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Control of Liquid Cooling Garments : Subjective versus Technical Control of Thermal Comfort

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Abstract. Liquid cooled garments (LCG) are a powerful tool for alleviating heat strain during work in hot conditions. However, the potential advantage of an LCG depends on a more or less proper control of the cooling liquid's temperature. To gain more knowledge on this subject two experimental studies concerning manual control by the wearer were carried out. In both studies the subjects had to exercise in a warm environment. In the first study the subjects (n=5) were asked to control the temperature directly. They used different strategies, ranging from gradual changes to oscillations of the suit temperature. This was accompanied by large differences of the chosen inlet temperature and the comfort level attained, although by repetition of the experiment it was possible to increase the subjective thermal comfort. In the second study a technical 'comfort' controller changed the inlet temperature of the LCG in the appropriate direction whenever the personal assessment of thermal sensation differed from the neutral state. The subjects (n=6) had no information about the control mode. The experiments showed that it was possible to maintain a comfortably neutral thermal sensation throughout nearly the whole experiment. This result, however, was partly in contrast to the objective thermal state of the subjects. Two of them had problems with their heat balance, expressed by the fact that their rectal temperature did not reach a steady state. The results of both studies indicate that manual or subjective control is not optimal and should therefore be replaced by an objective control of the thermal state.
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Keywords: liquid cooling garment, subjective control, technical control, thermal state

Introduction

The human body is provided with a temperature controller which is able to maintain a proper thermal balance in moderate environmental conditions by vasomotor changes only. However, if heat gain or heat loss increases, more powerful effector mechanisms must be activated to maintain the thermal balance. In the cold an increasing metabolic rate due to shivering may compensate for the higher heat loss to the environment and, in contrast, the evaporation of sweat fulfils the need for sufficient heat loss in hot conditions (Werner, 1993). An extreme situation arises when work has to be done in an environment where the necessary heat loss is impaired. The resulting heat stress not only diminishes the perceived thermal comfort and the work capacity but also involves the risk of heat collapse or heat stroke. To prevent any extreme physiological state, limits for heat strain have been proposed. For example, the highest physiologically tolerable heat storage is considered to be near 175 Wh, a value corresponding to a mean body temperature of about 40°C (Nunneley, 1970; Webb, 1971). However, to guarantee the full physiological and mental work capacity, heat storage should be less than 88 Wh which means that the body temperature rise should be limited to 1.2°C (Kuznetz, 1980).

Despite technological advances, workplaces still exist where the two stressors, work and hot environmental conditions, act simultaneously. A very popular example is the extravehicular activity of astronauts. Depending on the radiation, temperature gradients of up to 300°C exist on the surface of an astronaut's suit when he moves on the moon or in the space. As a shelter from both the high radiative heat load on the sunny side as well as from the cold load on the shadowed side, the astronauts wear a metalized pressure suit. With such a suit all pathways for an effective heat transfer are blocked and all the generated metabolic heat must be removed by means of artificial body cooling to prevent harmful body heat storage. Similiar situations, where working people must be protected from their environment exist on earth too, for example for fire fighters, workers in the steel and glass industry, miners, military flight personal etc.. Simple, but nevertheless effective systems for artificial body cooling consist of a vest incorporating pockets in which small containers filled with ice or frozen gels are carried. More complex systems have been developed for use in air- and spacecrafts

(Allan, 1988; Nunneley, 1970). Here one can distinguish between two basic principles, air cooling by forced convection and water cooling by means of special suits which include a system of cooling tubes distributed over a great part of the body surface, generally perfused by water. The latter system showed a greater efficiency, was simple but tough in construction and more convenient for the wearer, as air-cooling systems may be very noisy (Nunneley, 1970).

Much research was done to clarify the question as to which sites of the body may be advantageous for cooling, how many tubes were necessary and how the tubes should be distributed over the body surface. In the case of mild work (pilots) a water perfused cooling vest may be sufficient to extract the generated and the impacting heat. However, moderate and heavy work require a whole-body cooling suit (overall) including the head, perhaps excluding the hands, the feet and the face.

Another field of research concerning the use of liquid cooling garments (LCG) dealt with the question of cooling control, since for the maintainance of the thermal balance, the heat removal rate must be adapted to the metabolic heat load. With regard to technique, two different ways of manipulating the heat removal rate are possible, firstly by changing the mass flow and secondly by varying the inlet temperature of the liquid, the second being most commonly employed. With regard to physiology, various principles are obvious, manual control by the wearer and automatic control depending either on the objective or the subjective thermal state of the person. In the first systematic approach we tested in two series of experiments the methods based either on manual or on automatic control of the subjective thermal state, while simultaneously analyzing the objective physiological state.

