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A FINITE ELEMENT MODEL OF BURN INJURY AND POST BURN COOLING PROCESS IN HUMAN SKIN

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Abstract- *After burn cooling has been used as first aid treatment throughout the history. Although there exists many experimental study demonstrating the success of such treatment in reducing pain and thermal injury, detail thermal history during heating and after burn cooling enables further understanding the burning severity and cooling efficacy on a heat transfer point of view. For this purpose, this research aims to develop a numerical model of burning and post-burn cooling process. A heating disk at elevated temperature is used to heat the skin which lead to burn. Different cooling methods, generally used as first aid treatment i.e., a natural convection to environment air, cooling at immersed water, force convection due to cold running water, direct contact to ice and cooling due to cryogenic spray is applied after burn. This paper demonstrates the influence of different types of cooling strategies on temperature and burn. Ice cooling was found the most efficient cooling method, followed by force convection-cooling due to cold running water and skin immersed in water bath in terms of reducing temperature and burn . However cryogenic cooling is found as least efficient cooling method compare to others.*

Keywords: Skin Burn, Finite Element Method, Post-burn Cooling, Damage Integral

1. INTRODUCTION

Skin is the largest organ of the body and function as sensory for temperature, touch, pain, protector of the underlying tissues, thermoregulation by heat conduction to environment and sweating and impermeability to both tissue fluid and environmental chemical. One of the most occurred trauma to skin is the skin burn. It was estimated that almost 265000 deaths every year due to burn injury. The frequently encounter reason of burn is fire or explosion among children and elderly. More than three fourth of the death due to burn are accidents happens at home. It is undoubtedly that burn is one of the major injuries to modern society. The main cause of burn is deposition excess thermal energy into biological bodies due to fire, explosion, radiation, electric source, in contact with chemicals, hot objects, and hot fluid. Interaction between the skin and hot object or fluid results in increase of the skin temperature. Thermal burn which occurs due to exposure to flames, contact with hot solid object or warm liquid is the primary concern of this study. Such contact or exposure increases the skin temperature above the damage threshold temperature (42^0C) and starts irreversible damage to the tissues which further lead to burn. Factors like thermal properties of the skin and source object, exposure duration and exposed temperature, heat flux are crucial factors for contributing to burn.

Skin consists of three layers of tissue: the epidermis, the outermost layer of the skin, the dermis is the layer of the skin beneath the epidermis and subcutaneous tissue, not part of the skin, and lies below the dermis that attaches the skin to underlying bone and muscle as well as supplying it with blood vessels and nerves. The general structure of the skin is the same over the entire body, with anatomical and physiological differences in some regions.

Depending upon the intensity burn is classified as minor first degree, superficial second degree, acute third and fourth degree. First-degree burn mainly affects the epidermal layer of the skin, where second-degree burn penetrates towards the dermal layer after affecting the epidermis. Depending upon the penetration second degree burn can further be classified as superficial or deep burn. The third degree or full-thickness burn is much severe, in which the epidermis and the entire dermis layer is affected and burn approaches towards the bones.

As the damage during burn is irreversible, hence it is not possible to lessen the wound has already occurred; however, it is possible to impede for further damage. Subsequent cooling has been used throughout history from ancient Egypt to modern days to reduce further damage and pain. Typical cooling methods are convection cooling with cold fluid [1-3], contact cooling using cooling pad or ice [4-5] and cryogenic spray cooling [5-7]. Several experimental studies have investigated the effect of cooling and found cooling beneficial to relieve pain, decrease mortality, and preventing burn propagation towards deep tissue.

