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Impact of Fabric Moisture Transport Properties on Physiological Responses when Wearing Protective Clothing

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Abstract This purpose of this study was to investigate the impact of fabric moisture transport properties (MTP) on physiological responses when wearing protective clothing. Ten healthy subjects wore two kinds of personal protective equipment (PPE) ensembles and exercised on a treadmill, worked on a computer, and moved a mannequin in an environment that simulated where health carers work. PPE1 consisted of cotton underwear and 100% polyethylene outerwear. PPE2 consisted of cotton underwear with moisture management function and outerwear made of waterproof breathable fabric. The results showed that there were significantly higher cumulative one-way transport capacity, liquid moisture management capacity, and wetting time in PPE2 than in PPE1 underwear. There was significantly higher water vapor permeability (WVP) in PPE2 than in PPE1 outerwear. Deep ear canal temperature, mean skin temperature, and chest wall skin and clothing microclimates (temperature and humidity) were significantly lower with PPE2 than PPE1. The level of plasma oxygen saturation was significantly higher with PPE 2 than PPE1. In the present study, due to the MTP of the fabrics, liquid sweat transferred from the skin surface to the opposite surface quickly and speeded up the processes of evaporation and heat dissipation. It was concluded that the fabric's MTP, when incorporated into protective clothing, is the main physiological mechanism for reduced heat stress.

Key words fabric moisture management properties, clothing microclimates, deep ear canal temperature, mean skin temperature, plasma oxygen saturation, water vapor permeability

Studies on moisture transfer in clothing have indicated that liquid water and moisture vapor transfer can play important roles for perceived comfort [1, 2]. As part of the physiological regulation of body temperature, the cooling effect of

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evaporation by perspiring, makes use of the very large heat of vaporization of water. Every gram of water evaporated is equivalent to the loss of 2.4 kJ [3]. In the clothing microclimates between the skin of the chest wall and the clothing, absorption of sweat by the garment and its transportation through the fabric, where it then evaporates, are related to the perception of clothing comfort [1]. The different water absorbing and water transporting properties of textiles have been shown to produce differences between hydrophilic and hydrophobic materials in the amount of sweat accumulated [4]; different kinds of fiber used in the composition of underwear [5, 6] and the various clothing layers [7] are important also. According to Bakkevig and Nielsen [6], the distribution of accumulated sweat in a clothing ensemble after heavy sweating depended on the kind of fabric used in the underwear. These differences may alter thermoregulatory responses, thermal strain, and thermal comfort during work and rest periods.

Furthermore, Li observed that the perception of dampness was positively correlated with relative humidity in the clothing microclimate. The perception of comfort was negatively related to the perception of dampness [8]. Nielsen and Endrusick recommended the use of the subjective sensations of wetness of skin and clothing as a sensitive tool to evaluate the thermal function of garments [9]. Therefore, fabric liquid moisture transport in fabrics plays an extremely important role in garment comfort [10].

Fabric liquid moisture transport properties (MPT) in multi-dimensions, called moisture management properties (MMP), influence the human perception of moisture sensations and comfort [1]. In order to improve the comfort of clothing, there is a need to investigate the liquid MMP. A new piece of experimental apparatus, called a moisture management tester (MMT), was developed by Hu et al. [1] and used to measure the behavior of dynamic liquid and moisture transfer in clothing materials and to characterize the MMP of textiles. Hu et al. [1] reported that the subjective perceptions of moisture after sweating (those of "clammy" and "damp") significantly correlated with the fabric's MMP. However, the relationship between MTP and thermoregulatory responses in medical carers, working in hospitals and other areas of infection control, remains to be studied systematically.

In the present study, we have focused on evaluating effects of fabric MTP on heat stress in healthy young volunteers wearing two different kinds of protective clothing ensembles. One is a commercially available ensemble of the type used in the avian influenza outbreak and in the SARS isolation ward during 2003 in Hong Kong; the other is a newly devised ensemble with moisture management fabric and a respirator with exhaust valves. The main objective of the present study was to clarify the physiological role of MTP by investigating how two different kinds of protective clothing ensembles, with different MTP, could influence thermoregulatory responses in a controlled intervention trial of multiple cross-over design upon health carers in a simulated working environment. This knowledge may contribute to clothing physiology and to the design of protective clothing.

Methods

Participants

The experimental protocol was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University prior to beginning the experiment. The participants gave informed consent to take part in this study.

The participants were 20- to 24-year-old healthy males (five) and females (five), and all were nursing students. They were recruited from the School of Nursing, The Hong Kong Polytechnic University. The physical characteristics (mean ± SD) were: 22.4 ± 0.55 years of age, 171.8 ± 3.42 cm height, 61.08 ± 4.72 kg body mass, 1.68 ± 0.08 m^2 body surface area, in the male subjects; and 22 ± 1.41 years of age, 157.4 ± 5.22 cm height, 47.17 ± 3.18 kg body mass, 1.41 ± 0.06 m^2 body surface area, in the female subjects.

Personal Protective Equipment tested

Two kinds of PPE ensembles were used as experimental clothing:

1. PPE1: 100% polyethylene barrierman, a commercially available pure cotton surgical scrub suit worn inside barrierman (S1), an N95 respirator (3M 1860) (3M Canada Company), and a disposable face shield;
2. PPE2: a waterproof breathable protective gown with a head cover, a surgical scrub suit worn inside gown (S2), and a respirator with exhaust valves and ventilation pipes (respirator A).

In PPE2, the S2 fabric was treated to allow moisture to be transferred away from the skin to the surface of the garment, where it could evaporate quickly to keep the body dry and comfortable [1]. Respirator A was worn inside the head cover to provide an independent breathing system through exhaust valves and ventilation pipes situated at the back. The length of each pipe was 42 cm. One end of each pipe was connected to inhalation valves, and the other was covered by a filter (made from the fabric used in a surgical mask) and protruded outward from the opening of the gown. The exhalation valves opened to release exhaled air and closed during inhalation. The inhalation valves performed in the opposite way, being open during inhalation and closed during exhalation. The air passed through a filter within the pipes and then entered the respirator through two ventilation pipes and inhalation valves.

Figure 1 The two kinds of PPE ensemble used. Left: PPE1; Right: PPE2.

