Coll. Antropol. **33** (2009) 2: 509–514
Original scientific paper

Comparison of Subjective and Objective Measurement of Sweat Transfer Rate

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A B S T R A C T

Sweat absorption is investigated using the subjective and objective methods. The subjective investigation analyses the physiological responses of male and female volunteers wearing two kinds of textile fabrics (cotton and polyester) during certain physical activity. The subjects were exposed to the different conditions of ambient temperature (23, 26, 29 and 32 °C) and constant relative humidity of 67 ± 3%. In the objective investigation the sweating guarded hotplate (SGHP) system was used that stimulates the processes of sweat transfer between the human skin, textile material and environment. The results of mass absorption obtained from the objective measurement on the sweating guarded hotplate show the similar trend as the results obtained during the subjective measurement.

Key words: *Sweat absorption, subjective measurement, objective measurement, infrared thermography*

Introduction

It is well known that the energy taken in a human body as food is such that only 15 to 30% is converted into useful work and the rest of 70 to 85% is wasted as heat. At any level of physical activity needed to maintain body temperature will result in an excess of heat energy and it must be dissipated. In order to maintain the thermal balance of the body there are four mechanisms that allow to lose heat to the environment. These mechanisms are: conduction, convection, radiation as well as evaporation. The clothing has the main role in the maintenance of heat balance because it modifies the heat loss from the skin surface. It plays a role in altering the moisture loss from the skin as well.

Heat transfer by sweat evaporation is always present, increasing in hot environmental conditions. If environment temperature increases, exceeding the values when the human being feels thermal comfort, hot skin starts to sweat secretion, causing a rapid increase in releasing body heat. Heat transfer by evaporation from the skin surface depends on the moisture quantity and the difference between the pressures of water vapour on the skin and in the environment.

The evaporative cooling is the main mechanism of the heat regulation in hot environmental conditions. The sweat is produced by the accrine sweat gland that is located almost over the entire body surface, but its flow is variable among body segments. A number of studies is related to the investigation of sweat secretion for different body parts[1–3].

A number of studies take into consideration textile layer and the influence of textile material to the changes of sweat secretion. Tests of a clothing thermal insulation were carried on a standing person and on a manikin under wind-free conditions with three ensembles of disposable medical clothing[4]. The results indicated that the measurements taken on the manikin were considerably more accurate. Wang et al. investigated the comfort of shirts made of different raw material using the wear trials and the forearm test[5]. It has been shown that wool and wool blends are less comfortable and in high-temperature environments the prickle increases. Gavin et al. compared the influence of fabrics that should enable better sweat transport and traditional fabrics to the thermoregulation during exercise in moderate heat[6]. It has been concluded that there is no difference in body physiologic parameters (mean body temperature, rectal, skin temperature and heart rate) or comfort sensation among different textile materials.

Theoretical part

The properties of human skin will vary over different body parts and change with time. They differ from sub-

Received for publication July 22, 2008

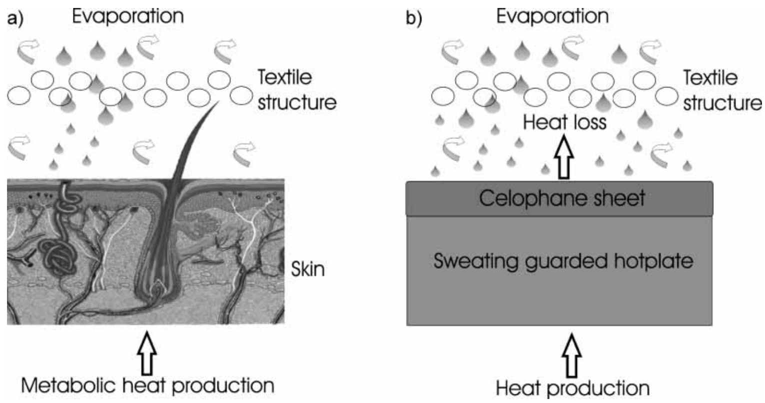

Fig. 1. Heat and vapour transfer a) through skin and fabric b) the sweating guarded hotplate principle.

ject to subject. Contrary to these differences, the skin has a common structure in human beings and in most cases it is similar in its function (Figure 1). The special structure of several partial skin areas depends on skin function. Human skin is composed of three primary layers: epidermis, dermis and hypodermis (Figure 1a). Under the dermis layer there is a fatty layer called panniculus adiposus.

