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Prediction of convective heat transfer coefficient of human upper and lower airway surfaces in steady and unsteady breathing conditions

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ABSTRACT

Bio-effluent and metabolic heat production from the human body and its breathing activity can strongly influence the microclimate around the body. On the other hand, local properties of the microclimate around the human body can also significantly affect the interaction between the body and the surrounding environment by way of local flow and heat transfer characteristics close to the body. Breathing is one of the most essential activities in our lives, and the basic functions of breathing include exchanging gases (supplying oxygen from ambient air and removing carbon dioxide from the blood) and exchanging heat and moisture (sensible and latent heat). As a consequence, human beings experience lifelong interaction with indoor environments via inhalation. In this study, two types of three-dimensional respiratory tract models were developed using computed tomography data of a healthy human males. Computational fluid dynamics simulations are performed to analyze the airflow and temperature distributions inside respiratory tract models under various breathing conditions. We used low-Reynolds-number-type k-ε model to predict airflow in the airway models. The flow pattern inside the viscous sub-layer and convective heat flux on the airway tissue surfaces and convective heat transfer coefficients were analyzed. Through this study, the numerical errors were successfully identical, so this discrepancy of two airway models were assumed due to the differences in airway geometries and reflected individual specificity. Averaged and local convective heat transfer coefficient distributions of the human airway were summarized as functions of breathing airflow rate.

1. Introduction

Optimization of energy efficiency and pursuit of a clean and healthy environment are becoming more important issues in the field of sustainable building design [1,2]. Overall, uniform control of indoor environments is not efficient from the view point of energy savings [3–6]. Accordingly, the control objectives for indoor environments have been expanded from the macro-spaces of entire rooms to the micro-environments of local domains, such as the occupied zone, the space around the human body, the breathing zone, and the respiratory system [7,8].

In accordance with the expansion and elaboration of indoor environmental design techniques, the prediction accuracy and targets of numerical simulation tools have also become more precise in their demands [9–12]. Recently, commercial numerical simulation tools have been used widely, and an integrated numerical procedure using computational fluid dynamics (CFD) and a computer-simulated person (CSP) have been applied in indoor environmental design, especially for the design of personalized ventilation system, optimization of local thermal comfort, and so on [13–17]. With the accuracy advances of micro-environmental design around the human body, developing comprehensive human models has become expected along with improving prediction accuracy for the physiological and psychological reactions and the effects on the human body caused by non-uniform environments formed around the body.

In regard to skin surface temperature control resulting from interaction between indoor thermal environments and the human body, many research achievements have emerged along with the various thermoregulation models proposed [18–22]. Furthermore,

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in order to estimate the unsteady and non-uniform thermal environment formed close to the human body, these thermoregulation models consider multiple nodes divided along the human body, and each thermoregulation model uses particular models to evaluate the heat transfer phenomenon between skin surfaces and surrounding environments, heat transfer and exchange caused by blood flow, and heat loss by respiration. In the previous thermoregulation model, especially with the heat and moisture transfer phenomenon through respiration, macroscopic results for convective and evaporative heat transfer coefficients were adopted by assuming the simplified cylindrical tubes generally used in heat transfer engineering fields [23]. In addition, those results were adopted in order to calculate the heat transfer rate of the respiratory tract on the assumption of physical uniformity inside the airway. This means that the prediction method concerning respiratory heat loss was simpler and of lower accuracy than heat transfer/heat exchange modeling for other parts/nodes of the human body. Hence, in order to contribute to the improvement of prediction accuracy of the thermoregulation model for skin surface temperature, detailed analysis of the sensible and latent heat transfer phenomena inside the respiratory tract is considered as crucial and important.

Furthermore, the respiratory tract system is the portal between the human body and the indoor environment; hence, this is also the body's first line of defense against harmful pollutants from the surrounding indoor air. An investigation of airflow characteristics in the human respiratory tract provides valuable information to enhance the understanding of the transportation of inhaled particles and/or gas-phase contaminants through respiration [24,25].

