Proceedings of 8th International Conference on Mechanical, Industrial and Energy Engineering 2024
02-04 January, 2025, Khulna, BANGLADESH
SciEn Conference Series: Engineering Vol. 3, 2025, pp 159-163 https://doi.org/10.38032/scse.2025.3.40

Development and Validation of a Bio-heat Transfer Model for Human Abdomen with a Relation Between Skin Temperature and Abdomen Fat

Abul Mukid M. Mukaddes[1], Mohammad Junaid[2] and Ryuji Shioya[3]*

[1] Department of Industrial and Production Engineering, Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh
[2] Department of Mechanical Engineering, Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh
[3] Faculty of Information and Arts, Toyo University, Japan

ABSTRACT
Fat in human abdomen plays an adverse role in the metabolic and cardiovascular medical problems. Heat transfer knowledge through the human tissue in particular abdominal tissue can indicate the amount of fat layers. Experimental measurement of abdominal layer temperatures is invasive, complex, and costly. Thus, a computational model is essential to non-invasively simulate temperature variations, simplifying research, reducing costs, and enabling efficient analysis of temperature distribution. This study focuses on developing a 3-D bio-heat transfer model for the human abdomen and validating it using experimental data and results from commercial software. The model consists of five layers of different thickness. The finite element method adopted in the ADVENTURE_Thermal was used to solve the bio-heat equation. Two abdomen models: slim and obese were compared to normal environmental conditions. The present computational model was validated with experimental results and commercial software COMSOL Multiphysics. Body core temperature is found same, but skin temperature is found different for models. The obese abdomen was found to have a lower skin temperature than that of slim abdomen. The low skin temperature indicates the presence of more fat in the abdomen. This variation emphasizes the influence of fat layer thickness on heat transfer and thermoregulation, showcasing the model's effectiveness in accurately simulating bio-heat transfer. The validated model serves as a dependable tool for future research and practical applications, such as the non-invasive evaluation of obesity-related health risks.

Keywords: Skin Temperature, Visceral Fat, Adventure_Thermal, Obesity

1. Introduction

Human abdomen consists of five layers: *skin, subcutaneous fat, muscle, visceral fat and viscera.* The thickness of layers is different. Fat and muscle layers may change due to the food intake, physical activities and other medications. Human body fat in the abdomen is subdivided into three layers subcutaneous, intramuscular and visceral fat. Subcutaneous fat is located between the skin and muscle layer and visceral fat is located between the muscle and viscera. Both can be increased due to high carbohydrate intake, less physical exercise and obesity. Both subcutaneous and visceral fat are strongly related to all obesity-caused complications [1]. Among all parts, abdomen have the highest level of fat. Fat above the standard value might cause severe cardiovascular diseases. So regular diagnosis to measure the amount of fat is recommended. Several abdominal obesity or fat measuring methods are available in the literature. Those are Computerized Tomography (CT) scan, waist circumference and waist to hip ratio (WHR).

Human body parts mainly consist of bone, muscle, fat and skin. Among them, fat has the lowest thermal conductivity. Again, the thermo-regulation system of the human body maintains a constant temperature of 37°C in its internal organ. The heat generated by metabolism or other sources is transferred to the environment through human skin in order to keep the body core temperature constant. Thus, the amount of fat and muscle interferes with the heat transfer through the human body from body core to skin.

K. Shimano et. al. [2] compared the abdomen skin temperature of two subjects (a slim and a fatty student) in a normal environmental condition. The fatty subjects are found with a lower skin temperature. Using these results, they performed a two-dimensional boundary element model to measure the heat flux through the skin. The popular bio-heat equation is not used there. He first shows the idea of measuring visceral fat using the skin temperature.

Measuring the temperature of different layers of the human abdomen experimentally is challenging and often highly expensive due to the invasive nature and complexity of the procedures involved. Therefore, there is a critical need to develop a computational model that can non-invasively simulate and observe temperature variations in the human abdomen. Such a model would significantly simplify the investigation process, reduce costs, and provide a practical and efficient tool for studying temperature distribution in various physiological conditions.

