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Towards thermal comfort prediction for the older population: a review of aging effect on the human body

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Abstract
Research has revealed that aging effect on the organs of the body and body functions can affect the response of the older person in a given environment. However human thermoregulation models used in the prediction of the comfort of the human body in a given environment have been designed to represent an average person. This research aims at developing a customized computer model for predicting thermal comfort of old persons and is based on IESD-Fiala model. From published literature, data on the effect of aging on the basal metabolic rate (BMR), cardiac output (C.O.), body weight (BW) and body surface area (BSA), height (HT) were extracted and used for the development of a 'typical' old person model. A transient simulation carried out to compare the skin temperatures of the average person (existing Fiala model) and old person (new model) under the same environmental conditions showed that the old person may feel cooler at the exposed skin areas i.e. hands and feet than the average person.

Keywords: Thermal comfort, aging, basal metabolic rate, cardiac output, body weight

1 Introduction

Over the years many human thermoregulation models have been developed for use in research and industrial practice. These models have the ability to predict the thermal responses of a typical human body in a given environment in terms of sweating, shivering, skin temperature, blood perfusion rate, and other physiological parameters. One similarity amongst most of the existing models is that the embedded data used in their design which represents the average of the adult population. With emerging information and findings on the effect of aging on the heat and cold tolerance of the elderly, there is need to critically look at the effects aging as a natural phenomenon have on the thermal comfort needs of the elderly. From research it has been found that as we age, we experience changes in our solid organs and body functions. Together, these changes lead to a diminished physiological reserve (Aalami 2003) (Grundy 2006) resulting in the inability of the body to maintain effective internal temperature needed for comfort.

Our approach was to isolate the various body parameters used in the development of an established model (IESD-Fiala model), collect published scientific findings on the effect of aging on their capabilities and use these findings to modify the existing model to represent older persons. This paper presents findings of the first stage of the development of a new model that represents the older population. It includes a review of the aging effect on some of the physical and physiological properties of the human body and their thermal balance implications. Simulation was used to demonstrate some effects of aging.

2 The Aging Population

The average age of the world's population is increasing(Kinsella 2009), even though on one hand it is seen as one of humanities greatest triumphs; it is also one of our greatest challenges. Declining fertility and improved health and longevity have generated rising numbers and proportions of the older population in most of the world(Kinsella, 2009). Interestingly there is no agreed definition of an older person(Tinker, 2002) but in general, those over 70 yr of age are considered old and those 21–40 yr of age are considered young. Those, 40–70 yr of age are considered to be intermediate in age. However, many studies have included individuals who are 60–70 yr as old(Morley, 2003). In this paper, the age of old person shall be taken to be 65 and above.

According to(Florez-Duquet, 1998) growing old or aging is the detrimental changes with time during post maturational life that underlie an increasing vulnerability to challenges thereby decreasing the ability of the organism to survive. It is also the inability of the organism to maintain homeostatic regulation when given a challenge(Florez-Duquet, 1998). In August 2003, more than 2000 deaths were attributed to the heat wave in England and Wales (Kovats, 2006). During the heat wave period, excess mortality was 33 per cent in those aged 75 and over, compared to 13.5 per cent in the under-75 age group. Statistics in France showed a strong correlation between excess death and age during the heat wave. The excess mortality was estimated at 20% for those aged 45-74 years, at 70% for the 75-94 year age group, and at 120% for people over 94 years(Pirard, 2005).

3 Methodology

In this paper, the IESD-Fiala model was used for investigating the impact of age-related changes on the human body. Like most human thermoregulatory models in existence, the IESD-Fiala model profiles the human body as two interacting systems, i.e. the controlled passive system (body structure) and the controlling active system (the thermoregulatory functions). The passive system of the model which is the focus of this paper is a multi-segmental, multi-layered representation of the human body with spatial subdivisions Figure 1. The body is idealised as spherical and cylindrical elements built of annular concentric tissue layers with the appropriate thermo physical properties and physiological functions.

