Thermal Comfort Aspects of Pesticide-protective Clothing Made with Nonwoven Fabrics

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Abstract : The purpose of this study was to evaluate the thermal resistance of pesticide-protective clothing and to investigate its subjective wear performance. Three different nonwoven fabrics, which provide barrier properties against water and pesticide, were used to manufacture the experimental clothing: spunbonded nonwoven (SB), spunbonded/meltblown/spunbonded nonwoven (SM), and spunlaced nonwoven (SL). The thermal insulation values of the experimental clothing were measured with a thermal manikin, and other wear trials were performed on human subjects in a climate chamber at 28°C, with 70% R.H. and air movement at less than 0.15m/s. Our results found that the thermal resistance was lower in the SB experimental clothing than in the others; that the mean skin temperature of subjects who wore the experimental clothing made with SL was significantly lower than that of subjects who wore the SB and SM clothing; and that the microclimate temperature and humidity with SB were significantly higher than that of the others. Overall, the experimental clothing made with SL was more comfortable than the others in terms of subjective wear sensations.

Key Words : pesticide-protective clothing, thermal resistance, nonwoven, thermal comfort, subjective wear sensation

I. INTRODUCTION

It is well known that the routes of pesticide entry into the human body are oral, respiratory, and dermal. Of these three main routes, the dermal exposure is considered the

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primary mechanism (Hansen *et al*., 1978; Taylor *et al*., 1978; Bajaj & Sengupta, 1992). Therefore, protective clothing has been recommended to reduce agricultural workers' risk from pesticide exposure.

Protective clothing must provide adequate protection against occupational hazards, but it should also be reasonably comfortable. Additionally, the thermal and moisture transport properties of protective clothing should be designed for specific climate conditions and activities. However, Culver (1976) has concluded that available protective clothing imposes physiological stresses that are largely unacceptable in the work environment. Freed *et al*. (1980) have noted that current protective clothing encases a large part of the body; consequently, it is not only extremely uncomfortable, but also a hazard in itself due to the wearer's risk of heat stroke. Branson *et al*. (1986) have reported that the protective clothing currently available at retail is unacceptable to many agricultural workers because of its poor heat dissipation characteristics. Also, Tamura *et al*. (1993) have reported that the fabrics commonly used to make protective clothing cause wearers to feel intolerable discomfort especially during the summer. These fabrics are impermeable; they do not allow heat and sweat from the human body to escape into the environment. In response to these problems, Branson *et al*. (1986) have suggested that there is a need for developing a fabric/design combination that would offer increased dermal protection from pesticides while retaining the comfort level of common work clothing.

The development of protective clothing with improved thermal comfort for less hazardous situations would have an increased chance of being adopted by workers. In this way, fluorochemical repellent finish was found to be an excellent barrier finish against pesticide with thermal comfort. Nonwoven fabrics have gained more acceptance as protective garments in medical and industrial areas because of their enhanced thermal properties and comfort. However, no previous work to establish not only thermal resistance with a thermal manikin but also subjective wear trials for evaluating thermal comfort properties of pesticide protective clothing made with nonwoven fabrics was found.

In light of this, we conducted experiments to develop comfortable pesticide-protective clothing which has water and pesticide-repellent properties; then we examined both the objective and subjective thermal comfort properties of the clothing in question.

II. METHODS

1. Experimental clothing

Three kinds of experimental fabrics were used to make clothing for this study: spunbonded nonwoven fabrics (SB), spunbonded/meltblown/spunbonded nonwoven fabrics (SM), and spunlaced nonwoven fabrics with a commercial fluorochemical finish (SL). All fabrics used in these experiments showed excellent barrier properties to water and pesticide (Table 1). The experimental clothing was a two-piece protective garment with a hood. The clothing was kept in a chamber at 28˚C, 70% R.H. for two hours before being worn.