Coldwater, ice, are amongst the most used medium for cooling. Clinical studies found cold water as an effective medium to relieve pain and decrease mortality rate in [8]. Lessening the tissue damage and pain subjected to ice cooling is reported at [9]. Advantages of cryogenic spray cooling method is discussed at [6, 7]

To reduce the severity of the burn and possible damage it is utmost necessary to understand the magnitude of burn and design the post burn treatment activities in the most efficient way. A time-temperature database of the burning tissue is a prerequisite for this. Hence this research develops a mathematical model of human skin subject to heating and subsequent cooling. There are two phases of this study, the heating phase, and the cooling. Heating is considered in contact with a hot disk, whereas in case of cooling different methods is considered, like both convection cooling to ambient air, water bath, force cooling to cold running water, contact cooling by ice, and cryogenic cooling. The efficacy of different cooling methods is evaluated by comparing the inured area under various degrees of burn for different cooling strategies. Result presents in this paper can be helpful for doctors and researchers in determining the appropriate cooling procedure as well as to broaden the scope of skin burn research and cooling applicator design.

2. COMPUTATIONAL MODEL

2.1 Human Skin Model

Human skin is modeled as three distinct regions heaving different materials properties. The regions are the epidermis, the outermost region of the skin, the dermis beneath it and the fat layer. Fig. 1 shows the schematic diagram of skin model where Ω1 (0.008 mm × 7mm) is the epidermis Ω2 (2.08 mm × 7mm) is the dermis and Ω1 (10mm × 7mm) is the fat region [10].

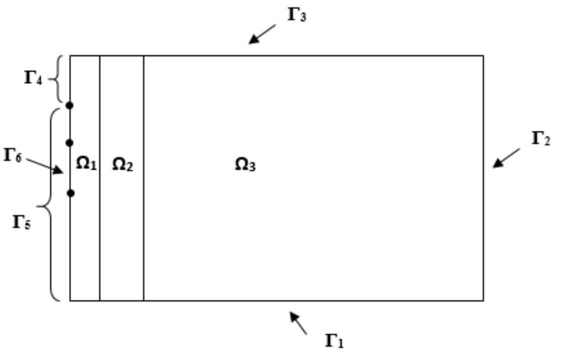

Fig.1: Schematic Diagram of the Computational Model

2.2 Mathematical Model

The transient temperature distribution within the skin is determined by the well-known Pennes Bioheat equation, which is expressed as

$$K_i \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial x^2} + \omega_b \rho_b c_b (T_a - T) + Q_m + Q_r = \rho_i C_i \frac{\partial T}{\partial t} \quad (1)$$

Where ρ, c, K are the density, specific heat, and thermal conductivity of the tissue respectively .c_b, ρ_b denote specific heat and density of blood respectively, ω_b is the blood perfusion, where T_a is arterial temperature, and T(x, t) is unknown skin temperature; Q_m is the metabolic heat generation, and Q_r (x,t) the heat source due to spatial heating with respect to time(t). As metabolic rate in the skin is almost negligible in skin tissue in our study we considered Q_m=0. No external heating is applied in our study, so Q_r (x,t)=0.

And the associate boundary conditions for heating disk and cooling are as following

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = 0$ on Γ_1 and Γ_3

$T = T_c$ on Γ_2

For heating stage $T = T_d$ on Γ_5 and

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_0(T_o - T)$ on Γ_4

For Natural Convection Cooling at ambient air

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_0(T_o - T)$ on Γ_5 and Γ_4

For Force Convection at water bath

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_f(T_f - T)$ on Γ_5 and Γ_4

For Convection Cooling using cold running water

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_f(T_f - T)$ on Γ_5 and

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_0(T_o - T)$ on Γ_4

For ICE Cooling $T = T_{ice}$ on Γ_5 and

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_0(T_o - T)$ on Γ_4

For Cryogenic Cooling

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_c(T_c - T)$ on Γ_6 and

$k\frac{\partial T}{\partial x}\eta_x + \frac{\partial T}{\partial y}\eta_y = -h_0(T_o - T)$ on Γ_4

Here T_c is the body core temperature, where T_d is the heating disk temperature, h_0 is the ambient heat transfer coefficient and T_o is the environmental temperature. h_f is the forced convection coefficient between water and skin, h_c is the convection coefficient between the freezing agent and skin, T_f temperature of water, T_c temperature of the freezing agent. Moreover, length of Γ_4 is 1.5mm, and Γ_6 is 8mm, where's Γ_6 lies at the center of the domain.