The overall data replicates an average person with respect to body weight (73.5 kg), body fat content (14%wt), and Dubois area (1.86 m²). The physiological data aggregates to a basal whole body heat output of 87.1W and basal cardiac output of 4.9 L min-1, which are appropriate for a reclining adult in a thermo-neutral environment of 30°C(Fiala, 1998). Detailed literature review was carried out on selected body parameters including, the musculoskeletal system, heart, skin and central nervous system to accumulate scientific information on the impact of age on their capabilities. Statistical reduction in basal metabolic rate (BMR), cardiac output (C.O.), body weight (BW) body surface area (BSA) and height (HT) of the older population group (sourced from literature survey) was used to represent an aged human body. The new model was used to study the respond of old persons and an average persons respond, in terms of peripheral temperature, to transient environmental conditions of (30-15-30) ^{0}C.

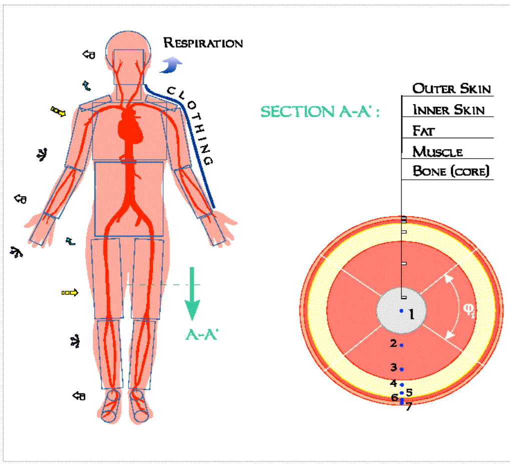

Figure 1 Passive system of IESD-Fiala model

4 Literature review

Literature review was conducted to accumulate scientific information and findings on the impact of age on selected components of the human body. These body parameters form part of the passive system of the IESD-Fiala model. They include the musculoskeletal system, heart, skin, and central nervous system.

4.1 Musculoskeletal system

Muscle represents 40% of body cell mass and is the largest pool of protein in the body. It is affected both by disease and by aging. Studies relating muscle mass to age suggest the loss of at least 30% of muscle mass up to the age of 80 years(Hyatt, 1990). This loss of muscle mass and strength which occur with aging is usually referred to as Sarcopenia. This is believed to play a major role in the pathogenesis of frailty and functional impairment that occurs with old age. Maximal muscle mass and strength is usually achieved in the 20s and 30s and gradually declines into middle age. At around the age of 60, loss of muscle tissue accelerates, often leading to progressive weakness (Spirduso, 1995).A follow-up study(Aniansson, 1986) of muscle strength, muscle morphology, and enzymatic activity in 23 men, 73-83 years of age, was performed 7 years after the first investigation. Its was found that, body weight was reduced by 2% and body cell mass by 6%, whereas the quadriceps muscle strength decreased 10%-22% over the 7-year period. According to (Knight, 2008b)anatomical and physiological changes in aged muscle tissue include reduction in motor neuron numbers, blood flow to the major muscle groups and reduction in the number of muscle fibres and fibre size. Also there is an increased deposition of fat at the expense of lean muscle tissue and mmitochondria within muscle fibres becoming less efficient at releasing energy during metabolism.

The skeletal system provides support, protects vulnerable regions and allows physical movement via a system of levers and articular joints. The bones also function as storage areas for fat, act as mineral reservoirs and house the red bone marrow responsible for blood-cell production(Knight, 2008b). With age, they undergo changes which may sometimes be avoided by engaging in light exercise. Maximal bone mass and density is usually attained between the ages of 25 and 30 and gradually decreases thereafter (Montague, 2005). Aged skeleton is commonly associated with the loss of calcium which leads to the bones taking on the porous sponge-like appearance indicative of osteoporosis.

4.2 Heart

The heart is responsible for the generation of blood pressure and also plays a major role in thermoregulation, distributing and dissipating heat throughout the body (Knight, 2008a). The mechanism by which the heart output (cardiac output) is maintained during exercise(Rodeheffer, 1984) is affected by aging. Aging is also associated with complex and diversified changes of cardiovascular structure and function where the heart becomes slightly hypertrophic and hyporesponsive to sympathetic stimuli, so that the exercise- induced increases in heart rate and myocardial contractility are blunted in older hearts. The aorta and major elastic arteries become elongated and stiffer(Ferrari, 2003).