2. Thermal resistance of experimental garment

The surface temperature controlled thermal manikin (Tanabe *et al.*, 1994) at Ochanomomizu University, Japan, was used to measure the thermal resistance of the experimental clothing. The manikin wore underwear made from cotton while the

<Table 1> Physical properties of experimental clothing

Legend	Fiber content(%)	Fabric Construction	Weight (g/m^2)	Thickness (mm)	Finish method
SB	Polyethylene 100	spunbonded	42.1	0.17	none
SM	Polypropylene	SMS	76.8	0.42	fluorochemical
SL	woodpulp55/ polyester45	spunlaced	68.1	0.33	fluorochemical
Legend	Oil repellency*	Air permeability ($cm^3/cm^2.sec$)	WVT** ($g/m^2.hr$)	Water penetration(g)***	
SB	0.0	0.05	226	0.040	
SM	7.5	17.30	400	0.037	
SL	6.5	38.10	403	0.047	

* AATCC Test Method 118 ** KS A 1013 *** AATCC Test Method 42

experimental clothing was tested. The climate chamber was controlled at 28˚C, 70% R.H. with an air velocity of 0.15m/s. The basic clothing insulation value (Icl) was calculated from previous equations (ASHRAE, 1993).

3. Experimental protocol for wear trials

Before the experiment, the subject was acclimatized in a climate chamber for 30 minutes. During this time the subject was dressed in the experimental clothing and then thermistor and humidity sensors were attached. The subjects repeated three exercise/rest cycles of 10 minutes exercise (3 met)-walking up and down steps, which were 0.2 m in height, to a specified cadence, followed by 10 minutes rest (1 met) in a chair. In order to simulate the amount of work performed in spraying pesticides, an activity pattern was established so that the metabolic cost of the activity was about 3 met.

4. Subjects

Four healthy male students participated in these experiments. Their mean age, height, and body weight were 22.5 (SD 0.55) years, 172 (SD 3.55) cm, and 62 (SD 5.3) kg, respectively. Their mean body surface area was 1.72 (SD 0.06) m^2 which was calculated according to DuBois and DuBois (1916).

5. Measurements

Skin temperature was measured continuously every minute in four places on the subjects; their weighed mean skin temperature (Tsk) was calculated by using Ramanathan's formula (1964). The microclimate temperature was measured in three places (the chest, back, and thigh) between underwear and clothing. The microclimate humidity was measured on these same points. In order to assess the total amount of sweat secreted in the course of the experiments, the subjects wearing underpants were weighed on a scale before and after the experiments. The amount of sweat trapped in the experimental clothing and underwear at the end of the experiment was calculated as the weight difference of the experimental clothing and the underwear before and after the experiment. For estimating evaporative heat loss from the skin surface of the subject, total latent heat loss and evaporative heat loss from respiration were calculated from the amount of sweat evaporated from the skin and rate of metabolic heat production. The evaporative heat loss from the skin surface (Esk) of the subject and skin wettedness (w) were calculated from the previous equations (ASHRAE, 1993). Subjects evaluated the subjective wearing sensation ratings of the garments immediately after they finished each rest and exercise period.

$$Esk = E - Eres$$

$$E = (w1 - w2) * hfg$$

$$Eres = [0.0173M(5.87 - Pa)] / A_D$$

$$w = Esk / Emax$$

$$Emax: he * (Ps,s - Pa)$$

Where,

AD : surface area of nude body, m^2

E: total latent heat loss, W/m^2

Emax: maximum evaporative heat loss, W/m^2

Eres: evaporative heat loss from respiration, W/m^2

Esk: evaporative heat loss from skin, W/m^2

M: rate of metabolic heat production, W/m^2

Pa: water vapor pressure in ambient air, kPa

Ps,s: saturated water vapor pressure at skin, kPa.

h_{fg}: heat of vaporization of water, kJ/kg

he: evaporative heat transfer coefficient, $W/(m^2. kPa)$

w1: total amount of produced sweat, g

w2: amount of sweat entrapped in clothing, g

w: skin wettedness

6. Data analysis

Analysis of variance and Duncan's multiple range test were used to analyze differences in the mean skin temperature, clothing microclimate temperature and humidity, and subjective wear sensation resulting from the fabric type of the experimental clothing.