Past experimental results show that the airflow has to pass through in the respiratory tract to reach 37 °C [26,27]. Airway temperature significantly increased within the nasal valve and turbinate part of the nasal airway. Measurements of the mean end-inspiratory temperature along the nasal cavity during inspiration at room temperature revealed values of 25.3 °C in the nasal vestibule, 29.8 °C in the nasal valve area, 32.3 °C in the anterior turbinate area (near to the head of the middle turbinate), and 33.9 °C in the nasopharynx [28]. The nasopharyngeal temperature was gained up to 34 °C according to results of different research papers [29,30]. The air temperature within the nasopharynx is close to the temperature of the nasal mucosa [31,32]. The contact time of inspired air with the mucosa lining of the anterior section of the nose providing sufficient warm the inspired air although the airflow has a high velocity in this part of the nose [33]. At the end of inspiration, the air temperature quickly increases during rest of breathing.

Experiments of temperature within the nasal cavity or human airway of the human are limited due to the complex anatomy and the very narrow nasal passageways. Furthermore, problems of temperature and humidity measurements are the tight spatial and limited time resolution. To fill this gap, CFD simulation was gradually applied to replace experimental work. Numerical simulation is utilized for manipulating and reflecting a real environment of complex geometries within a computational model. Technical improvement led to a large number of CFD studies within the last decade providing incremental knowledge research about the complex functions of human airways [34–36]. CFD simulations have performed to predict airflow pattern characteristics in combination with intranasal air temperature under various conditions [37–40]. CFD is considered a practical technique to reveal the relationship between intranasal airflow and heat transfer. Changes in temperature are strongly affected by airflow patterns. Numerical simulations applying CFD might provide a detailed information and visualization of airflow patterns within the entire respiratory tract even during a breathing cycle. Therefore airflow characteristics like turbulence characteristics, average air-velocity, volume flow, pressure conditions, distribution patterns and path lines should be investigated for varying inhalation airflow rates. Most of up to date studies simulated a steady inflow. CFD simulations of human airway temperature as functions of convective heat transfer and airflow during a steady and unsteady breathing condition have not been substantially discussed.

Against this background, this paper reports on the numerical prediction of airflow and temperature distribution in the human respiratory system as a function of the breathing airflow rate, targeting two types of numerical airway models (Model A and Model B). In addition, convective heat transfer phenomena in the airway

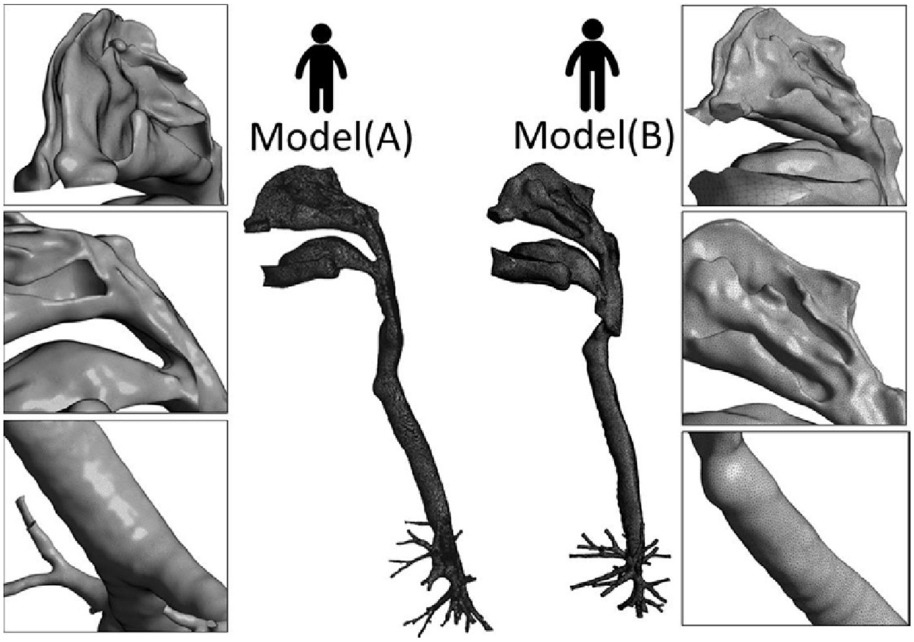

Fig. 1. Two types of numerical airway models (Model A and Model B).