2.3 Finite Element Discretization

Using the Weighted Residual Method, the weak form of Eq. (1) is derived as

$$0 = \int_A [W\rho C \frac{\partial T}{\partial t} + K \frac{\partial W}{\partial x}\frac{\partial T}{\partial x} + CWT - Wq] - W\oint_\Gamma [k\frac{\partial T}{\partial x}\eta_x + k\frac{\partial T}{\partial y}\eta_y]ds \quad (2)$$

Where $C = \omega_b \rho_b c_b$ and $f = CT_a$, W is the weighted function and q is the secondary variable. For convective boundary as $k\frac{\partial T}{\partial x}\eta_x + k\frac{\partial T}{\partial y}\eta_y = -h(T - T_0)$, the boundary integral modified as following to account for the convective heat transfer term. Here, h is the convective heat transfer coefficient, T_∞ is the ambient temperature.

$$0 = \int_\Omega [w\rho c \frac{\partial T}{\partial t} + k\frac{\partial w}{\partial x}\frac{\partial T}{\partial x} + k\frac{\partial w}{\partial y}\frac{\partial T}{\partial y} + CwT - wf]dxdy - w\oint_\Gamma [-h(T - T_o)]ds \quad (3)$$

Using a quadratic approximation function as $T_h^e(x) = \sum_{j=1}^{e} \varphi_j^e(x)\, T_j^e$. The finite element model of the governing differential equation is thus derived as

$$0 = \sum_{j=1}^{n} \left\{ \int_\Omega \rho c \psi_i^e \psi_j^e \frac{\partial T_j^e}{\partial t} dxdy + \int_\Omega \left[\left\{ k \frac{\partial \psi_i^e}{\partial x} \frac{\partial \psi_j^e}{\partial x} + k \frac{\partial \psi_i^e}{\partial y} \frac{\partial \psi_j^e}{\partial y} + C \psi_i^e \psi_j^e \right\} dxdy + \oint_\Gamma h \psi_i^e \psi_j^e ds \right] T_j^e - \int_\Omega f \psi_i^e dxdy - \oint_\Gamma \psi_i^e h T_o ds \right\} \quad (4)$$

The simplified form of Eq. (4) is written as

$$0 = \sum_{j=1}^{n} \{ C_{ij}^e \dot{T}_{ij}^e + [K_{ij}^e + H_{ij}^e] T_{ij}^e - q_j^e - Q_j^e \} \quad (5)$$

Here, $C_{ij}^e = \int_\Omega \rho c \psi_i^e \psi_j^e$; $K_{ij}^e = \int_\Omega K \frac{\partial \psi_i^e}{\partial x} \frac{\partial \psi_j^e}{\partial x} + K \frac{\partial \psi_i^e}{\partial y} \frac{\partial \psi_j^e}{\partial y} + C \psi_i^e \psi_j^e$; $H_{ij}^e = h \oint_\Gamma \psi_i^e \psi_j^e$; $q_i^e = f \int_\Omega \psi_i^e dA$; $Q_i^e = \oint_\Gamma h_0 T_0 \psi_i^e ds$

In matrix notation Eq. (5) can be expressed as

$$[C]\{\dot{T}\} + [K]\{T\} = \{q\} + \{Q\} \quad (6)$$

Where C is the capacitance matrix, K is the heat conductive matrix, and T is unknown temperature, and others are known vectors.

2.4 Time Discretization

A simple time integration scheme for Eq. 6 was derived. In that case, the matrix differential equation can be discretized on time as:

$$C \frac{T^{n+1} - T^n}{\Delta t} + \alpha K T^{n+1} + (1-\alpha) K T^n = Q + q \quad (7)$$

Where T^{n+1} and T^n are the vectors of unknown nodal values at times $n\Delta t$ and $(n+1)\Delta t$ respectively, α is the weighting factor which must be chosen in the interval between 0 and 1. The standard approximation for time derivative was used as $\dot{T} = \frac{T^{n+1} - T^n}{\Delta t}$

When the value of α is considered 0.5, the process is called the popular Crank-Nicolson method. The discretized Eq.7 can be written as:

$$\left(C \frac{1}{\Delta T} + \alpha K \right) T^{n+1} = \left[C \frac{1}{\Delta T} - (1-\alpha) K \right] T^n + q + Q \quad (8)$$

At first, Eq. 8 was solved using an iterative procedure. The initial temperature is known and then the temperature of the next step can be calculated from the solution of Eq. 8.