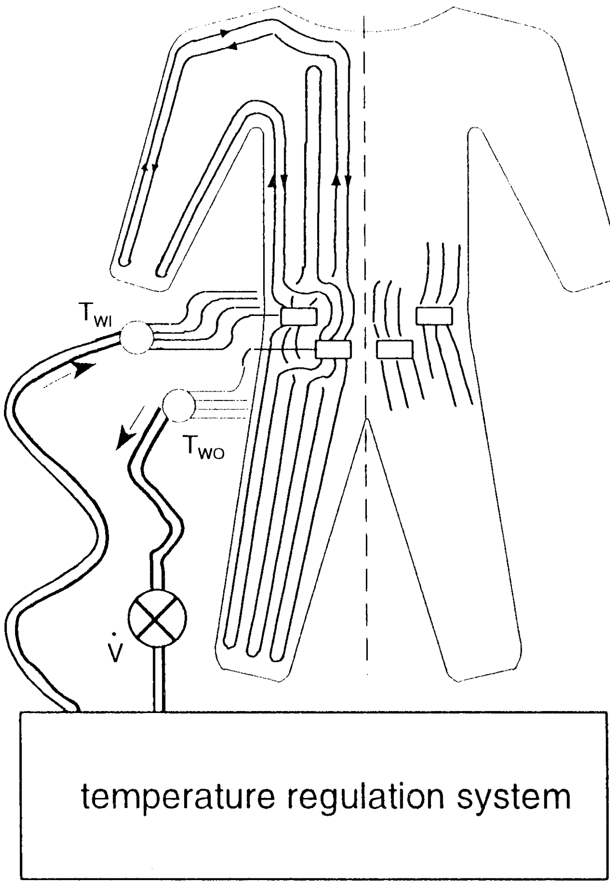

Fig. 1 The cooling system. Flow pattern and basic measurements for the calculation of heat removal rate (P_{suit}).T_{WI}, T_{WO}: water inlet/outlet temperature; $\dot{V}$: volume flow of water.

Methods

The cooling suit and its operation

All experiments were carried out in a climatic chamber. The environmental conditions were 35°C and 40% relative humidity. Wind speed was below 0.05 m·s^{-1}. These conditions were considered to represent an average microclimate in the air layer between a LCG and an outer protection garment.

The LCG (ILC-Dover) was of the same type as used by the NASA during the Apollo missions (Kuznetz, 1980). The suit covers the whole body excluding head, hands and feet. It consists of two nylon layers. The cooling tubes (PVC, 91m in total, 1.6mm/3.2mm inner/outer diameter) are woven in the outer layer which is wide-meshed. The inner layer, fitted between the cooling tubes and the skin, is intended to provide homogeneous heat transition, while simultaneously enhancing the wearing comfort. Four distinct cooling loops exist within this type of LCG. Two loops supply the left and the right front, and the two others the left and right back. The flow pattern is identical in each loop. The starting point is a manifold on the waist where the main stream is distributed into the small heat-exchange tubes. From there the cool water is led over the trunk via the shoulder and the arm to the wrist and nearly the same way back to the outlet manifold. The same applies to the lower part of each cooling loop. Water flow to the LCG was supplied by a temperature control system located outside the climatic chamber. Both were connected via two insulated PVC-tubes (4m). Two temperature sensors (PT100) placed in the water stream just in front of the inlet manifold (T_{WI}) and behind the outlet manifold (T_{WO}) measured the temperature gradient across the suit. Volume flow of water ($\dot{V}$) was sensed by means of a flow rate transmitter (Litre Meter Limited). Flow rate was approximately 1.8 l·min^{-1} throughout all experiments, while inlet temperature was changed manually or automatically depending on the type of experiment. With these measurements, heat removal rate (P_{suit}) was calculated using ρ as density and c as specific heat of water:

