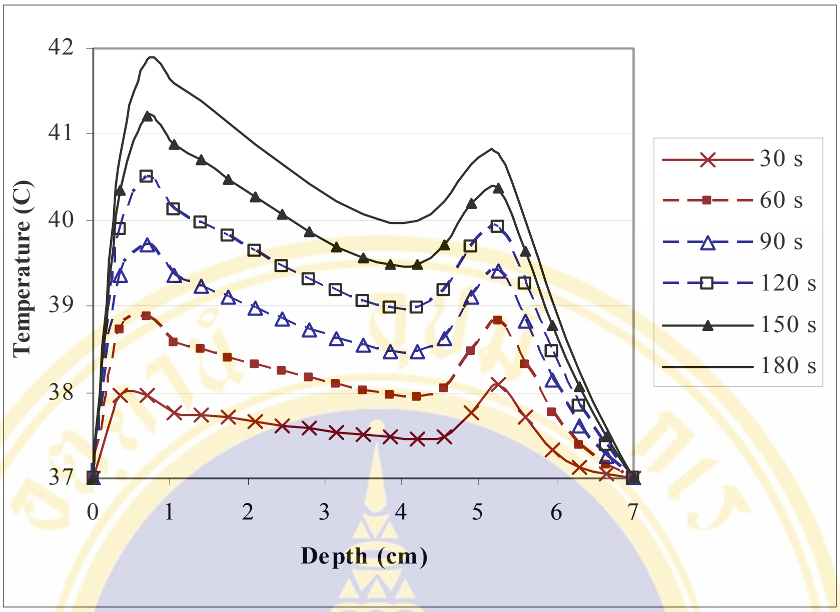


Figure 5.44 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model. Temperature are plotted at every 30 sec., ultrasound intensity = 0.5 W/cm^2.

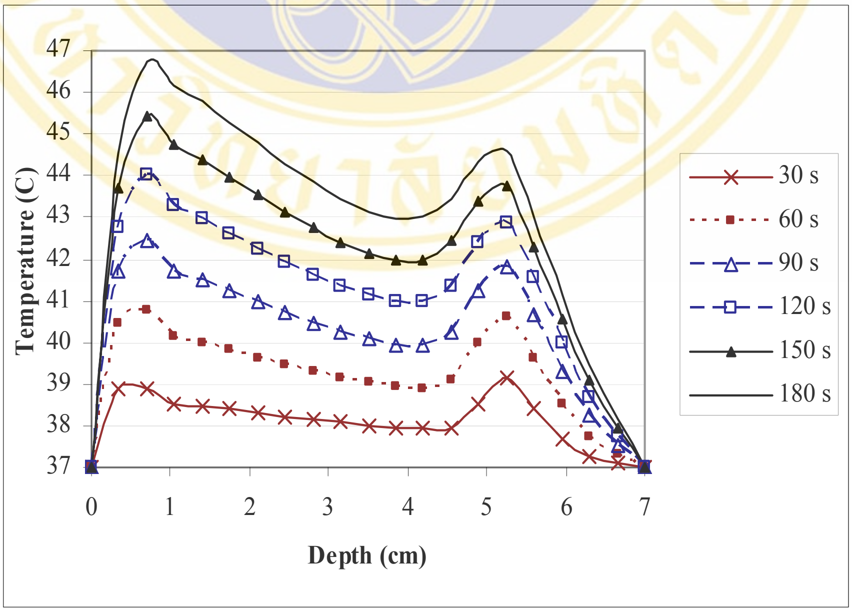


Figure 5.45 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model. Temperature are plotted at every 30 sec., ultrasound intensity = 1 W/cm^2.

(3) *Graph Plots at Specific Point in Model*. Figures 5.46 and 5.47 display the result of temperature versus time (180 seconds) of three-layered models that are applied by ultrasound intensity of 0.5 and 1 W/cm^2, respectively. Depths of interest are at middle fat (0.5 cm. from the upper surface of fat), middle muscle (2 cm. from the upper surface of muscle), muscle in front of bone (0.1 cm above bone surface), and inside bone (0.5 cm. from the upper surface of bone). To review these results, see Tables 3 and 4 in Appendix E.

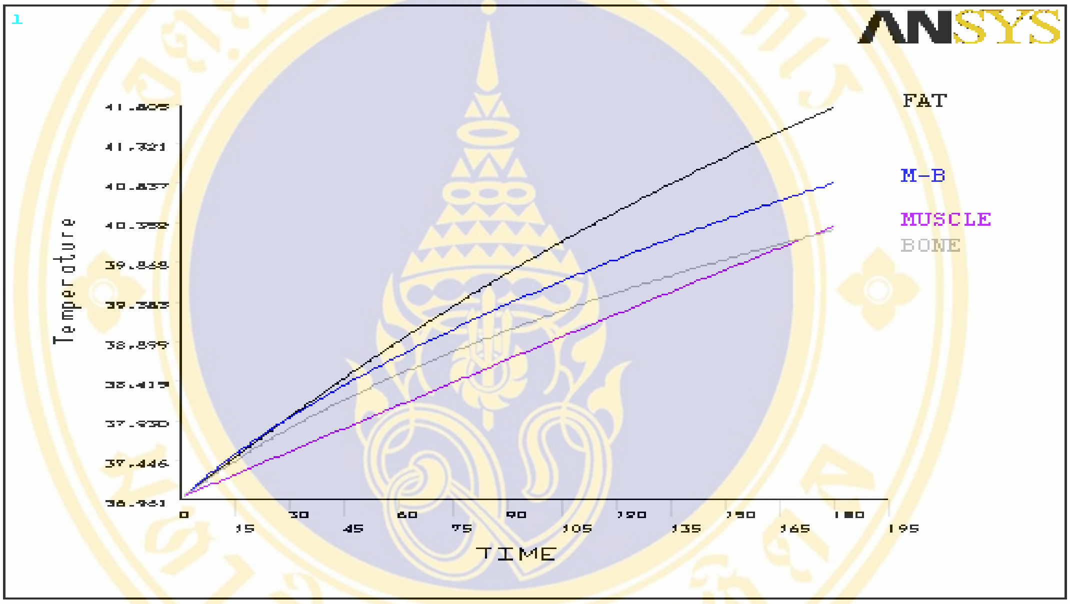


Figure 5.46 Temperature versus time when apply intensity of 0.5 W/cm^2, 180 seconds, to three-layered model. FAT=0.5 cm below the upper surface of fat, MUSCLE=2 cm below the upper surface of muscle, M-B=0.1 cm above the bone surface, and BONE=0.5 cm below the upper surface of bone.

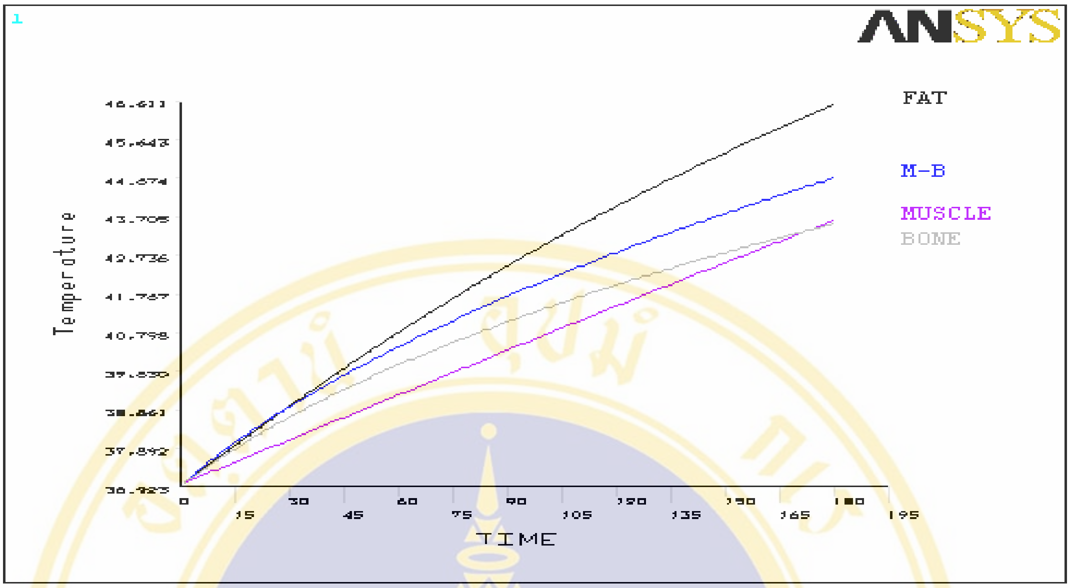
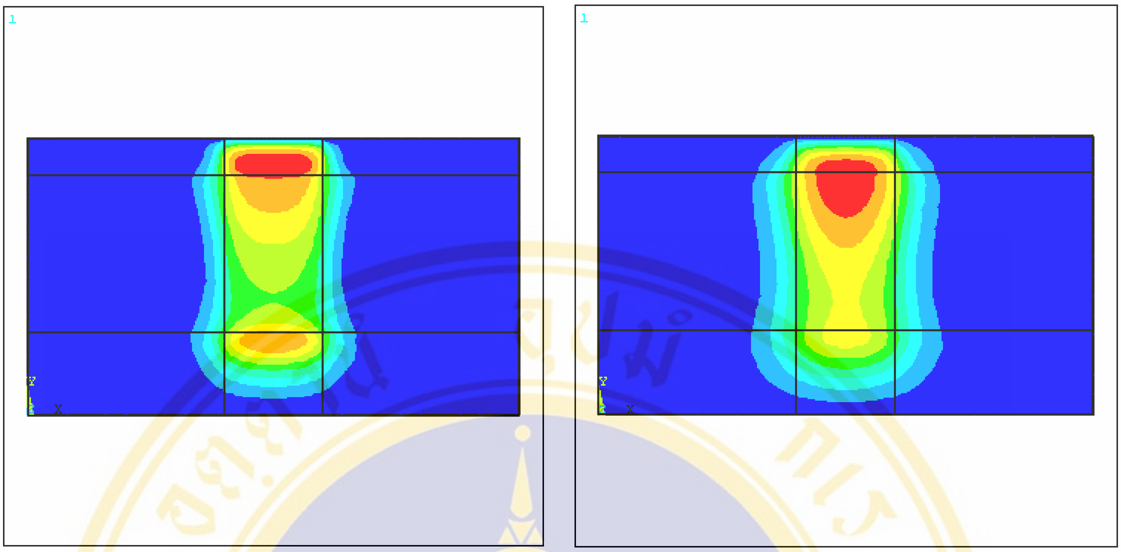


Figure 5.47 Temperature versus time when apply intensity of 1 W/cm^2, 180 seconds, to three-layered model. FAT=0.5 cm below the upper surface of fat, MUSCLE=2 cm below the upper surface of muscle, M-B=0.1 cm above the bone surface, and BONE=0.5 cm below the upper surface of bone.