According to (Minson, 1998) the lower Skin blood Flow (SkBF) in older men during heating was associated with a lower cardiac output and a reduced ability to redistribute blood from the visceral circulation. The cardiac responses to passive heat stress were also altered as an effect of chronological age. During quiet supine rest, cardiac output tended to be lower and systemic vascular resistance higher in the older men (Taylor, 1992). Work done by (Brandfonbrener, 1955) also revealed that there was a significant link between aging and reduction in cardiac output.

4.3 Skin

Like all organs, the skin is subject to the degenerative process of chronological and intrinsic aging. However, its exposed interface with the environment also makes it subject to aging due to exposure and damage from the sun and its ultraviolet light rays (photo aging)(Nigam, 2008). As we age, the skin becomes thinner; this is because the underlying fat, so abundant at infancy, is slowly lost. The thickest layer of skin known as the dermis which contains blood capillaries, which provide oxygen and nourishment to all skin cells is also affected by aging. The dermal tissue atrophies with age and its thickness decreases by about 20% in older people (Nigam, 2008)

According to (Weiss, 1992) in their study of skin perfusion of the dorsum of the foot by determining the capillary blood flow velocity (CBFV) using laser Doppler flowmetry LDF in ten young and 12 elderly men, at 32°C skin temperature, the CBFV oscillations (vasomotions) are of higher median amplitude in young people than in elderly subjects. At 44°C skin temperature, the median CBFV peak in the young was also higher than in the aged subjects. It seems therefore likely that the diminution in LDF of the aged stems from changes in dermal capillary architecture. This is in accordance with previous reports of decreased number of capillary loops in the dermis, and a 30% reduction in the venule cross-section in skin specimens of elderly people(Anders, 1985).

4.4 Central Nervous system

The nervous system, along with the endocrine system, controls and integrates the activities of the major organs receiving and processing sensory input from skin, eyes, ears and responds through effector organs (Knight 2008). It has been estimated that brain mass drops by around 10% between the ages of 20 and 90 years. From the age of 20–60 years, neural losses are only around 0.1% per year but the process speeds up thereafter (Esiri, 2007). In old age, cerebral blood flow will have decreased by around 20% (Joynt, 2000), primarily due to the loss of elasticity and lumen diameter in aged blood vessels. In terms of neurotransmitters in the body there is an age-related decline in the synthesis of many and their receptors(Knight 2008).

The spinal cord which forms the backbone of the central nervous system is not left out in the aging phenomenon. There is a gradual age-related loss of neural tissue from the spinal cord.

Up to 46% of neurons may be lost in humans over the age of 50 (Esiri, 2007). With age, the peripheral nerve cells often show a progressive degeneration of the myelin sheath (insulatory layer around the axon)(Knight 2008). This slows the conduction of nerve impulses by around 5–10% (Joynt, 2000). The progressive loss of neurons, a reduction in impulse velocity and changes within the spinal cord typically lead to a slowing in reaction times (Spirduso, 1995). This can create problems on encountering painful or harmful stimuli. According to(Knight 2008), slowing of nerve conduction and depletion of neurotransmitters often slows the processing of information and, as a result, some tasks may take longer to complete in older age.

4.5 Thermoregulation

The human body has a very effective temperature regulatory system, which ensures that the body's core temperature is kept at approximately 37°C. When the body becomes too warm, two processes are initiated: first the blood vessels vasodilated, increasing the blood flow through the skin and subsequently one begins to sweat. Sweating is an effective cooling tool, because the energy required for the sweat to evaporate is taken from the skin. If the body is getting too cold, the first reaction is for the blood vessels to vasoconstrict, reducing the blood flow through the skin. The second reaction is to increase the internal heat production by stimulating the muscles, which causes shivering. This system is also very effective, and it can increase the body's heat production dramatically. These cardiovascular responses govern the transfer of heat from the body core to body surface (Fiala, 1998). In (Frank, 2000) it was found that aging is associated with reduced intensity of the vasoconstriction and shivering responses during cold challenge. The ability to perceive cold is also somewhat impaired, shivering and the associated heat production are decreased in older individuals. All three major cold-defense responses are in some way impaired with age.