The objective of this research is to develop a bio-heat transfer model for the human abdomen and validate it against K. Shimano's experimental results. Additionally, comparing the model's outcomes with the results obtained from commercial software is also a key objective of this study.

Two computational models; slim and obese have been developed by Adventure_CAD [3]. The mesh was generated, and boundary conditions are set up using other open-source Adventure modules [3]. The Adventure_Themal, which was modified to solve Penne's bio-heat equation for the skin burn

*Corresponding Author Email Address: mukaddes-ipe@sust.edu

analysis [4]. This time Penne's bio-heat equation adopted in the Adventure_Thermal was used to analyze heat transfer through the multi-layered human abdomen. The parallel finite element method, named otherwise domain decomposition method was used here. A relation between the skin temperature and the fat layer was found. Then, the bio-heat transfer model for the human abdomen was validated with the experimental results and that of commercial software COMSOL Multiphysics [5].

2. Methods and Materials

2.1 Heat transfer concept in the human abdomen

It is proved that the human body keeps its core temperature constant (37°C) by the thermoregulation system. Heat is generated within the body mainly through metabolism. Other sources might also generate heat. That heat is transferred to the environment through human skin by heat convection, evaporation and radiation. Heat is transferred from the internal part to the skin by conduction. This conduction heat transfer process depends on the thermal conductivity and layer thickness according to the equation (1). For the small thermal conductivity, if layer thickness is increased, the temperature difference will also be increased. In that case, to keep the body core temperature constant, skin temperature will be reduced.

$$q = -k\frac{\Delta T}{\Delta x} \tag{1}$$

Among the layers of abdomen, viscera fat and subcutaneous fat have the lowest thermal conductivity. Obesity comes from excess viscera and subcutaneous fat. The amount of fat accelerates or decelerates the heat transfer from the body core to the environment. Thus, a change in the fat thickness will change the heat transfer, thereby the skin temperature as core temperature is fixed.

2.2 Governing equations

The following Penne's bio-heat equation [4] was used as the main governing equation to obtain the temperature distribution through the human tissue.

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + q_m + \rho_b c_b \omega_b (T_a - T) \tag{2}$$

$$k\frac{dT}{dn} = h(T - T_\infty) \tag{3}$$

The nomenclature is given at the end of the paper. The first term of left side of equation (2) is the unsteady term.
The first and third terms of the right side of equation (1) represent heat conduction and blood perfusion. Blood perfusion and metabolic heat generation (q_m) are added to introduce bio-heat concept in the conventional heat transfer equation. In this research, the steady state terms of bio-heat equation were used. Convection boundary conditions were used on the skin surface. Heat dissipates through skin surface by convection, radiation, sweating and emission. An overall heat transfer co-efficient was used considering all the cases.

2.3 Flow of Analysis

We have been developing Adventure_Thermal as a bio-heat equation solver. Conventional heat transfer problems can also be solved by this module. It is an open-source software to solve large scale 3-D steady and non-steady heat conduction problem. The flow of analysis starts with developing solid geometry and ends with temperature visualization. Detail steps are given below.

Solid geometry: A 3-D CAD model consisting of the viscera, viscera fat, muscle, subcutaneous fat and skin was developed by Adventure_CAD.

Mesh generation: Quadratic tetrahedral mesh was generated using the Adventure_Tetmesh.

Domain decompose: Since the Adventure_Thermal has been developed to perform the parallel finite element analysis of the heat transfer problem, a domain decomposition software is required to prepare the data for the parallel finite element analysis. Adventure_Metis was used for this purpose.

Boundary conditions set up: Adventure_BCtool was used to set up the heat convection boundary conditions.

Adventure_Thermal: This module is the solver to solve the large-scale heat transfer problem. The solution of bio-heat equation has been added to this module through this research and was used to find the temperature distribution through the developed model. The conjugate gradient method, special Gauss elimination and sparse matrix storage techniques were particularly used for this analysis.

Temperature visualization: Temperature distribution through the 3-D model was visualized using the Adventure_Posttool.

Analysis by commercial software: The COMSOL multiphysics [6] is a powefull software to solve the bio-heat problem. The complete process from the CAD development to the visualization was performed by the software.