III. RESULTS

1. Thermal resistance of experimental clothing

The results of the measured thermal resistance of the experimental clothing are illustrated in <Table 2>. The basic clothing insulation of the underwear used in this study was 0.28 clo and that of the SB, SM, and SL clothing were 0.70 clo, 0.74 clo, and 0.73 clo, respectively. There were significant differences in the basic clothing insulation provided by the experimental clothing. The basic clothing insulation of SB showed lower that that of SM and SL (Table2).

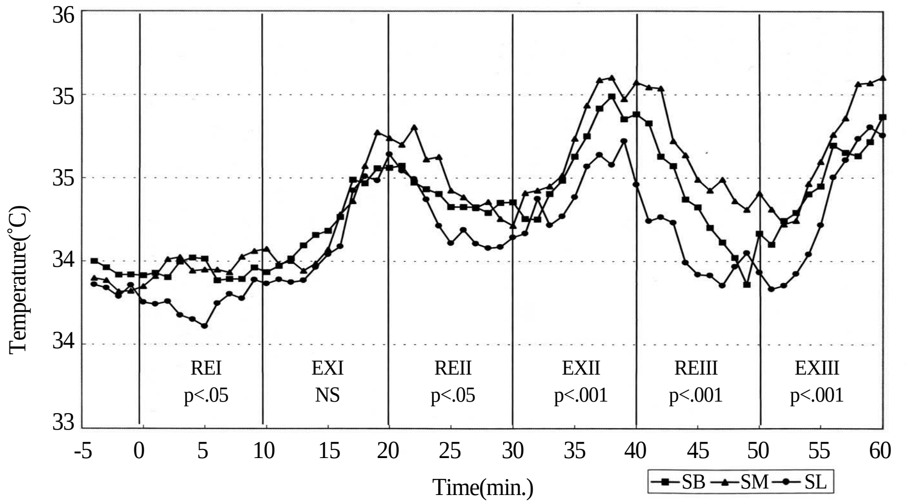
2. Mean skin temperature

The mean weighed skin temperature (Tsk) of the four subjects for each clothing system is plotted in <Fig. 1>. The Tsk curves of all the experimental clothing were very similar. However, at the beginning of the experiment there was a noticeable variation between the different fabrics. The Tsk curves increased during all the exercise periods, regardless of the fabric used in the experimental clothing, and decreased during all the rest periods after

<Table 2> The basic clothing insulation of the experimental clothing

	SB	SM	SL	F value (p)
clo	0.70a	0.74b	0.73b	52.16 (0.00)

* Means with the same letter are not significantly different (p<.05).



<Fig. 1> Mean skin temperature during rest (RE) and exercise (EX).

<Table 3> ANOVA and Duncan's multiple range test: mean skin temperature

	SB	SM	SL	F value (p)
REI	34.05b*	34.04b	33.75a	4.05 (0.02)
EXI	34.27a	34.40a	34.18a	1.73 (0.18)
REII	34.46b	34.51b	34.24a	3.45 (0.03)
EXII	34.75b	34.80b	34.43a	8.11 (0.00)
REIII	34.60b	34.47b	34.02a	23.48 (0.00)
EXIII	34.72b	34.69b	34.26a	10.60 (0.00)

* Means with the same letter are not significantly different ($p<.05$).

exercise. Except in the first period of exercise (EXI), there were significant differences in the Tsk of the wearers of the different types of experimental clothing (Table 3). The Tsk of subjects who wore experimental clothing made with the SL was lower than that of the SB and SM according to Duncan's multiple range test.