Studies by (Kenney, 1996) revealed that when exposed to whole body cooling sufficient to lower skin temperature by -6°C over a 2-h period, older men vasoconstricted their limbs (forearms) to a lesser extent than did younger men and it likely results from direct effects of aging on the reflex peripheral vascular response to cooling. Peripheral vasoconstriction is an early and sustained physiological response to cold air exposure which minimizes heat flux from the body core to the air. This peripheral vascular response is of particular importance on the limbs, which have a high surface area-to mass ratio this provides a first line of defense against hypothermia by minimizing convective heat loss. In a study of heat stress between young and older individuals, older individuals typically respond with attenuated individual sweat gland outputs, decreased skin blood flows, reduced cardiac outputs and smaller redistributions of blood flow from the splanchnic and renal circulations (Kenney, 2003).

In a study by (Inbar, 2004) in comparing the thermoregulatory responses to excise in dry heat among prepubertal boys, young adults and older men, it was found out that age and age related characteristics affect the overall rate of heat gain as well as the mechanisms through which this heat is dissipated. It was concluded that elderly subjects appear to be the least efficient thermoregulators**.** It was also found that during early passive heating, there is a reduced skin blood flow response in older men (Pierzga, 2003). In (Anderson, 1996) it was found that peripheral thermosensitivity appears to be progressively attenuated with age, and elderly individuals are at a disadvantage with regard to defending against core temperature perturbations.

4.6 The aging effect diagram

In order to effectively implement the various effects of aging and their inter-relationship, Figure 2 was arrived at after review of literature which confirmed that aging does affect the performance of body organs including muscle, heart, central nervous system, and skin. As captured in Figure 2, loss of active muscle fiber due to aging leads to a reduction in the neural systems function and also the basal metabolic rate of the body. In principle this may lead to a reduction in the vasoconstriction and vasodilatation potential of the body which may compromise the shivering and sweating capabilities of the body, thus affecting the bodies comfort state. As outlined earlier in the literature review, aging effect on the heart may lead to a reduction in the cardiac output which is related to the blood perfusion capabilities of the body and this may also affect the shivering and sweating capabilities of the body.

Skin fragility identified as a result of aging may affect skin blood perfusion and the loss of skin glands which leads to a reduction in the sweating capabilities of the body. From the literature reviewed it came to light that as we age we eventually experience some loss of mental lucidity and independence as a result of aging. People 60 years and older could experience decline, in neural tissue, peripheral nerve cells and a reduction in impulse velocity which have the potential of affecting the neural control systems leading a reduction in the ability to sense and send timely signal which are needed to activate vasoconstriction and vasodilatation. This and others including the activity level of older persons which is affected by loss of muscle strength may compromise the comfort state of the body.