5.3.2 Steady State Temperature of Three-Layered Tissue

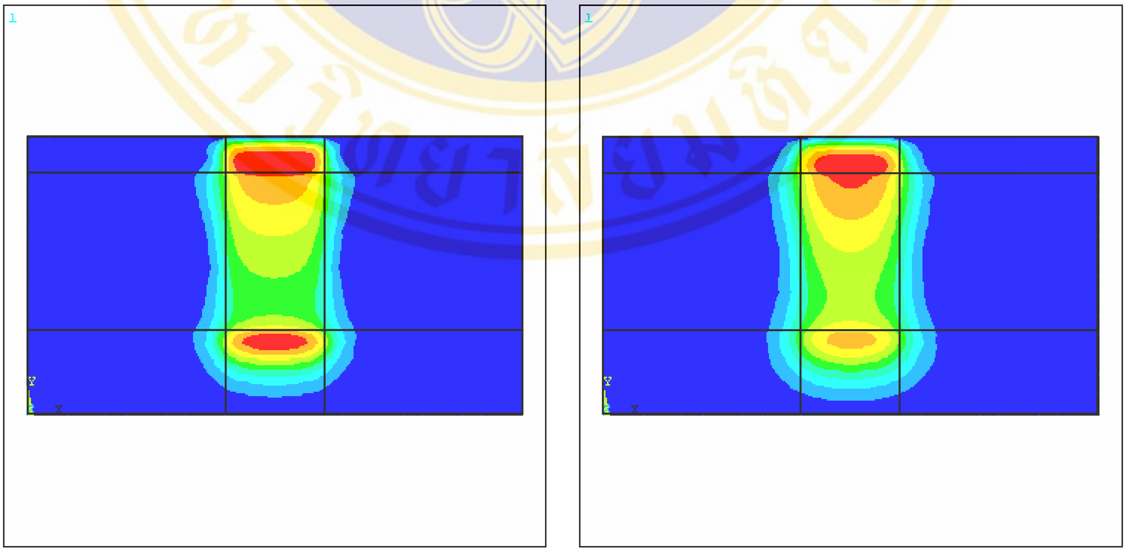
Different tissue type and depth under ultrasound field, are the factors that cause temperature reaches to steady state at different value and its time. Three-layered models are sonicated by ultrasound intensity equal to 0.5 and 1 W/cm^2, which have 1 hour of treatment duration. Four depth of interested that will be reviewed results, are same to previous study. These are consisted of the depth at 0.5 cm. below the upper surface of fat, at 2 cm. below the upper surface of muscle, at 0.1 cm. above the bone surface, and at 0.5 cm. below the upper surface of bone. Thus, temperature results of these models are shown in the following sub-sections.

(1) *Contour displays.* Temperature distribution in three-layered tissue at 3,600 seconds of ultrasound application is high. Animation allows user to review temperature changes over time. It is used to observe time within treatment temperature range, approximate 40 to 45°C. Therefore, this section displays temperature distribution when maximum temperature are in these range. The results when application intensity equal to 0.5 and 1 W/cm^2, are displayed in Figures 5.48 and 5.49, respectively:



(A) Maximum temperature = 40.007°C
when application time = 137 seconds.

Figure 5.48 Temperature distribution within three-layered tissue when maximum temperature are approximate 40 and 45°C. Ultrasound intensity = 0.5 W/cm^2.



(A) Maximum temperature = 40.015°C
when application time = 79 seconds.

(B) Maximum temperature = 44.979°C
when application time = 171 seconds.

Figure 5.49 Temperature distribution within three-layered tissue when maximum temperature are approximate 40 and 45°C. Ultrasound intensity = 1 W/cm^2.

(2) *Path Operation*. Temperature results of vertical path plotting of three-layered models that are applied by 0.5 and 1 W/cm^2, are shown in Figures 5.50 and 5.51, respectively. Temperature results are plotted at every 600 seconds until complete 3,600 seconds. To review these results, see Tables 5 and 6 in Appendix E.

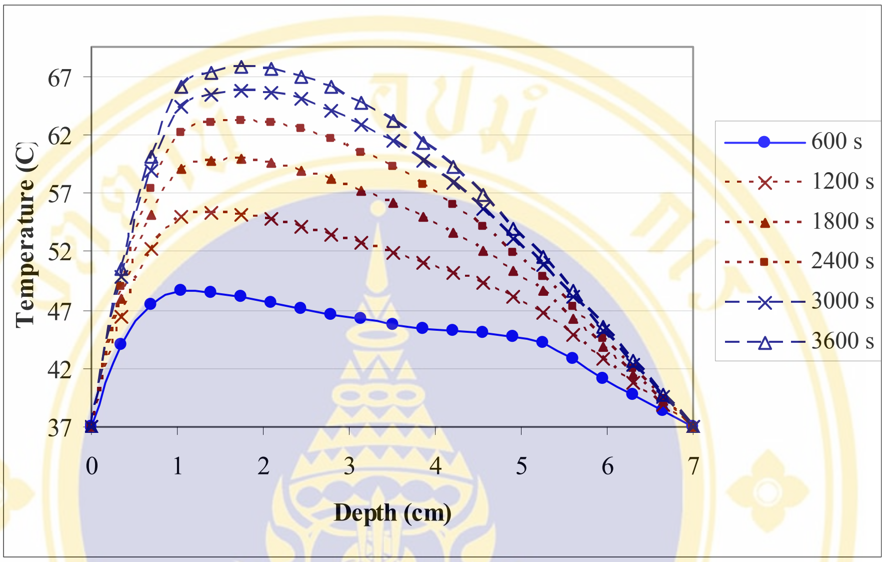


Figure 5.50 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model. Temperature are plotted at every 600 sec., ultrasound intensity = 0.5 W/cm^2.

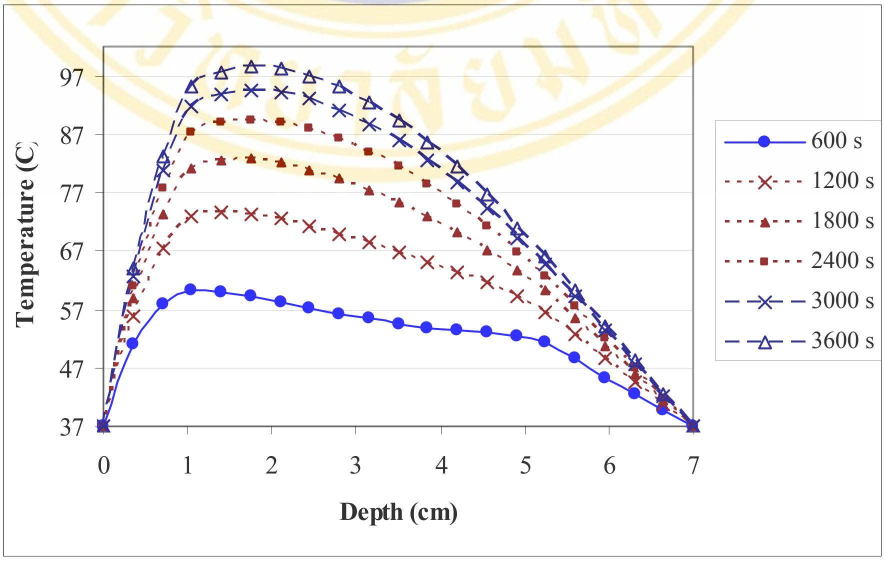


Figure 5.51 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model. Temperature are plotted at every 600 sec., ultrasound intensity = 1 W/cm^2.

(2) *Graph Plots at Specific Point in Model*. Figures 5.52 and 5.53 display the result of temperature versus time (3,600 seconds) of three-layered models that are applied by ultrasound intensity of 0.5 and 1 W/cm^2, respectively. Temperature results at four depth levels of interested are shown below. To review these results, see Tables 7 and 8 in Appendix E.

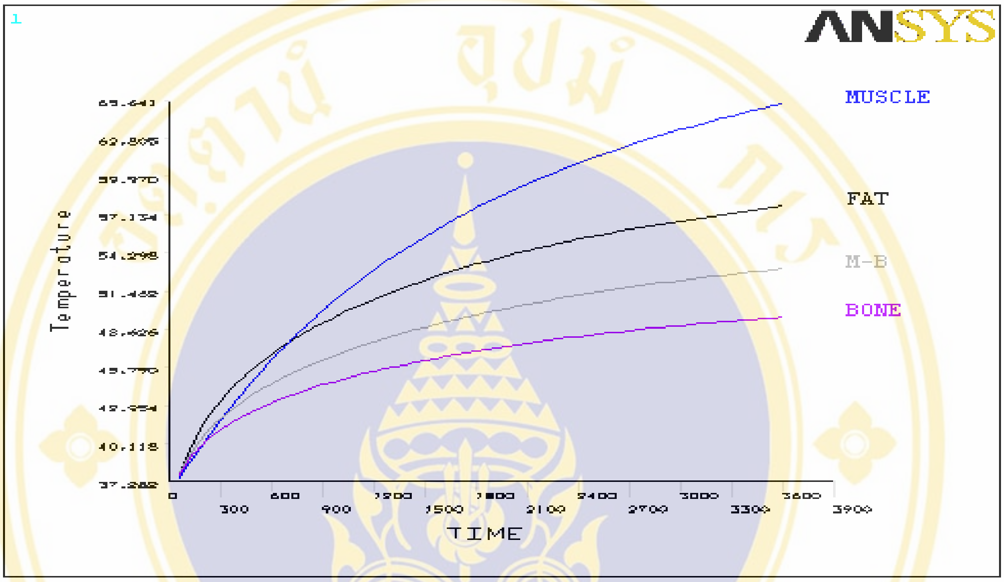


Figure 5.52 Temperature versus time when apply intensity of 0.5 W/cm^2 to three-layered model, for 3,600 sec. of application time.

