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EVALUATING THE INFLUENCE OF TISSUE PROPERTIES ON THE CORE TEMPERATURE USING A 3D WHOLE BODY MODEL

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INTRODUCTION

Accumulation of heat in the human body during firefighting activities for a sustained time period causes body temperature to reach critical levels. This increase in body temperature leads to a build-up of heat stress. Elevated heat stress can lead to adverse health effects, including unconsciousness and/or cardiac arrest [1]. Thus, accurate prediction of thermal response of the human body during firefighting scenarios is of high importance. Determination of the core body temperature (T_c) using computational method requires a reasonable estimate of tissue properties and numerical formulation to calculate thermal response of the human body. In a previous study, we have utilized a computational whole body model to determine the T_c of firefighters during firefighting training drills [1]. The study evaluated firefighting data that included periodic work (Sc) and rest (R). Tissue properties of humans at rest show significant variation among different individuals [2, 3], but the effect of variation in each property on the core body temperature (T_c) has not been quantified.

Hence, the objective of the current study is to determine the influence of variation in tissue properties on the T_c. These properties include: density (ρ), specific heat (c), thermal conductivity (k), blood perfusion (ω) and metabolic rate (q_m). McIntosh *et al*. [2] and Duck [3] have specified a range of estimated values for the tissue properties of humans for resting condition. These ranges have been utilized in determining the influence of tissue properties on T_c.

METHODS

The whole body model was developed using a combination of different geometric shapes such as cylinder, cuboid, and sphere to represent the limbs, torso, and head, respectively. The computational model was based on a human being with a height of 1.80 m, weight of 80 kg, and body surface area of 1.90 m^2 [1]. The model was divided into four domains: head, muscle, organ, and gut.

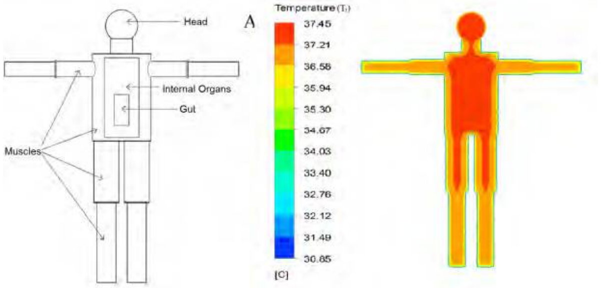

FIGURE.1: GEOMETRY OF THE WHOLE BODY MODEL (A) INITIAL TEMPERATURE FIELD IN 25°C AIR (B)

The transient thermal response of the whole body model was determined by solving two equations simultaneously: 1) Pennes bioheat equation, to evaluate the temperature distribution in the body and 2) The energy balance equation, to determine the change in blood temperature due to a transient tissue-blood heat exchange. Pennes equation is defined as:

$$\rho_t c_t \frac{dT_t}{dt} = k_t \nabla^2 T_t + q_m + \rho_{blood} c_{blood} \omega (T_{blood} - T_t) \qquad (1)$$

where ω is the blood perfusion rate, ρ_t is the density of the tissue, c_t is the specific heat of the tissue, k_t is the thermal conductivity of the tissue, T_{blood} is the blood temperature, T_t is the tissue temperature and q_m is the heat generated due to metabolism. T_{blood} in the human body was represented as a lumped system and was computed using the energy balance equation as shown below.

$$(\rho c V)_{blood} \frac{dT_{blood}}{dt} = -(\rho c \omega_{avg})_{tissue} V_{body} (T_{blood} - T_{wt}) \qquad (2)$$

where V_{blood} is the total volume of blood in the body, ω_{avg} is the average blood perfusion, and T_{wt} is the weighted average tissue temperature.

The values of metabolic rate (q_m) and blood perfusion (ω) for individual tissues [2] were assigned to the four domains of the computational model. The q_m for each domain (eg. Organ) was determined by calculating the weighted average of the metabolic rates of all internal organs/tissues (eg. heart, lungs, liver etc.) representing different domains. Details of different domains are presented in Table 1. A similar approach was adopted for determining the range of ω. Further, a single weighted average value of density, specific heat, and thermal conductivity were also computed for the whole body from the available tissue properties as shown in Table 2. Other input parameters to the model, such as the heart rate time series and details of a firefighting suit, were similar to those described in our previous study [1]. T_c was computed by varying one input parameter at a time while keeping all the other tissue properties at their baseline values presented in Tables 1 and 2. Eleven numerical computations were executed: one with baseline values and the rest by varying limiting the (maxima and minima) values of tissue properties. It should be noted that only the steady-state q_m and ω were varied. The transient variations of q_m and ω were dependent on the heart rate time series and T_c, respectively [1, 4].