2.5 Burn Quantification

Several models are developed by the researchers in the literature to quantify thermal burn. Henriques model is one of them. He insisted that Arrhenius rate equation can be used for the rate of tissue damage [11]. His developed equation for burn quantification is known as Henriques burn integral is used to quantify burn in this study. The equation can be expressed as

$$\varphi = \int_0^t P \exp\left(-\frac{\Delta E}{RT}\right) dt \quad (9)$$

Where φ is the damage index, P is the pre-exponential factor, ΔE is the activation energy, R is the molar gas constant, and T is the skin temperature (K). The damage index φ is the measure injury. A value of 0.53 of the damage index corresponds to first degree burn, similarly for second-degree burn φ = 1 and for third-degree burn $\varphi = 10^4$.

3. NUMERICAL RESULT AND DISCUSSION

The numerical solution has two-stage one is the heating stage from t=0s to t=15s, when the skin is heated with a heating disk and cooling starts afterward. The different cooling methods used in this study are as follow

Case 1. Natural convection to ambient air
Case 2. Convection Cooling by Water
 Case 2.2 Skin Immersed in Water Bath
 Case 2.3 Cooling by cold running water
Case 3. Contact Cooling by Ice
Case 4: Cooling by Cryogenic Spray

The thermal properties and other control values used in this research is presented in Table 1 [1, 2, 10, 12]

Table 1: Tissue Properties and Parameters Value

Parameter	Value
Thermal conductivity(K):	
Epidermis	0.255 W/m^2
Dermis	0.523 W/m^2
Sub-Cutaneous tissue	0.167 W/m^2
Blood Perfusion (ω_b):	
Epidermis	0 ml/s/ml
Dermis	0.00125 ml/s/ml
Sub-Cutaneous tissue	0.00125 ml/s/ml
Density (ρ)	
Epidermis	1200 kg/m^3
Dermis	1200 kg/m^3
Sub-Cutaneous tissue	1000 kg/m^3
Specific heat (C)	
Epidermis	3598 Jkg^{-1} ^{0}C^{-1}
Dermis	3222 Jkg^{-1} ^{0}C^{-1}
Sub-Cutaneous tissue	2760 Jkg^{-1} ^{0}C^{-1}
Density of Blood (ρ_b)	1100 kg/m^3
Specific heat of blood (C_b)	3300 Jkg$^{-1 0}$C^{-1}
Temperature of artery (T_a)	37 °C
Heat convection coefficient	
Convection to air (h_a)	7 W/m^2 °C
Water Bath (h_f)	500 W/m^2 °C
Running Water (h_f)	1000 W/m^2 °C
Cryogenic Cooling (h_c)	2200 W/m^2 °C
Temperature	
Ambient Air (T_a)	25 °C
ICE (T_{ice})	15 °C
Freezing Element (T_c)	-6 °C
Water	10 °C
Pre Exponential Factor	7.39×10^{39} 1/s
Activation Energy	2.577×10^5 Jkg^{-1}k^{-1}
Molar Gas Constant	8.316 Jkg^{-1}mol^{-1}

3.1 Skin Heating

Skin temperature after heating 15s with a heating disk is showing in Fig. 2. A maximum temperature of 90^0C is showing at the skin surface in contact with the heating disk. While rest of the skin surface areas are indicating a low temperature. That happens as heat exchange to ambient air. Here maximum temperature region exists at the epidermis area followed by the dermis. However, the fat seems less affected by the heating compare to other layers.