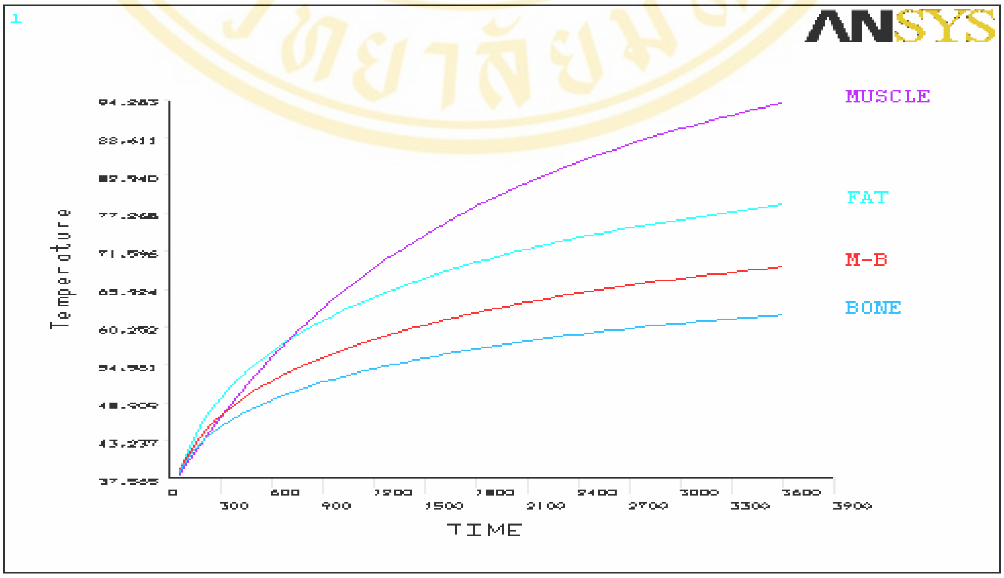


Figure 5.53 Temperature versus time when apply intensity of 1 W/cm^2 to three-layered model, for 3,600 sec. of application time.

CHAPTER 6
DISCUSSIONS

This chapter discusses the result by focusing on three aspects: 1. Capabilities of a command log file. This aspect discusses capabilities and limitations of a command log file to analyse temperature distribution in any material under any condition of ultrasound usage. 2. Various boundary condition settings and temperature distribution within single tissue type model of fat, muscle, and bone. The temperature results of different thicknesses of models and widths of surrounding area outside ultrasound beam will be discussed in this aspect. 3. Temperature distribution within three-layered model of fat, muscle, and bone. This aspect discusses the temperature distribution within three-layered model which including detailed temperature changes within short duration and steady state temperature within long duration of ultrasound application.

6.1 Capabilities of A Command Log File

Because of the complicated interaction between therapeutic ultrasound and human tissue, execution ANSYS functions simply by picking buttons through GUI is not enough. To achieve temperature results, the personalized ANSYS commands are created and saved to a command log file, .LGW file format. This commands log file includes mathematical operation that cannot be communicated via GUI. It can be used to re-execute various therapeutic ultrasound analyses. Several studies investigated the temperature distribution with various conditions (11,15,16,17,18,20,26). Because of the variety of investigation techniques, exposure time, intensity value, tissue properties, tissue size, etc., the temperature result of previous studies can not be compared together. Thus, a command log file is written to analyse temperature distribution in any material under various conditions. As reading in a command log file, ***ASK** command asks user to input personalized values. If user does not input any value, a default value which is specified on the command earlier, will be assigned to the parameter. The parameters include the values of ultrasound intensity, material properties, model size, head sound diameter, element size, initial temperature, boundary temperature, application time, and time steps for observation. Moreover, user may edit this command log file easily before using it as program input, by common program editor such as notepad. This method allows user to change element type, analysis type (transient, steady state analysis, etc.), output control, load type, etc. Therefore, defining them to a command log file assists user to analyse thermal problem as required. After reading in a command log file, it executes ANSYS preprocessor until ceasing before initial solution. User can make some changes before starting the solution processor. Postprocessor is not included in this command log file because it contains several commands that allow user to review results in various forms. Animation commands can produce 2-D simulation of result, which is an animated sequence of a contoured display varying over time. Moreover, animation, .AVI file format, can be displayed by several common display programs. Therefore, therapist can review temperature results conveniently. To review contour results at a specific time, contour plotting in POST1 allows user to perform this easily. Path plotting lists or contour displays the variation of a temperature along a predefined path through the model. These also are advantageous to treatment planning, such as path plotting along tissue depth that helps therapist to satisfy appropriate temperature at depth of lesion. In addition to concern about level of tissue temperature, the rate of temperature rise in any point of tissue can also be considered. Because of the capability of time-history postprocessor, therapist can review temperature change over time at a certain depth of lesion, through both graph plotting and data listing. Fat, muscle, and bone temperature results can be obtained by executing this command log file. Therefore, therapist can use these results to decide how to plan ultrasound application to patients.

To understand the limitation of this command log file, the memory available on user computer should be considered. User must specify memory requested for total workspace and database through dialog box on an ANSYS interactive. Choosing a higher number allows more space for solution of large models. If computer has not enough memory, ANSYS shows warning message and ceases processing. User must manage memory or make some change to models, and then run ANSYS again. The other limitation is that a command log file cannot be used with other ANSYS versions.

But it is a guidance for development by other ANSYS versions. For model defining, this command log file cannot analyze nonhomogeneous material. It can be used to analyses, at most, three layers of rectangular model geometry. User must analyses only ultrasound application of continuous wave and stationary technique. Material also has linear properties, such as thermal conductivity that is not changed over time.

6.2 Various Boundary Condition Settings and Temperature Distribution within Single Tissue Type Model of Fat, Muscle, and Bone

User must specify fixed temperature values to the boundary of model of various sizes. Lehmann et al. (26) found that the cooler the applicator surface or the surrounding coupling medium involves the temperature peak at the deeper area inside the tissue. This study showed that the boundary temperature involves temperature distribution within model. Temperature results of three model sizes of each tissue type can be discussed as follows.

6.2.1 Different Thicknesses of Fat, Muscle, and Bone.

Temperature along the central axis of the ultrasound beam decayed exponentially with increase in depth of fat and muscle models (Figure 5.4 and 5.9). For each tissue type, temperature distribution within the models of varying thickness does not essential difference. Maximum temperature of all fat models are equal to 66.688°C (Figure 5.1-5.3), and muscle models are 55.414°C (Figure 5.6-5.8) at 10 minutes of 1 W/cm^2 application. Therefore, temperature distributions in single fat or muscle model depend on intensity distribution within depth of penetration identically. Moreover, homogeneous single tissue is not influenced by intensity reflection. The rate of temperature rise over time, even in varying thickness of fat and muscle, is constant at same depth of all models (from 37 to 64.613°C within 10 minutes at 1 cm. depth of fat (Figure 5.5), and from 37 to 49.0671°C within 10 minutes at 4 cm. depth of muscle (Figure 5.10)). For three bone models with thickness values equal to 2.3, 1.7, and 1.1 cm, maximum temperature at 10 minutes of application are 51.738, 50.168, and 46.956°C, respectively (Figure 5.11-5.13). Thus, thinner bone layer reach maximum at a value lower than thicker bone layer at any specific time (Figure 5.14).

Because bone can attenuate intensity enormously, intensity rapidly decayed until near to zero quite near to the bone surface, quite different from fat and muscle which decayed slightly and exponentially. Therefore, temperature quickly rises to reach a steady state temperature (Figure 5.15). For bone thickness of 2.3 cm., temperature at 1 cm. depth reaches a steady state temperature about 49.22°C, 360 seconds after application. But for thinner bone, thickness of 1.7 cm., temperature at same depth reaches a steady state temperature about 46.453°C, 285 seconds after application. And bone thickness of 1.1 cm., a steady state temperature at same depth approximate 39.02°C, 90 seconds after application. These data indicate that the steady state temperature of thinner layer is lower but reaches it more rapidly than thicker layer. For all tissue types, the location of peak temperature shifts downward the increase of tissue depth of the thicker models.

6.2.2 Different Widths of Surrounding Area Outside Ultrasound Beam of Fat, Muscle, and Bone.

Boundary conditions at various widths of surrounding tissue influence maximum temperature level with the same trend in all models. Models that have no surrounding tissue reach to maximum temperature lower than that have surrounding tissue significantly. For models that have surrounding tissue, maximum temperatures are slightly increased with their widths. At 10 minutes of 1 W/cm^2 application, differences of maximum temperatures of fat models with surrounding tissue are less than 0.1°C. For muscle and bone models, differences of maximum temperatures are lower than 0.1°C where surrounding tissue width is more than about 2 cm. Because surrounding tissue affects temperature distribution, user should include it into model in consideration of human anatomy. Therefore, analysis of one dimensional tissue model, like model of no surrounding tissue, can make some mistake to consequent result. Even the temperature along the central axis of the ultrasound beam decayed exponentially, model with no surrounding tissue still has lower temperatures than other models (Figure 5.22, 5.31, 5.40). As consider result on models' cross section at same depth, heat spreads away from the beam centre and decrease rapidly at both sides. Temperature peaks in the middle of ultrasound beam. Models with no surrounding tissue, that means no area for heat to spread away, still have lower peak temperatures than other models (Figure 5.23, 5.32, 5.41). Thus, wider model reaches maximum temperature higher than narrower model. Moreover, wider model allows heat transfer to surrounding area broader than narrower model. From heat conduction to both sides in models of surrounding width of 5 cm., it increases surrounding tissue temperature more than 0.5 °C, within width far away from beam about 1.85 cm. in fat, 2 cm. in muscle, and 2.5 cm. in bone. They indicate how to set appropriate width of model that will not waste computer memory and also obtain precise result. The rates of temperature rise over time have the same trend for all models that have surrounding tissue. For fat models (Figure 5.24), temperature at 1 cm depth increased from 37°C within 10 minutes after application to 64.3289 and 64.4394°C, in models that have 1 and 5 cm. surrounding tissue widths, respectively. For muscle models (Figure 5.33), temperature at 4 cm. depth increased from 37°C to 48.6472 and 48.8241°C, in models of 1 and 5 cm. surrounding tissue widths, respectively. Temperature in bone at 1 cm. depth (Figure 5.42) reached 50.789 and 51.3766°C in models of 1 and 5 cm. surrounding tissue widths. Similar to other results, models with no surrounding tissue still have lowest temperature.

6.3 Temperature Distribution within Three-Layered Model of Fat, Muscle, and Bone

6.3.1 Temperature Distribution within Three-Layered Model at Clinical Treatment Time

Maximum temperature within tissue model is affected by incident intensity value. Higher intensity, 1 W/cm^2, causes maximum temperature to reach 46.769°C when ultrasound energy is applied for 180 seconds (Figure 5.43). But the model that is applied by a lower intensity of 0.5 W/cm2 has a lesser maximum temperature that equals 41.884°C.

