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Study of Temperature Variation in Human Peripheral Region During Wound Healing Process due to Plastic Surgery

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Abstract

In this paper, investigations are made to analyze the human body temperature during wound healing process due to surgery. Wound is considered after the skin graft. Skin graft is a technique used in plastic surgery. Skin is the first line of defense between the human and environment, it is very susceptible to damage. Internal body or core temperature (T_b) is one of the clinical vital signs along with pulse and respiratory rates. Any disturbance in body temperature will drive complexities in wound healing process. These studies are important in the mechanism of establishing the limits of thermal regulation of human body during the healing process in different situations and conditions. The Finite element method is used to analyze tissues temperature for normal tissues (donor site) and abnormal tissues (tissues after surgery). Appropriate boundary conditions have been framed. Numerical results are obtained using Crank Nicolson Method.

Mathematics Subject Classification: 65M50, 65M60, 80A20, 92B05

Keywords: Wound healing, Finite element method, Crank Nicolson method. Surgery

Introduction

A wound is a physical injury to the body consisting breaking of the skin or mucous membrane, or an opening made in the skin or a membrane of the body incidental to a surgical operation or procedure[4]. The healing of wounds caused by accident, assault and surgical operations has always been a central consideration in surgical practice because any breach in continuity of skin or mucous membrane exposes the deeper tissues to the danger of infections. Wound healing involves a complex series of interactions between different cell types, cytokine mediators, and the extracellular matrix. The phases of normal wound healing include hemostasis, inflammation, proliferation, and remodeling. Each phase of wound healing is distinct, although the wound healing process is continuous, with each phase overlapping the next. Successful wound healing requires adequate blood and nutrients to be supplied to the site of damage, the overall health and nutritional status of the patient influences the outcome of the damaged tissue[2].

Role of enzymes cannot be neglected if wound is considered because the miracle of life would be impossible without enzymes. Enzymes are protein chemicals, which carry a vital energy factor needed for every chemical action, and reaction that occurs in our body. The health of our organs and glands is completely dependent upon our enzyme making abilities. Functioning of enzymes properly depends upon two major factors i.e pH value and temperature. Enzymes work properly in between 20-37^{o}C body temperature[1].

The equation (1.1) has been used by Perl [22] to solve a simple case of equation (1.1) for a spherical symmetric heat source embedded in an infinite tissue medium assuming above parameters as constant. Cooper and Trezek [17,18] found an analytic solution of heat diffusion equation for brain tissue with negligible effect of blood flow and metabolic heat generation. Saxena and Bindra[19] studied temperature variation assuming the mass blood flow rate and thermal conductivity as position dependent. Saxena and Bindra[20] used quadratic shape functions in variational finite element method to solve a one dimensional steady state problem. Besides this some attempts have been made to study temperature distribution in skin and subcutaneous tissues involving abnormalities like tumors. Saxena and Pardasani [13,14,15] have used finite element method to study temperature distribution in skin and subcutaneous tissues involving uniformly and non uniformly perfused tumors. A two dimensional infinite element model [12] and finite element model [11] have been developed by Pardasani and Shakya to observe steady state temperature distribution for tumor region of human body.

Very few attempts have been made to study temperature variation due to surgery. Adoms [5-8] made an attempt to find healing time using growth factor for Critical size defect for different shapes of wound. Some other models have been

developed incorporating physiological parameters like mitosis, cell proliferation, cell death, capillary density, oxygen supply [9,10,16]. Results were obtained numerically for local hyperthermia treatment conditions using a function of temperature and the dimensionless "physiological" time[24] for the blood perfusion variation.

Very few scientists have studied temperature variations caused due healing process after the skin grafting. So far only a few mathematical models have been developed for unsteady case in this regard [21]. We have developed a one dimensional finite element model using quadratic interpolation to move towards more realistic situation.