Table 1 PPC evaluated.

PPC	Fabric code	Manufacturer or Source	Fiber	Construction
S1	A	Dongfeng*	100% cotton	Woven
S2	B	Polyu**	100% cotton	Woven
Barrierman	C	DuPont Tyvek	Polyethylene	Nonwoven
Protective gown with a head cover	D	Polyu**	waterproof breathable fabrics	Woven

*Henan Dongfeng Shangshui Health Product Company of China (Dongfeng).
**Hong Kong Polytechnic University

In addition, the participants wore gloves and polypropylene shoe covers in the PPE trials. Those used in PPE1 are commercially available and those used in PPE2 were newly designed. Figure 1 illustrates the two ensembles used in the experiment. Clothing fabrics were evaluated (Table 1) and their physical properties are listed in Table 2. The underwear fabrics of PPE1 and PPE2 were designated as Fabric A and Fabric B, respectively. The outerwear fabrics of PPE1 and PPE2 were designated as Fabric C and Fabric D, respectively. Before testing the physical properties of the clothing fabrics, all garments and samples were laundered and air-dried to remove any chemicals in the textiles.

Moisture Management Measurements

By means of the MMT developed by Hu et al. [1], four kinds of fabrics from two layers of both PPE ensembles were tested.

All testing occurred in an air-conditioned room (temperature of 21 ± 1°C and a relative humidity of 65 ± 2%) according to the American Society for Testing and Materi-

Table 2 Mean fabric physical characteristics.

Fabric		Fabric weight (gm/m^2)	Fabric Thickness (mm)	Fabric count (yarns per inch) (warp, filling)		Moistur regain (%)	Air permeability (cc/s/cm^2 at 100pa)	Thermal conductance (w/m^2.k)
A	Mean	146. 40	0.40	54.90	69.30	7.76	45.83	0.051
	SD	1.83	0.008	1.19	2.79	0.57	2.34	0.003
B	Mean	209. 80	0.78	63.20	62.00	6.19	22.01	0.07
	SD	0.42	0.013	3.16	2.31	0.52	0.99	0.001
C*	Mean	45.20	0.29	N/A		0.09	0.26	0.044
	SD	0.15	0.013	N/A		0.05	0.06	0.008
D	Mean	121. 80	0.28	52.40	66.50	2.41	0.03	0.048
	SD	0.42	0.006	0.52	0.85	1.15	0.01	0.002

*Nonwoven fabrics. Others are woven.
N/A: Not available

als (ASTM) D1776 [11]. For each kind of fabric, ten pieces were cut (90 × 90 mm squares), washed in an ultrasonic cleaner, and ironed to remove any excessive water and wrinkles. The specimens were then stored in the air-conditioned room for at least 24 h. To simulate sweating, a special solution (synthetic sweat) was introduced onto the fabric's top surface during the test, prepared according to the standard American Association of Textile Chemists and Colorists (AATCC) 15 [12]. During the tests, the same quantity of solution (0.15 g) was injected automatically onto each specimen's top surface by the MMT. Ten indices were used to determine the fabric's MMP [13].

In order to interpret the values of the indices more easily, an improved test method was developed [14]. In this method, the indices can be graded and converted from value to grade based on a five grade scale (1–5). The five grades of indices represent: 1 – poor, 2 – fair, 3 – good, 4 – very good, 5 – excellent. Also, an overall evaluation of fabric character was given [14].

The connection between grades and numerical values of ten indices are presented below [13, 14]:

1. Wetting time *WTt* (top surface) and *WTb* (bottom surface): Grade 1: ≥ 120, no wetting; Grade 2: 20–119, slow; Grade 3: 5–19, medium; Grade 4: 3–5, fast, and Grade 5: < 3, very fast.
2. Maximum absorption rates *MARt* (top surface) and *MARb* (bottom surface): Grade 1: 0–10, very slow; Grade 2: 10–30, slow; Grade 3: 30–50, medium; Grade 4: 50–100, fast, and Grade 5: > 100, very fast.
3. Maximum wetted radii *MWRt* (top surface) and *MWRb* (bottom surface): Grade 1: 0–7, no wetting; Grade 2: 7–12, small; Grade 3: 12–17, medium; Grade 4: 17–22, large, and Grade 5: > 22, very large.
4. Spreading speeds *SSt* (top surface) and *SSb* (bottom surface): Grade 1: 0–1, very slow; Grade 2: 1–2, slow; Grade 3: 2–3, medium; Grade 4: 3–4, fast, and Grade 5: > 4, very fast.
5. Cumulative one-way transport capacity (*OWTC*): Grade 1: < 50, poor; Grade 2: 50–100, fair; Grade 3: 100–200, good; Grade 4: 200–400, very good, and Grade 5: > 400, excellent.
6. Overall moisture management capacity (*OMMC*): Grade 1: 0–0.2, poor; Grade 2: 0.2–0.4, fair; Grade 3: 0.4–0.6, good; Grade 4: 0.6–0.8, very good, and Grade 5: > 0.8, excellent.

Water Vapor Permeability Measurements

A WVP test was used to determine the rate of water vapor diffusion through the specimen [15]. Fabric samples were conditioned for at least 24 hours in standard atmospheric conditions before testing, according to ASTM D 1776 [11]. For each kind of fabric, ten specimens were tested in accordance with ASTM E96 [16]. The specimen under test was sealed over the open mouth of a dish containing water and placed in the standard testing atmosphere. After a period of time to establish equilibrium, successive weighings of the dish were made and the rate of water vapor transfer through the specimen was calculated.