TABLE 1: BASELINE VALUE AND ITS VARIATION ALONG WITH VALUES FROM THE PREVIOUS STUDY OF ω AND q_m

Domain	Current study		Previous Study [1]	
	ω (1/s) [2]	q_m (W/m^3) [2]	ω (1/s)	q_m (W/m^3)
Head	0.00574±13%	9865.5 ± 18.4%	0.00833	9225.0
Muscle	0.00055±35%	597.5 ± 18.4%	0.00050	553.5
Organ	0.00425±30%	4529.6 ± 18.4%	0.00126	1401.5
Gut	0.01330±52%	6994.0 ± 18.4%	-	-

TABLE 2: BASELINE VALUE AND ITS VARIATION ALONG WITH VALUES FROM THE PREVIOUS STUDY OF k, ρ AND c

Property	Current Study	Previous Study [1]
k (W/m.K)	0.41 ± 7.0% [2, 3]	0.50
ρ (kg/m^3)	1055 ± 4.3% [2, 3]	1060
c (J/kg.K)	2698 ± 14.8% [2, 3]	3166

RESULTS

Our previous study [1] reported a maximum difference of 0.3°C between computed and experimental T_c during firefighting activity (Figure 2). The tissue properties used in this study can be found in Table 1 and 2. Comparison of the baseline T_c obtained from the current study with the experimental T_c [1] showed a deviation of 1.6°C, or 4.1% (maximum % increase between baseline T_c and experimental T_c) as presented in Figure 3.

Temperature deviations presented in this section refer to the *maximum* deviation observed in T_c with respect to baseline T_c due to the variation in input parameters. A temperature rise of 0.5°C (a 5.5% increase with respect to experimental T_c) due to an increase in the steady-state q_m is evident in Figure 3. When *c decreased,* a noticeable increase of 0.38°C (a 5.2% increase with respect to experimental T_c) in T_c (Figure 3) was observed. An increase of 0.1°C in T_c was noted when ω was varied to its lower bound. Minimal deviations in T_c were observed due to the variations in k and ρ. A maximum variation of 0.01°C in T_c was observed when k was varied by 7%. A 4.3% change in ρ resulted in a difference of 0.01°C from the baseline T_c.

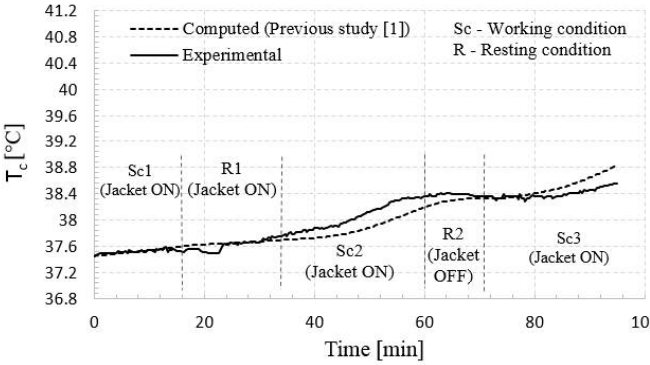

FIGURE 2: COMPUTED AND EXPERIMENTAL T_C DURING FIREFIGHTING ACTIVITY [1]

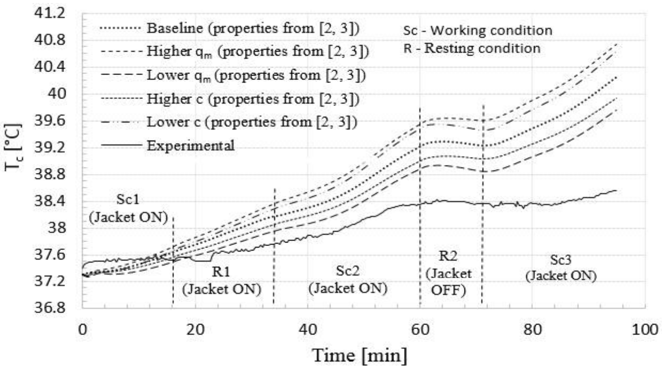

FIGURE.3: COMPUTED T_c DURING FIREFIGHTING ACTIVITY WITH BASELINE AND VARIATIONS OF q_m AND c ALONG WITH EXPERIMENTAL T_c

DISCUSSION

The effect of variations in the steady-state values of the tissue properties on T_c using a whole body model was demonstrated in this study. Effects of change in q_m and c on T_c were significant as compared to the influence of ρ, ω and k. The notable difference between T_c from the current and previous studies can be attributed to the variability in the q_m and c listed in Table 1 and 2.

Assumptions and Limitations. The property values listed in Table 1 and Table 2 shows large variability. The T_c values can be improved with better accuracy of tissue properties.

Future Scope. The current study will be extended to find the uncertainty of T_c due to combined effect of the variation in the tissue properties and input parameters.

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