Mathematical Formulation

The heat transport mechanism occuring in the living tissues have been formulated which was based solely upon purely physical and chemical laws like Fick's perfusion principle for convective heat and mass transfer in infinite tissues volume derived by Perl [21] is

$$\left(\frac{\partial}{\partial x}\right)\left(K\frac{\partial T}{\partial x}\right)+M\left(T_b-T\right)+S=\rho c\frac{\partial T}{\partial t} \qquad 1.1$$

$$where\ M=m_b c_b$$

Here S, K, ρ, c, m_b, c_b, T and T_b are effect of metabolic heat generation, thermal conductivity, tissue density, specific heat of tissue, blood mass flow rate, specific heat of blood, unknown nodal temperature and temperature of blood respectively.

It is assumed, initially the outer surface of the skin to be insulated at time *t=0* and hence the initial condition is given by [12]

$$T(x,0)=T_b \qquad 1.2$$

The body core temperature (the inner most layer) always remains same with respect to time i.e.

$$T=T_b \quad for \quad t\geq 0 \qquad 1.3$$

The outer surface of the body is exposed to the environment and heat loss at this surface takes place due to conduction, convection, radiation and evaporation. Thus the boundary conditions is [12]

$$-K\frac{\partial T}{\partial n}=h(T-T_a)+LE \quad for \quad t>0 \qquad 1.4$$

Where h, T_a, L, E and $\partial T/\partial n$ are heat transfer coefficient, atmospheric temperature, the latent heat, rate of evaporation and the partial derivatives of T along the normal to the skin surface respectively.

The skin and subdermal tissues (SST) region has different values of physiological parameters like thermal conductivity (K), blood mass flow rate (M) and rate of metabolism (S). The skin consists of two layers i.e. epidermis and dermis. In epidermis layer, no blood cells are found so the values of M, S are assumed to be zero and K has constant value for this layer only. As we go towards the sub-dermis layer, these values are variable in dermis and almost constant in sub-dermis. But in the case of abnormality like healing process due to surgery these parameters are increasing function of time. In this model we have assumed that

For normal case (Tissues of donor site)

$$K^e(x) = \sum_{r=0}^{1} \alpha_r{}^e x^r,\ M^e(x) = \sum_{r=0}^{1} \beta_r{}^e\ x^r, S^e(x) = \sum_{r=0}^{1} \gamma_r{}^e x^r$$

For abnormal case (Tissues after surgery)

$$K^e(x,t) = \xi(t) \sum_{r=0}^{1} \alpha_r{}^e x^r,\ M^e(x,t) = \psi(t) \sum_{r=0}^{1} \beta_r{}^e\ x^r, S^e(x,t) = \zeta(t) \sum_{r=0}^{1} \gamma_r{}^e x^r$$

Where

$$\xi(t) = \left(\nu_0{}^e + \nu_1{}^e e^{-\nu t}\right),\ \ \psi(t) = \left(\eta_0{}^e + \eta_1{}^e e^{-\eta t}\right),\ \ \zeta(t) = \left(\theta_0{}^e + \theta_1{}^e e^{-\theta t}\right)$$

$\nu_0, \nu_1, \eta_0, \eta_1, \theta_0, \theta_1$ are unknown constants

Use of Finite Element Method for quadratic element

In present study the whole SST region is discretized using the quadratic interpolation model instead of taking linear interpolation model. A quadratic interpolation model can give more accurate results than that of the linear models. In quadratic model, it is assumed that every element has three nodes rather than having two nodes like linear model. A one dimensional element can be expressed using quadratic interpolation model as

$$\mathrm{T}^e(x,t) = \varepsilon_1 + \varepsilon_2 x + \varepsilon_3 x^2 = [N(x)]\overline{T}^e$$

Where

$$[N(x)] = \begin{bmatrix} N_i(x) & N_j(x) & N_k(x) \end{bmatrix},\quad \overline{T}^e = \begin{bmatrix} T_i & T_j & T_k \end{bmatrix}'$$

i, j and k denote the local node numbers corresponding to global nodes 1(end left), 2 (middle) and 3 (right end), respectively.

$$N_i(x)=\left(1-\frac{2x}{l^{(e)}}\right)\left(1-\frac{x}{l^{(e)}}\right),\quad N_j(x)=\frac{4x}{l^{(e)}}\left(1-\frac{x}{l^{(e)}}\right), N_k(x)=-\frac{x}{l^{(e)}}\left(1-\frac{2x}{l^{(e)}}\right)$$