$$P_{suit} = \rho \cdot c \cdot \dot{V} \cdot (T_{WO} - T_{WI}) \quad (1)$$

The worst case error of the heat removal rate was estimated to be ±7W, based on the single errors of temperature (0.05°C) and flow rate measurement (0.02 l·min⁻¹). This heat removal rate inherently reflects a mixture of the metabolic heat, produced by the wearer, and the heat exchange with the environment. So at this point, one has to decide whether to insulate the LCG completely from the environment, as Webb et al. (1972) did in their calorimetric studies with the aim of measuring only the heat generated by the subject, or to allow heat exchange with the environment as a simulation of a more realistic situation. In our experiments, the LCG was covered with an overall allowing a residual heat gain from the environment. This heat gain ($P_{suit,amb}$) was estimated for the appropriate temperature range of the cooling liquid and the climatic condition (equation 2) in an experiment where the covered LCG was filled with polystyrene flocks and seated on the cycle ergometer as in the regular experiments whereby an additional ventilator was used to simulate the higher wind speed at the pedalling legs.

$$P_{suit,amb} = 89{,}5\,W - 3{,}67 \cdot \frac{W}{°C} \cdot T_{WI}$$
$$T_{amb} = 35°C,\ r = -0.99,\ p < 0.01 \quad (2)$$

Physiological measurements

Skin temperatures were sensed with thermocouples at ten sites. Mean skin temperature was then calculated with weighting coefficients according to the well-known 12 points Hardy/DuBois-formula, the only difference being that the temperature of the thigh as well as that of calf had been measured only once. The measuring sites and their weighting coefficients (in brackets) had been: forehead (0.07), chest (0.116), abdomen (0.116), back (0.118), thigh (0.19), calf (0.13), upper arm (0.07), lower arm (0.07), hand (0.05) and foot (0.07). Rectal temperature was measured 10 cm behind the anal sphincter (thermocouple; Ellab, Denmark).

An open mask system was used to determine the metabolic rate. The subject carried a face mask connected to a large tube through which air was sucked. The volume flow in this tube ($\dot{V}_{main}$), being sensed by a turbine flow transducer (Flow Technology, Phoenix), was approximately 180 l·min⁻¹. The inspired air was taken from the main stream. A differential oxygen analyzer (Magnos 4G, Hartmann & Braun) was fed with dry air samples taken from the main stream before and behind the mask, providing an output signal directly proportional to the oxygen concentration difference (ΔC_{O2}) between the two samples. Additionally temperature, pressure and relative humidity were registered at several sites in the analyzing system so that a standardized volume flow ($\dot{V}_{main,STPD}$; STPD: standard temperature pressure and dry) and concentration difference ($\Delta C_{O2,dry}$) could be calculated. An almost identical procedure was used for the determination of the carbon dioxide production. The respiratory quotient (RQ) was calculated from oxygen consumption ($\dot{V}_{O2}$) and carbon dioxide production ($\dot{V}_{CO2}$) production

$$RQ = \frac{\dot{V}_{CO2}}{\dot{V}_{O2}} \quad (3)$$

leading to the caloric equivalent (E)

$$E = (16{,}1,\ +5 \cdot \mathrm{RQ})\ \mathrm{kJ \cdot l^{-1}} \quad (4)$$

and finally to the metabolic rate (MR).

$$MR = E \cdot \dot{V}_{O2} \quad (5)$$

Exercise was performed on an electrically braked cycle-ergometer (Ergoline) in a semi-supine position. A built-in microcomputer controlled the torque so that the exercise rate (ER) was independent of the pedalling rate. Nevertheless the subjects were advised to pedal within the range from 40 to 60 rpm. The ergometer also included an automatic blood pressure monitor. Metabolic heat production (HP) was calculated from metabolic rate and exercise rate (ER):

$$HP = MR - ER \quad (6)$$

With two scaled turn-switches the subjects could indicate their thermal sensation and their thermal comfort. In the case of thermal sensation the possible votes were "very cold", "cold", "cool", "slightly cool", "neutral", "slightly warm", "warm", "hot" and "very hot" and in the case of thermal comfort "uncomfortable", "slightly uncomfortable", "neutral", "slightly comfortable" and "comfortable". Heart rate was monitored optically using an earclip.

