An Improved Mathematical Model of Thermal Physiological Response of Naked Infants

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***Abstract**:* In this paper, an improved 9-node mathematical model of thermal physiological response of infants is developed by integrating Gagge's two-node model and Stolwijk's multi-node model. Considering the individual difference of infant's body weight and size, the relationship between basic geometric parameters of infants and their thermal physiological parameters has been established in this model, so that the new naked infant model can be used for different size of infants, term infants and premature infants. To investigate the core and skin temperature distribution on infants, a set of numerical simulations have been carried out for naked, premature and term infants. By comparing the predictions of the model with the published data, this model was validated in the aspects of neutral thermal environment and skin temperature distribution. It was found that this model is satisfactory.

***Keywords*:** Physiological response, infant, thermal comfort, mathematical model, numerical simulation, temperature distribution.

1. Introduction

To know the thermal state of infants and to keep them warm and comfortable under different environment is a very important issue for survival and health of infants, especially for premature infants. Without appropriate clothing and/or medical equipment to keep infants warm and maintain thermal balance, they can suffer from illnesses and syndromes such as hypothermia and hyperthermia[1]. For instance, when infants are nursed at environment temperatures or are transported from one place to another, at which the temperature is out of the thermal neutral range, the risk of hypothermia increases, because the efficiency of their thermoregulatory processes are limited. On the other hand, if bedding and clothing hinder efficient transfer of endogenous heat to the environment, hyperthermia may result[2], because infants are unable to remove their blankets in response to overheating. Therefore, to find an effective way that can predict the thermal state of infants in different environments and situations is a valuable research project.

Using mathematical model to predict and simulate the human thermal behavior is a very useful tool for studying thermal regulation capability of human body. Many related research work have been carried out in this field. Gagge et al. [3] developed a two-node model for describing the thermoregulatory system of the human body, in which the human body is comprised of two concentric shells, one is the skin represented by a thin shell, the other is the body interior represented by a central core. The model is based on a standard man, with body surface area equivalent to the Dubois area ($1.8m^2$), mass 70.0kg, and height 1.77m. Stolwijk [4] developed a multi-node model, in which human body is divided into head, trunk, arms, hands, legs, and feet. Each segment is subdivided into four concentric layers, representing the core, muscle, fat, and skin layers. An additional central blood compartment, representing the large arteries and veins, is the last node in the 25-node model. In such multi-node model developed by Stolwijk, the regulating system consists of two general components: the controlled system and controlling system. This model is based on a man with surface area of $1.89m^2$ and body mass of 74.4kg.

However as far as infants are considered, their physiological thermoregulatory processes are different from adults [5-9]. (1) Infants have a large surface area relative to their body weight than adult. For example, a term infant with a birth weight of 3kg has a body surface to body volume ratio three times greater than that of an adult, and a premature infant with birth weight 1.5kg has a ratio four times greater. (2) At birth the brain accounts for approximately two-thirds of basal metabolic rate, and at 1 year for about 50%. (3) The infants have thinner skin and subcutaneous fat

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layer; this is even more marked in premature infants. The skin of the newborn and premature infant has greater thermal conductance than that of an adult; they consequently lose more heat and water per unit of surface area than the adult. (4) Preterm infants are unable to shiver, cannot curl up and are usually nursed naked. This adds to the difficulty in maintaining their body temperature. (5) The preterm infant is also unable to sweat until a few weeks old, whereas the term infant can sweat from birth. As both of the models mentioned above are all based on the standard of human adults, these models cannot be directly used for infants. In this paper, based on Gagge's two-node model and Stolwijk's multi-node model, a new 9-node thermoregulation model used for naked and clothed infants was developed by considering the infant's body size and physiological function of thermoregulation.

2. Mathematical description of the system

On the basis of Stolwijk's multi-node model [4], the regulating system of the new 9-node infant's model also consists of two general components: controlled system and controlling system.

2.1 Controlled system of the model

In the controlled system of the model, the whole infant body is divided into four body segments, as shown in Figure 1, which includes head, trunk, arms and legs. The head is represented as an appropriate size sphere; the trunk, arms and legs are represented as appropriate size cylinders. Each segment is subdivided into two concentric layers, the outer layer represents the skin of the segment and the inner layer represents the core of the segment. An additional central blood compartment, representing the large arteries and veins, is the last node of the 9-node infant model.

In this new model, all the physical values of infant used in the model, including body volume, surface area and weight, are calculated through seven basic geometric values, the radius of head, the radius and length of trunk, arms and legs. That is, the body volume and surface area of each segment can be calculated directly on these seven geometric values. To decrease the number of calculations, the arms and legs are represented by two cylinders, one for each pair; the values are later doubled. Considering the skin thickness of each segment, 0.12cm for head, 0.15cm for trunk, 0.08cm for arms and 0.09cm for legs [4, 10], the volume of skin of each segment can be obtained. Subtracting skin volume form body volume, the volume of core for each segment can be obtained. Considering the density of core and skin of each node, the weight of core and skin of each node can be obtained. The volume and weight of blood can be calculated by total body weight and the density of blood, that is, the volume of blood is 52-83ml/kg for male infants and 50-75ml/kg for female infants [11]. The value of density [12], specific heat [12], blood flow [13,14], division of the metabolic rate [12], and conductance of each part [15] are listed in Table 1.

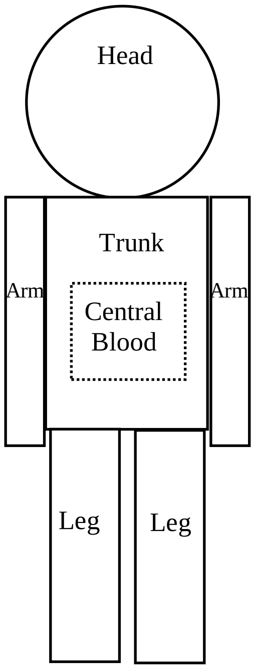

Figure 1 9-node model of infant.

In this infant model, different way of heat transfer in infant body and exchange with environment are considered. Firstly, heat is transferred between skin and core by conduction between each segment. Secondly, the body and the environment exchange heat by two ways, one is by conduction, convention, radiation and evaporation through the skin, the other is by respiration directly with the core of the body. Thirdly, heat exchanges with all other compartments via the convection heat transfer occurring with the blood flow to each compartment.