Where $l^{(e)}=(x_k-x_i)$

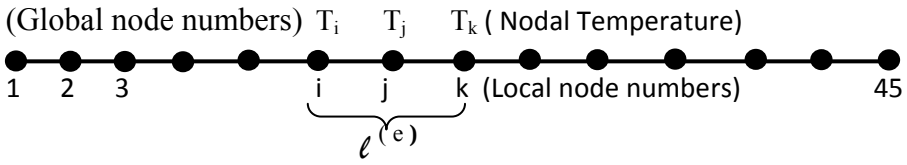

Fig. 1: A quadratic element model

The variational form of the eqn. (1.1) for the e[th] element is given by

$$I^e=\frac{1}{2}\int_{x_i}^{x_k}\left[K^e\left(\frac{\partial T^e}{\partial x}\right)^2+M^e(T_b-T^e)^2-2S^eT^e+\rho c\ \frac{\partial (T^e)^2}{\partial t}\right]dx \qquad 1.5$$
$$+\frac{1}{2}\left[h(T^e-T_a)^2+2LET^e\right]$$

Here second term of the eq. (1.5) is valid for the elements adjoining the outermost surface of the skin and taken equal to zero for remaining elements.

After differentiating (1.5) with respect to each nodal temperature, the matrix form can be expressed as

$$\frac{dI^e}{d\overline{T}^e}=\left[A_1^e\right]\left[\overline{T}^e\right]+\left[A_2^e\right]\left[\overline{T}^e\right]-\left[A_3^e\right]+[A_4^e]\left\{\frac{\partial \overline{T}^e}{\partial t}\right\}+[A_5^e]\left[\overline{T}^e\right]+[A_6^e] \qquad 1.6$$

Where

$$\left.\begin{aligned}&\left[A_1^e\right]=\int_e K^e[B^e]'[D_1^e][B^e]dx,\ \left[A_2^e\right]=\int_e M^e[N^e]'[N^e]dx\\&\left[A_3^e\right]=\int_e (M^eT_b+S^e)[N^e]'dx,\ \left[A_4^e\right]=\int_e \rho c[N^e]'[N^e]dx\\&[A_5^e]=h[N^e]'[N^e],\ [A_6^e]=(LE-hT_a][N^e]'\end{aligned}\right\}$$

Here in (1.6) the matrices $\left[A_1^{(e)}\right]_{3x3}, \left[A_2^e\right]_{3x3}, \left[A_3^e\right]_{3x1}$ *and* $\left[A_4^e\right]_{3x3}$ are functions of three nodal temperature T_i^e, T_j^e and T_k^e while $[A_5^e]_{3x3}$ *and* $[A_6^e]_{3x1}$ are function of T_k^e only.

Assembly of Elements:

In the present study a one dimensional finite element method is used to find nodal temperatures variation in heat flow during wound healing process due to surgery. Here we assumed that the SST region of human body is divided into 22 layers having total thickness of 1.1 cm. The sub-dermis, dermis and epidermis layers consist of 10, 8 and 4 layers respectively. These layers are assumed as quadratic elements having 45 nodes. Each element is assumed to have thickness of 0.05 cm. and 3 nodes.