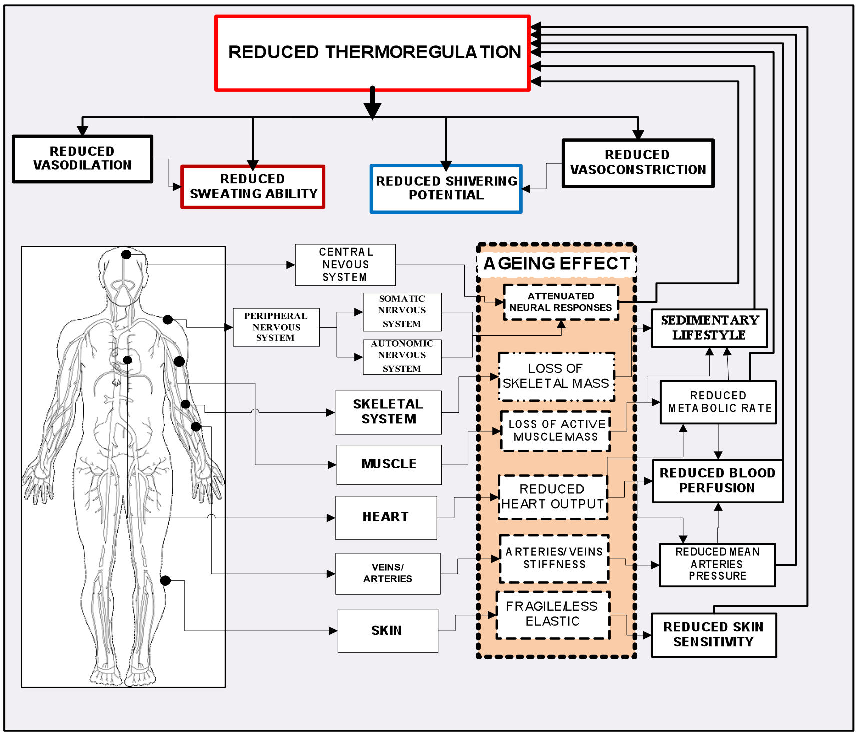

Figure 2 Aging effects on the human body and thermal physiology implications

5 Revised model

The first step to adapt the IESD-Fiala model for evaluating thermal comfort for the older population is to model a “typical” older person from the statistical data sourced from literature. In line with this, the 2050 world projected population figures (Holtz-Eakin, 2005) were used to determine the median age of the group between 65yrs – 100yrs. The calculated age was 75yrs, which served as the reference age of the older population in the extraction of data for the basal metabolic rate (BMR), cardiac output (CO) and body weight (BW), body surface area (BSA) and height (HT) in this study.

In this paper work done by Aub-Du Bois Figure 3 on BMR for humans as reported in (Bruen, 1930), (Henry, 2005), (Henry, 2000) was used for the extraction of the percentage depreciation with respect to age. Using the reference median age, data was extracted and compared with the existing value in the IESD-Fiala model which revealed a notable depreciation of 19.2%. Percentage depreciation on cardiac output extracted from (Brandfonbrener, 1955), Figure 4 was found to be (14.4%) compared with the average persons value. The mean body weight of a typical 75yrs old person was sourced from the data set of (Ogden, 2004) Figure 5. The resultant value represents 10% reduction compared to the IESD-Fiala model. The same research (Ogden, 2004) was used to establish the trend in age to height reduction. It was discovered that there was a slight decline in height with respect to age as shown in Figure 6. Percentage depreciation in height for the older person (75yrs) was (3.5 %).

In calculating the Body Surface Area (BSA), Dubois formula (DuBois, 1916) as stated in equation 1 was used and this can be traced to the IESD-Fiala model. The body surface area and the height are closely linked. With the new values for height and weight known a new body surface area was calculated. The resultant value represents 3.5% depreciation on the original value in the IEDS-Fiala model.

$$BSA(m^2) = 0.007184 \times weight\ (\text{kg})^{0.425} \times height\ (\text{cm})^{0.725} \quad (1)$$

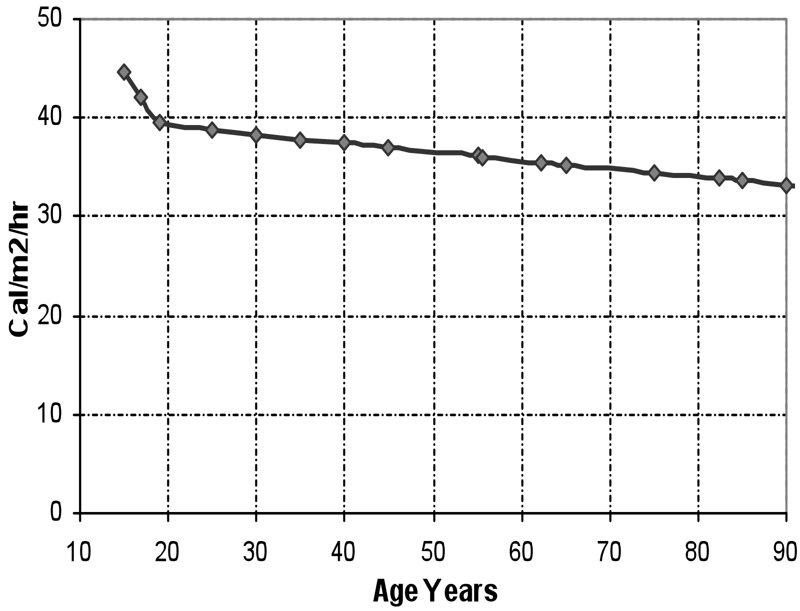

Figure 3 Age and Basal Metabolic Rate (BMR) (Bruen, 1930)