Physiological parameter measurements

Deep ear canal temperature was measured using an ear cuff probe (Nikkiso-YSI, Japan) inserted into the canal of the left ear, the canal being heavily insulated by cotton wool to avoid influence of the surrounding air temperature. With these precautions, it was considered that the measured temperatures would reflect tympanic membrane temperature relatively closely. Skin temperatures were measured with temperature probes attached at four sites at: chest (T_{chest}), upper arm ($T_{upper\ arm}$), upper leg ($T_{upper\ leg}$), and lower leg ($T_{lower\ leg}$) [17]. The clothing microclimate (temperature and humidity) between the chest wall skin and clothing (at sites level with those used to measure chest wall skin temperature) were measured by a temperature probe (Nikkiso-YSI, Japan) and a humidity sensor (Osaka, Japan). All temperatures were recorded continuously and temperature readings were stored in the data logger LT-8A (Nikkiso-YSI, Japan) every min, and then sampled by a computer through a converter. Humidity was recorded continuously and humidity readings were stored in a thermal recorder (Especmic, Japan) every min, and then inputted into a computer. Heart rate was measured every min by a Polar Heart Rate Monitor (Polar Electro, U.S.A). Blood pressure and plasma oxygen saturation (SpO_2) were measured: before and after morning exercise on the treadmill; after working at the computer and moving a mannequin during the morning; after lunch; after afternoon exercise and working at the computer; and before the end of the trials. A Critikon Dinamap Compact Blood Pressure Monitor (Model C071) was used.

Prior to the study, each subject underwent the Polar Fitness Test on a motor-driven treadmill to estimate individual maximal aerobic power and to enable prediction of maximum heart rate value, using the Polar Heart Rate Monitor (S 810i^{TM}). The 4 km/h intensity of exercise and 25 min work times on the treadmill twice a day were chosen as workloads which were similar to those experienced in the hospital ward, and represented approximately 23% of maximum work capacity for the subjects while not wearing protective clothing (as calculated from the initial maximal exercise tests) [18].

Experimental protocol

A rigid procedure was followed to standardize the initial heat content of the experimental clothing, thus eliminating this as a factor of variation for heat exchange during the experiment. The clothing and respirators were stored in the experimental laboratory (T_a = 25 ± 1°C, RH = 60 ± 3 %) for at least 2 h before the experimental procedure began. In this controlled human intervention trial concerning physiological effects of protective clothing, each of the 10 subjects completed 7 hours of standardized activities on each of two separate days, these activities having been designed to simulate hospital/health care work.

On a study day, each participant wore, in randomized order, one of two kinds of protective clothing and was equipped with the sensors to measure temperature, humidity, heart rate, and blood pressure (see above) before 10:00 a.m., after having voided his or her bladder completely. Deep ear canal temperature, skin temperatures at four sites, clothing microclimates (temperature and humidity), heart rate, blood pressure, and plasma oxygen saturation were measured from 10:00 a.m. onwards. After 20 min in the sitting position (R1), the subjects exercised on the treadmill for 25 min at a level walking speed of 4 km/h (E1). They then worked at set tasks on a computer station (to print a paper and simulate healthcare workers dealing with medical documents) for the next 60 min (C1). Then the subjects moved a mannequin (to simulate helping a patient) and walked at their own pace 20 times across the room (about 10 m per traverse). Breakfast and lunch were provided before 10:00 a.m. and 1:00 p.m., respectively. Food and water intake were strictly controlled to be equal for each volunteer on each occasion.

After lunch the volunteers rested until 2:00 p.m. Then, they repeated the exercise and computer tasks (E2 and C2). The subjects then took off the protective ensemble at 5:00 p.m. after resting (R2). Therefore, each type of protective clothing was worn by each participant for 7 h during the course of the study. It should be noted that, in PPE 1 and 2 ensembles, the head cover and face shield were worn for only 1 h in the morning and 1 h in the afternoon, when performing exercises and working on the computer. The respirators were removed during lunch and R2. There was an interval of 3 days between the 2 study days.

Calculations and statistical analysis

In order to obtain satisfactory data of skin temperature, the Ramanathan method was used in our experiment, because in this method, the skin temperature measurement at chest, upper arm, upper leg, and lower leg would not affect the subjects' activities [17, 19]. The mean skin temperature was calculated from the equation of Ramanathan [17]: mean skin temperature = 0.3 (T_{chest} + $T_{upper\ arm}$) + 0.2 ($T_{upper\ leg}$ + $T_{lower\ leg}$).

The patterns of heart rate, blood pressure, plasma oxygen saturation, mean skin temperature, deep ear canal temperature, and clothing microclimates (temperature and humidity) were analyzed by a two-factor analysis of variance with repeated measures (main effects were type of clothing, two levels, and time of day, eight sessions). When ANOVA revealed a significant effect of time, Bonferroni multiple tests were used to identify significant differences between the time points. For chest microclimate humidity, mean values of posterior 50 min during the morning and afternoon were compared. A one-way ANOVA was performed on the MTP data. All differences reported were regarded as significant at the $p < 0.05$ level.

Results

Moisture Management Measurements

The results are summarized in Table 3 and Figure 2. Table 3 reveals that fabric B had the highest liquid overall moisture management capacity (*OMMC* = 0.72) and one-way trans-

Table 3 Summary of fabric moisture management properties and P values of influencing factors between A and B (inner layer of PPE), and between C and D (outer layer of PPE).

Fabric		WT_t	WT_b	MAR_t	MAR_b	MWR_t	MWR_b	SS_t	SS_b	$OWTC$	$OMMC$
A	Mean	3.00	2.88	64.86	50.99	30	30	5.46	5.53	31.96	0.45
	SD	0.32	0.72	5.36	7.38	0	0	0.35	0.65	42.67	0.06
B	Mean	9.13	5.97	100.01	28.04	22	30	2.90	5.01	456.54	0.72
	SD	4.15	3.10	147.22	10.24	6.32	0	1.34	0.35	241.76	0.16
C	Mean	13.75	119.95	314.87	0	5.00	0	0.36	0	–988.60	0
	SD	1.39	0.003	130.61	0	0	0	0.04	0	27.72	0
D	Mean	12.15	119.95	121.98	4.31	4.50	0.50	0.33	0.50	–809.07	0.09
	SD	1.23	0.003	28.35	13.63	2.84	1.58	0.18	1.59	606.74	0.26
Between A and B		$P < 0.001$	$P < 0.01$	$P > 0.05$	$P < 0.001$	$P = 0.001$	N/A	$P < 0.001$	$P < 0.05$	$P < 0.001$	$P < 0.001$
Between C and D		$P < 0.05$	$P > 0.05$	$P = 0.001$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$

For definitions of WT_t, WT_b, MAR_t, MAR_b, MWR_t, MWR_b, SS_t, SS_b, $OWTC$ and $OMMC$ see Methods.

fer capacity ($OWTC$ = 456.54), showing that liquid sweat could be easily and quickly transferred from the skin to the outer surface to keep the skin dry. This fabric also had a relatively large spreading rate (SS_b = 5.01 mm/s) and the largest wetted radius (MWR_b = 30 mm) on the bottom surface, indicating that liquid can be spread from the bottom surface more quickly. In the fingerprint of MMP (Figure 2B), these four parameters were graded 4.5–5 and excellent, and fabric B was accordingly designated as a fabric which enabled moisture management to occur.