Validation: The result of this research was validated with the result from COMSOL and experimental results [2].

3. Computational Model

3.1 Model geometry

The CT scan model is asymmetric but for simplicity, a symmetric abdomen solid model was developed using the Adventure_CAD. The model consists of five layers of different thickness as shown in figure 1. Two models: *slim and obese* were developed. Slim model (figure 1) has relatively thin visceral and subcutaneous layers whereas obese model (figure 2) has thick visceral and subcutaneous layers.

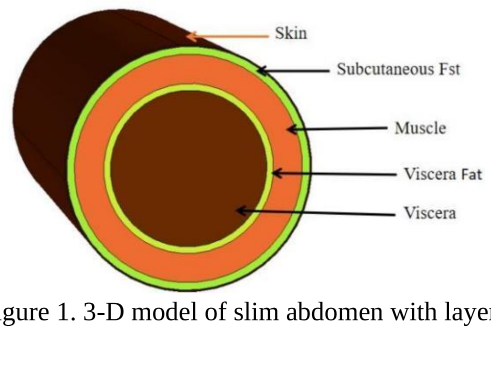

Figure 1. 3-D model of slim abdomen with layers

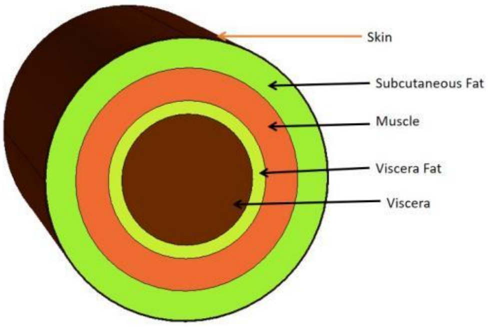

Figure 2. 3-D model of obese abdomen with layers

The thickness of layers was calculated from the CT scan image of two student's abdomen [2]. The detail parameters are given in Table 2. The muscle, fat, and viscera are not really symmetric, but we assumed it symmetric keeping its area same as CT scan models.

3.2 Mesh statistics

Fine mesh was used for both slim and obese abdomen models shown in figure 3 and figure 4. The number of elements 270456 and 468659 respectively.

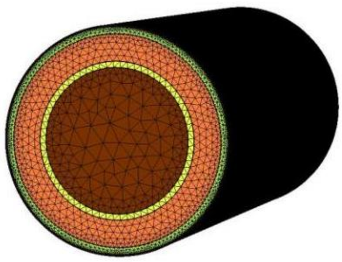

Figure 3. Mesh of slim abdomen

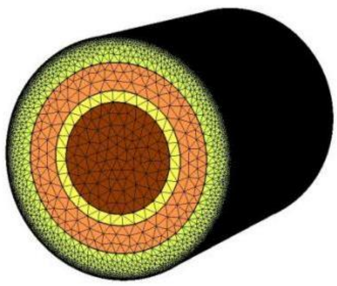

Figure 4. Mesh of obese abdomen

Table 1 Relevant data of two male volunteers [2]

Volunteer	Model A	Model B
Ethnicity	Japanese	Japanese
Age	21	23
Height	167 cm	170 cm
Weight	52kg	93kg
Abdominal Circumferences	68 cm	102 cm
Subcutaneous fat	43 cm^2	305 cm^2
Visceral fat	26 cm^2	95 cm^2

3.3 Physiological properties

The bio-heat transfer model for abdomen was developed by using the thermophysical and basal physiological properties of tissue materials, based on literature [7,8, 9]. Detail physiological properties are given in Table 1. The radius of the layers is calculated from model A (slim) and model B (obese) of [2]. The parameters of two subjects used for the experiment in [2] are given in Table 2. The thickness of subcutaneous and visceral fat was calculated from the area given in Table 2. The abdominal circumferences remained the same as those of two volunteers. The muscle and viscera thickness were adjusted.