In comparison between single- and three-layered tissue models, their temperature distributions along the central axis of the ultrasound beam are different. The different tissue properties play a significant role in altering temperature profile. These selectively cause heat different areas in the three-layered tissue model. Intensity reflections at different tissue interfaces also affect temperature results because thermal changes depend on the amount of energy converted into heat at any point in model. Therefore, temperature distribution along the depth of a three tissue-layered model does not decay exponentially like single-layered model. Temperature distribution profile along the central axis of beam is similar between models of 0.5 and 1 W/cm^2 applications (Figure 5.44-5.45). The difference is only in temperature levels, where higher incident intensity produces a higher temperature. At the first 25-30 seconds of application to both models, maximum temperature is present inside bone, near its surface. This trend is caused by high attenuation coefficient of the bone. Even bone, lowest specific heat layer, obtains decayed intensity with very low amount, highest attenuation coefficient of bone extremely construct highest heat generation rate. After that, the rate of temperature rise of fat is increased, until it reaches a maximum temperature. Long duration of application causes intensity to accumulate at depth. Therefore, superficial area that accumulates intensity higher than deeper one will have a rapid increase in the rate of heat generation. Once the energy is delivered to the tissue, the rise of temperature will depend on the ultrasound intensity and thermal properties of tissue. If ultrasound is applied for a long time, thermal conductivity will take the effect. Tissue thermal gradient is increased with continuous wave application. Bone that has highest thermal conductivity and lowest specific heat, has a decreased rate of temperature rise because of increasing heat conduction to surrounding area. If our consider at the therapeutic temperature of 43°C in muscle, the results showed that the temperature in the middle of muscle layer reached 43°C after 1 W/cm^2 of ultrasound intensity applied approximately 165 seconds. At this application time, peak temperature inside fat and bone approximately 46.2°C and 44.5°C, respectively. The ultrasound application by lower ultrasound intensity reaches these temperatures with the same profile, but reaches them at longer time. Thus, when the middle of muscle reaches a critical temperature, the thermal pain is evoked in fat and bone surface. Therapist should adapt a treatment procedure appropriately to the depth of lesion.

Although the temperature values from the results of several past studies cannot be compared with the results in this study because of the variation in applied conditions, their trends of temperature distributions reasonably agree with the results of this study. The bone tissue was selectively heat and also the fat-muscle interface (17). Lele and Parker (27) investigated the temperature distribution in the cut thigh muscle of beef and the dog muscle, when sonicated by 0.9 and 1.8 MHz CW ultrasound. They reported that the peak temperature was attained over a very small volume and the axial location of the hot zone shifted towards the surface at the higher frequency of ultrasound. But in the case of dog muscle which had the bone inside, there was a second hot region in the deeper tissue. Chan et al. (11) obtained temperature results from a linear mathematical model of three plane-layer tissues with the highest temperature at the bone tissue. The difference between results of Chan et al. (11) and this study is produced by several factors, such as the different tissue properties, thickness, and source of heat generation. Lehmann et al. (15) measured the temperature distribution in pig thigh and found that the rates of temperature changes were at the spongy bone, bone surface, and the soft tissue in front of bone, respectively. Although their temperature values, in pig tissue, were not equal to human tissue, the trend of temperature distribution could be utilized to demonstrate human tissue. Chaipinyo K. (17) measured the temperature change in cat thigh with the same ultrasound frequency and application technique as used in this research. The results in cat from Chaipinyo K. (17) and in human from this research have similar trends of temperature changes from higher to lower temperature at subcutaneous tissue, the tissue in front of the bone, and muscle, respectively. But the temperature values in cat are lower than the ones obtained in this research due to a lower initial temperature and differences in tissue properties and tissue volume. Moreover, Lehmann et al. (14) found that the trend of temperature changes in pig is similar to the result in cat of Chaipinyo K. (17) and in human of this research. The difference of rates of temperature changes between two animals studied above and in this research can be explained by their tissue properties. At the same area of measurement, rates of temperature changes in human of this research are higher than the rates in pig, except at subcutaneous fat. Comparing tissue properties between pig and human, specific heat and attenuation coefficient of (only) fat layer of pig are seem to be higher than corresponding values in human. Therefore, the fat layer of pig is able to store thermal energy and can attenuate intensity higher than human.

6.3.2 Steady State Temperature of Three-Layered Tissue

For vigorous effects of ultrasound treatment, temperatures must be brought to the maximal tolerated level which can be done by staying just below the pain threshold. Thus, tissue temperature distribution is observed where maximum temperature is approximately in the treatment range between 40 and 45°C. For the analysis with ultrasound intensity of 0.5 W/cm^2 (Figure 5.48), maximum temperature within three-layered tissue reaches 40.007°C and 45°C at treatment times of 137 and 372 seconds, respectively. The maximum temperature of analysis with intensity of 1 W/cm^2 (Figure 5.49) reaches 40.015°C and 44.979°C at treatment times of 79 and 171 seconds, respectively. For analysis with both intensity values, at temperature approximately 40°C, there are two hot zones which are in fat and bone. At temperature approximately 45°C, the rate of temperature rise in bone decrease. From the discussion of the previous sub-section, the location of maximum temperature is first presented inside bone, and is then inside fat. For this section, results from prolonged application time show that the location of hot zone in fat is then shifted toward muscle layer.

From path plotting along vertical axis of three-layered models of incident intensity 0.5 and 1 W/cm^2 (Figure 5.50-5.51), the models are shown to have similar temperature profiles, and the higher temperature level is present in model of higher incident intensity. For a long application time, the location of peak temperature shifts into muscle. At 1 hour treatment time, temperatures at specific points in the middle of fat, muscle, in front of bone surface, and inside bone near its surface, do not reach steady state temperatures. But the rate of temperature change at every point is decreases towards a steady state temperature. Although the decrease in the rate of temperature changes in model of intensity of 0.5 W/cm^2 (Figure 5.52) is similar to that of 1 W/cm^2 (Figure 5.53), temperature of lower incident intensity is lesser than that of a higher one. At the application time approximately 700 seconds, temperature at a point in the middle of muscle is higher than temperatures at other specific points. This result shows again that the location of peak temperature shifts downward from fat into muscle, and that the muscle has a higher rate of temperature rise. Thus, if the location of this point is shifted toward muscle surface, its temperature, at a lesser time, will be higher than other temperatures at specific points. The results from ANSYS analysis will be used to plan a treatment procedure appropriately to the depth of lesion. Because fat reaches a critical temperature earlier than muscle, so, to reduce temperature in fat, therapist may employ the moving (head sound) technique.

On the whole, the results as obtained in this study may be regarded as satisfactory when viewed in comparison with results of previous studies. Hence the techniques used in this thesis work are valid and worth a further study in depth.

CHAPTER 7

CONCLUSION

A command log file is created by a series of ANSYS command. It can be used to analyse various therapeutic ultrasound conditions. User can specify several ultrasound usages as desired. ANSYS allows user to construct 2-D simulation of temperature results. It can be displayed with several frames in rapid succession. To review results in detail, table and graphical display are also available. As tissue and geometric properties can be defined according to a specific clinical treatment, therapist can predict temperature changes within an area of interest. Thus, therapist can introduce appropriate temperature level and duration of temperature elevation to a specific area of lesion.

The analysis of a single tissue type shows that temperature distribution is proportional to intensity distribution. Fat and muscle temperatures decay exponentially with depth. However, bone temperature decayed rapidly due to its superficial area. The analysis of different thicknesses shows that the location of peak temperature shifts downward the tissue depth at the thicker models. Moreover, the steady state temperature of thinner layer is lower but reached it more rapidly than thicker layer, especially bone. For the analysis of various widths of surrounding area outside ultrasound beam, the results show the difference in maximum temperature level with the same trend of distribution. Models that have no surrounding tissue reach to maximum temperature lower than that have surrounding tissue significantly. For models that have surrounding tissue, maximum temperatures are slightly increased with their widths. Heat spreads away from the beam centre and decrease rapidly at both sides. The wider model allows heat transfer to surrounding area broader than narrower model.

For three tissue type model, temperature distributions differ from a single tissue type. The selective heat occurred because of different tissue properties and intensity reflection at tissue interfaces. The location of hot zone is first presented inside bone, then inside fat, and finally its shifts toward muscle. Once the energy is delivered to the tissue, the rise of temperature will depend on intensity and the thermal properties, and, if ultrasound is applied for a long time, thermal conductivity will begin to take effect. All parameters, including boundary condition, tissue thickness, and physical properties that can influence changes in temperature distribution, are adjustable by the use of this command log file.

Further studies about the addition of the effect of blood flow and metabolism to model could be constructive to achieve more accurate temperature results. Nonlinear material properties which are affected by temperature changes should also be considered. Moreover, increasing number of layers (more than three layers) would allow user to analyse over a wide range of models. Whether the techniques as used in this project can be extended to cover non-uniform structures with non-uniform level thicknesses remains to be an interesting investigation. Another topic well worth a further research is to be able to review the change in temperature distribution under the application of moving technique presently used in ultrasound therapy.

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APPENDIX

APPENDIX

Appendix A

ANSYS Finite Element Program Environment.

1. Entering a Processor

In general, user enter a processor by selecting it from the ANSYS Main Menu in the Graphic User Interface (GUI). For example, choosing **Main Menu>Preprocessor** takes user into PREP7, or use a command, such as **/PREP7**.

2. Exiting from a Processor or ANSYS

To return to the Begin level from a processor, pick **Main Menu>Finish** or issue the **FINISH** or **/QUIT** command. User can move from one processor to another without returning to the Begin level. Simply pick the processor user want to enter, or issue the appropriate command. To leave the ANSYS program (and return to the system level), pick **Utility Menu>File>Exit**, which brings up the “Exit from ANSYS” dialog box, or use the **/EXIT** command. By default, the program saves the model and loads options of the database automatically and writes them to the database file, *Jobname*.DB. If a backup of the current database file already exists, ANSYS writes it to *Jobname*.DBB. Options in the dialog box (and on the **/EXIT** command) allow user to save other portions of the database or to quit without saving.

3. The ANSYS Database

In one large database, the ANSYS program stores all input data (model dimensions, material properties, etc.) and result data (temperature, etc.) in an organized fashion. The main advantage of the database is that user can list, display, modify, or delete any specific data item quickly and easily. No matter which processor user are in, user are working with the same database. This gives user basic access to the model and loads portions of the database from anywhere in the program. “Basic access” means the ability to select, list, or display an item.

4. Defining or Deleting Database Items

To define or delete items from the database, user must be in the appropriate processor. For example, user can define nodes, elements, and other geometry only in

PREP7. User can specify and apply loads in either the PREP7 or the SOLUTION processor. However, user can select geometry items, list, or display them from anywhere in the program, including the Begin level.