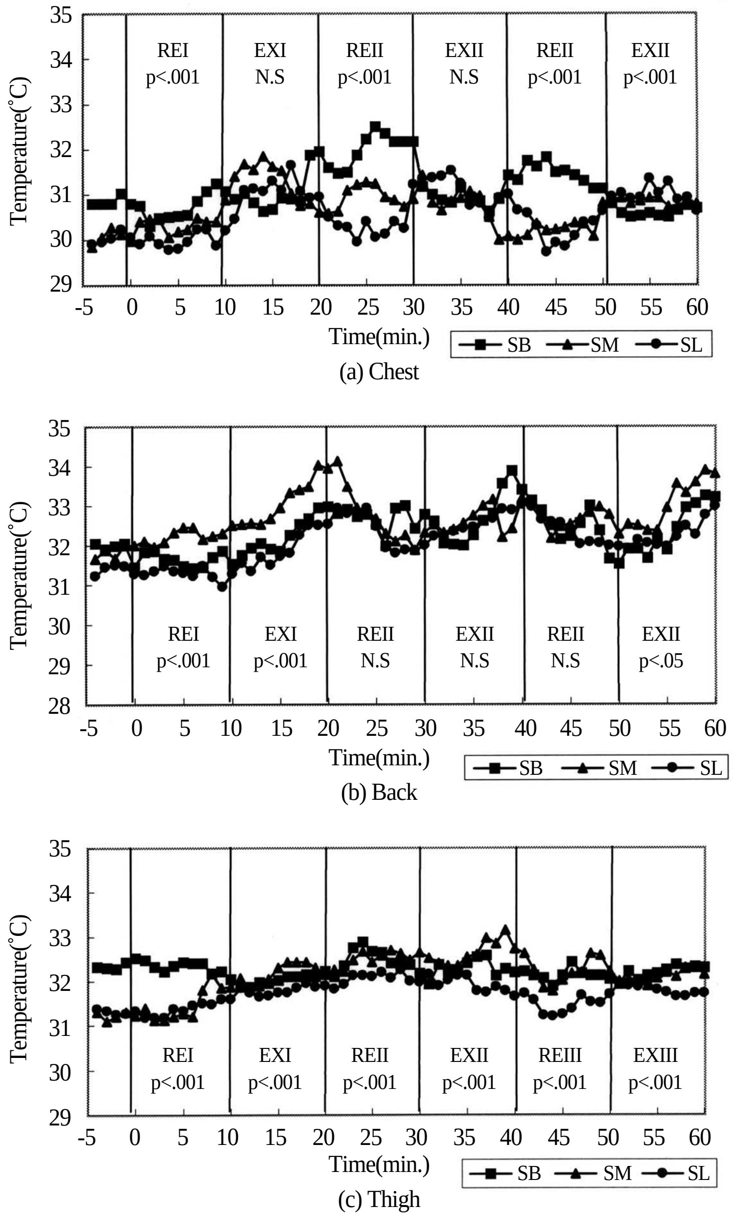
3. Microclimate temperature and humidity

The changes of mean microclimate temperature (Tcl) at the chest, back and thigh in each type of experimental garment are presented in <Fig. 2>. The trends of microclimate temperature at the chest and thigh were not similar to the trend of mean skin temperature, but microclimate temperature at the back showed a trend similar to the mean skin temperature. There were partially significant differences among Tcl of the types of experimental clothing according to the rest and exercise period in all three areas (Table 4). In the chest area, the subjects who wore the experimental clothing made with SL showed the lowest Tcl during all periods of rest, but the subjects who wore experimental clothing made with SB showed the lowest Tcl during the third period of exercise (EXIII). The Tcl at the

<Table 4> ANOVA and Duncan's multiple range test: microclimate temperature

		SB	SM	SL	F value (p)
	REI	30.73c*	30.38b	29.99a	23.20 (0.00)
C	EXI	31.05a	31.27a	31.07a	0.92 (0.41)
H	REII	32.00c	30.94b	30.34a	64.88 (0.00)
E	EXII	30.97cb	30.72a	31.08ab	2.76 (0.08)
S	REIII	31.44c	30.27c	30.24a	63.02 (0.00)
T	EXIII	30.60a	30.83b	30.98c	17.95 (0.00)
	REI	31.64c	32.25a	31.28b	85.34 (0.00)
B	EXI	32.28bc	33.14ab	31.94a	15.11 (0.00)
A	REII	32.68a	32.69a	32.34a	1.47 (0.24)
C	EXII	32.71a	32.65a	32.57a	0.22 (0.80)
K	REIII	32.40a	32.66a	32.32a	1.82 (0.18)
	EXIII	32.44b	33.09a	32.26b	6.38 (0.00)
	REI	32.30b	31.50b	31.38a	38.96 (0.00)
T	EXI	32.04b	32.19c	31.80a	15.88 (0.00)
H	REII	32.47b	32.51b	32.06a	17.12 (0.00)
I	EXII	32.29b	32.64c	31.91a	27.51 (0.00)
G	REIII	32.13b	32.23b	31.47a	33.68 (0.00)
H	EXIII	32.20b	32.11b	31.79a	27.37 (0.00)

* Means with the same letter are not significantly different ($p<.05$).