Skin plays a basic role in the homothermic function of maintaining the internal body temperature of about 37 °C. If the whole body becomes too hot, the blood flows through dermis and through epidermis to the outer skin surface. If heat loss is higher than sweating skin surface, then remaining evaporative heat may get lost by evaporation. Local skin heating may cause blood vessel enlargement and sweating.

The functional role of clothing is to keep the body in an acceptable thermal state in different thermal environments. The factors affecting thermal garment behaviour will include dry thermal insulation, humidity transfer and evaporation through the garment (e.g. sweat, rain), heat exchange (conduction, convection, evaporation, radiation), compression (e.g. strong winds), air penetration and body postures[7].

The dry heat loss (*HDRY*) from the human body surface to the environment could experimentally be determined on the basis of the thermal balance equation. The equation is[8,9]:

$$H_{DRY} = C + R = M - W - E_{sk} - E_{res} - Cres - S \qquad (1)$$

where H_{DRY} is dry heat loss, C is convective heat loss, R is radiative heat loss, M is metabolic heat production, W is external work rate, E_{sk} is evaporative heat loss rate, $E_{res} + C_{res}$ is evaporative and convective respiratory heat loss rate, S is body heat storage rate.The evaporative heat loss E_{sk} from a subject can be calculated according to the following formula[10]:

$$E_{sk} = \frac{3{,}06}{A_{Du}} \cdot 10^{-3}\left(256 \cdot \overline{T_{sk}} - 3360 - p_a\right) \qquad (2)$$

where E_{sk} is evaporative heat loss, A_{Du} is DuBois area, T_{sk} is skin temperature, p_a is the water vapour pressure in ambient air.

The loss of heat due to the respiration $E_{res} + C_{res}$ could be calculated using the following equation[11]:

$$C_{res} + E_{res} = 0.0014 \cdot (34 - T_a) + 0.0173 \cdot M \cdot (5.87 - p_a) \qquad (3)$$

where $E_{res} + C_{res}$ is heat loss due to the respiration, M is metabolic heat production, T_a is air temperature, p_a is ambient pressure.

Material and Methods

Subjective measuring techniques can be useful for measuring thermal body loads. Under these environmental conditions, a subject's ability to judge rationally may affect the results. The subject's body wants to keep as high heat as possible, and the body wants to dispose of the remaining heat based on psychological characteristics. The common approach to heat is when the subject is highly motivated to keep the heat in relation to the environment.

The investigation of evaporation trough textile fabric was carried out using two types of knitted fabrics:

1. 100% cotton single jersey fabric and
2. 100% polyester single jersey fabric.

The weight of fabrics is 148 g/m^2 and the thickness 0.4 mm. Such fabrics are commercially used for the production of underwear or different types of next-to-skin-wear and are in direct contact with the human skin. The investigated fabrics have similar constructional parameters (horizontal density is 15 loops per 1 cm and vertical density 18 loops per 1 cm) and are produced on the same knitting machine under the same conditions. In the second phase of material preparation, the fabrics were used to produce T-shirts in two sizes for males and females.