Fabrics C and D, on the other hand, had poor liquid MMP with very low wetted radii and spreading rates (MWR_b = 0 and 0.50 mm and SS_b = 0 and 0.50 mm/s for C and D, respectively) on the bottom surface. These fabrics also showed a negative one-way transfer capacity ($OWTC$ = –988.60 and –809.07 for C and D), as well as very low liquid moisture management capacity ($OMMC$ = 0 and 0.09 for C and D) and absorption properties on the bottom surface (MAR_b = 0 and 4.31 for C and D), indicating that the liquid (sweat) could not diffuse easily from the skin surface to the opposite side and so would accumulate on the top surface of the fabric. These parameters were graded 1 and poor by the fingerprint of MMP (Figures 2 C, D), and fabric C and D were consequently designated as being waterproof fabrics.

Fabrics A had fair (grade 2) one-way transfer abilities ($OWTC$ = 31.96), good (grade 3) liquid moisture management capacity ($OMMC$ = 0.45), excellent (grade 5) wetted areas, and the highest spreading rates (MWR_t = 30 and MWR_b = 30 mm, and SS_t = 5.46 and SS_b = 5.53 mm/s for C and D, respectively) on both sides. Moreover, this fabric also had very good absorption properties on the bottom surface (MAR_b = 50.99). These results indicate that liquid sweat can be absorbed from the skin surface to the fabric and spread quickly on both surfaces of the fabric with a large wetted area. Therefore, fabric A was designated as being a fast-absorbing and quick-drying fabric (Figure 2A).

Fabrics A and B formed the underwear and fabrics C and D formed the outerwear. One-way ANOVA indicated a significantly higher one-way transfer ability and liquid moisture management capacity in B than in A ($F = 29.91$, $P < 0.001$ and $F = 23.84$, $P < 0.001$). Wetting times on both sides were also significantly higher in B than in A ($F = 21.83$, $P < 0.001$ for top wetting time and $F = 9.39$, $P < 0.01$ for bottom wetting time, respectively). On the other hand, there were significantly higher spreading rates on both sides in A than in B ($F = 34.04$, $P < 0.001$ for top Spreading Speed and $F = 4.92$, $P < 0.05$ for bottom Spreading Speed, respectively). Absorption properties on the bottom surface and wetted radius on the top surface were also significantly higher in A than in B ($F = 33.07$, $P < 0.001$ and $F = 16.00$, $P = 0.001$, respectively). There were no significant differences in the liquid MMP between fabrics C and D, except for WT_t ($F = 6.55$, $P < 0.05$) and MAR_t ($F = 16.62$, $P = 0.001$).

Water Vapor Permeability Measurements

Figure 3 shows the WVP for the different clothing layers. One-way ANOVA analysis indicated that there were no significant differences in WVP in the underwear fabrics between PPE1 and PPE2. However, there was significantly higher WVP in outerwear fabrics in PPE1 than PPE2 ($F = 9.00$, $P < 0.01$).

Temperature and Humidity

Figure 4 shows the temporal changes in deep ear canal and mean skin temperatures. Deep ear canal temperature