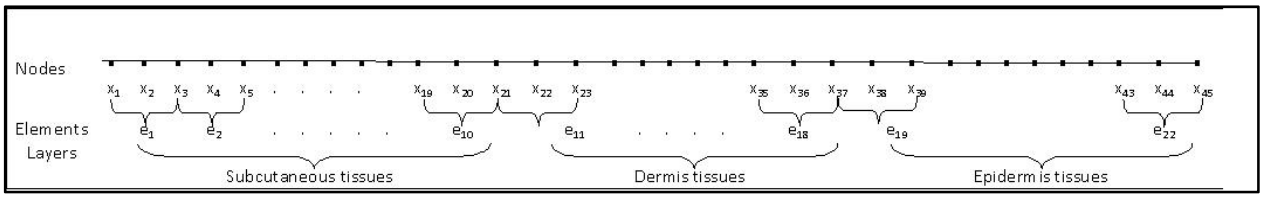

Table1: Systematic classification of elements and nodal distribution

As per the assumption, the integral I^e is evaluated and assembled as

$$I = \sum_{e=1}^{Nd} I^e \quad \text{Nd=22 } (elements) \tag{1.7}$$

Using (1.7), we get $$\frac{dI}{d\overline{T}^e} = \sum_{e=1}^{Nd} \frac{dI^e}{d\overline{T}^e} \tag{1.8}$$

Where

$$\frac{dI}{d\overline{T}^e} = \left[\frac{\partial I}{\partial T_i} \quad \frac{\partial I}{\partial T_j} \quad \frac{\partial I}{\partial T_k}\right]', \quad \overline{T}^{(e)} = \left[T_i \quad T_j \quad T_k\right]'$$

n=Total no. of nodes

Where $\overline{T}^e$ is matrix representing the nodal temperature associated with the element (e).

Here $$\frac{dI}{d\overline{T}} = \sum_{e=1}^{Nd} D^e \frac{dI^e}{d\overline{T}^e} \tag{1.9}$$

Where

$$D^{e'} = \begin{bmatrix} 0 & 0 & 0 & . & 1 & 0 & 0 & . & . & . \\ 0 & 0 & 0 & . & 0 & 1 & 0 & . & . & . \\ 0 & 0 & 0 & . & 0 & 0 & 1 & . & . & . \end{bmatrix}_{(3\times 45)} \begin{matrix} i^{th}\ row \\ j^{th}\ row \\ k^{th} row \end{matrix}$$

$$\frac{dI}{d\overline{T}} = \left[\frac{\partial I}{\partial T_1} \quad \frac{\partial I}{\partial T_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad \frac{\partial I}{\partial T_n} \right]', \overline{T} = \left[T_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad T_n \right]'$$

n=Total no. of nodes

To minimize eq. (1.9), we ge $\quad \frac{dI}{d\overline{T}} = 0 \qquad 1.10$

Numerical Results and Discussions:

Using (eq. (1.7)-(1.10) a system of simultaneous differential equation is obtained as follows

$$[P]_{45x45}\left[\frac{d\overline{T}}{dt}\right]_{45x1} + [Q]_{45x45}\left[\overline{T}\right]_{45x1} = [R]_{45x1} \qquad 1.11$$

Where

$$P = \left[D^e\right]\left[A_4^e\right]\left[D^e\right]',\ Q = \left[D^e\right]\left[A_1^e + A_2^e + A_5^e\right]\left[D^e\right]',\ R = D^e\left[A_3^e - A_6^e\right]$$

A computer program using MATLAB is developed. A Crank Nicolson Technique has been employed to solve the set of differential equations (1.11) to obtain nodal temperatures which give temperature profile for each node.

The values for physical and physiological parameters [21] are taken as follows:

K_1=0.060 (cal/ cm min ^oC), K_2=0.045 (cal/ cm min ^oC), K_3=0.030 (cal/ cm min ^oC), h=0.009 (cal/ cm^2min ^oC),c=0.830 (cal/ gm ^oC), ρ =1.090 (gm/cm^3), L= 579.0 (cal/gm).T_b=37 ^oC

The numerical calculations have been made for three cases of atmospheric temperatures.

1. T_a= 15^{o}C, M=0.003 cal/ cm^3min. ^{o}C, S=0.0357 cal/ cm^3min,E=0 gm/ cm^2min.
2. T_a = 23 ^{o}C, M=0.018 cal/ cm^3min. ^{o}C, S=0.018 cal/ cm^3min,E=0, 0.24x10^{-3} and 0.48x10^{-3}gm/ cm^2min.

