What is the Best Clothing to Prevent Heat and Cold Stress? Experiences with Thermal Manikin

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ABSTRACT

The present study summarizes the current knowledge of the heat and cold stress which might significantly affect military activities and might also occur among travellers who are not well adapted to weather variations during their journey. The selection of the best clothing is a very important factor in preserving thermal comfort. Our experiences with thermal manikin are also represented in this paper.

Keywords: Cold stress, clothing, heat stress, thermal comfort, thermal manikin

¿Cuál es la Mejor Ropa para Evitar el Calor y el Estrés del Frío? Experiencias con Maniquíes Térmicos

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RESUMEN

El presente trabajo resume los conocimientos actuales sobre el calor y el estrés por frío, que puede afectar significativamente la preparación militar, y pueden también ocurrir entre viajeros no bien adaptados a los cambios de tiempo y temperatura durante su viaje. La selección de la ropa mejor y más adecuada es también un factor muy importante para evitar el calor y el estrés por frío, y mantener el confort térmico. Nuestras experiencias con maniquíes térmicos también aparecen en este documento.

Palabras clave: Ropa, estrés por frío, estrés térmico, confort térmico, maniquí térmico

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INTRODUCTION

Heat-related illness occurs generally when the body's temperature control system becomes overloaded and sweating is not enough to dissipate the heat (1). In heat stress, a person's body temperature rises rapidly and the very high body temperatures may damage vital organs. Cold stress means the loss of heat to the environment, and in such cases the body's first response is to conserve body heat by reducing blood circulation through the skin. Thermal insulation and moisture vapour resistance of clothing are the two most important clothing properties with respect to thermal comfort and to the selection of the best clothing for functional clothing design and thermal environmental engineering. These two properties can be measured by tests on human subjects or by using sweating manikins (2, 3).

HEAT STRESS

Heat stress is a group of conditions due to over-exposure in excess environmental temperature and includes heat stroke, heat cramps and heat exhaustion (1).

Heat stroke

Heat stroke is the most serious heat-related illness, occurring when the body becomes unable to control its temperature: In such cases, the body's temperature rises rapidly and the sweating mechanism fails, so the body is unable to cool down. This may cause death or permanent disability if emergency treatment is not provided (1).

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Heat exhaustion, heat cramps, heat rash
Heat exhaustion may develop after several days of exposure to high temperatures and inadequate replacement of fluids. Heat cramps are muscle pains – usually in the abdomen, arms, or legs – which may occur in association with sweating during strenuous activity. In such cases, sweating depletes the body's salt and moisture. Heat rash is a skin irritation caused by excessive sweating during hot, humid weather (1).

Heat stress reduction
The five major types of engineering controls used to reduce heat stress in hot environments are ventilation, air cooling, fans, shielding and insulation. Fluid replacement in the form of cool water, one cup of drink in every 20 minutes, should be available. Reflective, loose clothing (aprons, jackets), which completely cover the body from neck to feet, can stop the skin from absorbing radiant heat (4).

Which is the best clothing to prevent heat stress?
In very hot weather conditions, loose-fitting, lightweight, light-coloured clothing should be worn. In the hot sun, a wide-brimmed hat may keep the head cool (1). Synthetic fabrics called wickaways (such as CoolMax or Dri-Fit) draw moisture away from the skin, so that cooling evaporation may occur. It is recommended to avoid wearing 100% cotton socks because the feet would be sweating a lot, and cotton tends to keep the feet wet, which may lead to blisters. The best choice is to wear synthetic blends made from polyester, acrylic or CoolMax, which draw moisture away (5).

COLD STRESS
Cold stress means the loss of heat to the environment. In such cases, the body's first response is to conserve body heat by reducing blood circulation through the skin. Factors that affect cold stress include low temperatures, wind and wetness.

Conditions affecting cold stress
- Ageing, allergies, poor circulation and illness
- Alcohol use, antidepressants or sedatives
- The body may have difficulty regulating temperature
- Wet clothing, windy conditions (6)

Cold stress hypothermia signs and symptoms
- Severe muscle stiffness
- Drowsiness or unconsciousness
- Ice cold skin
- Death is a possibility
- Pernio
- J wave on electrocardiogram [ECG] (6).

Frostbite
Frostbite occurs when the skin actually freezes and loses water. The skin becomes pale, hard and numb and it usually affects the extremities such as the fingers and hands, toes and feet, ears and nose.