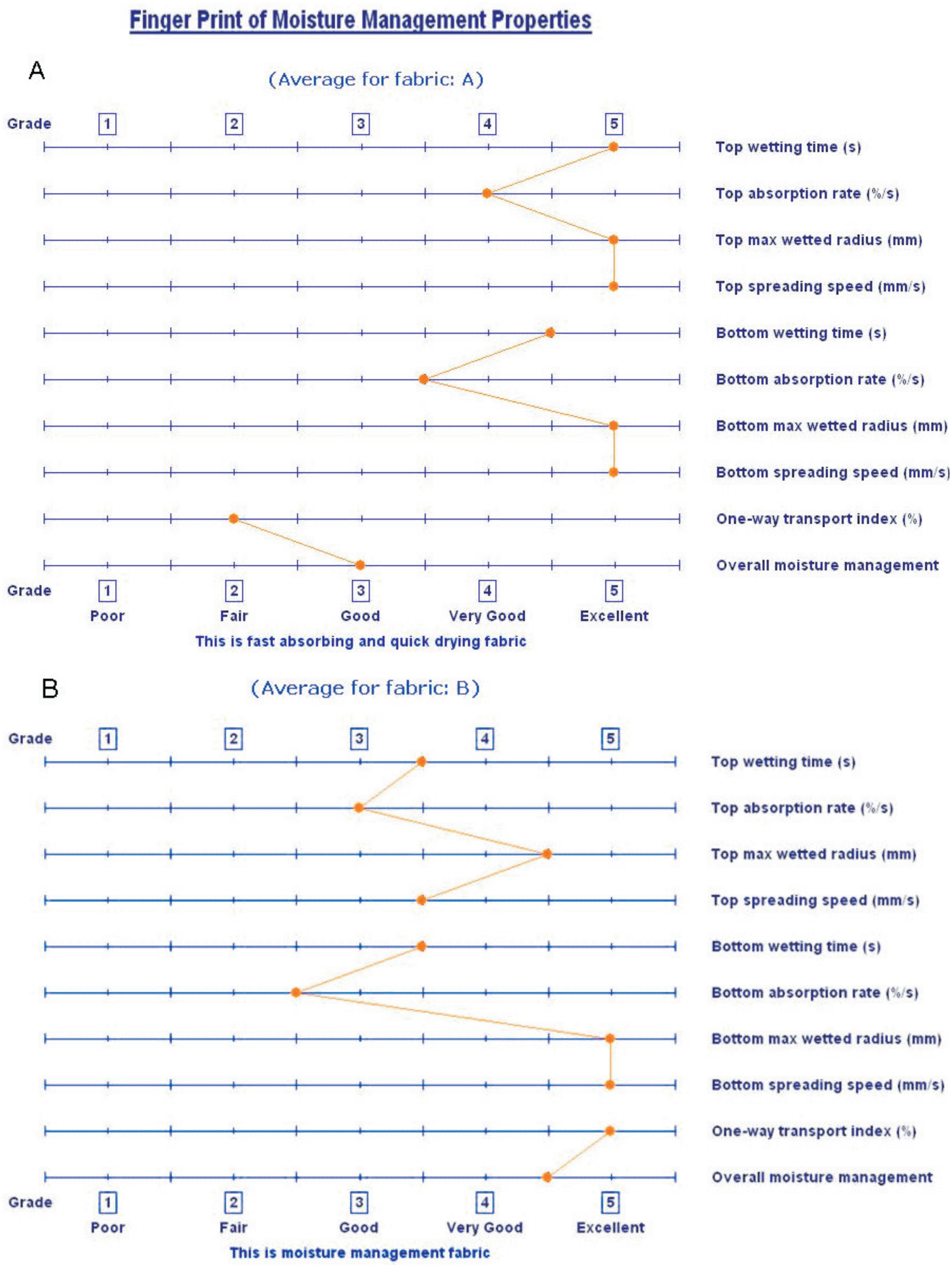
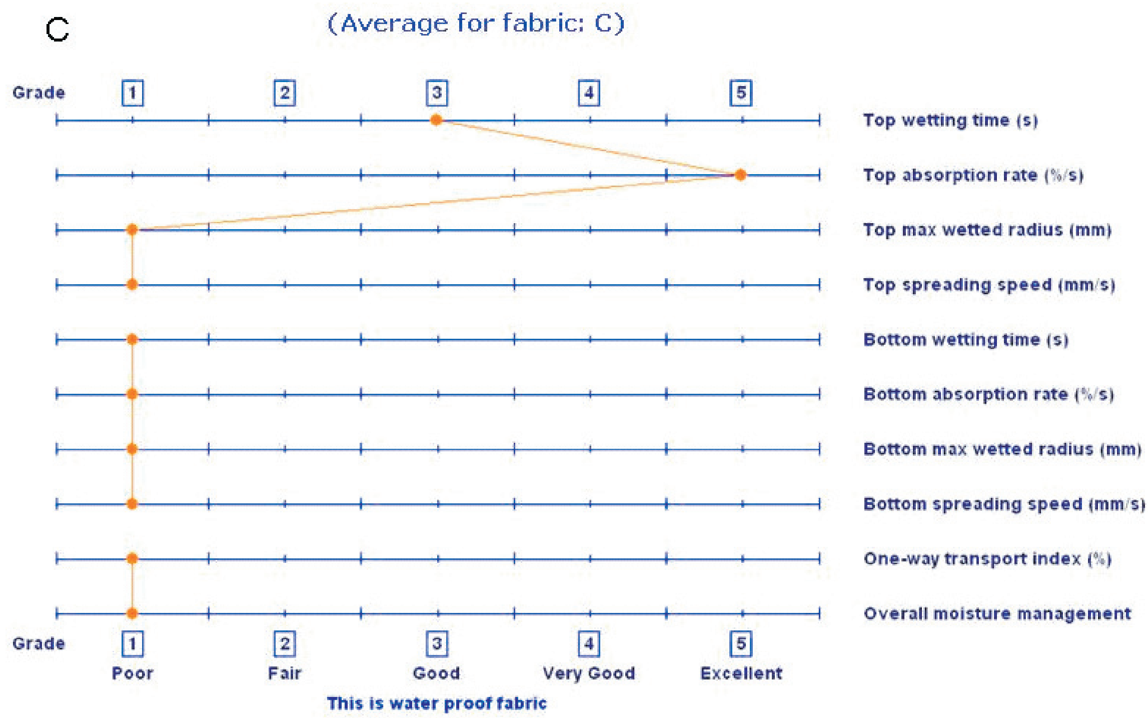


Figure 2 Fingerprints of MMP in fabrics A (A), B (B), C (C), and D (D). The values are means ± SD ($n = 10$). For definitions of fabrics A, B, C, and D, see Table 1.



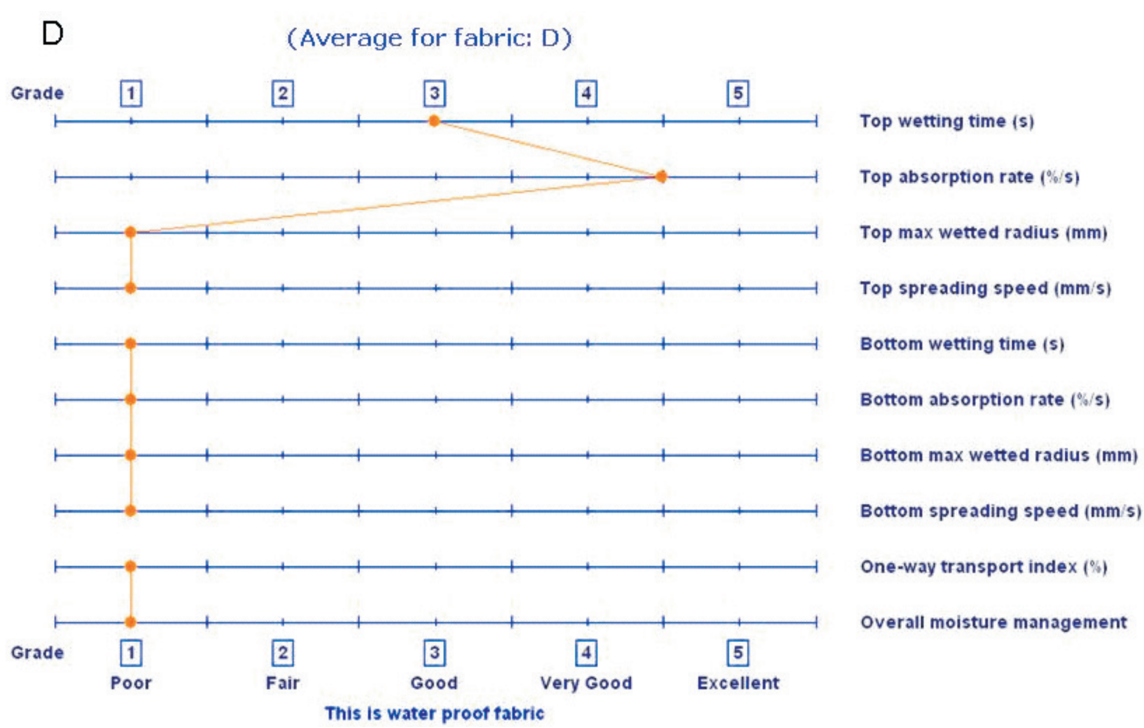


Figure 2 Fingerprints of MMP in fabrics A (A), B (B), C (C), and D (D). The values are means ± SD ($n = 10$). For definitions of fabrics A, B, C, and D, see Table 1. *(Continued)*

