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ORIGINAL ARTICLE

Finite element approach to study the behavior of fluid distribution in the dermal regions of human body due to thermal stress

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Abstract The human body is a complex structure where the balance of mass and heat transport in all tissues is necessary for its normal functioning. The stabilities of intracellular and extracellular fluids are important physiological factors responsible for homoeostasis. To estimate the effects of thermal stress on the behavior of extracellular fluid concentration in human dermal regions, a mathematical model based on diffusion equation along with appropriate boundary conditions has been formulated. Atmospheric temperature, evaporation rate, moisture concentration and other factors affecting the fluid concentration were taken into account. The variational finite element approach has been employed to solve the model and the results were interpreted graphically.

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1. Introduction

In a normal adult human body 60% of total body weight consists of fluid. The body fluid is classified as intracellular fluid (ICF) and extracellular fluid (ECF). Intracellular fluid contributes two-third to the total body fluid and is located inside the cells. Extracellular fluid which include lymph fluid, interstitial fluid and plasma, contributes one-third to the total body fluid and is located outside the cells, Guyton [1]. The fluid loss in the body occurs mostly from extracellular fluids. The fluid loss may take place due to unmonitored use of diuretics, dehydration, severe vomiting, diarrhea, fever, diaphoresis, bleeding etc. The immediate effects of fluid loss are body weight loss, thirst, concentrated urine, increase heat rate, low blood pressure, decrease blood circulation rate, inadequate tissue perfusion and inefficient transport of substrates to muscle. On the other hand excessive fluid gain is due to failure to excrete fluids from body. The excessive of fluid leads to increase of hydrostatic pressure, dyspnoea, weight gain,

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decreased pulse, increased respirations, cerebral edema etc., as discussed by Black and Hawks [2]. Therefore for normal functioning of the human body the balance between fluid loss and fluid intake is very important. Since the human skin is one of the most important tissue which controls the fluid concentration in human body. Thus it is imperative to study the behavior of fluid concentration in human skin and subcutaneous tissue at adverse environment conditions.

The skin and its accessory structures make up the integumentary system and provide the body with overall protection. The integumentary system mainly consists of three regions; epidermis, dermis and hypodermis. Epidermis is avascular and composed of keratinized and stratified squamous epithelial. It is made up of four or five layers of epithelial cells, depending on its location in human body. In this study, we have divided it into two main layers as stratum corneum and stratum germinativum based on the presence of squamous and keratinized cells in stratum corneum, and melanocytes and basal layer (consisting of cuboidal cells) in stratum germinativum. Dermis is considered as the core of the integumentary system contains lymph, blood vessels, nerves and other structures such as hair follicles and sweat glands. The dermis consists of two layers as papillary layer and reticular layer of connective tissue that compose an interconnected mesh of elastin and collagenous fibers produced by fibroblasts as discussed by Stuhr et al. [3]. Papillary layer is made up of loose, areolar connective tissue, which means the collagen and elastin fibers of this layer form a loose mesh. Within the papillary layer are fibroblasts, a small number of fat cells, and an abundance of small blood vessels. In addition, the papillary layer contains phagocytes, defensive cells that help to fight against bacteria and other infections that breaches the skin. Underlying the papillary layer is the much thicker reticular layer composed of dense and irregular connective tissue. This layer is well vascularized and has a rich sensory and sympathetic nerve supply. The reticular layer appears reticulated due to a tight meshwork of fibers, Stuhr et al. [3]. The inner most layer hypodermis (also called the subcutaneous layer or superficial fascia) is a layer directly below the dermis and serves to connect the skin to the underlying fascia (fibrous tissue) of the bones and muscles. The hypodermis consists of well vascularized, loose, areolar connective tissue and adipose tissue.

In this study we shall estimate the disturbance to the dermal fluid concentration due to thermal stress. Earlier Khanday and Saxena [4] used diffusion equation and have estimated the volumetric pattern of fluid at various skin and subcutaneous layers by making use of Lagrange's interpolation method. Chao et al. [5] studied the heat and water migration in regional skin and subcutaneous tissue. Experimental study was carried out by Wakabayashi et al. [6] on ten Japanese and ten Malaysian males with matched physical characteristics such as height, body weight and peak oxygen consumption, and investigated the effect of hydration differences on body fluid and temperature regulation between tropical and temperate indigenes exercising in the heat. Mcginty et al. [7] proposed a mathematical model of a drug-eluting stent and obtained an analytical solution for the drug concentration both in the target cells and the interstitial region of the tissue in terms of the drug release concentration at the interface between the polymer and the tissue. Taylor [8] and Khanday [9] studied the sweating in extreme environments: heat loss, heat adaptation, body fluid distribution and thermal strain. Nakagawa et al. [10] demonstrated in vivo measurement of the water content in the dermis by confocal Raman spectroscopy.

To estimate the pattern of fluid concentration at various environmental conditions the present study is based on transient mass diffusion equation. The diffusivity and metabolic fluid regulation are taken to be heterogeneous and variational finite element technique will be employed to solve the formulated model. The role of atmospheric temperature T_a, evaporation rate E and moisture concentration C_a is taken into account for reasonable outcomes. The result earlier proved by Khanday and Saxena [4] is based on the steady state diffusion equation but due to radial approach and transient behavior of the model, this study can give insight into the fluid concentration of limbs and other irregular geometric organs dynamically.

2. Mathematical model

The one dimensional transient mass diffusion equation for fluid transport in skin and subcutaneous tissue is given as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(Dr\frac{\partial C}{\partial r}\right) + R = \frac{\partial C}{\partial t} \tag{1}$$

where $C(r,t)$ is the fluid concentration in the tissue, r is the radial distance of layer from the outer skin surface, t denotes the time, D is the mass diffusivity of fluid in the tissue and R is the rate of metabolic fluid generation.

In order to study the process and distribution of fluid in dermal regions of human body by variational finite element method, we consider the domain: skin and subcutaneous tissue consisting of five layers viz. stratum corneum ($l_0 \leqslant r < l_1$), stratum germinativum ($l_1 \leqslant r < l_2$), papillary layer ($l_2 \leqslant r < l_3$), reticular layer ($l_3 \leqslant r < l_4$) and sub-dermal layer ($l_4 \leqslant r < l_5$). The division of skin and subcutaneous tissue into the five segments is based on the properties viz. diffusivity, fluid regulation, density of vessels and blood circulation, as discussed by Khanday and Saxena [4]. The five interfaces joining the sub-domain are: external atmosphere – stratum corneum, stratum corneum – stratum germinativum, stratum germinativum – papillary layer, papillary layer – reticular layer, reticular layer – subdermal layer.

The boundary condition at the interface between external atmosphere and stratum corneum is taken as:

$$D\frac{\partial C}{\partial r}\bigg|_{r=l_0} = h(C - C_a) + LET_a \tag{2}$$

where h is the mass transfer coefficient, C_a is the moisture concentration in the environment, T_a is the atmospheric temperature, L is the latent heat and E is the evaporation rate. Also, the boundary condition at the inner surface of subcutaneous tissue is taken as:

$$C = C_s \tag{3}$$

where C_s is the moisture concentration of the subdermal layer.

2.1. Variational finite element formulation

The numerical solution based on finite element method is considered to be one of the optimal and feasible numerical methods as discussed by Khanday and Saxena [11], Khanday et al. [12,13], Akshara et al. [14]. Moreover this method gives better