<Fig. 2> Clothing microclimate temperature during rest (RE) and exercise (EX)

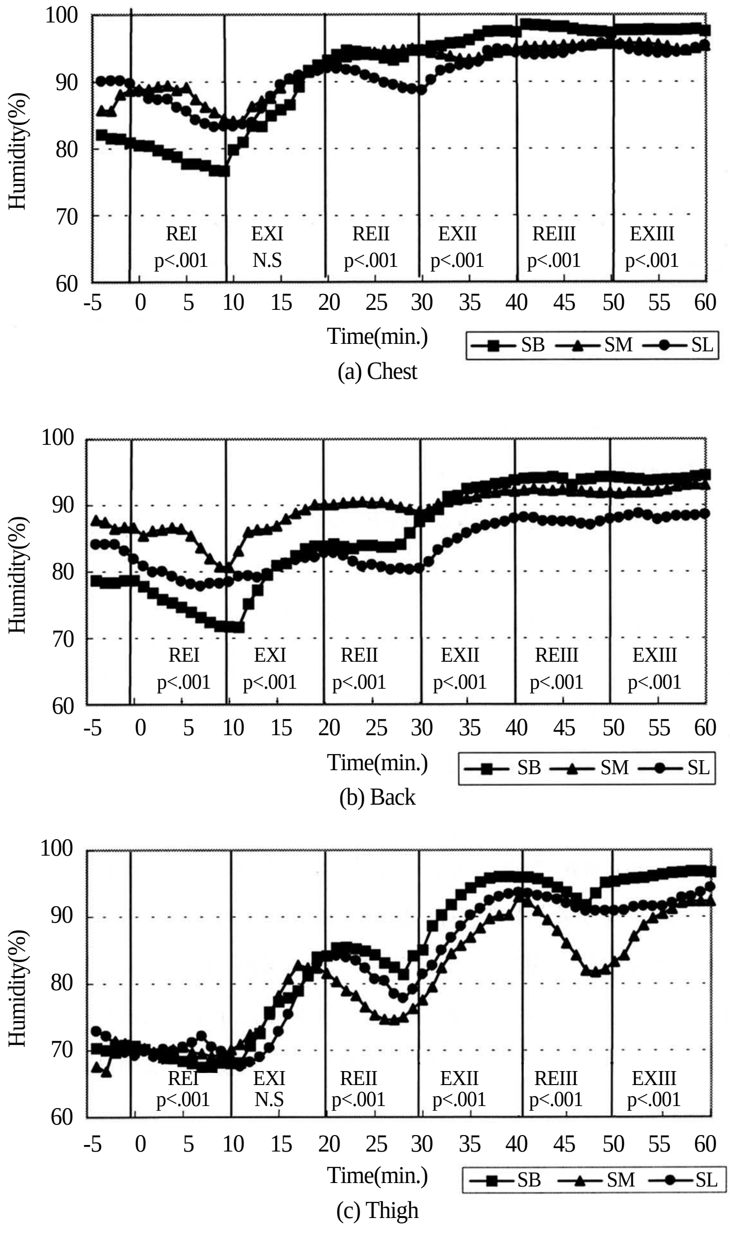
back of subjects who wore SL clothing were lower than that of the others through the first rest (REI) and exercise period (EXI). Also, the Tcl at the thigh of SL clothing was lower than that of the others in all rest and exercise periods.