3. T_a = 33 ^oC, M=0.0315 cal/ cm^3min. ^oC, S=0.018 cal/ cm^3min,E= 0.24x1010^{-3} and 0.48x10^{-3} gm/ cm^2min

The following values have been assigned to physical and physiological parameters

i. For sub-dermis region:

$$\alpha_o^e = K_1, \alpha_1^e = 0, \beta_0^e = M^e, \beta_1^e = 0, \gamma_0^e = S^e, \gamma_1^e = 0,$$

ii. For dermal region:

$$\alpha_o^e = \left(\frac{K_1 x_{37} - K_3 x_{21}}{(x_{37} - x_{21})}\right), \alpha_1^e = \left(\frac{K_3 - K_1}{(x_{37} - x_{21})}\right), \beta_0^e = \left(\frac{M_1 x_{37} - M_3 x_{21}}{(x_{37} - x_{21})}\right), \beta_1^e = \left(\frac{M_3 - M_1}{(x_{37} - x_{21})}\right),$$

$$\gamma_0^e = \left(\frac{S_1 x_{37} - S_3 x_{21}}{(x_{37} - x_{21})}\right), \gamma_1^e = \left(\frac{S_3 - S_1}{(x_{37} - x_{21})}\right), M_3 = S_3 = 0; M_1 = M, S_1 = S$$

iii For epidermis region :

$$\alpha_o^e = K_3, \alpha_1^e = 0, \beta_0^e = 0, \beta_1^e = 0, \gamma_0^e = 0, \gamma_1^e = 0,$$

Here for the sake of clarity, the graphs have been plotted between the nodal tissue temperature profile body core tissues at T_1, nodal temperature of subcutaneous tissues at T_{17}, dermal tissues at T_{33}, epidermal tissues at T_{45} and time (t) for both the cases (normal and abnormal).

The basic physiological functioning of normal and abnormal tissues (operated tissues) during healing process is different from each other. As we assumed that values of physiological parameters of abnormal tissues are increasing function of time so these will take some time to have values like normal tissues. The values of $\xi, \psi \text{ and } \zeta$ are assumed for abnormal tissues as

$$\xi(0) = 1/2, \quad \xi(\infty) = 1; \psi(0) = 0, \quad \psi(\infty) = 1; \zeta(0) = 1/20, \zeta(\infty) = 1$$

In the present paper, we have analyzed the thermal variations of human body for two cases

Case 1: For normal tissues (Healthy tissues or donor site)
Case 2: For abnormal tissues (tissues after surgery)

Results are obtained for both the cases normal and abnormal tissues. It is assumed that initially body region is insulated [12]. Therefore the nodal temperature of the whole region at t=0 is equal to the core temperature i.e.37 ^oC. It is clear from all the graphs that with the increase in time the temperature decreases very fast for first 10 minutes for normal and for 20 minutes for abnormal tissues. This is due to the fact that with the changes in isothermal conditions mass transfer process occurs, which leads to the evaporation of water. This evaporation lowers down the tissue temperature. This fall in temperature is higher in abnormal tissues than that of the normal ones. For the case 1 (normal

tissues), the temperature becomes almost steady after 20 minutes [21]. In case 2 (abnormal tissues) after attaining the minimum value the temperature began to rise for about 70 minutes with no evaporation (Fig. 2 & 3) and 100 minutes with different rates of evaporation (Fig. 4-7). This may be due to the fact that initially the thermal conductivity, the rate of blood flow and metabolic activity of the transplanted tissues in the wound are very small in comparison to normal tissues but with the increase in time the value of these parameters also increases. After some time temperature reaches steady state because latent heat of evaporation is equal to the rate of heat transfer to the water at the skin surface. In both the cases (Case 1 & 2) time at which temperature profile showing steady state varies with layers and different atmospheric temperature. For case 2, after 50 (Fig. 2 and 3) and 120 minutes (Fig. 4-7), the temperatures profile reach at steady state and become equal to that of the normal tissues.

In all the graphs, the fall in tissues temperature is more at the skin surface (epidermis) in comparison to the interior tissues (dermal and subdermal) because more heat loss accurse at the surface due to conduction, convection, radiation and evaporation.

