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Human males and females body thermoregulation: Perfusion effect analysis

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ABSTRACT

Skin temperature is a common physiological parameter that reflects thermal responses. Blood perfusion is an important part of the physiological processes that the human body undergoes in order to maintain homeostasis. This study focuses on the effect of perfusion on the temperature distribution in human males and females body in different thermal environment. The study has been carried out for one dimensional steady cases using finite element method. The input parameter of the model is the blood perfusion or volumetric flow rate within the tissue. The appropriate physical and physiological parameters together with suitable boundary conditions that affect the heat regulations have been incorporated in the model. The study is to have a better understanding that how does thermoregulation change in human males and females skin layered due to perfusion.

1. Introduction

The thermal regulatory system is the means by which the living body maintains a relatively constant core temperature. Thermal homeostasis in humans is mainly achieved by regulation of the level of blood flow in the skin. Accordingly blood perfusion through the vessels in the skin surface constantly adjusts to the skin temperature and heat loss rate changes as a result. In this way, fluctuations in skin blood flow are subjected to thermoregulation. The blood flow is very decisive part of the human thermal functions. It plays a major role in regulating the temperature throughout the body. About 50 – 80% of the heat flow in the tissue is carried in or out of the tissue by the blood flow. Blood is known to have a dual influence on the thermal energy balance. First it can be a heat source or sink, depending on the local tissue temperature. During winter time blood is transported from the heart to warm the rest of the body. On the other hand, during hyperthermia treatment for certain diseases where the tissue temperature is elevated to as high as 45 °C by external devices, the relatively cold blood forms cold tracks that can decrease the treatment efficacy. The second influence of the blood flow is that it can enhance heat dissipation from the inside of the body to the environment to maintain a normal body temperature (Avolio, 1980).

In any body segment, the blood exiting in the arteries and flowing into the capillaries is divided into blood flowing in the core (exchanges heat by perfusion in the core) and blood flowing into the skin layers (exchanges heat by perfusion in the skin) after crossing the core tissue (Pennes, 1948). Blood perfusion is the local, multi-directional flow of blood through the capillaries and intercellular spaces of living tissue. It measures the volumetric flow rate of blood through a given volume of tissue over time. The rate of perfusion of blood through different tissues and organs varies over the time course of a normal day's activities, depending on factors such as physical activity, physiological stimulus and environmental conditions. Perfusion is responsible for transporting the required oxygen and nutrients for cell-life, as well as the removal of waste products. The constant exchange of blood allows for thermal regulation of the human body, as it is the blood flow that carries heat from the body's core to the tissues in the extremities. The thermoregulatory process allows for the measurement of blood perfusion.

The control of human body temperature is a complex mechanism involving hormones, blood flow to the skin, respiration, and metabolic rate. Temperature is an important parameter in the diagnosis and treatment for many diseases. The control mechanism can be altered by certain pathologic (fever) and external (hyperthermia treatment) events. Further, many disease processes are characterized by alterations in blood perfusion and some therapeutic (e.g. heating-cooling pads), pathophysiologic (e.g. inflammation and cancer), many environmental (e. g. heat stress

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and hypothermia) interventions result in either an increase or decrease in blood flow in a target tissue (Valvano, 2005).

Our body temperature would typically rise 12 °C in 1 h if no heat is lost by blood flow. Thus, blood circulation plays a crucial role in thermoregulation and mass transport. The quantitative prediction of the relationship between hemodynamic and heat transfer is of great interest, because it is related to human thermal comfort, drug delivery, and noninvasive measurement. For these reasons, it is very useful in a clinical context to know what the absolute level of blood perfusion is within a given tissue and its roles in thermoregulation. Beside these the complexity of the vasculature and vessel geometry, temperature response of the vasculature to external and internal effects is also a complex task. In a living system, the blood flow rate and the vessel size may change as a response to local temperature, local pH value, and the concentration of local O_2 and CO_2 levels and the small thermal length scale involved in the microvasculature. Thermally significant blood vessels are generally in a thermal scale of less than 300 μm. So it has been difficult to build temperature-measuring devices with sufficient resolution to measure temperature fluctuation. For these reasons we should model the thermoregulation due to blood perfusion.

Blood flow velocity and vessel radius is the controlling parameter determining the thermal equilibration between the blood and tissue. The blood perfusion is defined as the blood volume exchange through a given volume of tissue. The blood perfusion rate for skin tissue changes numerically under a fixed volume of the vessels. An average blood perfusion in males is greater than in females. In general males have higher body volume and vessel diameters (Guyton and Hall, 2009). The absolute value of basal blood flow is greater in males who have larger forearms (Raison et al., 1991). These results suggest that the differences in the body size, forearm volume and vessel diameters or blood flow velocity should be taken into account when perfusion is compared between genders. For evaluating the blood perfusion rate in each body segment, Avolio model procedure determines the artery and vein blood flows, which are given by Milnor (1989) and Nichols and O'Rourke (1998).