The mean microclimate humidity (Hcl) at the chest, back, and thigh of the subjects wearing the experimental clothing is described in <Fig. 3>. There were partially significant differences among Hcl of the experimental clothing according to the rest and exercise periods in all areas (Table 5). The Hcl at all areas of the three types of experimental clothing showed similar patterns of change, but there was a difference according to fabric type. Until the first rest period (REI), the Hcl of the subjects wearing the experimental clothing decreased slowly, but it was higher than the humidity of the climate chamber, except for the Hcl of the thigh area. When the exercise period began, the Hcl of the subjects at all areas began to increase very

<Table 5> ANOVA and Duncan's multiple range test: microclimate humidity

		SB	SM	SL	F value (p)
	REI	78.43a*	87.33c	85.20b	69.37 (0.00)
C	EXI	87.19a	89.19a	88.72a	0.90 (0.41)
H	REII	94.18b	94.34b	90.27a	73.99 (0.00)
E	EXII	96.54c	94.07b	93.00a	27.88 (0.00)
S	REIII	97.97c	95.42b	94.73a	118.34 (0.00)
T	EXIII	97.74c	95.38b	94.70a	212.61 (0.00)
	REI	74.33a	84.34c	78.95b	66.34 (0.00)
B	EXI	79.92b	87.48a	80.81b	21.89 (0.00)
A	REII	84.41b	90.02c	81.03a	230.32 (0.00)
C	EXII	91.86b	91.09b	85.53a	42.35 (0.00)
K	REIII	93.98c	92.10b	87.57a	1059.05 (0.00)
	EXIII	94.02c	92.38b	88.28a	569.42 (0.00)
	REI	68.50a	69.86b	70.14c	11.58 (0.00)
T	EXI	77.06a	77.96a	75.07a	0.71 (0.50)
H	REII	84.12c	76.72a	81.15b	37.74 (0.00)
I	EXII	93.72b	87.02a	89.65a	8.96 (0.00)
G	REIII	94.31c	85.98a	91.83b	29.49 (0.00)
H	EXIII	96.34c	90.02a	92.22b	35.67 (0.00)

* Means with the same letter are not significantly different (p<.05).



<Fig. 3> Clothing microclimate humidity during rest (RE) and exercise (EX)

sharply, and this trend continued to the end of the experiments. However, the Hcl at the thigh area decreased during the rest period. The Hcl at the chest and back of the subjects was the lowest when the SL was worn. At the thigh, it was lowest when the SM was worn, but it was the highest when the SB was worn, regardless of body area.

4. Evaporative heat loss

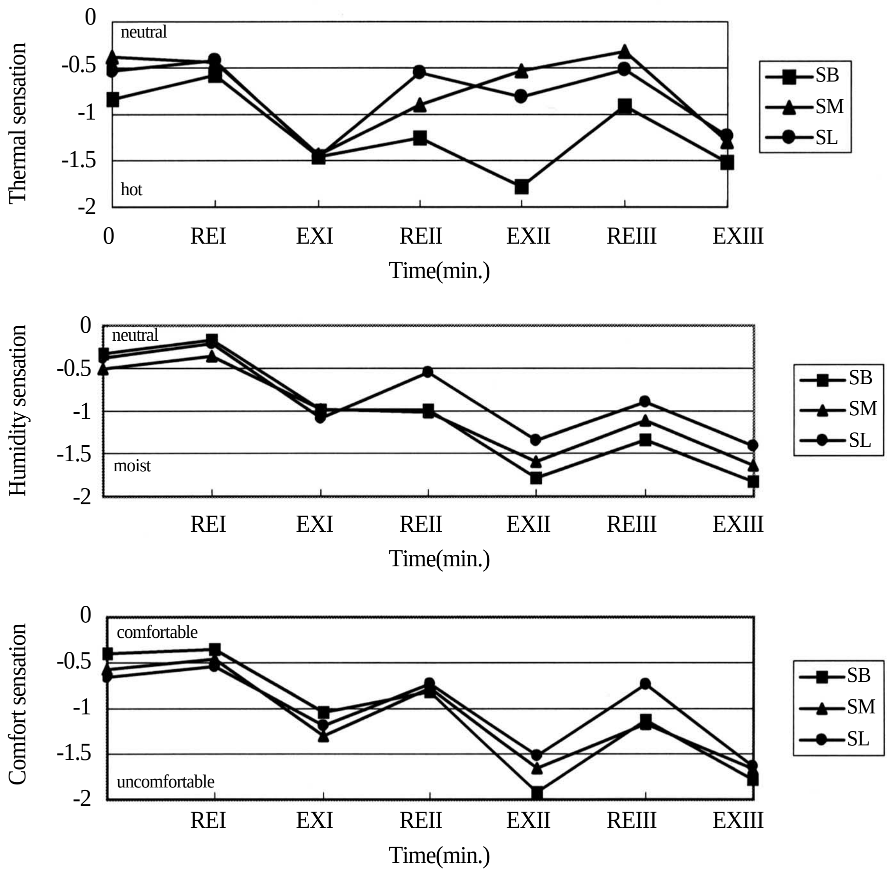
The total sweat secretion of the subject and the amount of retention in the experimental clothing during the experiment are described in <Table 6>. The total amount of sweat varied according to the experimental clothing worn; it was the lowest on subjects wearing SM, but the greatest on subjects wearing SB. Although the underwear was made from the same cotton fabric, the amount of sweat trapped in them was different depending on the experimental clothing. The amount of sweat trapped in the underwear beneath the SB experimental clothing was greater than that of the others. The evaporative heat loss from the skin surface was higher in subjects wearing the SB than in subjects wearing the SL or SM.