5. Saving the Database

Because the database contains all our input data, user should frequently save copies of it to a file. To do this, pick **Utility Menu>File>Save as Jobname.DB** or issue the **SAVE** command. Either choice writes the database to the file *Jobname*.DB. To specify a different file name, pick Utility **Menu>File>Save as** or use the appropriate fields on the **SAVE** command. Any save operation first writes a backup of the current database file (if the database already exists) to *Jobname*.DBB. If a *Jobname*.DBB file already exists, the new back-up file overwrites it.

6. Restoring Database Contents

To restore data from the database file, pick **Utility Menu>File>Resume Jobname.DB** or issue the **RESUME** command. This read the file *Jobname*.DB. To specify a different file name, pick **Utility Menu>File> Resume from** or use the appropriate fields on the **RESUME** command. User can save or resume the database from anywhere in the ANSYS program, including the Begin level. A resume operation replaces the data that currently is in memory with the data in the named database file. Using the save and resume operations together is useful when user want to "test" a function or command.

7. Clearing the Database

While building a model, if user want to clear out the database contents and start over, choose **Utility Menu>File>Clear & Start New** or issue the **/CLEAR** command. Either method clears the database stored in memory. Clearing the database has the same effect as leaving and re-entering the ANSYS program, but does not require user to exit.

8. ANSYS Program Files

The ANSYS program writes and reads many files for data storage and retrieveal. File names follow this pattern:

Name.Ext

Name defaults to the jobname, which user can specify while entering the ANSYS program or choosing **Utility Menu>File>Change Jobname** (equivalent to issue the

/FILNAME command). The default jobname is FILE (or file).Ext is a unique, two- to four-character ANSYS identifier that identifies the contents of the file. For example, Jobname.DB is the database file, Jobname.EMAT is the element matrix file.

9. Communicating With the ANSYS Program

Communicating Via the Graphical User Interface (GUI)

The GUI consists of six main regions, or windows that allow user to enter input data and execute ANSYS functions simply by picking buttons with a mouse or typing in responses to prompts. All user should use the GUI for interactive ANSYS work.

1. Utility Menu: Contains utility functions that are available throughout the ANSYS session, such as file controls, selecting, and graphics controls. User will exit the ANSYS program through this menu.
2. Main Menu: Contains the primary ANSYS functions, organized by processors. These functions include preprocessor, solution, general postprocessor, etc.
3. Toolbar: Contains push buttons that execute commonly used ANSYS commands and functions. User may add our own push buttons by defining abbreviations.
4. Input Window: Shows program prompt messages and allows user to type in commands directly. All previously typed-in commands also appear in this window for easy reference and access.
5. Graphics Window: A window where graphics displays are drawn.
6. Output Window: Receives text output from the program. It is usually positioned behind the other windows and can be brought to the front when necessary.

Communicating Via Commands

Commands are the instructions that direct the ANSYS program. ANSYS has more than 800 commands, each designed for a specific function. Most commands are associated with specific (one or more) processors, and work only with that processor of those processors. To use a function, user can either type in the appropriate command or access that function from the GUI (which internally issues the appropriate command). A typical command consists of a command name in the first field, usually followed by a comma and several more fields (containing arguments). A comma separates each field. Commands that begin with a *slash* (/) usually perform general program control tasks, such as entry to routines, file management, and graphics controls. Commands that begin with a *star* (*) are part of the ANSYS Parametric Design Language (APDL). Command *arguments* may take a number or an alphanumeric label, depending on their purpose. Some commands (for example, /PREP7, FINISH, etc.) have no arguments, so the entire command consists of just the command name.

Command Macro Files

User can record a frequently used sequence of ANSYS commands in a macro file, thus creating a personalized ANSYS command. If user enter a command name that ANSYS does not recognize, it searches for a macro file by that name (with an extension of .MAC or .mac). If the file exists, ANSYS executes it.

Appendix B

More information of array parameter defining, parametric operations and functions.

- To define an array parameter, user should first declare its type and dimensions using one of these methods:

  Command: ***DIM**

  GUI: **Utility Menu>Parameters>Array Parameters>Define/Edit**

For ARRAY and TABLE type parameters, user may then perform these operations:

- To graphically edit numerical array parameters, use one of these methods:

  Command: ***VEDIT**

  GUI: **Utility Menu>Parameters>Array Parameters>Define/Edit**

- To define the array elements, use one of these methods:

  Command: ***VFILL**

  GUI: **Utility Menu> Parameters>Array Parameters>Fill**

To define CHAR, ARRAY, or TABLE array parameters, use the "=" command. The "=" command is the same as the one used for scalar parameters, except that user now define a column of data (up to ten entries per "=" command). The ***VFILL** command (or its GUI path) allows user to "fill" a numeric array parameter vector with constantly increasing or decreasing values (RAMP), random numbers (RAND), random samples of Gaussian (GDIS), or simply a string often constants (DATA) (similar to the "=" command).

- To read numeric or alphanumeric data from a file, use one of these methods:

  Command: ***VREAD**

  GUI: **Utility Menu>Parameters>ArrayParameters>Read from File**

- To define a numerical array parameter vector (character array parameters cannot be defined using this operation) with ANSYS-supplied values:

  Command: ***VGET**

  GUI: **Utility Menu>Parameters>Get Array Data**

- To delete an array parameter, simply leave the right hand side of the "=" command blank.

For the operations among array parameters, just as parametric expressions and functions allow operations among scalar parameters. Two classes of operations can be identified: operations on column vectors, known as *vector operations*, and operations on entire matrices, known as *matrix operations.* Vector operations are simply a set of operations, such as addition, subtraction, sine, cosine, dot product, etc., repeated over a sequence of array elements. Do-loops can be employed for this purpose, but a more convenient way is to use the vector operation commands:

- To operate on two array parameters, use one of these methods:
  Command: ***VOPER**
  GUI: **Utility Menu>Parameters>Array Operations>Vector Operations**
- To perform a function on a single array parameter, use one of these methods:
  Command: ***VFUN**
  GUI: **Utility Menu>Parameters>Array Operations>Vector Functions**
- To determine the properties of an array parameter, use one of these methods:
  Command: ***VSCFUN**
  GUI: **Utility Menu >Parameters>Array Operations>Vector>-Scalar Func**
- To form an array parameter by interpolation of a table, use one of these methods:

  Command: ***VITRP**

  GUI: **Utility Menu >Parameters>Array Operations>Vector Interpolate**
- To specify the number of rows to be used in array parameter operations, use one of these methods:

  Command: ***VLEN**

  GUI: **Utility Menu>Parameters>Array Operations>Operation Settings**
- To specify an array parameter as a masking vector, use one of these methods:

  Command: ***VMASK**

  GUI: **Utility Menu >Parameters>Array Operations>Operation Settings**

Matrix operations are mathematical operations between numerical array parameter matrices, such as matrix multiplication, and solving simultaneous equations. The following matrix operation commands are available:

- To perform matrix operations on array parameter matrices, use one of these methods:
  Command: ***MOPER**
  GUI: **Utility Menu>Parameters>Array Operations>Matrix Operations**
- To copy or transpose an array parameter matrix, use one of these methods:
  Command: ***MFUN**
  GUI: **Utility Menu>Parameters>Array Operations>Matrix Functions**

Appendix C

Table of tissue temperature results from various boundary condition setting, which different tissue thickness, are shown below.

Table 1 Temperature versus time at same depth 1 cm. of 3 fat models, thickness = 49.4, 37, and 24.7 cm., and intensity = 1 W/cm^2.

Time (s.)	Temperature (°C) of 3 fat models, thickness=49.4, 37, 24.7 cm.	Time (s.)	Temperature (°C) of 3 fat models, thickness=49.4, 37, 24.7 cm.
0	37	315	54.0681
15	37.4671	330	54.7337
30	38.4011	345	55.3847
45	39.3344	360	56.0215
60	40.2655	375	56.6446
75	41.1921	390	57.2544
90	42.1113	405	57.8513
105	43.0204	420	58.4358
120	43.9171	435	59.0082
135	44.7995	450	59.569
150	45.6662	465	60.1185
165	46.5164	480	60.6571
180	47.3492	495	61.1852
195	48.1645	510	61.703
210	48.9622	525	62.211
225	49.7422	540	62.7094
240	50.5048	555	63.1985
255	51.2502	570	63.6786
270	51.9789	585	64.15
285	52.6911	600	64.613
300	53.3874		

Table 2 Temperature versus time at same depth 4 cm. of 3 muscle models, thickness = 28.8, 21.6, and 14.4 cm., and intensity = 1 W/cm^2.

Time (s.)	Temperature (°C) of 3 muscle models, thickness=28.8, 21.6, 14.4 cm.	Time (s.)	Temperature (°C) of 3 muscle models, thickness=28.8, 21.6, 14.4 cm.
0	37	315	43.818
15	37.1753	330	44.1183
30	37.526	345	44.4157
45	37.877	360	44.7102
60	38.2279	375	45.0017
75	38.5781	390	45.2905
90	38.9271	405	45.5764
105	39.2743	420	45.8597
120	39.6192	435	46.1404
135	39.9615	450	46.4184
150	40.3008	465	46.6939
165	40.6371	480	46.967
180	40.9701	495	47.2376
195	41.2998	510	47.5058
210	41.6262	525	47.7716
225	41.9492	540	48.0352
240	42.2688	555	48.2965
255	42.5851	570	48.5555
270	42.8982	585	48.8124
285	43.2079	600	49.0671
300	43.5145		

Table 3 Temperature versus time at same depth 1 cm. of 3 bone models, thickness = 2.3, 1.7, and 1.1 cm., and intensity = 1 W/cm^2.