- The blood flow rate in the artery is given by

$$\dot{m}_{artery} = \rho_{blood}\pi r^2_{artery} v(t) \tag{1.1}$$

- The blood flow rate in the vein is given by

$$\dot{m}_{vein} = \frac{\omega}{2}\rho_{blood} r^2_{artery} \int_0^{2\pi/\omega} v(t)dt \tag{1.2}$$

where ρ_{blood}, r_{artery}, $v(t)$ and ω is the blood density, artery radius, velocity in the corresponding artery and angular frequency respectively. These relations for blood flow in vessels suggest that perfusion blood flow rates depend on the geometry of the body and can be determined on the basis of the position of blood vessel with respect to each body segment. So females have a lower skin perfusion rate compared to males' skin perfusion rate.

There have been a large number of publications dealing with the thermoregulation of males due to change of environmental temperature but very few with females (Timbal et al., 1969; Scholander et al., 1985; Horstman and Christensen, 1982; Freeman et al., 1970). The dimorphism in body structure, limb properties, surface area, insulating muscles and fat mass, thickness, vessel geometry distribution between males and females, which result in females lower skin blood flow and consequently lower skin temperature compared to males. However there are few situations where females' body temperature may be a little higher than males. Pregnancy and hormonal contraceptives

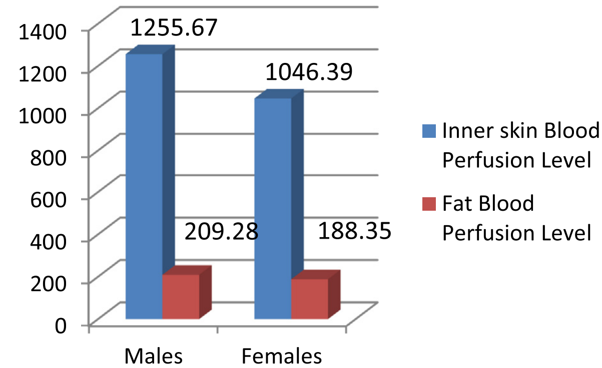

Fig. 1. Two blood perfusion levels (w/m^3/°C) of human males (Guyton and Hall, 2009; Raison et al., 1991; Chato, 1980; Gurung and Saxena, 2010; Acharya et al., 2013; Fiala et al., 1999) and females under consideration in the model.

increase core temperature about 0.5 °C to 1.0 °C. The range in oral temperature for males and females normal body is 35.7–37.7 °C and 33.2–38.1 °C respectively (Martha et al., 2002). As well rectal temperatures for males and females normal body is 36.7–37.5 °C and 3..8–37.1 °C respectively. We have taken the males skin perfusion rate from published data of thermoneutral zone and then considered the appropriate females skin perfusion rate that shows the females normal body temperature profiles of thermoneutral zone. The relationship for blood perfusion rate between human males and females' dermal parts for the model are considered as shown in Fig. 1.

2. Model formulation

Skin membrane can be examined at various levels of complexity. In mathematical treatments of temperature distribution in dermal layers, the membrane can be regarded as a physical and physiological barrier with complex structure. Schematic diagram of temperature distribution model in the layers of dermal parts of human body is as shown in Fig. 2.

The thickness of stratum corneum, stratum germinativum, papillary region, reticular region and subcutaneous tissue have been considered as l_1, $l_2 - l_1$, $l_3 - l_2$, $l_4 - l_3$, $l_5 - l_4$ respectively and T_0, T_1, T_2, T_3, T_4 and $T_5 = T_b$ are the nodal temperatures at a distances $x=0$, $x=l_1$, $x=l_2$, $x=l_3$, $x=l_4$ and $x=l_5$ and $T^{(i)}$, $i=1, 2, 3, 4, 5$ be the temperature function in the layers stratum corneum, stratum germinativum, papillary region, reticular region and subcutaneous tissue respectively.

Heat regulation in human body is characterized by blood flow in the blood vessels, metabolism and the conduction in tissue. The processes that govern the heat transfer in in-vivo tissue of human body at rest are perfusion, diffusion and metabolic heat generation. Thus the rate of change in total heat (Q) in a tissue element with respect to time t can be symbolically expressed as (Gurung and Saxena, 2010).

$$\frac{\partial Q}{\partial t} = \left.\frac{\partial Q}{\partial t}\right|_{perfusion} + \left.\frac{\partial Q}{\partial t}\right|_{diffusion} + \left.\frac{\partial Q}{\partial t}\right|_{metabolic} \tag{2.1}$$

The heat transfer between the blood and tissue is proportional to the temperature differences between the arterial blood temperature T_a (entering) and the venous blood temperature T_v (outgoing). The proportionality factor ω_b is called rate of perfusion. The total heat released is equal to the total amount of blood perfusing tissue volume q multiplied by its density ρ_b, specific heat c_b, and the temperature difference between the artery and vein is