Fig. 3 shows the damage profile after 15s heating. The iso lines represent the damage index **φ**. The three-level 0.53, 1 and 10000, are chosen to represent the first, second and third-degree burn contour, respectively. From Fig. 3 up to 15s, there is not third-degree burn. Where the first-degree burns after affecting the epidermis progressed towards the dermis and even affected the fat region. Following the first degree burn the second degree burn also reached the fat tissues. However, the skin surface area in contact with environmental air is less affected.

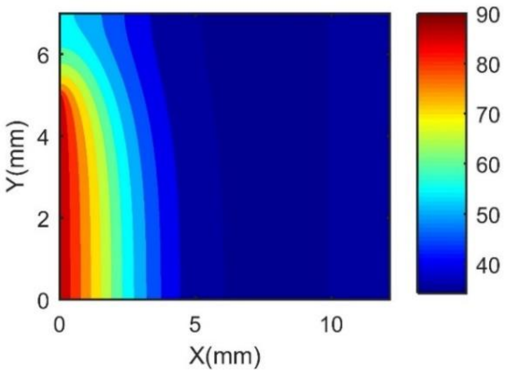

Fig 2. Tissue Temperature after heating

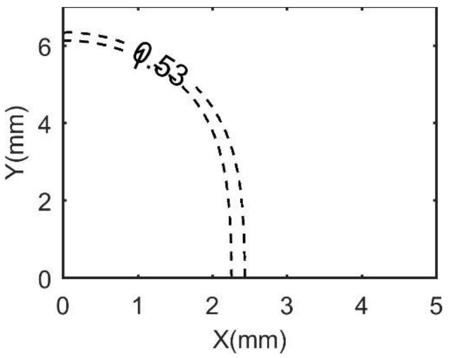

Fig. 3: Injury Profile after heating

3.2 Skin Cooling

Tissue temperature response subject to different cooling strategy is showing in Fig. 4 to Fig. 8. Here Fig. 4 shows the skin temperature subject natural convection cooling at ambient air, Fig. 5 shows result for cooling by skin immersed in water bath. Fig. 6, Fig. 7 and Fig. 8 show the result for cooling by cold running water, direct contact with ice, and cryogenic spray, respectively. For all the cases the skin is cooled for a period of 35s. For natural convection cooling as shown in Fig. 4 a maximum temperature of 55^0C is recorded at the skin surface. This value is higher than the damage threshold temperature (42^0C). Hence further damage continued after applying ambient air cooling. However, for skin immersed in water cooling, the maximum tissue temperature after 35s is almost 45^0C, and for water jet cooling it is 40^0C. So in force water cooling temperature of the skin tissue reduces enough to reach below the damage threshold temperature. However, in case of skin immersed in water cooling, the maximum temperature is slightly over the threshold value which indicates further damage at a negligible rate still inured there. Both Fig. 5 and Fig. 6 shows lower temperature at the skin surface areas which are exposed to convection cooling. So skin surface area is most sensitive to cooling compare to others.

Fig.6 indicates that due to ice cooling, the temperature of the epidermis drops rapidly and reaches to ice temperature at boundaries in contact with ice. A higher temperature is shown in the dermis region. So dermis layer is less affected due to cooling compared to the epidermis. However, from this figure it is apparent that fats temperature is least influenced by cooling.

In the case of cryogenic spray cooling, there is an extreme low-temperature region at the spot of the spray, which is below 0^0C after 50s, much lower than the body core temperature. Nevertheless, the extreme low temperature at the spray spot area, the epidermis, and dermis still undergo temperature higher than the damage threshold temperature as shown in Fig.8. Here the maximum temperature at the epidermis and dermis is almost 45^0C, which reveals that still damage continues there. On the other hand, the spray spot temperature reduced extremely which further could result in hypothermia or tissue freezing. Similar to that prolonged exposure to ice cooling may result in such effect. It to be noted that for all the cooling techniques almost 35^0C is recorded at the fat region which is very close to the body core temperature. Hence fat tissues are more affected by the body core temperature rather than cooling.