5. Subjective sensation

The changes in subjective sensations during the rest and exercise periods are presented in <Fig. 4>. The rating of overall subjective thermal sensations showed a little variation in the three types of experimental clothing and did not reflect any systematic differences of the mean skin temperature. Additionally, the rating of the overall subjective humidity sensation

<Table 6> Total amount of produced sweat and skin wettedness

	SB	SM	SL
Total amount of produced sweat (g)	286.0	237.0	259.0
Amount of sweat entrapped in underwear (g)	51.0	27.0	26.0
Amount of sweat entrapped in clothing (g)	5.5	1.5	5.2
Evaporative heat loss from skin surface (W/m^2)	103.4	84.9	93.7
w (skin wettedness)	0.60	0.52	0.58



<Fig. 4> Subjective thermal, humidity, and comfort sensation during rest (RE) and exercise (EX)

did not reflect a difference in the microclimate humidity. After every exercise period, all subjective sensations of the subjects were assessed as hotter, wetter, and more uncomfortable than before exercise, but the rest period showed the opposite pattern. The SL clothing was assessed as more comfortable than the SM and SB clothing in terms of the subjective thermal, humidity, and comfort sensations

IV. DISCUSSION

Although SB clothing had the lowest thermal insulation, this does not imply that it was more comfortable in thermal sensation than that of the others. The amount of sweat provided during all exercise was greater in the subjects wearing the SB clothing than in the subjects wearing SM and SL. In addition, the underwear worn beneath the SB trapped slightly more sweat than that worn beneath the SM and SL. Because the underwear was worn beneath the pesticide-protective clothing, the fabric of the pesticide-protective clothing did not lie on the skin surface except at the limbs. Each fabric's ability to absorb and transfer water could have influenced the amount of sweat. Therefore, it seemed that the evaporative heat loss of the pesticide-protective clothing could be affected by fabric's ability to absorb and transfer water. Unfortunately, since the thermal manikin used in this study can not measure the resistance to the evaporative heat loss of each fabric, we assumed that the resistance of evaporative heat loss of each fabric could be replaced by the water vapor permeability of each fabric. However, the evaporative heat loss was higher in the SB clothing than in the SM and SL clothing. As this experiment was performed under the conditions of high temperatures and high humidity, it seems that the evaporative heat loss could not occur as expected. Also, the sweat production was much higher when SB garments were worn. These measurements can be found in the graph concerning change of microclimate humidity.