Table 2 Physiological properties of abdomen layers [2]

Tissues	Radius of Slim Body(cm)	Radius of Fatty body (cm)	Thermal conductivity (W/m.C)	Density (Kg/m^3)	Specific heat (J/kg °C)	Blood perfusion (1/s)	Metabolicheat generation (W/m^3)
Viscera	6.85	7.48	0.53	1,000	3,694	4.31	4100
Vis. fat	7.44	9.14	0.21	850	2,300	.003 6	58
Muscle	10	12.7	0.42	1,085	3,768	0.53 8	684
Sub. fat	10.6 6	16.08	0.16	850	2,300	.003 6	58
Skin	10.8 2	16.24	0.47	1,085	3,680	1.44	368

4. Numerical results

4.1 Boundary conditions

Heat convection type boundary conditions were set on the skin surface. The environmental temperature was taken as 30°C and heat transfer co-efficient was taken at the value of 7 W/m^2 °C. The body core temperature is 37°C.

4.2 Temperature distribution

The temperature profile using both the present study and commercial software, COMSOL is shown in figure 5, 6 and 7. In all cases, body core temperature remains constant around 37°C. The figure clearly shows that heat flows from the viscera to the skin surface. Viscera keeps it constant temperature. Comparison between slim and obese abdomen shows that obese abdomen has low skin temperature. It means that the thicker viscera fat and subcutaneous fat works as thermal resistance. The same results are found in the COMSOL.

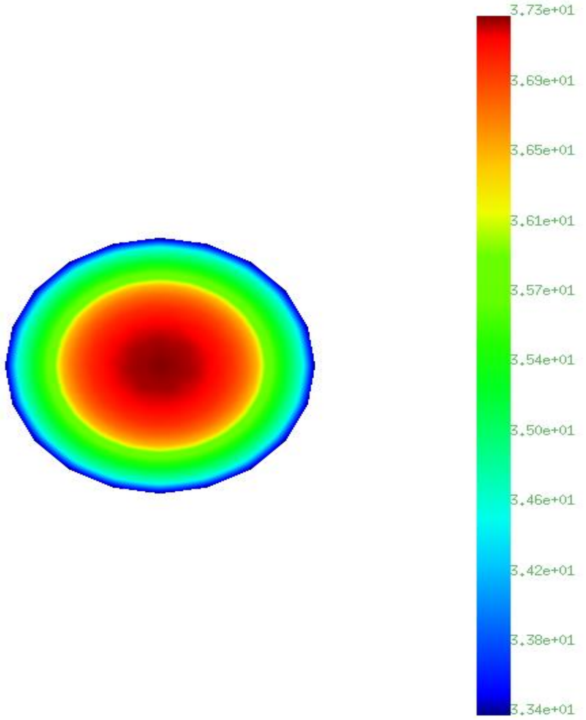

Figure 5. Temperature distribution of slim abdomen (max 37.27 °C and min 33.42°C) by Adventure System

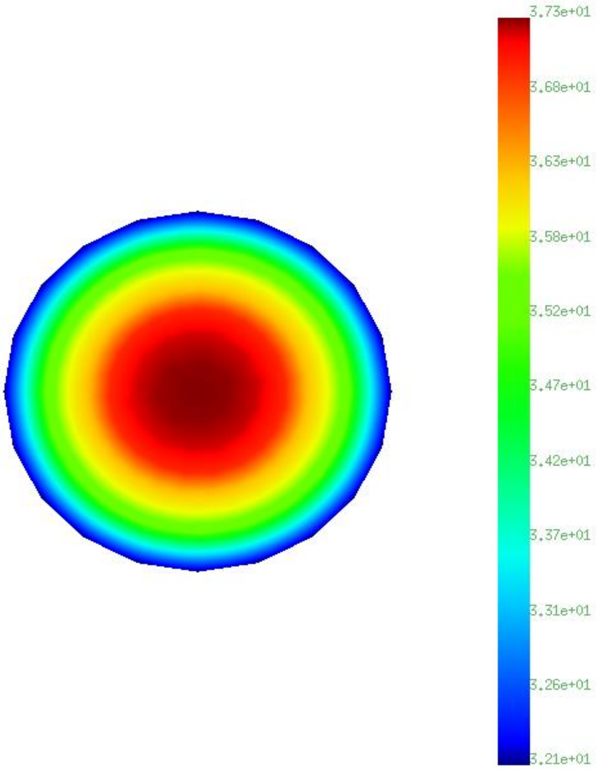

Figure 6. Temperature distribution of obese abdomen (max 37.32°C and min 32°C) by Adventure System