Time(s.)	Temp. (°C) of bone, thickness = 2.3 cm	Temp. (°C) of bone, thickness = 1.7 cm	Temp. (°C) of bone, thickness = 1.1 cm
0	37	37	37
15	37.6242	37.6221	37.343
30	39.0869	39.0713	37.98
45	40.7449	40.6896	38.4935
60	42.2275	42.0948	38.7985
75	43.4274	43.1756	38.9391
90	44.4071	43.9984	39.0183
105	45.2132	44.6196	39.0578
120	45.8789	45.0853	39.0788
135	46.4342	45.4362	39.0896
150	46.8989	45.7	39.0955
165	47.2897	45.8991	39.0983
180	47.6194	46.0495	39.1001
195	47.8982	46.1632	39.1008
210	48.1346	46.2494	39.1014
225	48.3353	46.3147	39.1015
240	48.506	46.3644	39.1017
255	48.6513	46.4022	39.1017
270	48.7753	46.431	39.1018
285	48.8811	46.4529	39.1018
300	48.9715	46.4697	39.1018
315	49.0488	46.4824	39.1018
330	49.115	46.4922	39.1018
345	49.1716	46.4997	39.1018
360	49.2202	46.5054	39.1018
375	49.2619	46.5098	39.1018
390	49.2976	46.5131	39.1018
405	49.3283	46.5157	39.1018
420	49.3547	46.5177	39.1018
435	49.3773	46.5192	39.1018
450	49.3968	46.5203	39.1018
465	49.4136	46.5212	39.1018
480	49.428	46.5219	39.1018
495	49.4404	46.5225	39.1018
510	49.4511	46.5229	39.1018
525	49.4603	46.5232	39.1018

Table 3 (Continued) Temperature versus time at same depth 1 cm. of 3 bone models, thickness = 2.3, 1.7, and 1.1 cm., and intensity = 1 W/cm^2.

Time(s.)	Temp. (°C) of bone, thickness = 2.3 cm	Temp. (°C) of bone, thickness = 1.7 cm	Temp. (°C) of bone, thickness = 1.1 cm
540	49.4683	46.5234	39.1018
555	49.4751	46.5236	39.1018
570	49.4811	46.5237	39.1018
585	49.4861	46.5238	39.1018
600	49.4905	46.5239	39.1018

Appendix D

Table of tissue temperature results from various boundary condition setting, different surrounding tissue area width, are shown below.

FAT

Table 1 Temperature (T) distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 fat models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

Depth (cm.)	T (°C) at SW=0 cm.	T (°C) at SW=1 cm.	T (°C) at SW=2 cm.	T (°C) at SW=3 cm.	T (°C) at SW=4 cm.	T (°C) at SW=5 cm.
0	37	37	37	37	37	37
0.7	58.134	60.571	60.619	60.636	60.647	60.654
1.4	62.669	66.193	66.269	66.3	66.32	66.335
2.1	61.798	65.352	65.445	65.489	65.519	65.54
2.8	59.75	63.005	63.104	63.154	63.188	63.213
3.5	57.659	60.627	60.716	60.761	60.791	60.813
4.2	55.719	58.458	58.528	58.561	58.583	58.599
4.9	53.858	56.345	56.402	56.425	56.44	56.451
5.6	51.628	53.694	53.745	53.765	53.777	53.786
6.3	47.417	48.682	48.717	48.731	48.739	48.745
7	37	37	37	37	37	37

Table 2 Temperature (T) distribution at time = 600 sec. on cross section of 6 fat models at depth = 1 cm., and ultrasound intensity = 1 W/cm^2. (**A.**) Fat models with surrounding tissue width (SW) = 0, 1, and 2 cm. (**B.**) Fat models with surrounding tissue width (SW) = 3, 4, and 5 cm.

Table 2 A. Temperature of fat with surrounding tissue width (SW) = 0, 1, and 2 cm.

x coordination on fat cross section(cm.)	T(°C) at SW=0 cm.
0	37
0.25	46.938
0.5	53.812
0.75	58.102
1	60.521
1.25	61.248
1.5	60.521
1.75	58.102
2	53.812
2.25	46.938
2.5	37

x coordination on fat cross section(cm.)	T(°C) at SW=1 cm.
0	37
0.45	42.705
0.9	51.211
1.35	59.297
1.8	63.224
2.25	64.329
2.7	63.224
3.15	59.297
3.6	51.211
4.05	42.705
4.5	37

x coordination on fat cross section(cm.)	T(°C) at SW=2 cm.
0	37
0.65	38.34
1.3	42.253
1.95	52.816
2.6	62.046
3.25	64.391
3.9	62.046
4.55	52.816
5.2	42.253
5.85	38.34
6.5	37

Table 2 B. Temperature of fat with surrounding tissue width (SW) = 3, 4, and 5 cm.

x coordination on fat cross section(cm.)	T(°C) at SW=3 cm.
0	37
0.85	37.202
1.7	38.56
2.55	45.435
3.4	60.198
4.25	64.414
5.1	60.198
5.95	45.435
6.8	38.56
7.65	37.202
8.5	37

x coordination on fat cross section(cm.)	T(°C) at SW=4 cm.
0	37
1.05	37.02
2.1	37.393
3.15	41.041
4.2	57.582
5.25	64.429
6.3	57.582
7.35	41.041
8.4	37.393
9.45	37.02
10.5	37

x coordination on fat cross section(cm.)	T(°C) at SW=5 cm.
0	37
1.25	37.001
2.5	37.076
3.75	38.735
5	54.02
6.25	64.439
7.5	54.02
8.75	38.735
10	37.076
11.25	37.001
12.5	37

Table 3 Temperature (T) versus time at depth 1 cm. of 6 fat models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and intensity = 1 W/cm^2.

Time (s.)	T(°C) at SW=0 cm.	T(°C) at SW=1 cm.	T(°C) at SW=2 cm.	T(°C) at SW=3 cm.	T(°C) at SW=4 cm.	T(°C) at SW=5 cm.
0	37	37	37	37	37	37
30	38.401	38.4011	38.4011	38.4011	38.4011	38.4011
60	40.2671	40.2674	40.2674	40.2674	40.2674	40.2674
90	42.1161	42.1195	42.1195	42.1195	42.1195	42.1195
120	43.9184	43.9343	43.9345	43.9345	43.9345	43.9345
150	45.6456	45.6917	45.6922	45.6923	45.6924	45.6925
180	47.2794	47.3797	47.381	47.3814	47.3817	47.3819
210	48.812	48.9934	48.9959	48.9969	48.9975	48.9979
240	50.242	50.532	50.5363	50.538	50.5391	50.5398
270	51.5724	51.9975	52.004	52.0067	52.0084	52.0095
300	52.8082	53.3929	53.4022	53.406	53.4084	53.4101
330	53.9554	54.7222	54.7346	54.7398	54.7431	54.7454
360	55.0203	55.9893	56.0053	56.0121	56.0164	56.0193
390	56.009	57.1984	57.2183	57.2269	57.2322	57.2359
420	56.9277	58.3532	58.3776	58.3879	58.3945	58.399
450	57.7817	59.4575	59.4867	59.499	59.5068	59.5122
480	58.5762	60.5145	60.5491	60.5634	60.5725	60.5789
510	59.316	61.5274	61.5679	61.5843	61.5948	61.6021
540	60.0053	62.4991	62.5461	62.5646	62.5766	62.5849
570	60.6481	63.4321	63.4863	63.507	63.5204	63.5299
600	61.2479	64.3289	64.391	64.414	64.4289	64.4394

MUSCLE

Table 4 Temperature (T) distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 muscle models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

Depth (cm.)	T (°C) at SW=0 cm.	T (°C) at SW=1 cm.	T (°C) at SW=2 cm.	T (°C) at SW=3 cm.	T (°C) at SW=4 cm.	T (°C) at SW=5 cm.
0	37	37	37	37	37	37
0.7	48.467	50.865	50.963	50.992	51.012	51.027
1.4	51.039	54.71	54.869	54.916	54.949	54.973
2.1	50.297	54.186	54.36	54.411	54.446	54.471
2.8	48.647	52.244	52.405	52.447	52.476	52.497
3.5	46.939	50.097	50.238	50.268	50.287	50.302
4.2	45.398	48.092	48.218	48.238	48.251	48.26
4.9	44.004	46.218	46.325	46.341	46.35	46.357
5.6	42.565	44.229	44.303	44.316	44.323	44.329
6.3	40.591	41.526	41.56	41.568	41.573	41.576
7	37	37	37	37	37	37

Table 5 Temperature (T) distribution at time = 600 sec. on cross section of 6 muscle models at depth = 4 cm., and ultrasound intensity = 1 W/cm^2. (**A.**) Muscle models with surrounding tissue width (SW) = 0, 1, and 2 cm. (**B.**) Muscle models with surrounding tissue width (SW) = 3, 4, and 5 cm.

Table 5 A. Temperature of muscle with surrounding tissue width (SW)=0, 1, and 2 cm.

x coordination on muscle cross section(cm.)	T(°C) at SW=0 cm.
0	37
0.25	40.285
0.5	42.778
0.75	44.48
1	45.501
1.25	45.82
1.5	45.501
1.75	44.48
2	42.778
2.25	40.285
2.5	37

x coordination on muscle cross section(cm.)	T(°C) at SW=1 cm.
0	37
0.45	39.871
0.9	43.283
1.35	46.375
1.8	48.107
2.25	48.647
2.7	48.107
3.15	46.375
3.6	43.283
4.05	39.871
4.5	37

x coordination on muscle cross section(cm.)	T(°C) at SW=2 cm.
0	37
0.65	38.2
1.3	40.323
1.95	44.273
2.6	47.721
3.25	48.777
3.9	47.721
4.55	44.273
5.2	40.323
5.85	38.2
6.5	37

Table 5 B. Temperature of muscle with surrounding tissue width (SW)=3, 4, and 5 cm.

x coordination on muscle cross section(cm.)	T(°C) at SW=3 cm.	x coordination on muscle cross section(cm.)	T(°C) at SW=4 cm.	x coordination on muscle cross section(cm.)	T(°C) at SW=5 cm.
0	37	0	37	0	37
0.85	37.348	1.05	37.075	1.25	37.012
1.7	38.452	2.1	37.562	2.5	37.186
2.55	41.662	3.15	39.799	3.75	38.572
3.4	46.97	4.2	45.975	5	44.717
4.25	48.799	5.25	48.814	6.25	48.824
5.1	46.97	6.3	45.975	7.5	44.717
5.95	41.662	7.35	39.799	8.75	38.572
6.8	38.452	8.4	37.562	10	37.186
7.65	37.348	9.45	37.075	11.25	37.012
8.5	37	10.5	37	12.5	37

Table 6 Temperature (T) versus time at depth 4 cm. of 6 muscle models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and intensity = 1 W/cm^2.