For the same rates of evaporation the decline in tissues temperature is more at lower atmospheric temperature (Fig. 2 & 3, Fig. 4 & 6 and Fig. 5 & 7).

For the same atmospheric temperature, the fall in tissue temperature increases as the rates of evaporation increases (Fig. 3, 4 & 5 and Fig. 6 & 7).

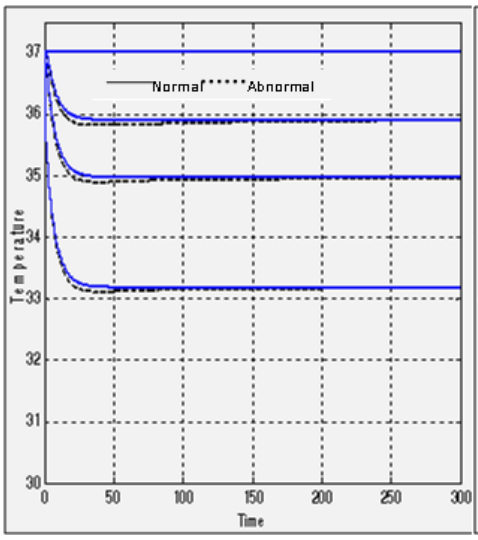

Fig.-2: Graph between temperatures T and time t for T_a=15° C, E= 0 gm/cm^2-min and $\eta = \theta = 0.01$

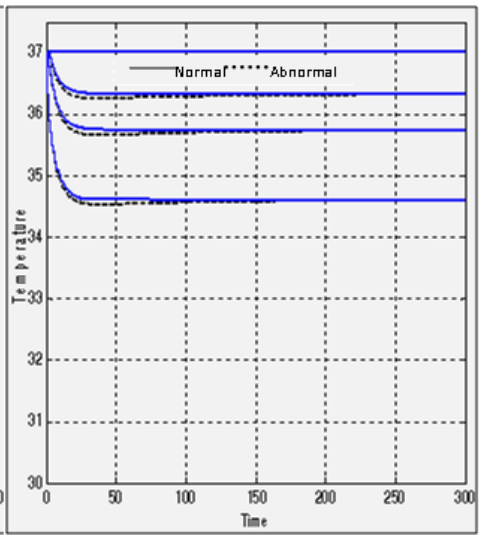

Fig.3: Graph between temperatures T and time t for T_a=23° C, E=0 gm/cm^2-min and $\eta = \theta = 0.01$

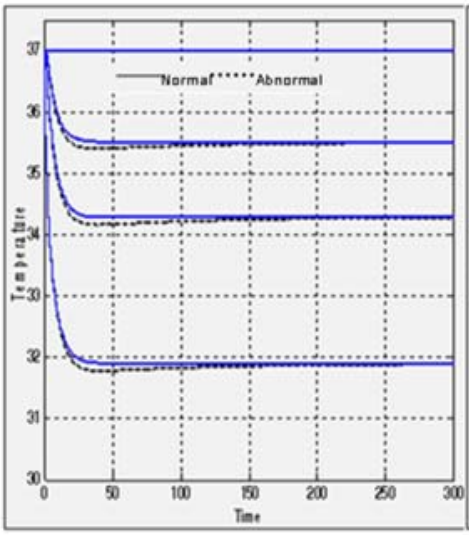

Fig.-4: Graph between temperatures T and time t for T_a=23° C, E= 0.24x10^{-3} gm/cm^2-min and $\eta = \theta = 0.01$

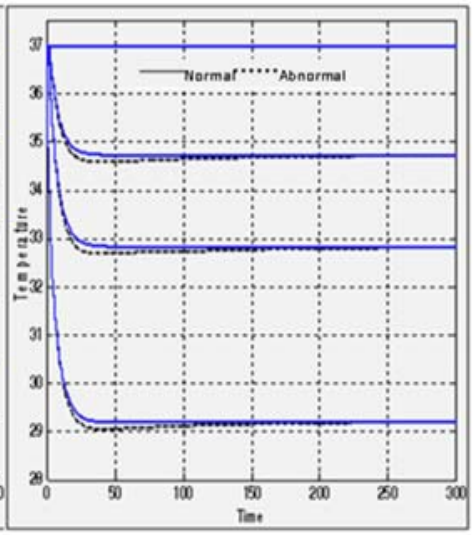

Fig 5 : Graph between temperatures T and time t for T_a=23° C, E= 0.48x10^{-3} gm/cm^2-min and $\eta = \theta = 0.01$