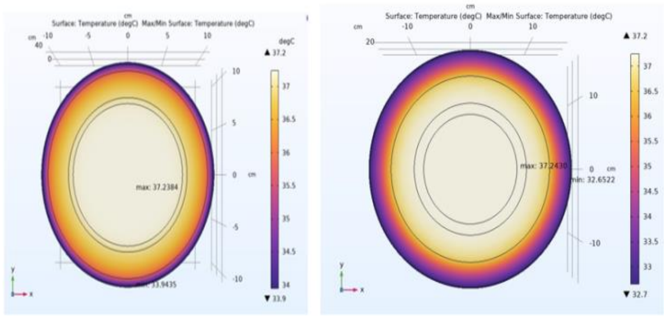

Figure 7. Temperature distribution of slim abdomen (max 37.27°C and min 33.94°C) fatty abdomen (max. 37.24°C and min 32.65°C)- COMSOL result.

4.3. Model Validation

The temperature profile generated by the Adventure Thermal (our developed module) seems to be the same as that that comes from COMSOL. See figure 5 to figure 7. Using the same boundary conditions and physiological properties, the body core temperature and skin temperature

The validation results confirm that the Adventure Thermal module is capable of accurately predicting temperature profiles in both slim and obese abdomens. Its predictions are highly consistent with COMSOL, a widely used commercial software, and closely match the experimental data from Shimano et al. This demonstrates the reliability and effectiveness of the developed module for simulating bio-heat transfer in the human abdomen. The slight differences observed are within acceptable limits, highlighting the robustness of the model for practical applications.

Furthermore, this model has significant potential for future research. It can be utilized to investigate the relationship between temperature variations and fat layer thickness in the human abdomen. By measuring these parameters, the healthcare system can use this non-invasive method to predict the risk factors associated with obesity, such as reduced heat dissipation, thermoregulatory challenges, or metabolic disorders. This capability makes the Adventure Thermal module a valuable tool for improving patient outcomes and advancing personalized medicine in the context of obesity-related health risks.

Table 3 Validation results (slim abdomen)

	Adventure _Thermal	COMSOL	Shimano et al.
Body core temperature	37.3	37.23	37
Skin Temperature	33.4	33.94	33.5

Table 4 Validation results (obese abdomen)

	Adventure _Thermal	COMSOL	Shimano, K et al.
Body core temperature	37.3	37.24	37
Skin Temperature	32.1	32.65	32.5

4.4. Temperature distribution in the radial direction

Heat generated in the body core is transferred to the environment through the skin. The temperature profile through the radial direction is also important. Figures 8 and 9 show the temperature profile for slim and obese abdomen in the radial direction. The figures show a significant change in the visceral and subcutaneous fat region. The temperature gradient is also different.

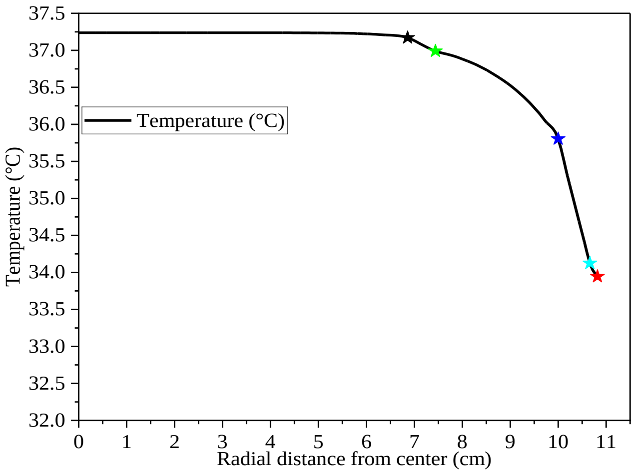

Figure 8. Temperature change in radial direction (slim abdomen)