Time (s.)	T(°C) at SW=0 cm.	T(°C) at SW=1 cm.	T(°C) at SW=2 cm.	T(°C) at SW=3 cm.	T(°C) at SW=4 cm.	T(°C) at SW=5 cm.
0	37	37	37	37	37	37
30	37.5257	37.5258	37.5258	37.5258	37.5258	37.5258
60	38.2263	38.2277	38.2277	38.2278	38.2278	38.2278
90	38.9172	38.9274	38.9276	38.9277	38.9277	38.9277
120	39.5839	39.6189	39.6197	39.6198	39.62	39.62
150	40.2162	40.2973	40.2992	40.2997	40.3	40.3002
180	40.81	40.9599	40.9637	40.9647	40.9654	40.9658
210	41.3646	41.6059	41.6121	41.6139	41.6151	41.6158
240	41.8811	42.2352	42.2445	42.2472	42.2489	42.2501
270	42.3613	42.8481	42.8611	42.8649	42.8673	42.869
300	42.8074	43.4452	43.4625	43.4675	43.4708	43.473
330	43.2215	44.0269	44.0494	44.0557	44.0599	44.0628
360	43.6057	44.594	44.6224	44.6303	44.6354	44.639
390	43.962	45.1468	45.1823	45.1917	45.1979	45.2022
420	44.2923	45.6858	45.7296	45.7406	45.7479	45.753
450	44.5983	46.2113	46.2649	46.2776	46.286	46.292
480	44.8818	46.7237	46.7887	46.8031	46.8127	46.8195
510	45.1443	47.2232	47.3014	47.3177	47.3285	47.3361
540	45.3872	47.7102	47.8034	47.8216	47.8336	47.8422
570	45.6119	48.1848	48.2952	48.3153	48.3286	48.3381
600	45.8198	48.6472	48.777	48.7991	48.8137	48.8241

BONE

Table 7 Temperature (T) distribution at time = 600 sec. on vertical line axis of ultrasound beam from upper to lower surface of 6 bone models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and ultrasound intensity = 1 W/cm^2.

Depth (cm.)	T(°C) at SW=0 cm.	T(°C) at SW=1 cm.	T(°C) at SW=2 cm.	T(°C) at SW=3 cm.	T(°C) at SW=4 cm.	T(°C) at SW=5 cm.
0	37	37	37	37	37	37
0.7	49.177	52.314	52.698	52.746	52.758	52.764
1.4	43.786	47.853	48.457	48.529	48.545	48.554
2.1	40.035	43.448	44.08	44.156	44.17	44.177
2.8	38.277	40.621	41.153	41.218	41.228	41.233
3.5	37.525	38.948	39.331	39.38	39.386	39.389
4.2	37.212	38	38.243	38.276	38.28	38.282
4.9	37.084	37.486	37.624	37.644	37.646	37.647
5.6	37.032	37.219	37.289	37.3	37.301	37.301
6.3	37.011	37.082	37.111	37.115	37.115	37.115
7	37	37	37	37	37	37

Table 8 Temperature (T) distribution at time = 600 sec. on cross section of 6 bone models at depth = 1 cm., and ultrasound intensity = 1 W/cm^2. (**A.**) Bone models with surrounding tissue width (SW) = 0, 1, and 2 cm. (**B.**) Bone models with surrounding tissue width (SW) = 3, 4, and 5 cm.

Table 8 A. Temperature of bone with surrounding tissue width (SW)=0, 1, and 2 cm.

x coordination on bone cross section(cm.)	T(°C) at SW=0 cm.
0	37
0.25	40.794
0.5	43.657
0.75	45.544
1	46.641
1.25	46.976
1.5	46.641
1.75	45.544
2	43.657
2.25	40.794
2.5	37

x coordination on bone cross section(cm.)	T(°C) at SW=1 cm.
0	37
0.45	40.348
0.9	44.436
1.35	48.159
1.8	50.184
2.25	50.789
2.7	50.184
3.15	48.159
3.6	44.436
4.05	40.348
4.5	37

x coordination on bone cross section(cm.)	T(°C) at SW=2 cm.
0	37
0.65	38.628
1.3	41.247
1.95	46.041
2.6	50.124
3.25	51.292
3.9	50.124
4.55	46.041
5.2	41.247
5.85	38.628
6.5	37

Table 8 B. Temperature of bone with surrounding tissue width (SW)=3, 4, and 5 cm.

x coordination on bone cross section(cm.)	T(°C) at SW=3 cm.	x coordination on bone cross section(cm.)	T(°C) at SW=4 cm.	x coordination on bone cross section(cm.)	T(°C) at SW=5 cm.
0	37	0	37	0	37
0.85	37.749	1.05	37.33	1.25	37.136
1.7	39.218	2.1	38.155	2.5	37.59
2.55	43.021	3.15	40.825	3.75	39.396
3.4	49.319	4.2	48.156	5	46.667
4.25	51.354	5.25	51.368	6.25	51.377
5.1	49.319	6.3	48.156	7.5	46.667
5.95	43.021	7.35	40.825	8.75	39.396
6.8	39.218	8.4	38.155	10	37.59
7.65	37.749	9.45	37.33	11.25	37.136
8.5	37	10.5	37	12.5	37

Table 9 Temperature (T) versus time at depth 1 cm. of 6 bone models, surrounding tissue width (SW) = 0, 1, 2, 3, 4, 5 cm., and intensity = 1 W/cm^2.

Time (s.)	T(°C) at SW=0 cm.	T(°C) at SW=1 cm.	T(°C) at SW=2 cm.	T(°C) at SW=3 cm.	T(°C) at SW=4 cm.	T(°C) at SW=5 cm.
0	37	37	37	37	37	37
30	39.0718	39.0867	39.0869	39.087	39.087	39.087
60	42.0629	42.2256	42.2283	42.2293	42.2299	42.2302
90	43.9085	44.4064	44.4157	44.419	44.4208	44.422
120	44.9992	45.8963	45.9146	45.9205	45.9238	45.926
150	45.6684	46.9596	46.9905	46.9988	47.0035	47.0065
180	46.0935	47.7486	47.7965	47.8068	47.8126	47.8164
210	46.3713	48.3516	48.4214	48.4335	48.4403	48.4448
240	46.5569	48.8235	48.9194	48.9333	48.941	48.9459
270	46.683	49.1995	49.3252	49.3409	49.3493	49.3548
300	46.7701	49.5035	49.6618	49.6795	49.6886	49.6945
330	46.8308	49.7524	49.9451	49.9653	49.9749	49.9811
360	46.8737	49.9583	50.1866	50.2096	50.2197	50.2262
390	46.9042	50.1301	50.3946	50.4207	50.4314	50.4382
420	46.926	50.2745	50.5752	50.6051	50.6162	50.6233
450	46.9418	50.3967	50.7333	50.7674	50.779	50.7863
480	46.9532	50.5006	50.8726	50.9114	50.9234	50.931
510	46.9616	50.5896	50.996	51.0399	51.0525	51.0602
540	46.9677	50.666	51.1059	51.1552	51.1685	51.1764
570	46.9722	50.7319	51.2042	51.2593	51.2732	51.2813
600	46.9755	50.789	51.2925	51.3537	51.3684	51.3766

Appendix E

Table of temperature results of three-layered model (fat, muscle, and bone) from various ultrasound treatment time, intensity of 0.5 and 1 W/cm^2, are shown below:

Table 1 Temperature distribution on vertical line axis of ultrasound beam of three-layered model, Temperature are plotted at every 30 sec., ultrasound intensity = 0.5 W/cm^2.

Depth (cm.)	T(°C) at 30 s.	T(°C) at 60 s.	T(°C) at 90 s.	T(°C) at 120 s.	T(°C) at 150 s.	T(°C) at 180 s.
0	37	37	37	37	37	37
0.35	37.952	38.723	39.354	39.89	40.356	40.768
0.7	37.955	38.875	39.726	40.507	41.222	41.879
1.05	37.772	38.571	39.361	40.132	40.876	41.59
1.4	37.744	38.497	39.245	39.981	40.7	41.398
1.75	37.699	38.408	39.112	39.806	40.486	41.149
2.1	37.653	38.317	38.977	39.628	40.267	40.891
2.45	37.61	38.232	38.85	39.46	40.059	40.645
2.8	37.572	38.155	38.735	39.307	39.87	40.42
3.15	37.538	38.086	38.632	39.171	39.702	40.224
3.5	37.508	38.025	38.541	39.055	39.564	40.067
3.85	37.481	37.974	38.473	38.976	39.479	39.977
4.2	37.459	37.948	38.461	38.982	39.499	40.003
4.55	37.475	38.041	38.62	39.181	39.715	40.221
4.9	37.756	38.483	39.119	39.686	40.199	40.667
5.25	38.083	38.815	39.412	39.924	40.378	40.785
5.6	37.709	38.319	38.828	39.266	39.652	39.997
5.95	37.34	37.759	38.142	38.483	38.786	39.056
6.3	37.136	37.37	37.617	37.847	38.055	38.241
6.65	37.046	37.145	37.263	37.379	37.484	37.579
7	37	37	37	37	37	37

Table 2 Temperature distribution on vertical line axis of ultrasound beam of three-layered model, Temperature are plotted at every 30 sec., ultrasound intensity = 1 W/cm^2.

Depth (cm.)	T(°C) at 30 s.	T(°C) at 60 s.	T(°C) at 90 s.	T(°C) at 120 s.	T(°C) at 150 s.	T(°C) at 180 s.
0	37	37	37	37	37	37
0.35	38.903	40.446	41.709	42.78	43.712	44.535
0.7	38.91	40.75	42.453	44.014	45.444	46.758
1.05	38.543	40.141	41.722	43.263	44.751	46.179
1.4	38.488	39.994	41.49	42.963	44.4	45.795
1.75	38.398	39.817	41.224	42.612	43.972	45.298
2.1	38.305	39.634	40.954	42.256	43.534	44.782
2.45	38.221	39.464	40.7	41.921	43.119	44.29
2.8	38.144	39.31	40.47	41.615	42.739	43.841
3.15	38.076	39.172	40.263	41.342	42.404	43.448
3.5	38.016	39.05	40.083	41.11	42.128	43.133
3.85	37.962	38.947	39.945	40.953	41.959	42.954
4.2	37.919	38.896	39.922	40.965	41.997	43.007
4.55	37.95	39.082	40.24	41.361	42.429	43.441
4.9	38.513	39.966	41.238	42.372	43.397	44.335
5.25	39.166	40.631	41.823	42.848	43.755	44.571
5.6	38.417	39.639	40.656	41.533	42.305	42.995
5.95	37.68	38.517	39.285	39.967	40.572	41.113
6.3	37.271	37.74	38.234	38.695	39.11	39.482
6.65	37.092	37.29	37.527	37.757	37.968	38.157
7	37	37	37	37	37	37

Table 3 Temperature versus time, every 5 sec., when apply intensity of 0.5 W/cm^2 to three-layered model. FAT = 0.5 cm. below the upper surface of fat, MUSCLE = 2 cm. below the upper surface of muscle, M-B = 0.1 cm. above the bone surface, and BONE = 0.5 cm. below the upper surface of bone.