Safety procedures
The proper treatment depends on the severity of the hypothermia and includes: moving to a warm area, staying active, removing wet clothes and replacing with dry ones or blankets, covering the head, wearing properly selected, insulated, and layered clothing, drinking warm sugary beverages and avoiding alcoholic drinks, caffeine and nicotine (6).

What is the best clothing to prevent cold stress?
- A fleece or wool hat is perfect for keeping the head warm during cold weather conditions, so too is a neck gaiter on a windy day to protect the neck and the face. Balaclava is a type of headgear that covers the whole head, except for the face and the eyes. They are usually made of wool or fleece (5).
- At the upper body, the moisture is drawn away from the first layer to the outer layers, and then evaporates. The layer of clothing closest to the body should be made from synthetic wickaways such as DryFit, Thinsulate, Thermax, CoolMax, polypropylene, or silk, so the sweat will be wicked away from the body, keeping the body dry and warm (5).
- The insulating layer is the second or middle layer, which is necessary to prevent cold stress, and should be made of materials such as fleece. This layer must continue drawing moisture away from the skin, while also achieving the perfect balance of trapping some air to keep the body warm. The best second layer fabrics are: thermafleece and thermax, akwatek, dryline, polartec, polyester fleece and microfleece (5).
- The wind- and waterproof outer layer should protect the body against wind and moisture, but at the same time lets both heat and moisture escape to prevent both overheating and chilling. The best fabrics for outer layer are: nylon, Supplex and Wind stopper ClimaFit, Gore-Tex and Microsuplex (5).

THERMAL MANIKIN
A thermal manikin (Fig. 1) was used for the investigation and the measurements of heat and cold stress. The thermal manikin is a model which is built from thermal measuring body, computer, control unit, data logger and which allows data processing and visualization. The measuring body is made of a plastic puppet the size of an average adult human body. The body is a polyester shell construction fixed with

Fig. 1: Thermal manikin in a seated position.

fiberglass. In the caverns of the manikin, there are the elements which give the mechanical keeping, and tubes that contain the hidden electrical cables which lead to different parts of the body. The body surface of the thermal manikin is split up into 16 parts in the standing position and 18 parts in the sitting position (Fig. 2). There are heating wires in

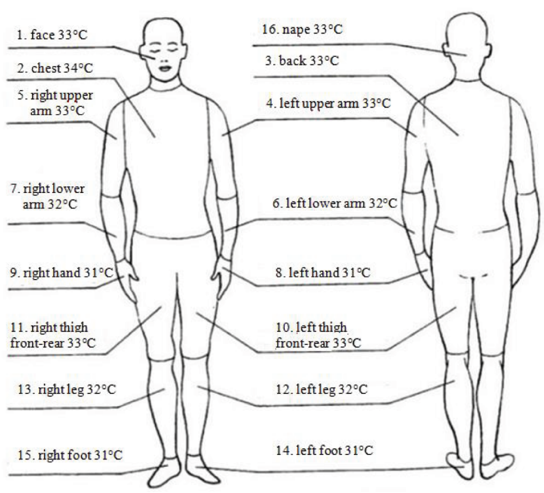

Fig. 2: Surface temperature of different parts of a thermal manikin.

each part of the body surface. The plastic layer gives the electrical insulation, on which there is an average of 0.4 mm thick aluminium layer to achieve uniform temperature distribution on the whole body surface. The principle of the measurement is to accurately measure the electrical power of the heated body part which ensures its required surface temperature (9). The required surface temperature of body parts was determined at comfort condition.

Thermal insulation of clothing

The heat loss and the heat sense of humans are greatly influenced by the thermal insulation of clothing. The convective and radiant heat transfer might be measured on the whole body surface with the thermal manikin. The heat loss of the whole body and the thermal insulation of clothing can be calculated by determining the surface temperature and heating power data that are measured at the different body parts of the thermal manikin. The total insulation, which is thermal insulation (thermal resistance) of clothing and boundary air layer around clothing, might be calculated as follows (7):

$$I_T = I_{cl} + \frac{I_a}{f_{cl}}$$

where:

I_T – total thermal insulation of clothing and boundary air layer, m^2K/W
I_{cl} – thermal insulation of clothing, m^2K/W
I_a – thermal insulation of boundary air layer, m^2K/W
f_{cl} – clothing area factor, *ie* the ratio of the outer surface area of the clothed body to the surface area of the nude body

To calculate the total thermal insulation, we have to measure the heat loss of the thermal manikin dressed in the requisite clothing. To calculate the boundary air layer around the body, we have to measure the heat loss of the nude thermal manikin.