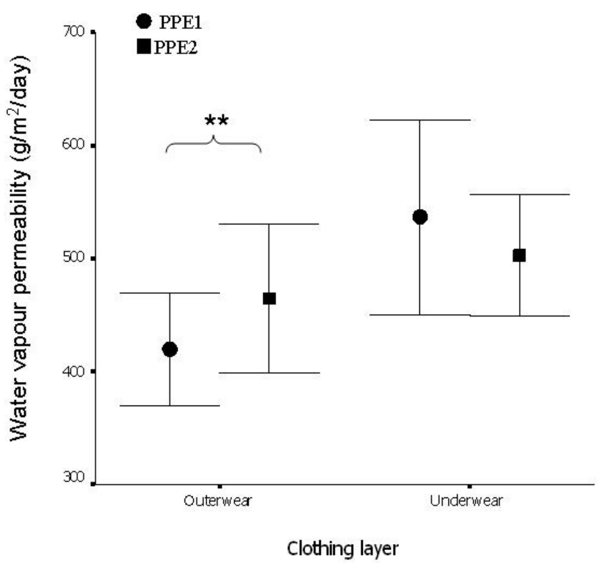


Figure 3 WVP at different clothing layers. The values are means ± SD (n = 10). **: $P < 0.01$. For definitions of PPE1and PPE2 see Methods section.

gradually increased, generally with a greater rise during exercises in the morning and afternoon (with the increases of work load), and decreased during working at the computer and at lunch. Mean deep ear canal temperature was significantly higher in PPE1 than in PPE2 ($F = 654.82$, $P < 0.001$). Moreover, the factor time (due to the different experimental activities) ($F = 91.47$, $P < 0.001$), and the interaction between the factors time and clothing were significant ($F = 102.60$, $P < 0.001$). Bonferroni multiple comparisons indicated that the deep ear canal temperature was significantly higher during the two exercise sessions than with other activities ($P < 0.001$). Mean skin temperature increased gradually, with the increase of workload during morning exercise, and was maintained at a higher level during the other times. Mean skin temperature was significantly higher in PPE1 than in PPE2 ($F = 621.46$, $P < 0.001$).

Figure 5 shows temporal changes in temperatures of the skin of the chest wall and the microclimate between the chest wall and the clothing. Both temperatures gradually increased after the start of the trial and fell during exercise in both the morning and afternoon. Moreover, both temperatures gradually increased throughout the experimental period to higher levels during the other activities. Both temperatures were significantly higher in PPE1 than in PPE2 ($F = 92.02$, $P < 0.001$ for chest skin and $F = 631.50$, $P < 0.001$ for chest microclimate).

Figure 6 shows temporal changes in humidity of the microclimate between the skin of the chest wall and clothing. The microclimate humidity greatly increased almost simultaneously with the start of exercises in the morning and afternoon and quickly declined soon after starting to work on the computer. Mean microclimate humidity during the experiments showed no significant difference with the two kinds of PPE ensemble. However, there was a significant time effect ($F = 284.89$, $P < 0.001$), and a significant interaction between the factors time and clothing ($F = 3.41$, $P < 0.01$). Bonferroni multiple comparisons

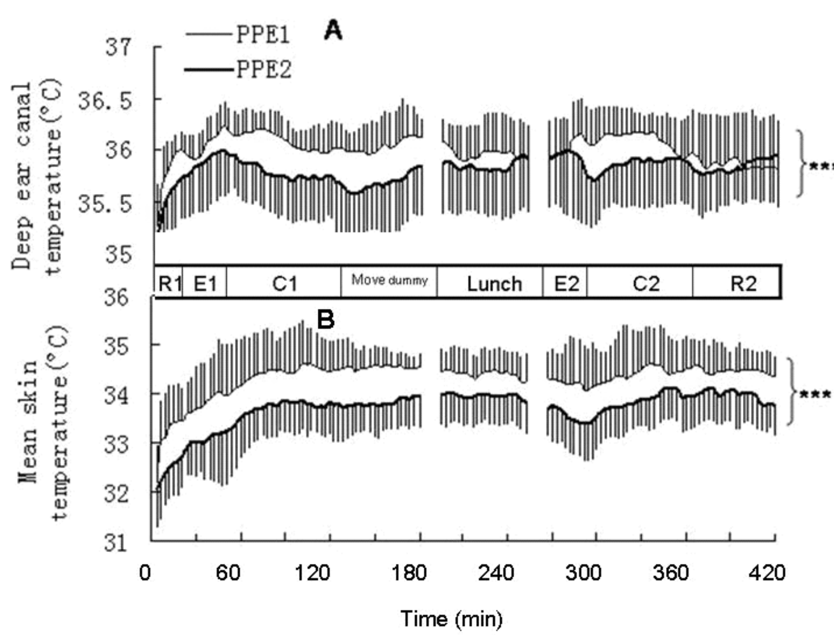


Figure 4 Comparison of temporal changes in deep ear canal temperatures (A) and mean skin temperature (B) between PPE1and PPE2. The values are means ± SD (n = 10). ***: $P < 0.001$. For definitions of PPE1and PPE2, as well as of R1, E1, C1, E2, C2, and R2, see Methods section.