Sweat rate (SWR) was recorded on the chest and on the thigh by means of a ventilated capsule, where a stream of air (2 l·min⁻¹) was directed onto a skin area (12.5 cm²) under the capsule. The evaporation of sweat increases the absolute humidity of the air, the difference between inlet and outlet being proportional to the sweat rate. The calculation of the absolute humidity requires the measurement of the temperature (T_{air}), the relative humidity (RH_{air}) and the pressure (P_{air}) of the air stream.

$$\varphi = RH_{air} \cdot \varphi_S(T_{air}) \cdot \frac{P_{air}}{1013\,mbar} \quad (7)$$

Here $\varphi_S(T_{air})$ is a polynomial evaluation of the absolute humidity of saturated air at temperature T_{air}. It was derived on the basis of vapour tables. Finally, with the knowledge of the air mass flow ($\dot{m}_{air}$), sweat rate could be calculated:

Table 1 Physical characteristics of the subjects of group 1. (m.: mean; s.d.: standard deviation)

	weight [kg]	height [m]	surface [m²]	$V_{02,max}$ [$l \cdot min^{-1}$]	age
S1	86	1.93	2.17	−/−	28
S2	81	1.92	2.1	2703	19
S3	80	1.83	2.02	2831	25
S4	72	1.74	1.86	2706	26
S5	91	1.92	2.21	−/−	34
m.	82	1.87	2.07	2747	26.4
s.d.	7.1	0.08	0.14	73	5.4

Table 2 Physical characteristics of the subjects of group 2. (m.: mean; s.d.: standard deviation)

	weight [kg]	height [m]	surface [m²]	$V_{02,max}$ [$l \cdot min^{-1}$]	age
S1	80	1.83	2.02	2831	25
S2	77	1.80	1.96	2859	25
S3	70	1.83	1.91	4056	26
S4	71	1.77	1.87	3012	26
S5	74	1.75	1.89	3668	22
S6	81	1.91	2.1	2871	23
m.	75.5	1.82	1.96	3382	24.5
s.d.	4.6	0.06	0.09	546	1.6

$$SWR = \dot{m}_{air} \cdot (\varphi_{out} - \varphi_{in}) \quad (8)$$

Subjects

Ten subjects participated in the experiments, all of them had been checked up firstly by an independent medical doctor. The purpose and the procedure of the experiments were explained and a written form of consent was signed by the subjects. Some typical physical characteristics of the subjects are shown in Tables 1 and 2. Surface area (A_D) was calculated from body mass (m) and height (h) using the well-known DuBois-formula:

$$A_D = 0.202 \cdot \dot{m}^{0.425} \cdot h^{0.725} \quad (9)$$

Maximum oxygen uptake was obtained during a preceeding experiment. There, exercise rate was increased stepwise, each step being 40 W high and lasting until oxygen consumption leveled for the particular exercise rate. The protocol was finished when the subjects stopped due to exhaustion or their oxygen uptake did not increase anymore.

Experimental procedures:

I) Subjective control of thermal comfort

In the first series of experiments we studied the ability of humans to cope with the control problem. The following questions were asked:

1) How successful is the human controller in maximizing his subjective thermal comfort, which was supposed to be the controlled variable?
2) Which strategies does he use?
3) Is it possible to increase the thermal comfort by training?

Therefore five subjects (group 1) wore the LCG while exercising on the cycle-ergometer in the climatic chamber (35°C, 40%). The experimental schedule was always the same, 30 minutes rest before and after a 75 minute exercise period. At the start of an experiment the LCG temperature was 32°C. To enable the subjective control of the inlet temperature, an unscaled potentiometer was placed near to the subject. The possible range for the inlet temperature was from 5°C to 45°C.

II) Technical control of thermal comfort

In the second series of experiments we tested whether the subjective thermal sensation/comfort were a suitable input signal for a technical controller. From earlier experiments we could assume that a neutral thermal sensation coincides with thermal comfort. Therefore, in order to maximize the subjective thermal comfort, the ratings for the thermal sensation directly changed the inlet temperature of the suit. Calculation was done automatically by a computer, the subjects having no knowledge about the control mode. Inlet temperature remained unchanged when a neutral thermal sensation was present and was changed with a velocity determined by the strength of the sensation, until the neutral thermal sensation was reached again. Six subjects (group 2) participated in this study, the environmental conditions were again 35°C at 40 % relative humidity. Here, the subjects had to rest for ninety minutes before a two hours lasting exercise period started. The schedule was finished with another resting period lasting one hour.

Results

I) Subjective control of thermal comfort

The experiments confirmed the assumption that the subjective thermal comfort was the controlled variable. Votes showing discomfort involved changes of T_{WI} in the opposite direction. Three different control strategies were detected:

1) Change of temperature with small successive steps not only at rest but also during exercise (Fig.2, left panel). The final value, which was kept constant for the rest of the exercise period, was reached within forty minutes. Other subjects used a similar strategy, however, more time was needed for the final state, and the amplitude of the chosen steps was greater.