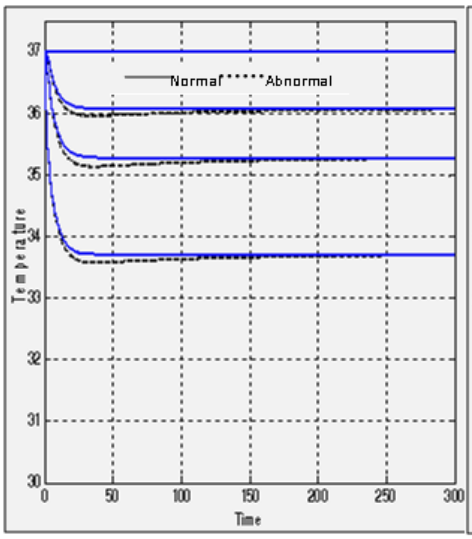

Fig.-6: Graph between temperatures T and time t for T_a=33° C, E= 0.24x10^{-3} gm/cm^2-min and $\eta = \theta = 0.01$

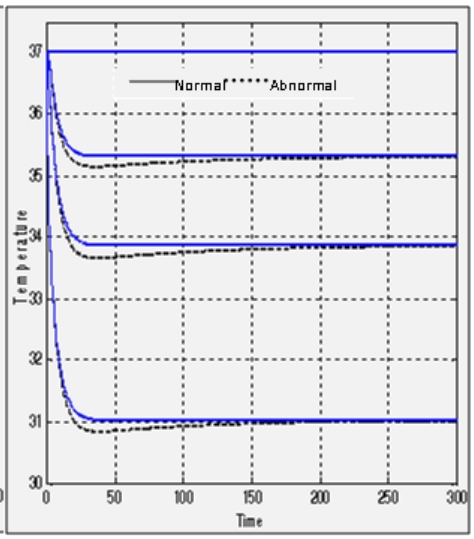

Fig.7: Graph between temperatures T and time t for T_a=33° C, E= 0.48x10^{-3} gm/cm^2-min and $\eta = \theta = 0.01$

Findings of the present study can be concluded as the rate of evaporation is directly proportional to the fall in tissue temperature. Metabolic activities play an important role to produce heat in the body. Heat is dissipated to the environment as sensible heat through the skin and as latent heat by evaporation. Latent heat represents the heat of vaporization of water as it evaporates. When the rate of evaporation is high, heat of evaporation is higher than the amount of heat supplied by the lower parts of the skin to the skin surface. Consequently, the temperature at the skin surface will drop. The changes in tissues temperature with different evaporation rate is also observed for normal and abnormal tissues. Here the abnormal tissues are defined as the tissues after surgery. Results show that, abnormal tissue temperature takes more time to obtain steady state than that of normal tissue.

Results obtained here are based on physiological facts. Variations in temperature distribution in the tissues are observed during wound healing after the surgery in the body region. The information obtained from the model can be of great use for analyzing the functioning of the enzymes during the healing process. As enzymes play an important role in healing process and functioning of enzymes depend upon the temperature, any disturbance in functioning of enzymes causes chronic wound.

Finite element method is more efficient than that of any other method because it incorporates all the geometries of the region. It has made possible to measure tissue temperature of peripheral region by wound healing process due to surgery. Such models can be further developed to study interesting relationship among various parameters of the body region and understand the thermal changes caused in the process. The information obtained from this model can be of great use to biomedical scientists for application in treatment of various diseases and helpful to develop protocols for medical purpose. This study is also helpful for evaluation of effectiveness of hyperthermic treatments. The assessments of the danger involved and heat dissipation rate in soft tissues can be made. It may also help in investigations of thermoregulatory mechanisms.

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