The parallel summation calculation method

The parallel summation calculation method determines the total thermal insulation as an area-weighted average of the local insulations.

$$I_{T,\ parallel} = \frac{\left[\left(\sum_i f_i \cdot T_i\right) - T_a\right] \cdot A}{\sum_i H_i} \qquad \frac{m^2 \cdot K}{W}$$

The serial summation calculation method

The serial summation calculation method is based on the measurement of total thermal insulation by summation of the local area-weighted thermal insulations:

$$I_{T,\ serial} = \sum_i f_i \left[\frac{(T_i - T_a) \cdot a_i}{H_i}\right] \qquad \frac{m^2 \cdot K}{W}$$

where:

f_i – area factor of section i of the thermal manikin, $f_i = ai/A$
a_i – surface area of section i of the manikin, m^2
A – total body surface area of the manikin, m^2
T_i – surface temperature of section i of the manikin, K
T_a – air temperature in the climate chamber, K
H_i – local heating power fed to section i of the manikin, W

When calculated by the parallel summation method, the total thermal insulation is usually 20% less than the values calculated by the serial method. The thermal insulation of boundary air layer around the nude body (I_a) should be calculated similarly to the method of calculation of total thermal insulation.

The clothing area factor – the value of f_{cl} – can be determined by measurement, but approximate, indirect calculation is also possible, which correlation can be used

(8):

$$f_{cl} = 1 + 0.28 \cdot I_{cl}$$

We use the clo unit for the thermal insulation of clothing I_{cl} (definition):

$$1 \text{ clo} = 0.155 \text{ m}^2\text{K/W}$$

RESULTS

Heat loss of the human body in different temperature

Heat loss of people depends on air temperature, radiant temperature of the surrounding surfaces, air velocity, relative humidity, activity and clothing. In the comfort of indoor spaces, heat loss of humans is less dependent on air velocity and humidity, therefore, during the investigations, we assumed these values were constant. During the investigations, the air velocity was v = 0 m/s, and the relative humidity was approximately φ = 50%. With these parameters, we measured the heat loss of the thermal manikin in different types of clothing.

The technical literature gives the heat loss of people as a function of the activity; the value of the heat loss in a wide range of temperatures has not been known, thus the determined relationships provide useful information for further research. We determined the heat loss of humans in different clothes as a function of the equivalent temperature. The measurements were carried out between -3 °C and +26 °C ambient temperature, with 1.0 clo normal business man clothing, 1.3 clo business man clothing with raincoat, and 1.5 clo business man clothing supplemented with fabric jacket. The examined range was wider than that of the comfort of indoor spaces, but the air velocity and relative humidity changes were not examined.

Heat loss of the whole human body

The measurement results provide useful relationships for medical science that were not yet known (Fig. 3).

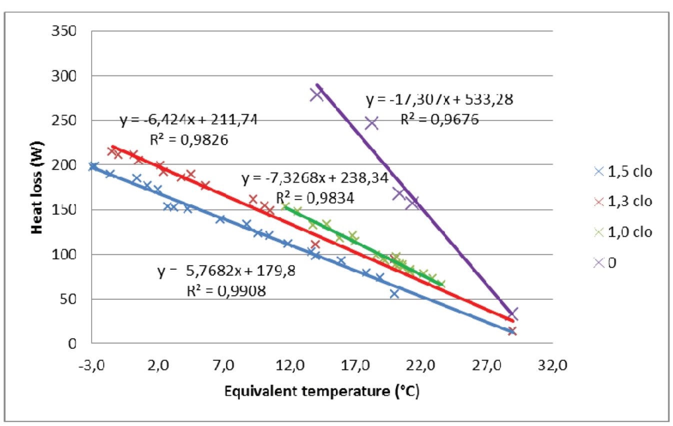

Fig. 3: Heat loss of humans as a function of the equivalent temperature in different clothes.

Heat loss of parts of the human body

The medical science and the comfort theory are not only interested in heat loss of the whole human body, but heat loss of the body parts as well. The equivalent temperature is important at the thermal comfort measurements made with thermal manikin. Equivalent temperature is the temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature, no air movement and the person has the same heat exchange by convection and radiation as under the actual conditions.