The measurements related to the transfer of water vapour were carried out using the objective measuring method, as well as the subjective method with human participants. For the objective measurement of water vapour resistance the sweating guarded hotplate was used. It has the ability to simulate the heat and moisture (sweat) transfer processes which occur next to human skin[12,13]. The device consists of a plate heated to a constant temperature matching the human skin temperature, i.e. 35 °C. The test section is in the centre of the plate, surrounded by the guard and lateral heater that prevents heat leakage[14]. The fabric sample is placed on the plate surface and the heat flux from the plate to the environment is measured. During the measurement of evaporative resistance, distilled water is fed to the surface of the plate. The plate is fitted by a cellophane sheet that is water vapour permeable and liquid impermeable and therefore simulates the skin and the processes that occur on its surface[15]. The sweating guarded hotplate principle is shown in Figure 1b. In order to obtain the differences in masses due to sweating, the fabrics were weighed before and after the experiment.

The sweating guarded hotplate is, according to many researchers, recognized as the most accurate technique for the determination of thermal properties, but it still has some limitations. The results obtained using the hotplate cannot be directly applicable to the clothing because it ignores the body surface area covered by textiles, the distribution of textile layers on the body, the clothing fit, variations in the temperature on different parts of the body and the effect of body position and movement[16].

Therefore, the test with volunteers was carried out in order to correlate the results obtained using the sweating guarded hotplate to the real-life situations. Eight volunteers (4 men and 4 women) participated in this experiment. Their physical characteristics including weight, height DuBois area and age are shown in the Table 1.

Subjects participating in the study were in good physical condition and were informed of the test procedures and possible risks. The subjects were requested to consume normal amounts of fluids on the day prior to the experiment and to take 0.5 litre of natural water 30 minutes before the experiment. Participants were not allowed to drink liquid during the exercise protocol. The exercise protocol was chosen to mimic the work of an industrial setting. During the experiment, the subjects were dressed in long trousers, socks, snickers and they changed the T-shirts. The systolic and diastolic blood pressure, as well as the heart rate was monitored before and after the activity. For both objective and subjective experiment four ambient conditions were defined. For all the conditions the relative humidity was kept constant at 67 ± 3%, while the temperature changed as follows:

- condition I: 23 ± 1 °C
- condition II: 26 ± 1 °C
- condition III: 29 ± 1 °C and
- condition IV: 32 ± 1 °C.

In the preparatory period, the subjects were dressed and left to relax in the chamber with the conditions defined. The weight of the T-shirts was measured before and after the end of the experiment.

The measurement with infrared camera

Thermal or infrared (IR) energy is radiation between 1 and 100 microns, at the wave lengths that are longer than the red part of visible light and shorter than microwaves. It is a non-visible light because its wavelength is too long to be detected by the human eye. Infrared thermography is the method of the use of an infrared imaging and measurement camera to »see« and »measure« thermal energy emitted from an object. The camera is a non-contact device which detects infrared energy (heat) and converts it into an electronic signal, which is processed to produce a thermal image on a video monitor and perform temperature calculations. In this paper an infrared camera was used to measure the temperature differences on the next-to-skin knitted fabric. The camera used has the following characteristics: type Flir P65, temperature sensitivity 0.08 °C at 30 °C, space resolution 1.3 mrad, detector Focal Plane Array (FPA), microbolometer 320 × 240 pixels, range resolution 7.5 to 13 μm.

Results

The summary of the physiologic measurements includes the systolic and diastolic blood pressure (BP) as well as the heart rate. The mentioned physiological parameters were measured both before and after the experiment. The summary of measurements is shown in Table 2.

In Figures 2 and 3 the changes in masses per one square meter of shirt (measured during subjective inves-

TABLE 1
PHYSICAL CHARACTERISTIC OF THE SUBJECTS

Subject	Sex	Body mass, kg	Height, m	DuBois area, m^2	Age, years
S1	M	90.0	1.69	2.00	52
S2	M	77.5	1.70	1.89	52
S3	M	80.0	1.73	1.94	49
S4	M	82.0	1.75	1.98	49
S5	F	52.5	1.62	1.54	30
S6	F	57.0	1.66	1.62	30
S7	F	55.0	1.65	1.60	30
S8	F	57.0	1.60	1.59	30