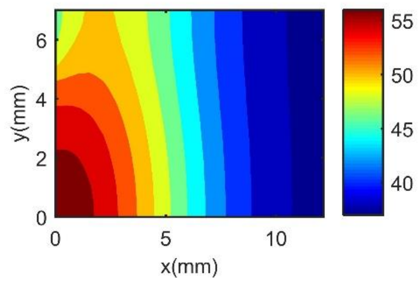

Fig. 4: Tissue temperature response to natural convection cooling at ambient air

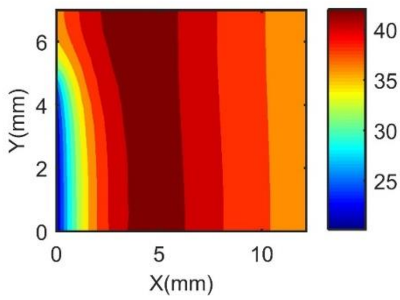

Fig. 5: Tissue temperature response to skin immersed at water bath cooling

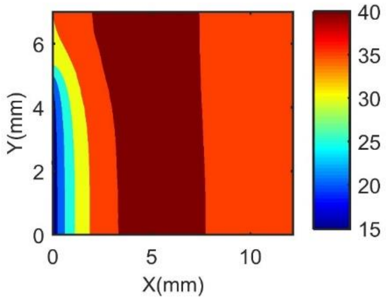

Fig. 6: Tissue temperature response to cold running water cooling

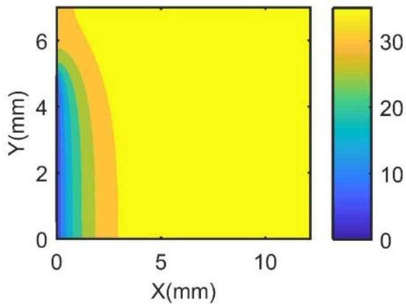

Fig. 7: Tissue temperature response to ICE cooling

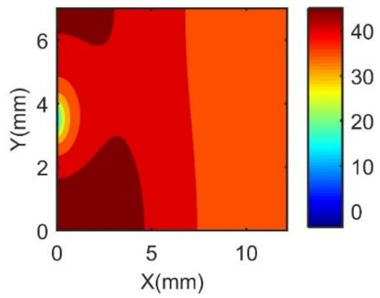

Fig. 8: Tissue temperature response to cryogenic cooling

3.3 Cooling Efficacy

The relative reduction of area affected by damage threshold temperature or burn with respect to ambient air is considered to calculate the cooling efficacy. So the expression for cooling efficacy is as follows

$$\epsilon(\%) = \frac{\Omega - \Omega_{\text{amb}}}{\Omega_{\text{amb}}} \times 100\%$$

Here Ω is the area affected by damage threshold or burn due to different cooling method where Ω_{amb} is the same for ambient air cooling.

Fig. 10 shows the cooling efficacy for damage threshold value point of view, where Fig. 11 and Fig. 12 shows the cooling efficacy on the first -degree and second-degree burn point of view. From damage threshold view a cooling efficacy 100% is showing after almost 32s for ICE cooling, 38s and 42s for cold running water cooling and bath cooling respectively. Where after 65s cryogenic cooling reaches approximately 52% efficiency.

For first-degree burn point of view, ice cooling shows maximum level of efficiency 45% after 65s. Where for cold running water, water bath and cryogenic cooling the maximum efficiency after 65s is almost 35%, 28%, and 24%. And for second-degree burn point of view the maximum efficiency level is almost 42% for ice cooling method followed by almost 25% by cold running water cooling, 24% by cryogenic cooling and 22% for water bath cooling after 65s.

So from damage threshold and burn point of view, the most efficient method considering the current setup is ice cooling. Both convection cooling by cold running water and water bath shows almost similar level of efficiency, although cold running water cooling is superior to water bath in terms of efficacy. Where cryogenic cooling method shows the lowest level of efficiency compared to other cooling techniques. It to be noted that cryogenic spray exposed to only 8mm area of the skin surface which is the lowest compared to other cooling methods, increasing the exposed area may increase its efficiency.