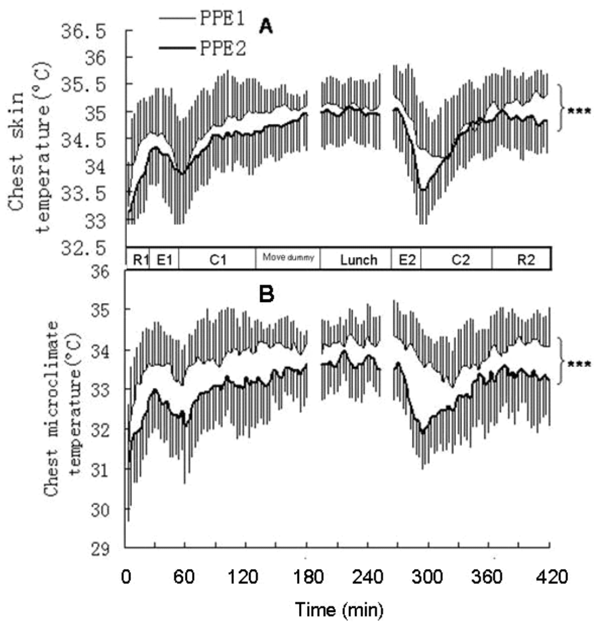


Figure 5 Comparison of temporal changes in chest wall skin temperature (A) and chest wall microclimate temperature (B) between PPE1and PPE2. The values are means ± SD (n = 10). ***: $P < 0.001$. For definitions of PPE1and PPE2, as well as of R1, E1, C1, E2, C2, and R2, see Methods section.

indicated that the microclimate humidity was significantly higher during the two exercise sessions compared with times of other activities ($P < 0.001$). One-way ANOVA showed that the mean humidity was significantly higher in PPE1 than in PPE2 when working on the computer, both in the morning and afternoon ($F = 26.56$, $P < 0.001$ and $F = 26.61$, $P < 0.001$). The mean humidity showed no significant difference between the two kinds of PPE ensemble when the subjects performed other activities.

Plasma Oxygen Saturation

Figure 7 shows temporal changes of plasma oxygen saturation in the two PPE ensembles. Plasma oxygen saturation was the lowest during the two exercise sessions in the morning and afternoon. The level of SpO_2 was significantly higher with the PPE2 ensemble ($F = 9.93$, $P < 0.01$). Bonferroni multiple comparisons found that SpO_2 was significantly lower in the two exercise sessions compared with the two resting sessions ($P = 0.001$ and $P < 0.01$). There were no significant differences during other activities.

There was no significant difference in heart rate and blood pressure with the two kinds of PPE ensemble.

Discussion

In this present study, similar gowns, underwear, respirators, face shields or head covers, gloves, and shoe covers were used with both protective clothing ensembles, but higher deep ear canal temperature, mean skin temperature, clothing microclimates (temperature and humidity), and lower plasma oxygen saturation were observed with the PPE1 rather than the PPE2 ensemble.

Many studies have reported that the processes of evaporation and heat dissipation through clothing depend on the properties and design of the clothing, on body movements, and on the environmental conditions [20, 21]. Furthermore, Wang and Yasuda [10] carried out a study on dynamic water vapor and heat transport through layered fabrics and concluded that the transport of liquid water affected the flux of water vapor. Moreover, the study indicated that subjective perceptions of moisture sensations in sweating, such as “clammy” and “damp”, were significantly correlated with some of the fabric’s MMP [1].

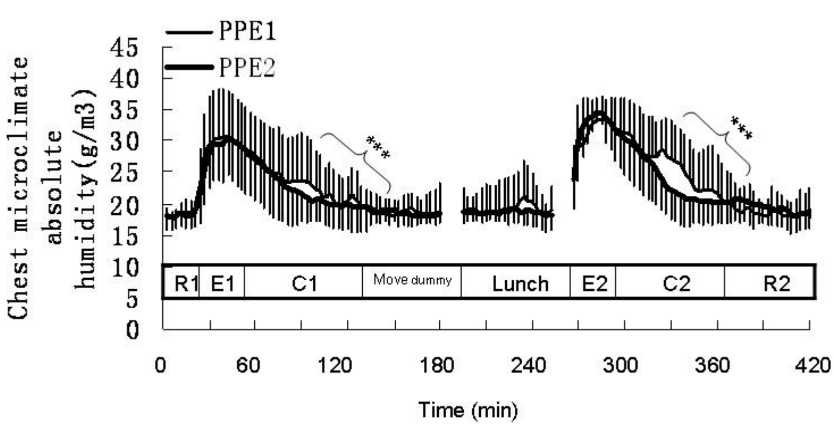


Figure 6 Comparison of temporal changes in absolute humidity of chest wall microclimate between PPE1and PPE2. The values are means ± SD (n = 10). ***: $P < 0.001$. For definitions of PPE1and PPE2, as well as of R1, E1, C1, E2, C2, and R2, see Methods section.

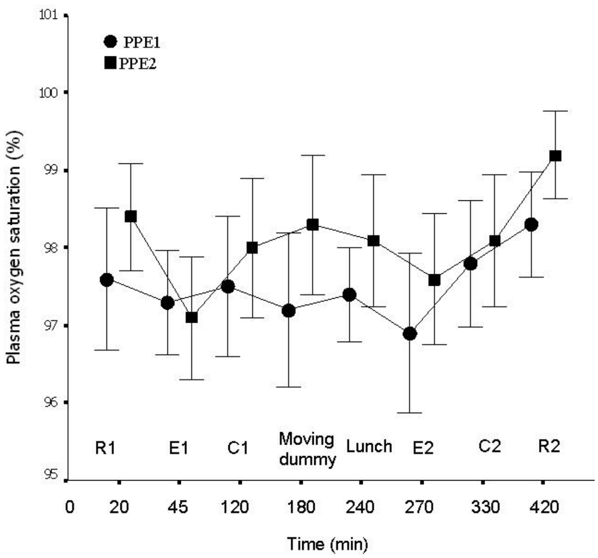


Figure 7 Comparison of temporal changes in plasma oxygen saturation between PPE1and PPE2 ensembles. The values are means ± SD ($n = 10$). **: $P < 0.01$. For definitions of PPE1and PPE2, as well as of R1, E1, C1, E2, C2, and R2, see Methods section.