Time(s.)	FAT	MUSCLE	M-B	BONE
0	37	37	37	37
5	37.1501	37.0841	37.1679	37.1342
10	37.3168	37.1777	37.3502	37.2887
15	37.483	37.2712	37.5187	37.4365
20	37.6484	37.3648	37.6766	37.5764
25	37.8125	37.4585	37.8261	37.7091
30	37.9748	37.5522	37.9685	37.8354
35	38.1352	37.6459	38.105	37.956
40	38.2933	37.7397	38.2363	38.0715
45	38.449	37.8334	38.3629	38.1824
50	38.6021	37.9272	38.4852	38.2892
55	38.7526	38.0209	38.6037	38.3922
60	38.9004	38.1146	38.7187	38.4917
65	39.0456	38.2082	38.8305	38.5881
70	39.1881	38.3017	38.9393	38.6816
75	39.328	38.3951	39.0452	38.7723
80	39.4654	38.4883	39.1486	38.8606
85	39.6002	38.5814	39.2495	38.9464
90	39.7326	38.6743	39.3481	39.0301
95	39.8625	38.767	39.4445	39.1117
100	39.9901	38.8595	39.5389	39.1913
105	40.1154	38.9518	39.6314	39.2691
110	40.2384	39.0439	39.722	39.3451
115	40.3593	39.1357	39.8109	39.4194
120	40.4781	39.2272	39.898	39.4922
125	40.5948	39.3185	39.9836	39.5634
130	40.7095	39.4095	40.0677	39.6332
135	40.8223	39.5002	40.1502	39.7016
140	40.9332	39.5907	40.2314	39.7687
145	41.0422	39.6809	40.3112	39.8345
150	41.1495	39.7708	40.3897	39.8991
155	41.2551	39.8604	40.467	39.9625
160	41.3589	39.9497	40.543	40.0248
165	41.4611	40.0387	40.6179	40.0859
170	41.5618	40.1275	40.6916	40.1461
175	41.6608	40.2159	40.7643	40.2052
180	41.7584	40.3041	40.8358	40.2633

Table 4 Temperature versus time, every 5 sec., when apply intensity of 1 W/cm^2 to three-layered model. FAT = 0.5 cm. below the upper surface of fat, MUSCLE = 2 cm. below the upper surface of muscle, M-B = 0.1 cm. above the bone surface, and BONE = 0.5 cm. below the upper surface of bone.

Time(s.)	FAT	MUSCLE	M-B	BONE
0	37	37	37	37
5	37.3002	37.1683	37.3357	37.2684
10	37.6335	37.3553	37.7004	37.5774
15	37.966	37.5424	38.0374	37.873
20	38.2968	37.7297	38.3532	38.1528
25	38.6249	37.917	38.6521	38.4182
30	38.9497	38.1044	38.9371	38.6708
35	39.2704	38.2918	39.2101	38.9119
40	39.5866	38.4793	39.4726	39.1429
45	39.898	38.6668	39.7257	39.3648
50	40.2042	38.8543	39.9704	39.5783
55	40.5052	39.0418	40.2075	39.7843
60	40.8008	39.2292	40.4375	39.9834
65	41.0912	39.4164	40.661	40.1762
70	41.3762	39.6034	40.8785	40.3631
75	41.6561	39.7902	41.0904	40.5447
80	41.9308	39.9767	41.2972	40.7211
85	42.2004	40.1628	41.499	40.8929
90	42.4651	40.3486	41.6962	41.0602
95	42.725	40.5341	41.8891	41.2234
100	42.9802	40.7191	42.0779	41.3826
105	43.2307	40.9036	42.2628	41.5382
110	43.4769	41.0877	42.444	41.6902
115	43.7186	41.2713	42.6217	41.8389
120	43.9562	41.4544	42.7961	41.9844
125	44.1896	41.637	42.9672	42.1269
130	44.4191	41.819	43.1353	42.2665
135	44.6446	42.0005	43.3005	42.4033
140	44.8664	42.1814	43.4628	42.5374
145	45.0845	42.3618	43.6225	42.669
150	45.299	42.5415	43.7795	42.7982
155	45.5101	42.7208	43.934	42.925
160	45.7178	42.8994	44.086	43.0495
165	45.9223	43.0775	44.2358	43.1719
170	46.1235	43.255	44.3832	43.2921
175	46.3217	43.4319	44.5285	43.4103
180	46.5168	43.6082	44.6717	43.5265

Table 5 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model, Temperature are plotted at every 600 sec. until complete 3,600 sec., ultrasound intensity = 0.5 W/cm^2.

Depth (cm.)	T(°C) at 600 s.	T(°C) at 1,200 s.	T(°C) at 1,800 s.	T(°C) at 2,400 s.	T(°C) at 3,000 s.	T(°C) at 3,600 s.
0	37	37	37	37	37	37
0.35	43.929	46.365	47.91	49.011	49.831	50.456
0.7	47.494	52.167	55.174	57.325	58.929	60.152
1.05	48.554	54.929	59.113	62.12	64.366	66.082
1.4	48.508	55.281	59.769	63	65.416	67.261
1.75	48.17	55.168	59.86	63.244	65.776	67.711
2.1	47.685	54.755	59.553	63.02	65.614	67.596
2.45	47.148	54.154	58.953	62.425	65.025	67.012
2.8	46.626	53.452	58.154	61.559	64.108	66.058
3.15	46.159	52.699	57.203	60.466	62.909	64.777
3.5	45.766	51.919	56.133	59.183	61.468	63.215
3.85	45.455	51.107	54.937	57.706	59.782	61.371
4.2	45.205	50.236	53.597	56.026	57.848	59.244
4.55	44.975	49.245	52.058	54.092	55.62	56.792
4.9	44.688	48.061	50.26	51.854	53.054	53.977
5.25	44.122	46.817	48.572	49.847	50.811	51.553
5.6	42.736	44.889	46.286	47.305	48.076	48.67
5.95	41.159	42.773	43.818	44.581	45.159	45.605
6.3	39.669	40.746	41.441	41.949	42.334	42.632
6.65	38.301	38.839	39.187	39.44	39.633	39.782
7	37	37	37	37	37	37

Table 6 Temperature distribution on vertical line axis of ultrasound beam from upper to lower surface of three-layered model, Temperature are plotted at every 600 sec. until complete 3,600 sec., ultrasound intensity = 1 W/cm^2.

Depth (cm.)	T(°C) at 600 s.	T(°C) at 1,200 s.	T(°C) at 1,800 s.	T(°C) at 2,400 s.	T(°C) at 3,000 s.	T(°C) at 3,600 s.
0	37	37	37	37	37	37
0.35	50.858	55.731	58.82	61.022	62.662	63.913
0.7	57.987	67.335	73.348	77.65	80.857	83.304
1.05	60.108	72.859	81.226	87.24	91.733	95.164
1.4	60.015	73.563	82.539	89.001	93.832	97.523
1.75	59.339	73.335	82.72	89.489	94.552	98.421
2.1	58.37	72.511	82.106	89.039	94.228	98.193
2.45	57.297	71.307	80.906	87.851	93.049	97.023
2.8	56.251	69.903	79.308	86.118	91.217	95.115
3.15	55.317	68.397	77.407	83.931	88.817	92.554
3.5	54.533	66.838	75.265	81.365	85.935	89.431
3.85	53.909	65.215	72.873	78.413	82.564	85.742
4.2	53.409	63.471	70.193	75.052	78.697	81.488
4.55	52.949	61.49	67.116	71.185	74.24	76.583
4.9	52.377	59.121	63.52	66.708	69.109	70.953
5.25	51.244	56.635	60.143	62.695	64.622	66.106
5.6	48.472	52.778	55.573	57.61	59.151	60.34
5.95	45.318	48.546	50.636	52.161	53.317	54.209
6.3	42.338	44.491	45.882	46.898	47.668	48.263
6.65	39.602	40.679	41.373	41.881	42.266	42.564
7	37	37	37	37	37	37

Table 7 Temperature versus time when apply intensity of 0.5 W/cm^2 to three-layered model, every 180 sec. until complete 3,600 sec. of application time.

Time (s.)	FAT	MUSCLE	M-B	BONE
0	37	37	37	37
180	41.1487	39.7732	40.3883	39.9008
360	44.1605	42.8213	42.6146	41.6733
540	46.2086	45.5212	44.1537	42.8538
720	47.7867	47.9079	45.3453	43.7507
900	49.0824	50.0185	46.3282	44.485
1,080	50.186	51.8914	47.1688	45.1107
1,260	51.1477	53.5615	47.9058	45.6588
1,440	51.9984	55.0585	48.5611	46.1464
1,620	52.7586	56.4071	49.1501	46.5849
1,800	53.4431	57.6273	49.683	46.9822
1,980	54.0629	58.7356	50.1679	47.3441
2,160	54.6266	59.7459	50.6106	47.675
2,340	55.141	60.6695	51.0164	47.9785
2,520	55.6119	61.5161	51.389	48.2575
2,700	56.0439	62.2938	51.7321	48.5146
2,880	56.4412	63.0096	52.0484	48.7519
3,060	56.8072	63.6696	52.3406	48.9712
3,240	57.1449	64.279	52.6108	49.1741
3,420	57.4568	64.8424	52.8609	49.362
3,600	57.7454	65.3638	53.0927	49.5362

Table 8 Temperature versus time when apply intensity of 1 W/cm^2 to three-layered model, every 180 sec. until complete 3,600 sec. of application time.

Time (s.)	FAT	MUSCLE	M-B	BONE
0	37	37	37	37
180	45.2973	42.5463	43.7767	42.8016
360	51.321	48.6425	48.2291	46.3465
540	55.4173	54.0424	51.3074	48.7076
720	58.5733	58.8158	53.6907	50.5014
900	61.1647	63.037	55.6564	51.9699
1,080	63.372	66.7827	57.3376	53.2215
1,260	65.2954	70.123	58.8117	54.3177
1,440	66.9968	73.1171	60.1221	55.2927
1,620	68.5173	75.8142	61.3002	56.1698
1,800	69.8863	78.2545	62.3659	56.9644
1,980	71.1259	80.4712	63.3357	57.6882
2,160	72.2532	82.4918	64.2212	58.35
2,340	73.282	84.339	65.0327	58.957
2,520	74.2237	86.0321	65.778	59.5151
2,700	75.0878	87.5875	66.4641	60.0293
2,880	75.8824	89.0192	67.0968	60.5038
3,060	76.6144	90.3392	67.6812	60.9424
3,240	77.2897	91.558	68.2215	61.3482
3,420	77.9137	92.6848	68.7218	61.724
3,600	78.4908	93.7277	69.1854	62.0725

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