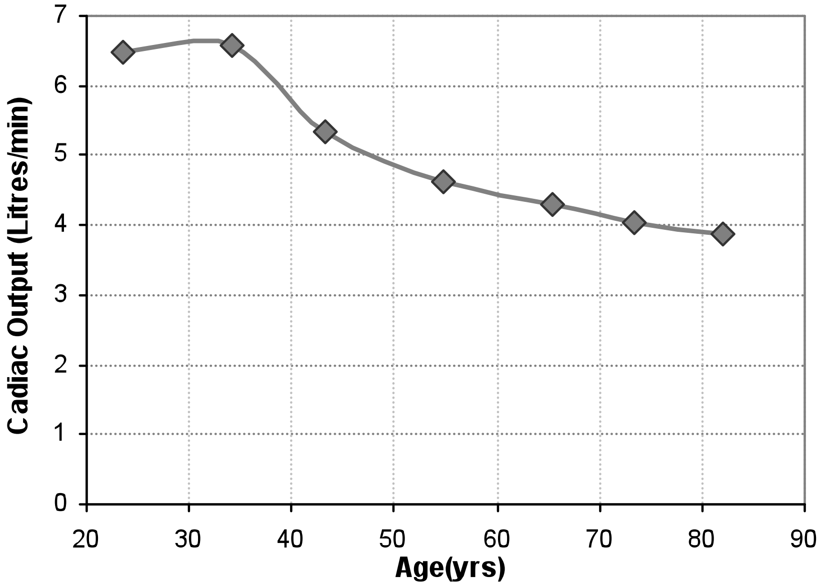

Figure 4 Age and Cardiac Output (CO) (Brandfonbrener, 1955).

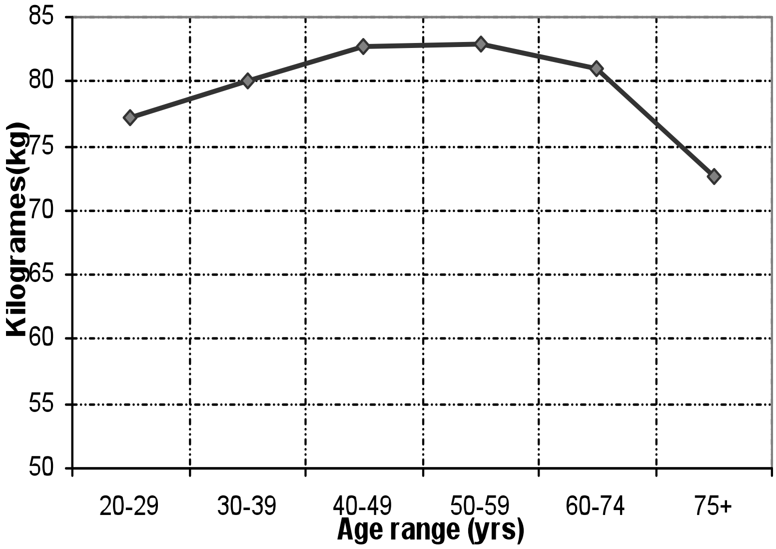

Figure 5 Age and Body Weight (Ogden, 2004)

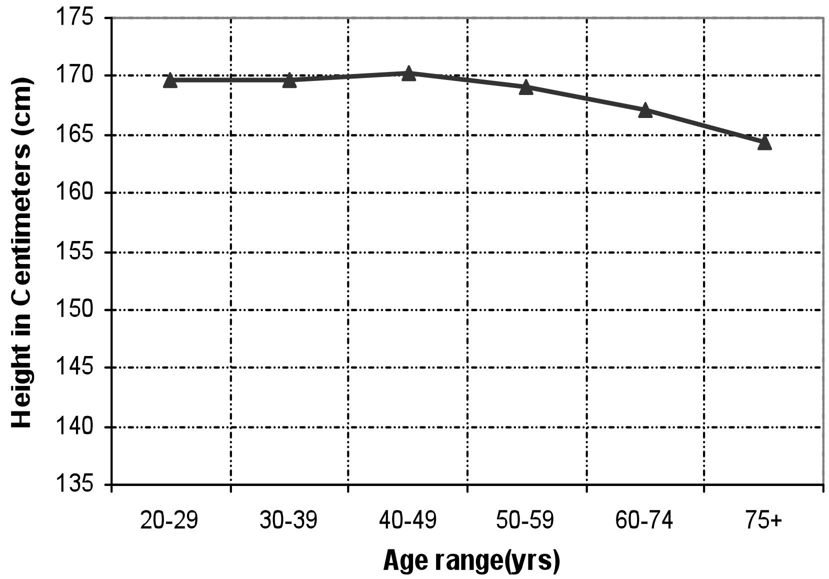

Figure 6 Age and Height (Ogden, 2004).