The first 10 minutes of walking increased the production of heat in the body and enhanced the blood circulation, which raised the temperature of the skin (Vokac *et al*., 1976). All skin temperatures of the subjects changed similarly with intermittent activity but were significantly lower in the subjects wearing the SL than those wearing the SB and SM clothing. The difference in mean skin temperature indicates a higher rate of heat loss from the skin of the wearers of SL clothing than the SB and SM clothing. The skin temperature was related to the rates of evaporative water loss which occurred as the fabrics were not touching the skin. Therefore, the heat loss caused by evaporation of sweat contributed greatly to the total heat loss from the skin. The air and water vapor permeability of the SL and SM clothing were higher than that of the SB clothing. Since the evaporative heat loss from the skin depends on the difference between the water vapor pressure at the skin and in the ambient environment (ASHRAE, 1993), the evaporative heat loss slows down in a higher humidity environment as the water vapor pressure gradient from the skin surface to the environment is suppressed. It is, therefore, the water vapor pressure gradient suppression/elevation caused by the difference of water vapor permeability of fabrics that is reflected in the skin temperature.

The clothing microclimate temperature and humidity of the experimental clothing showed differences according to body area. Compared with the others, the experimental clothing made with the SB showed a higher microclimate temperature in all the areas. At the chest and back, the microclimate humidity of the SL was lower than that of the others. Also, the microclimate humidity of SM clothing was lower than that the others at the thigh area. This seems to imply that the physical parameter of the fabrics, especially their air and water vapor permeability, contributed mainly to the differences of microclimate temperature and humidity. The increase of temperature was attributed to the heat absorption arising from the transient changes of humidity in the clothing. Because of the steadily changing intensity of energy metabolism in the course of walking, the heat of absorption derived from the internal source of humidity could play an important role in the comfort properties of fabrics. The sweating rate of subjects varied according to which experimental clothing they wore, but the subjects wearing SB showed the highest sweating rate. In the case of air permeable clothing, for example SM and SL clothing, part of the trapped air was forced out and replaced from the environment by alternating pressure changes.

It is expected that all three objective measures would be an important determinant of subjective sensation. The general subjective sensation of thermal comfort was related to the mean skin temperature irrespective of the location of the cold and warm surface areas (Vokac *et al*., 1971). In this study the thermal comfort sensation did not reflect the degree of difference in the mean skin temperature. But, the rate of humidity and overall comfort sensation did reflect the degree of difference in the mean skin temperature and the microclimate temperature and humidity. The SB clothing was evaluated as hotter and more uncomfortable than the others, while the SL clothing, which had higher air and water permeable properties, was evaluated as more comfortable.

The subjective comfort sensation of clothing is a complex synthesis of many kinds of physiological responses of the individuals, of the physical response of the individuals, and of the physical properties of the clothing materials. The skin temperature as an index of warmth or discomfort has been widely used but has disadvantages influenced by sweating. Further, the presence of moisture is highly important in a subjective assessment of comfort. Particularly in the beginning of experiment, the subjects' microclimate humidity was over the climate chambers' relative humidity. In this humid environment, as the rate of water evaporation slows, the skin may become hydrated. Since the water on the skin surface may be lead to sensation as thermal, humidity and overall comfort separately in this experiment, it does not to reflect the real skin temperature or real microclimate temperature and humidity.

CONCLUSIONS

This study was undertaken to estimate the objective and subjective thermal comfort properties of pesticide-protective clothing made from three different types of nonwoven fabrics with barrier properties for pesticide and water.

The SB clothing showed lower thermal insulation than the SM and SL clothing. The amount of sweating the subjects experienced was less when wearing the SM clothing than when they wore the SB clothing. The mean skin temperature of the subjects wearing clothing made with the SM and SL was significantly lower than that of the SB clothing. The microclimate temperature and the humidity of the SL clothing were lower than the SB clothing. There were no significant differences in the subjective thermal sensations, humidity sensations, and comfort sensations among the wearers of the three experimental kinds of clothing. This finding was in contrast to the differences of the mean skin temperature and microclimate.

Therefore, the results of this study suggest that the fluorochemical-finished nonwoven fabric which constituted the SL clothing would be a functional and comfortable material for the manufacture of pesticide-protective clothing.

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