The PPEs used in this study had different fabric properties. The underwear of PPE1 was a conventional 100% cotton fabric with fast-absorbing and quick-drying characteristics. A part of moisture can be absorbed by the underwear fabric of PPE1 and another part of moisture can be transferred to the gap between the underwear and outerwear from next to the skin surface. The moisture was partly held in this gap because 100% polyethylene barrierman outerwear of PPE1 was waterproof fabric and permitted less moisture to pass through. As a result, the chest microclimate humidity was significantly higher in PPE1 (Figure 6). By contrast, the underwear of PPE2 was treated to allow moisture to be transferred away from the skin to the surface of the garment. There were significantly higher one-way transfer ability, liquid moisture management capacity, and wetting time on both sides with the PPE2 ensemble (Table 3 and Figure 2). By means of these properties, liquid sweat may be transferred from next to the skin surface to the opposite surface of the underwear more quickly in PPE2. Moreover, the outerwear of PPE2 was made from waterproof breathable fabrics with higher WVP and thermal conductance (Table 2 and Figure 3); these properties let the sweat and heat between underwear and outerwear move to the exterior surface of the outerwear fabric quickly and so speed up the evaporation process. The processes by which fabrics of protective clothing enable sweat to be transmitted from the body are shown in Figure 8.

As a result, the chest microclimate humidity was significantly lower in PPE2 (Figure 6). It is reasonable that such differences only appeared during two sessions when working at a computer, since these sessions immediately followed two exercise sessions, where the chest microclimate humidity greatly increased. The liquid MTP of PPE2 let the sharply increased moisture during two exercise sessions be dissipated as the moisture was transported away from the chest skin and its microclimate to the surface of the garment, where it could be evaporated quickly. Consequently, the chest microclimate humidity was significantly lower in PPE2 when working on the computer (Figure 6). The chest microclimate humidity was identical during E1 and E2 (Figure 6). This occurred due to a much higher production of sweat during E1 and E2, suggesting a limitation of MTP depending on the amount of sweat present. Since the evap-

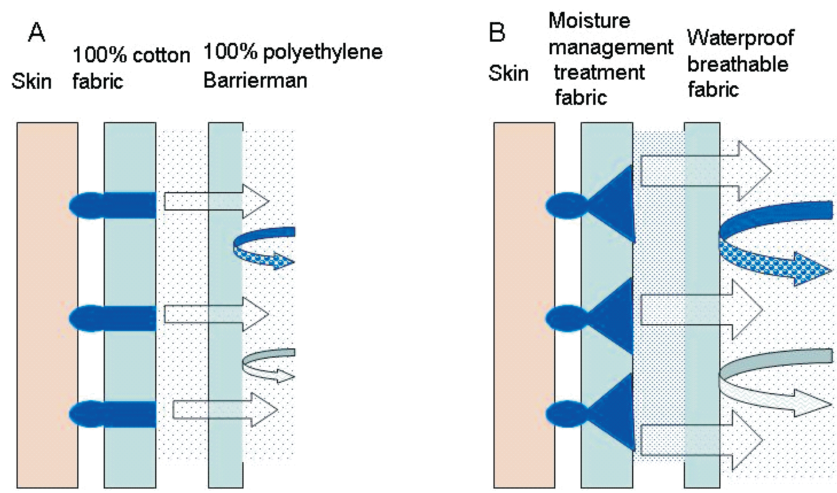


Figure 8 The processes by which fabrics of PPE1 (A) and PPE2 (B) enable sweat to be transmitted from the body.

oration made use of the very large heat of vaporization of water, the chest microclimate and chest skin temperatures were therefore significantly lower in PPE2 (Figure 5). These properties of the outerwear fabric in PPE2, in combination with the *OMMC* and *OWTC* of the underwear fabric, may be responsible for the reduced mean skin temperature and deep ear canal temperature (Figure 4).

Both PPEs used in this study also had differences in respirator design. The respirator in PPE1 was a common N95 respirator (3M 1860), whereas the respirator A in PPE2, with exhaust valves and ventilation pipes, was specially designed. The exhalation valves of respirator A were closed when air was inhaled and opened when air was exhaled. The inhalation valves behave in the opposite way, being opened during inhalation and closed during exhalation. Our previous study found that these differences concerning air exchange between the inner and outer mask surfaces made the microclimate on the inner surface of the mask better (i.e. lower temperature and humidity) [22]. Furthermore, a lower ear canal temperature was related to wearing a respirator with exhaust valves [22]. Ear canal temperature is likely to have reflected membrane temperature closely, because the ear canal was heavily insulated by cotton wool, so reducing the influence of the air temperature of the surroundings. As clearly shown in Figure 4, the increase of ear canal temperature during exercise was suppressed significantly more when wearing PPE2, indicating that selective brain-cooling mechanisms might have occurred more effectively with respirator A, possibly by inhaling air with a lower humidity and temperature through the nose [23]. Moreover, lower chest wall skin and microclimate temperatures in PPE2 may, to some extent, reflect lower core temperature [24, 25].

The level of SpO_2 was significantly higher with the PPE2 ensemble. Different temperature changes during the trials might account for this result. Plasma oxygen saturation is the degree to which O_2-binding sites on hemoglobin are occupied or filled. The oxygen dissociation curve relates percentage saturation of the O_2 carrying power of hemoglobin to the PO_2, and has a characteristic sigmoid shape [3]. When the body temperature in PPE1 was higher, the oxygen dissociation curve moved toward the right and forced more O_2 to be released; as a result, SpO_2 was decreased with the PPE1 ensemble. Furthermore, a similar shift in the oxygen dissociation curve might have been caused by the increased deep ear canal temperature, so lowering oxygen saturation during the two exercise sessions in the morning and afternoon with both PPE ensembles.

Therefore, thermal stress was significantly reduced with the PPE2 ensemble. The respirators were removed during lunch and R2, while the protective clothing was worn throughout the whole experiment. It was concluded that the fabric's MTP in protective clothing are the main physiological reason for reducing heat stress in a simulated working conditions of healthcare workers. A reduction of heat stress is also of physiological significance in preventing the suppression of immunological responses which may occur under stress conditions [26, 27].

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