These values, as summarized in Table 1, were imported into the Fiala model where modifications were made for the transient simulation experiments to be carried out. The simulation was conducted using the Original Fiala model (FM) representing the average person and the older person's model (OP).

Item	**Typical person (Fiala model)**	**Typical old person (75yrs)**	**Change**
BMR (W)	87	70	-19.2%
Cardiac Output (L/min)	4.73	4.05	-14.4%
Body Weight (kg)	73.3	66	-10%
Height (m)	1.72	1.66	-3.5%
Body Surface Area (m2)	1.86	1.73	- 7%

Table 1 BMR, cardiac output, body weight, height and body surface area of a typical person and a typical old person

6 Transient environment experiment

A transient simulation was carried out using the original IESD-Fiala model (FM) and the model of an older person (OP) which is under development to compare the dynamic responses to changing thermal environments of hot, cold and hot i.e. (30-15-30)^{0}C. In this simulation a subject is assumed wearing only shorts relaxed for 90 min in a pre-test chamber at 24^0C dry bulb (Ta) with an air velocity (va) of 0.1m/s, relative humidity (RH) of 40% and activity level of 1.0 met. Immediately following this exposure, they were moved to the test chamber where the room temperature was set at 30^0C for 60min then changed to 15^0C for 120min and finally changed to 30^0C for another 60min. The test subjects' activity level was 1.1met and the relative humidity (RH) was 40%, air velocity (va) was (0.1) m/s. Figure 7 shows the test scenario.

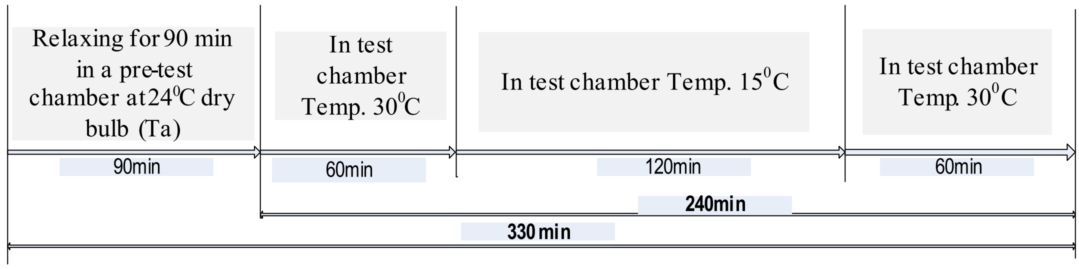

Figure 7 Simulation scenarios.

7 Results

Figure 8, 9, 10 and 11 show the skin temperature results from the transient simulation carried out. Four peripheral parameters were measured during the experiment i.e. hand (palm), foot, lower arm and lower leg. The difference in the temperature recorded at the hand (palm) Figure 8 shows that if an older person (75yrs) and a average person were exposed to the same conditions in the experiment, the difference in the temperature recorded at the hand (palm) at the beginning of the exposure (30) ^{0}C would be insignificant but is likely to increase after 30min. At 60min, the average person's temperature may be higher by 1^0C as compared to the old person. In the cold environment of 15^0C, there may be a lag in the older person's temperature. This may also be the case when the subjects move back into the condition of hot (30^0C).

Over the test period the difference in the temperature recorded at the foot Figure 9 was also lower in the older person than the average person. This was the same for the lower arm Figure 10 and the lower leg Figure 11. These parts of the body constitute the peripheral zones. The lag in the temperature of the older person to the typical person was pronounced at the change points of the test condition Figure 8. At the end of the simulation, all the parameters measured show that the older person's temperature was lower than that of the average person. These results of the older person is as a result of reduction in basal metabolic rate (BMR), cardiac output (C.O.), body weight (BW) body surface area (BSA) and height (HT).