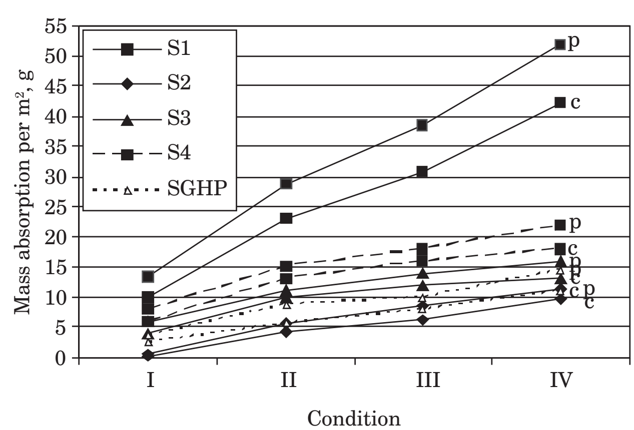

Fig. 2. Mass absorption per m^2 for male volunteers and sweating guarded hotplate.

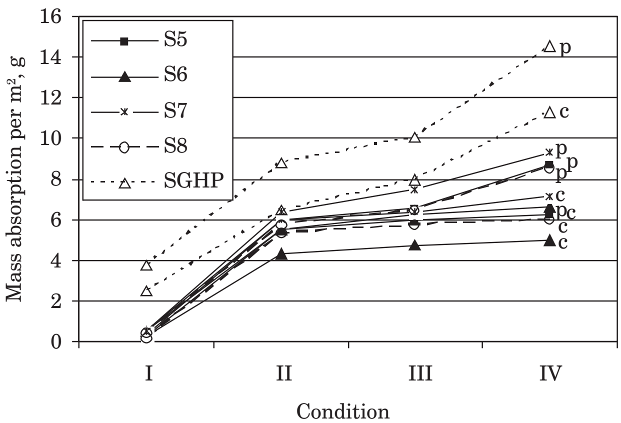

Fig. 3. Mass absorption per m^2 for female volunteers and sweating guarded hotplate.

tigation) and fabric (measured during objective investigation) are given. Figure 2 shows the results of measurement for male volunteers (S1, S2, S3 and S4) and sweating guarded hotplate (SGHP), while Figure 3 shows the results for female volunteers (S5, S6, S7 and S8) and sweating guarded hotplate (SGHP). Different materials are assigned as »c« for cotton and »p« for polyester.

Four typical temperature points for the volunteer S1 worn polyester T-shirt in ambient condition II (t=26 ± 1 °C, RH=67 ± 3%) are shown in Figure 4. As seen from Figure 4 (ambient temperature Sp1 is 26.9 °C, head temperature Sp2 is 34.1 °C, point of the lowest temperature Sp3 is 28.1 °C) the point of the highest temperature Sp4 is 32.4 °C.

Digital camera was used for the presentation of the volunteer S1 that wore polyester T-shirt in ambient con-

TABLE 2
THE SUMMARY OF THE PHYSIOLOGIC MEASUREMENTS FOR MALE VOLUNTEERS

Subject	Ambient condition	Fabric (c-cotton p-polyester)	Systolic/ diastolic blood pressure (mm Hg)		Heart rate before/after experiment (beats/min)
			before experiment	after experiment	
S1	I	c	144/91	160/101	73/75
		p	149/98	166/101	71/83
	II	c	174/112	187/117	81/85
		p	157/109	158/110	85/88
	III	c	128/95	136/97	76/81
		p	141/96	151/98	75/78
	IV	c	143/111	153/119	80/87
		p	165/105	166/110	78/91
S2	I	c	135/81	139/84	85/89
		p	119/79	126/83	80/96
	II	c	133/67	139/72	68/69
		p	129/70	132/74	71/72
	III	c	122/76	127/77	81/87
		p	104/69	114/79	75/85
	IV	c	137/75	153/77	71/83
		p	122/81	127/85	78/91
S3	I	c	120/75	125/76	80/90
		p	128/81	130/83	75/83
	II	c	130/72	133/74	77/82
		p	135/70	136/72	74/83
	III	c	128/75	133/77	77/81
		p	120/72	127/73	81/83
	IV	c	115/70	117/72	85/88
		p	118/70	125/70	84/90
S4	I	c	142/90	144/91	83/85
		p	144/92	145/93	81/88
	II	c	137/85	140/88	75/81
		p	135/84	142/88	73/77
	III	c	141/90	150/98	71/73
		p	144/91	150/90	70/77
	IV	c	140/90	148/92	81/84
		p	144/91	149/93	82/88

