IMPACT OF DRYING OF WET CLOTHING ON HUMAN HEAT LOSS

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INTRODUCTION

Production and evaporation of sweat plays a major rôle in human thermoregulation. When clothing is worn sweat will frequently accumulate in this, and the immediate evaporative cooling of the skin may then be reduced. Evaporation of the accumulated sweat will take place from the clothing at a later time. The wet clothing will dry on the human body using heat from the skin for the evaporation. The textile materials influence sweat accumulation in a clothing ensemble with regard to amount and location of sweat. However, we do not know how this difference in sweat accumulation influences the cooling of the skin during consecutive drying of clothing on man.

The main purpose of this study was to investigate how the location of the accumulated sweat and the textile materials in a clothing ensemble influenced evaporation rate and heat loss from a thermal manikin during drying of a partly wet clothing ensemble. In addition, the effect of walking movements and increased air velocity during drying was studied.

METHOD

A 3-layered clothing system was used. The underwear was manufactured in a 1-by-1 rib-knit construction from either wool (W) or polypropylene (P), the middle layer in a plated construction with a fleecy inner surface from either wool (W) or polyester (P), and the outer layer in a plain weave from either 100% cotton (C) or 65% polyester/35% cotton (P). The combinations PPP and WWC were tested. Measured on a thermal manikin (TM) their insulation values, I_{cl}, were 0.90 and 0.97 clo, respectively. One layer was humidified. Humidification of the garments took place by inserting top and bottom of a layer in separate plastic bags before adding 100 and 75 gram, respectively, sealing the bags and placing them in an oven at 50°C for at least eight hours before the experiment.

All experiments were conducted in a climatic chamber (T_a = 10°C; r.h. = 70%; $V_a < 0.1\ \mathrm{m \cdot s^{-1}}$). Experiments were done with the manikin in a standing position with or without being exposed to an increased air velocity of $1\ \mathrm{m \cdot s^{-1}}$, or the manikin was brought to simulate walking movements with 60 steps per minute. TM was placed on a balance, and dressed in a clothing ensemble identical to the test clothing. Recording of heat loss from TM began and a thermal steady-state was obtained prior to the beginning of the actual experiment. The humidified clothing layer of the test clothing was now taken from the oven and together with the other garments weighed individually on a balance. The pre-experimental clothing was removed from the manikin, and TM was dressed in the experimental clothing ensemble. Walking movements or the wind box were started immediately after completing the dressing procedure of the manikin, when applicable. Recording of weight loss from the dressed TM started just after this. The procedure of changing the clothing on the manikin was standardized as much as possible, and lasted approximately 20 minutes. Recordings of weight and heat loss continued until the clothing was dry. At the end of the test each garment was weighed again. Separate experiments were done with change of dry clothing on the manikin in order to measure the heat loss exclusively due to the change of clothing. This "dry" value was subtracted from the "wet" values.

RESULTS

Evaporation of water from the clothing took place in two phases: an initial fast phase with an almost linear evaporation rate followed by a slower curved drying out phase. An evaporation rate was calculated for the linear "130 to 70 gram" water content period (Table 1). Heat loss from the thermal manikin increased abruptly to a new level during the change of clothing and the first phase of drying. Then it slowly decreased to the steady-state level for the actual combination of clothing insulation worn, body movements, and air velocity. Only a part of the drying energy was contributed from TM.

Fiber type material had a significant influence on evaporation from the clothing and on the percentage of drying energy consumed from TM. Evaporation took place at a much faster rate from the ensemble manufactured from man-made synthetic materials compared to the ensemble manufactured from natural hygroscopic fibers. As a consequence drying time was much longer with WWC than with PPP. The differences in evaporation were reflected in the time course of heat loss from the thermal manikin during drying. With PPP heat loss was considerably higher the first two hours compared with WWC. However, heat loss

Table 1. Initial evaporation rate and percentage of evaporation energy consumed from TM in the various tests.

	Clothing composition Layer with water	PPP inner	PPP middle	PPP outer	WWC inner	WWC middle	WWC outer
Evaporation	standing	1.61	1.35	1.49	0.63	0.68	0.56
rate	+ movements	1.86	1.78	1.49	0.76	0.88	0.83
($g \cdot min^{-1}$)	+ wind	1.81	1.66	2.18	0.64	0.74	0.72
Percentage of	standing	64	50	23	51	28	13
energy from	+ movements	58	50	35	63	34	24
TM (%)	+ wind	82	45	27	87	42	24

remained slightly increased for a much longer period of time with WWC than PPP. Totally, drying of PPP on the standing thermal manikin in still air consumed significantly more energy than drying of WWC.

The location of the water in the clothing did not have a major influence on evaporation rate, although evaporation seemed to be slower the further away from the manikin surface the water had been placed. With water placed in the cotton outer layer of WWC, drying time was extended considerably. The location of the water in the clothing had a significant influence on the percentage of drying energy taken from the thermal manikin. Both with natural and man-made textile materials energy consumption from TM during drying of the wetted clothing was significantly higher the closer to the manikin surface, the water was localized. When the outer clothing layer dried, less than 25% of the energy used for evaporation was consumed from the manikin standing in still air.

Walking movements increased steady-state heat loss from 78 and 86 $W \cdot m^{-2}$ to 94 and 99 $W \cdot m^{-2}$ with WWC and PPP, respectively. The movements of the limbs slightly increased the evaporation rate from the clothing regardless of where the water had been placed. The energy contribution from TM to drying of the outer clothing layer was increased by more than 10% due to the walking movements. With woolen clothing an increase in energy contribution from TM was also seen when water evaporated from the inner and middle layers; however, with man-made textile materials in the clothing no such increase in the manikin's share of evaporation energy could be observed in this study.

With an increased air velocity of 1.0 $m \cdot s^{-1}$, steady-state heat loss from the standing TM increased to 92 and 101 $W \cdot m^{-2}$ with WWC and PPP, respectively. Evaporation was much faster from the clothing manufactured from synthetic textile materials in the wind, and more the further out in the clothing the water had been placed. With the ensemble of natural fibers, the wind effect on evaporation was only significant when the water had been placed in the outer layer. The manikin's share of the evaporation energy was significantly increased during drying of the inner layer. For drying of the middle and outer clothing layer, wind increased the energy consumed from TM when the clothing was made from wool/cotton, whereas no significant effect was observed when the garments were made from synthetic materials.

CONCLUSIONS

It can be concluded from this study, that drying rate and drying time of wet clothing primarily are determined by textile material. However, they are also affected by location of the sweat in the clothing, by external air velocity and body movements. The heat energy delivered from the skin to the evaporation during drying is primarily determined by the location of the sweat in the clothing, but textile material, external air velocity and body movements does also have an effect.

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