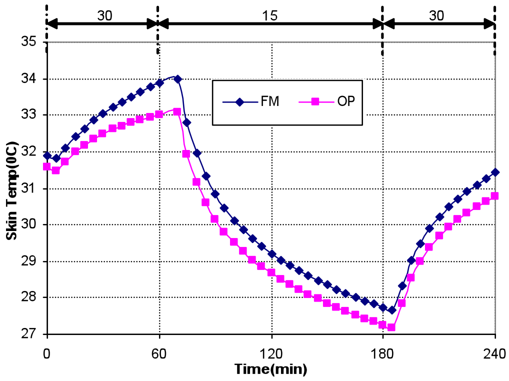

Figure 8 Hand (palm) skin temperature

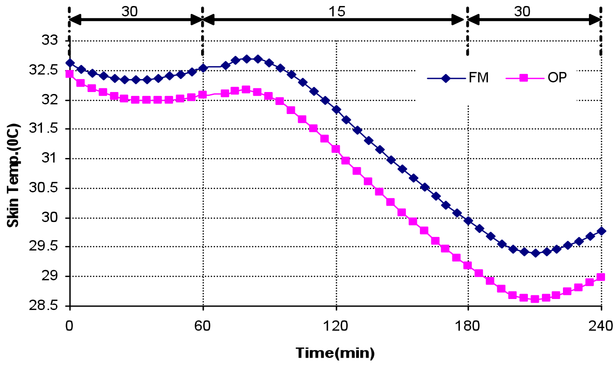

Figure 9 Foot skin temperature

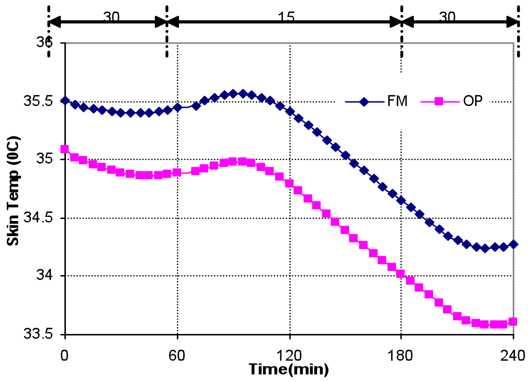

Figure 10 Lower arm skin temperature

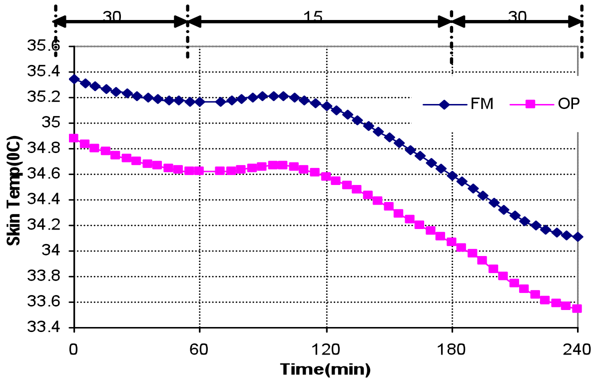

Figure 11 Lower leg skin temperature

8 Conclusion

As we seek to find new ways of improving the energy efficiency of our buildings and at the same time creating conducive internal environments which satisfy our thermal comfort needs, it is essential that the relationship between the human body and the aging factor is clearly understood. This may provide us with the opportunity to evaluate thermal comfort needs of specific groups of people. Aging as a natural phenomenon has effects on the capacity of the body ranging from changes in our organs to body functions. The study examined the effect age-related depreciation on the basal metabolic rate (BMR), cardiac output (CO), body weight (BW), body surface area (BSA) and height (HT). It started by reviewing literature on selected body parameters including, the musculoskeletal system, heart, skin and central nervous system. Statistical reduction in basal metabolic rate (BMR), cardiac output (C.O.), body weight (BW) body surface area (BSA), and height (HT) of the older population group (sourced from literature survey) and used to modify and exiting human thermoregulation model.

A transient computer simulation experiment was carried out to evaluate the reaction of the older person (new model) and average person (IESD-Fiala model) to a range of transient temperature's of (30-15-30)^{0}C. The results from the simulations suggest that under the test conditions skin temperatures on the hand (palm), foot, lower arm, and lower leg were lower in the older person than in the average person. This findings may lead credence earlier findings in literature(Inbar, 2004) that age related characteristics affect the overall rate of heat gain as well as the mechanisms through which this heat is dissipated and also (Anderson, 1996) peripheral thermosensitivity appears to be progressively attenuated with age. This study was the first stage of the developmental process of the new older person's model. Many other aspects of aging have not been considered in the present work, including fat content and thermoregulatory functions. In(Zhang, 2001) is was found that body fat influences both conduction heat transfer and blood flow. The impact of these factors will be investigated in future studies.

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