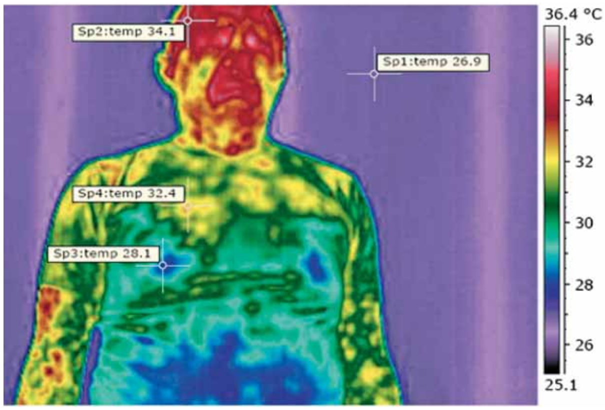

Fig. 4. Some typical points in ambient condition II in infrared light.

dition I (t=23 ± 1 °C) and ambient condition IV (t=32 ± 1 °C), both in visible light (Figure 5). Sweat absorption area on the T-shirt, being the area of increased sweating is represented crosshatched.

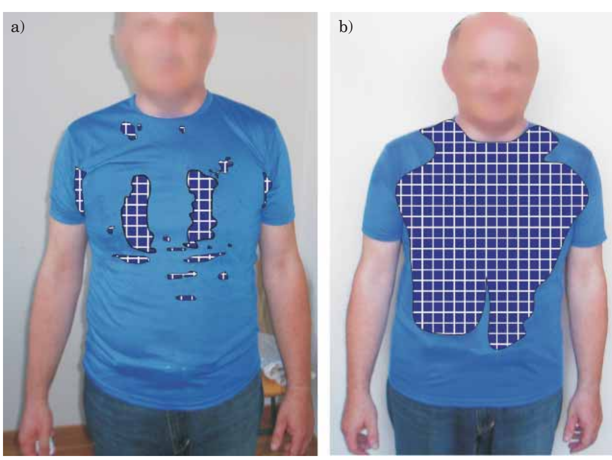

Fig. 5. The crosshatched zones of the wet fabrics in visible light a) ambient condition I , b) ambient condition IV.

Discussion and Conclusions

The male volunteers that participated in the experiment are of the similar age (49–52 years) and height (1.69–1.75 m), but have different weight (S1 90.0 kg, S2 77.5 kg, S3 80 kg, S4 82 kg). The shirt was tighter for the volunteer S1 and the air convection between the body and garment was limited in comparison to the convection for the volunteers S2, S3 and S4.

Figure 2 shows that the mass absorption for each textile material is significantly higher for the volunteer S1. If the influence of the raw material is taken into consideration, it has been confirmed that there was intensive sweating and mass absorption when the volunteers wore the polyester shirt.

By increasing the ambient temperature from 23 °C to 32 °C the sweating of male volunteers (S1–S4) and female volunteers (S5–S8) can be observed in measuring the absorbed sweat in the knitted fabric (Figure 2–3). Higher sweating was obtained in volunteer S1. Absorption values for condition I (t=23 ± 1 °C) and IV (t=32 ± 1 °C) in male volunteer S1 for the cotton knitted fabric is 10.0 g/m^2 and 42.3 g/m^2 respectvely, and for polyester it is 13.5 g/m^2 and 51.9 g/m^2 respectively. Sweat absorption for condition I and IV for male volunteers S2, S3 and S4 when wearing both cotton and polyester knitted fabric is significantly lower. When using the objective measurement of absorption and using the SGHP instrument, the absorption values obtained are very similar to the male volunteers S2 and S3. Less sweating of female volunteeers and thus less sweat absorpton was obtained at an ambient temperature of from 23 °C to 32 °C and a relative humidity of 67 ± 3%. Absorption values as well as sweat values are less distinctive in female volunteers.