We determined the specific heat loss for the body surface area unit and heat loss of the whole human body as a function of the equivalent temperature. The measurements were carried out first when the thermal manikin was nude and then when wearing different clothing. All parts of the body which were covered completely by clothing (*eg* the back, the upper arm) and the body parts without clothing (*eg* the face) were examined. We measured the heat loss and the specific heat loss of the human body parts (18 parts) as a function of the equivalent temperature, when 0 clo, 1.0 clo, 1.3 clo and 1.5 clo clothing covered the body (9).

Results showed that heat loss of the body parts changed linearly as a function of the equivalent temperature. Without clothing, the variance was between 0.8769 and 0.9959 (except the back, which was 0.759), in 1.0 clo clothing it was between 0.8356 and 0.9617, in 1.3 clo clothing it was between 0.9655 and 0.9936, and in 1.5 clo clothing the variance was between 0.7759 and 0.9961. For example, in Fig. 4 we can see the specific heat loss of the face, chest and head as a function of the equivalent temperature, when 1.3 clo clothing covers the body.

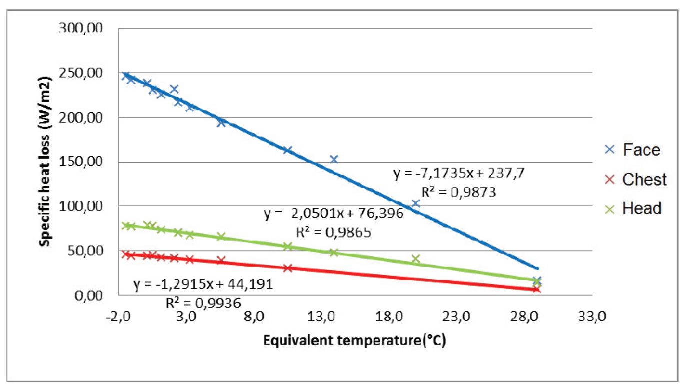

Fig. 4: The specific heat loss of the face, chest and head when 1.3 clo clothing covers the body.

The identified relationships show different heat loss of the body parts, which provide important information for thermal discomfort investigations in the comfort theory and in medical science for research of different diseases.

The heat loss of the whole human body as a function of the equivalent temperature, with different clothing is as follows (9):

0.0 clo clothing	$Q = -17{,}307\ t_{eq} + 533{,}28$ [W]	$R^2 = 0.9676$
1.0 clo clothing	$Q = -7{,}3268\ t_{eq} + 238{,}34$ [W]	$R^2 = 0.9834$
1.3 clo clothing	$Q = -6{,}424\ t_{eq} + 211{,}74$ [W]	$R^2 = 0.9826$
1.5 clo clothing	$Q = -5{,}7682\ t_{eq} + 179{,}8$ [W]	$R^2 = 0.9908$

DISCUSSION

The very interesting and important question "what is the best clothing to prevent heat and cold stress?" is often posed. Clothing physiology, the science of clothing and the human vital context, often embraces this topic.

The goal is to reach to a point when design lets people wear appropriate clothing under all circumstances of both heat and cold stress and to provide the best microclimate for the body. While it is influenced by a number of factors, in the strictest sense, clothing physiology mainly deals with the effects of clothing on the heat and moisture finances of the human body, as well as the effects of clothing on the skin – softness, adhesion and skin irritation by potential roughness of clothes (8).

Clothing has a strict function, and the conditions in which they are worn determine the choice, time and type of clothing to wear optimally.

In addition to being practical, beautiful, comfortable and easy to keep clean, clothing has a very important physiological role, and from that resulting demands must be satisfied.

The comfort and fit of clothing is as important as its function. This includes ensuring freedom of movement and the appropriate layout, and that clothing induces a pleasant feeling on the skin, even in changing weather conditions. However, the most important goal is the regulation of body temperature in both heat and cold stress (3).

In our study, we determined the specific heat loss for the body surface area unit and the heat loss of the whole human body as a function of the equivalent temperature. We concluded that the function is linear, and the variance value was between 0.9676 and 0.9908 (9). Our results highlight the important role of thermal manikins in choosing the best clothing for changeable weather conditions.

In summary, our results confirm that suitable clothing is an important factor in avoiding heat and cold stress, and thermal manikin measurements may help to predict this.

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