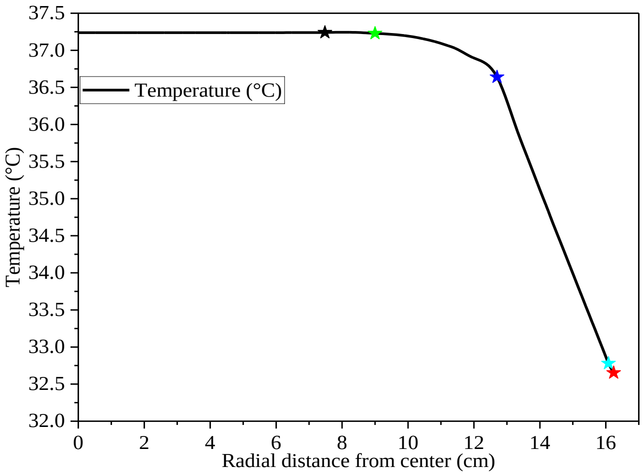

Figure 9. Temperature changes in radial direction (obese abdomen)

The differences in the temperature profiles between the slim and obese abdomen are primarily due to the insulating properties of fat and its impact on heat conduction and blood flow. Obese individuals experience slower heat transfer because of thicker fat layers and reduced perfusion, while slim individuals exhibit more efficient heat dissipation due to thinner fat layers and higher thermal conductivity. These mechanisms highlight the critical role of body composition in thermoregulation and energy balance.

5. Conclusion

A finite element bio-heat transfer model was successfully developed for the human abdomen, incorporating two distinct models: slim and obese. These models were analyzed and compared under similar boundary conditions to investigate temperature distribution. The results were validated against experimental data from Shimano et al. and commercial software (COMSOL Multiphysics), showing strong agreement and confirming the validity of the developed model. The findings revealed that the skin temperature of the obese abdomen is lower than that of the slim abdomen, primarily due to the insulating properties of thicker visceral and subcutaneous fat layers. This difference highlights the impact of fat layer thickness on heat transfer and thermoregulation, demonstrating the model's capability to simulate bio-heat transfer accurately. The validated model provides a reliable tool for future research and practical applications, including non-invasive assessment of obesity-related risk factors.

References

[1] Hamdy O, Porramatikul S, Al-Ozairi E. Metabolic obesity: the paradox between visceral and subcutaneous fat. Curr. Diabetes Rev. vol. 2(4), pp. 367-73, 2006.
[2] Shimano, K. & Shimano, Y. Heat transfer analysis in the human abdomen with a focus upon correlation between the amount of visceral fat and skin temperature. WIT Transactions on Information and Communication Technologies. vol. 45 pp. 197-208, 2013.
[3] Adventure system : https://adventure.sys.t.u-tokyo.ac.jp/
[4] Mukaddes, A M M and Junaid, M. Running water as first aid for burn and early hypothermia: A numerical investigation on human skin, Burns Open, Vol. 8, Issue 2, pp. 105-111, 2024.
[5] https://www.comsol.com/
[6] Pennes, H. H. Analysis of tissue and arterial blood temperature in the resting human forearm. J. Appl. Physiol. vol. 1, pp. 93–122, 1948.
[7] Fiala D, Lomas KJ, Stohrer M. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. J Appl Physiol. Vol. 87(5): pp. 1957-72. 1999.
[8] Chato, J. C. Selected thermophysical properties of biological materials. In: Heat Transfer in Medicine and Biology-Analysis and Application, Newyork:plenum, vol. 2, pp. 413-418, 1985.
[9] Werner J, Buse M. Temperature profiles with respect to inhomogeneity and geometry of the human body. J Appl Physiol (1985). 1988 Sep;65(3):1110-8.

Nomenclature:

ω_b: blood perfusion rate $(1/s)$
ρ_b: density of blood $(\mathrm{kg/m^3})$
ρ: density of the tissue $(\mathrm{kg/m^3})$
T_α: fluid temperature (°C)
h: heat transfer coefficient $(\mathrm{W/m^2}$ °C)
T_b: known blood temperature (°C)
$q_m$metabolic heat generation rate (W/m^3)
C_p: specific heat (J/kg °C)
C_b: specific heat of blood (J/kg °C)
k: thermal conductivity of the tissue (W/m °C)
T: unknown tissue temperature (°C)