The results of objective and subjective measurement indicate more intensive sweating and mass absorption when the volunteers wore the polyester shirt. The thermographic image of volunteer S1 presented in Figure 4 shows the points of the lowest and highest upper body temperature. If compared to the images obtained using the IR camera in visible light, it could be concluded that the point of the lowest body temperature (Sp3) refers to the area where the fabric is intensively wetted, while the point of the highest body temperature (Sp4) refers to the area of dry fabric.

Figure 5 shows the comparison of sweating in the ambient temperature with lowest and highest temperature. It is well seen that the zones of intensive sweating in the lowest ambient temperature are the under arm and chest. In the highest ambient temperature, the sweating zone is spread through the whole upper part of the body except the part of shoulders and upper arm. The sweat absorption on the shirt in the part of the lower front part is not visible because the trousers were under the shirt that absorbed the sweat and enabled its transfer to the upper textile layer.

In the warm ambient conditions, the body adapts itself by increasing the rate of sweating. In such conditions, the important function of clothing material is to regulate the transfer of sweat from the skin surface to the environment. Therefore, the ability of textile material to manage the process of sweat transfer is a significant property that affects the subjective feeling of human comfort.

On the basis of the discussion, it could be concluded that the results have clearly shown that the moisture absorption of investigated fabrics depends on the environmental conditions as well as on the moisture regain of the fibers (defined regain for cotton is 8% and for polyester 0.5%). It is well known that the hydrophilic cotton absorbs moisture intensively that the hydrophobic polyester. At the same time, the transport of moisture from the skin through underwear to the outher layer of clothing is much better if wearing the cotton fabric, too. Therefore, the intention was not to confirm the well known fact, but to define the differences in sweat rate wearing cotton and polyester. At the beginning of subjective investigation, the volunteers didn't perceive the difference between the two materials, but after the investigation they reported the sensation of higher skin wettednes in polyester shirt. They also described the sensation wearing polyester shirt using the terms dampy, clingy and less comfortable.

The aim of the paper was to compare the sweating rate obtained using the objective measuring methods (in this paper the sweating guarded hotplate apparatus) and using the subjects that performed certain activity.

The future experiments related to this topic may be focused at subjective investigation only. In order to evaluate the subjective sweating sensation, the questionnaries with subjective rating scales for moisture and thermal sensation should be given to the subjects before and after the activity.

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USPOREDBA SUBJEKTIVNIH I OBJEKTIVNIH METODA MJERENJA INTENZITETA ZNOJENJA

SAŽETAK

Apsorpcija znoja istraživana je koristeći subjektivne i objektivne metode. Subjektivnim metodama istraživani su fiziološki pokazatelji muških i ženskih volontera odjevenih u dvije vrste pletene odjeće (pamučna i poliesterska) tijekom određene fizičke aktivnosti. Volonteri su izloženi različitim temperaturama okoline (23, 26, 29 i 32 °C) i konstantnoj relativnoj vlažnosti od 67 ± 3%. U objektivnoj metodi mjerenja korišten je tzv. sustav vruće ploče (engl. Sweating guarded Hot Plate – SGHP) koji mjeri procese prijelaza znoja između čovjekove kože, tekstilnog materijala i okoline. Rezultati apsorpcije znoja dobiveni objektivnom metodom mjerenja na vrućoj ploči pokazuju sličan trend kao i rezultati dobiveni tijekom mjerenja subjektivnom metodom.