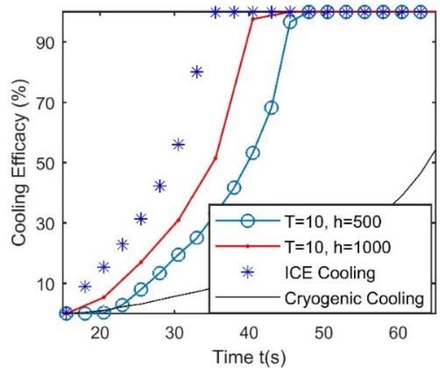

Fig. 9: Cooling Efficacy on Damage Threshold Temperature Point of View

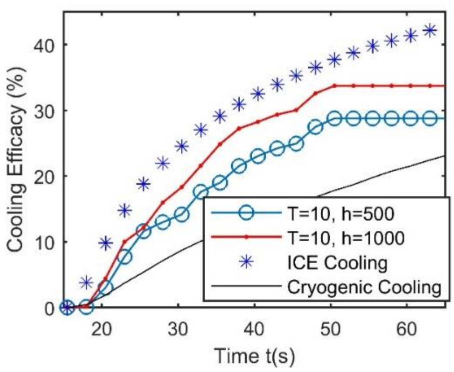

Fig. 10: Cooling Efficacy on First Degree Burn Point of View

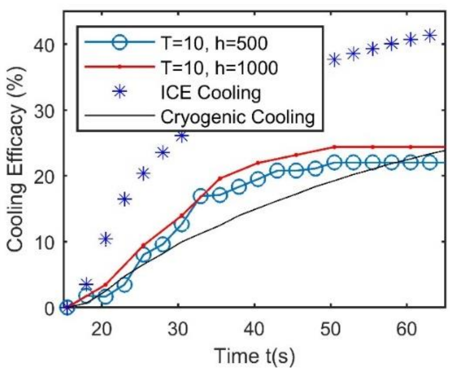

Fig. 11: Cooling Efficacy on Second Burn Degree Point of View

4. CONCLUSION

This study represents a Finite Element Model of human skin subject to alternative heating and cooling technique. Skin is heated with a heating disk in the heating stage and the cooling is applied on the heated skin afterwards. The effect of various cooling method i.e. natural convection cooling to ambient air, cooling by immersing skin in water bath and force cooling by cold running water, contact cooling to ice and cryogenic cooling, on the temperature and burn is analyzed briefly. Cooling efficacy for different cooling techniques is evaluated in comparison to natural convection cooling to air on a temperature and damage point of view. It was found that cooling by direct contact with ice shows the highest efficiency followed by forced convection cooling using cool water jet and cooling by water bath. However, cryogenic cooling shows the minimum level of efficiency compares to others strategies. In addition, in both ice cooling and cryogenic spray cooling temperature of the skin tissues drops extremely which the possibility of detrimental effect due to hypothermia or tissue freezing. Regardless the different strategies of cooling and heating, the epidermis seems most sensitive followed by dermis, whereas the fat layer shows least sensitivity for both heating and cooling. The result describe in this paper could be useful for determining the level of burn injury and designing proper treatment procedure to reduce further damage. Moreover, the developed mathematical model and computer program can be used or further extend to simulate and implement more sophisticated burning and post burn cooling procedure.

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6. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(^{0}C)
h	Heat Transfer	W/(m^2. ^{0}C)
K	Coefficient	W/(m^2. ^{0}C)
C	Thermal Conductivity	Jkg^{-1} ^{0}C^{-1}
P	Specific Heat	Kg/m^3
ω_b	Density	1/s
P	Blood Perfusion Rate	1/s
t	Pre Exponential Factor	s
ΔE	Time	Jkg^{-1}k^{-1}
R	Activation Energy	JKmol^{-1}K^{-1}
Q_m	Molar Gas Constant	W/m^3
Q_r	Metabolic Heat	W/m^3
	External Heat	
ϵ	Cooling Efficacy	Dimentio-nless
φ	Damage Index	Dimentio-nless