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Modeling of Bio-Heat Transfer Trough Human Tissues by Using COMSOL Multiphysics

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ABSTRACT

This paper implements thorough simulations to study human skin bio-heat transfer through two thermal scenarios including skin-to-object contact (Case 1) as well as fluid convection exposure (Case 2). The simulation approach provides thorough bio-heat transfer analysis of human skin through two thermal situations that combine heated object surface contact (Case 1) with free-flowing hot fluid exposure (Case 2). The researchers built a three-dimensional finite element model of human skin using Penne's bio-heat equation implemented in COMSOL Multiphysics® software that simulated the epidermis and dermis with subcutaneous compartment. The simulation examined skin temperature patterns to evaluate burn wounds severity in two simulated conditions: direct surface contact with heat and exposure to free-flowing hot liquid.

When exposed directly to heat the skin temperature increases faster than when exposed to convection resulting in swifter progression toward second and third-degree burn tissue. Convection heat transfer from flowing hot fluid in Case 2 allows skin to release heat which ultimately slows down burn severity. These findings highlight the significant differences in thermal injury mechanisms and suggest that the thermal exposure conditions should be carefully considered in burn treatment and safety designs.

Keywords: Bio-heat transfer, Penne's equation, human skin burn, finite element analysis, thermal injuries.

Introduction

Thermal injuries, particularly burn injuries [1], are one of the most important preventable causes of morbidity and mortality globally. They are commonly due to contact with hot objects, hot liquid, or fire, or when in contact with source of high radiant heat. The extent of burn depends on the temperature of heat and the time of the exposure to the heat source [2]. Studying the process in which heat is transported through biological tissues and how it applies to burn victims is woefully important to enhance the strategies they must treat these patients, product development, and protection of workers.

The heat transport in living tissues is described with bio-heat transfer where Penne's bio-heat equation is used commonly. This equation has been duly incorporated in the study of the warm properties of tissues such as the skin, with respect to the environmental heat load [3]. The skin itself is a complex, layered organ that varies in thickness and thermal properties across its three distinct layers: the outermost layer epidermis, second layer dermis and the third layer subcutaneous tissue.

This study aims to explore the effects of thermal exposure on human skin under two conditions: The first case is when the skin is on direct contact with a heated object, say a hot disk, the second case is when the skin is exposed to convection heat from a freely circulating hot fluid. The first goal is to analyse temperature profiles and burn depth in these two cases employing FEM with COMSOL Multiphysics® software. The findings of the present research may be useful for clinical use and protective actions in connection with burn injuries.

Methodology

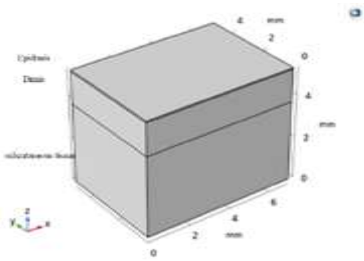
Penne's Bio-Heat Equation

The Penne's bio-heat equation describes heat transfer within biological tissues:

$$\rho c_p \, \partial T/\partial t = \nabla \cdot (k \nabla T) + \rho_b \omega_b c_b (T_b - T) + Q_{met} + Q$$

Skin Model and Simulation Setup

The skin model includes three main tissue layers with respective thicknesses measuring 0.075 mm epidermis and 1.5 mm dermis and 3.75 mm subcutaneous tissue. Operating material properties are determined from experimental data by applying thermal conductivity measurements to density and specific heat data.



Each layer has distinct material properties, including thermal conductivity, specific heat, density and Blood Perfusion Rate. These properties are provided in Table 1.

Skin Layer	**Thermal Conductivity ($\frac{W}{m}K$)**	**Specific Heat ($\frac{W}{Kg}K$)**	**Density ($\frac{Kg}{m^3}$)**	**Blood Perfusion Rate ($\frac{mL}{s}mL$)**
Epidermis	0.21	3598	1200	0
Dermis	0.37	3222	1000	0.00125
Subcutaneous Tissue	0.16	2760	1000	0.00125

Simulation Setup

The simulation is set up using COMSOL Multiphysics, with the following conditions for the two cases:

- **Case 1** (Direct Contact with a Heated Object): In this case the skin is exposed to hot disk of 64 degree Celsius. The boundary condition for the disk is $T = T_d$ where, T_d is the temperature of the disk. Mainly there is conduction, but they have convection heat loss with reference to the surrounding air.
- **Case 2** (Convection from a Hot Fluid): The skin is directly exposed to a free flow of hot water at 64 degrees Celsius. The boundary condition is given by:

$$-k\,\partial T/\partial z = h_w(T_f - T)$$

where h_w is the heat transfer coefficient for the fluid, and T_f is the temperature of the fluid. Heat dissipation occurs through convection from the skin to the fluid.

Henrique's burn integral equation is used to calculate burn severity. The damage index (Ω) is derived as:

$$\Omega = \int_0^t P e^{-\Delta E/RT(t)}\, dt$$

where P is the pre-exponential factor, ΔE is the activation energy, R is the molar gas constant. From Ω value the burns are categorized into first-degree, second-degree, and third-degree burn depending on the damage index.

Results and Discussion

Temperature Distribution

Case 1: The heat transfer rate in epidermis is very high due to direct contact with the hot disk; the surface temperature of skin increases to almost 50°C in few seconds.

Case 2: In the convection case, the fluid carries heat away more effectively resulting in a slower rise of temperature in the skin layers.

Burn Severity

Table 2 presents the time required for each degree of burn at two different skin depths:

Case	**Point 1 (Epidermis)**	**Point 2 (Dermis)**
Case 1	3, 10, 25	6, 15, 25
Case 2	6, 15, 40	10, 25, 75

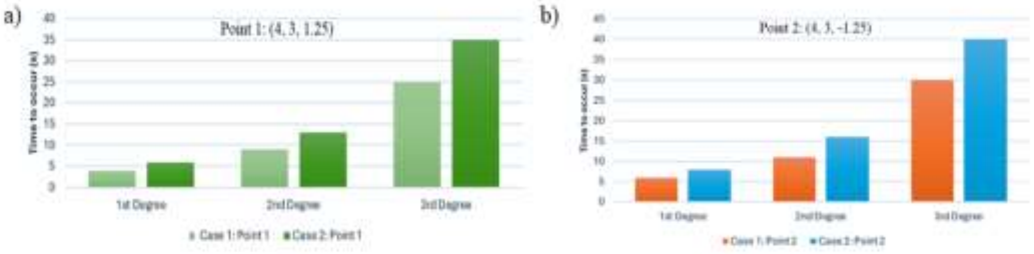


Figure 1 Burn Intensity Analysis (a) Point 1; (b) Point 2

As obtained from the results the skin reaches first-degree burn within 5 sec in Case 1 while in the simulation for Case 2, it takes longer because of convection heat dissipation.

Insights

The analysis confirms our hypothesis that localized heating poses a higher risk to Case 1 and this resulted in severe burns. Convection in Case 2 slows down burn processes, underlining the necessity to develop individual protection strategies depending on thermal risk conditions.

Conclusions

The purpose of this undertaking is to establish how thermal exposure conditions impact on burn depth in human skin. The analysis of simulation data shows that contact with a hot object (Case 1) causes more rapid and deeper burns than hot fluid convection (Case 2), which enables heat to be discharged and burned less actively. The conclusions drawn from these studies can be helpful for the development of new treatments for burns as well as for the enhancement of safety resources. Further research can also comprise radiation effects and the experimental confirmation of the model for the purpose of increasing the precision of burn severity predictions.

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