2) Lowering of temperature in not more than two steps during the exercise period.

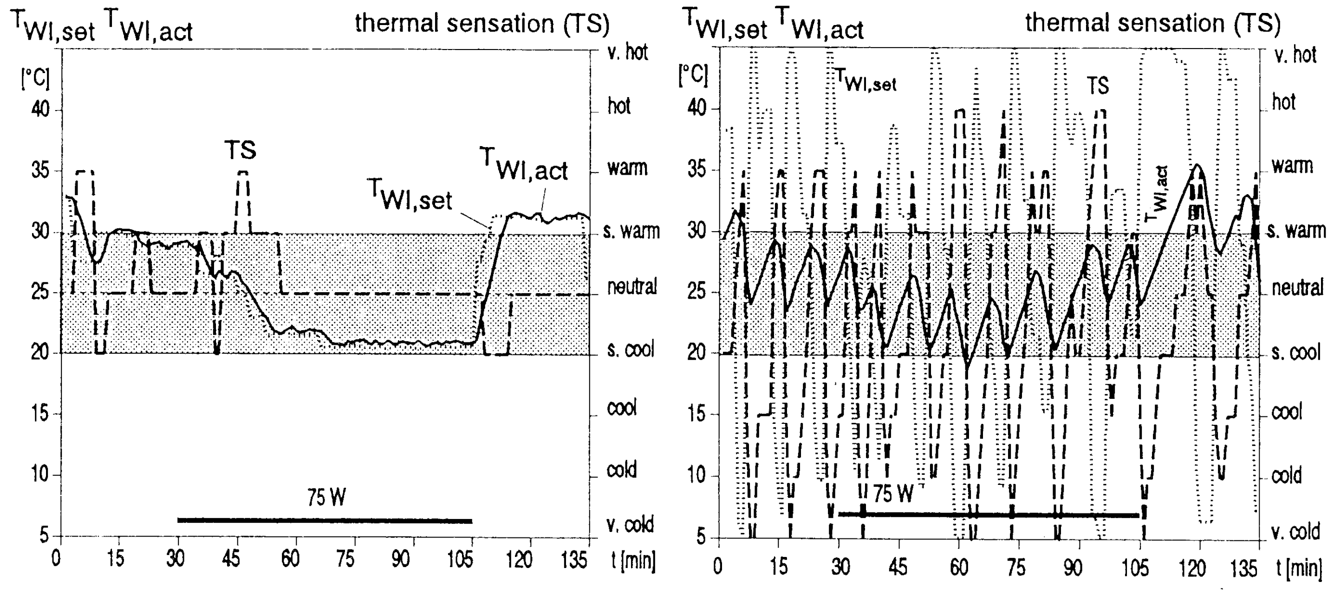

Fig. 2 Examples of two different control strategies: Time courses of the chosen and the actual water inlet temperature ($T_{WI,set}$, $T_{WI,act}$) and of the thermal sensation (TS). The sensations within the dotted area represent comfort, those outside this area represent discomfort.

3) Oscillations of LCG-temperature amplitude about 3°C around a mean value (Fig.2, right panel). It was not possible to keep the temperature constant for a longer period, neither at rest nor during exercise.

The amount of cooling differed greatly among the subjects (Fig.3) and the same holds for the individual time course of T_{WI} and the period needed to reach the final temperature.

Metabolic rate was 104 ± 17 W at rest and 432 ± 34 W during exercise. Steady state rectal temperature rise was 0.51 ± 0.15°C ($p < 0.01$) starting at 37.24 ± 0.2°C. Mean skin temperature was lowered from 34.91 ± 0.61°C by 1.87 ± 1.15°C ($p < 0.05$). However, a steady state was not reached in any of the experiments, although inlet temperature was already constant. This clearly emphasizes the fact that heat removal from the shell was always higher than heat gain from the core (and the environment). Regarding the mean inlet temperature of the LCG ($T_{WI,m}$: mean value of T_{WI} during exercise), only a weak trend between this value and the rise in rectal temperature could be demonstrated ($T_{WI,m} = 30.17 - 20.14 \cdot \Delta T_{rest}$, $r = -0.85$ $p < 0.1$).

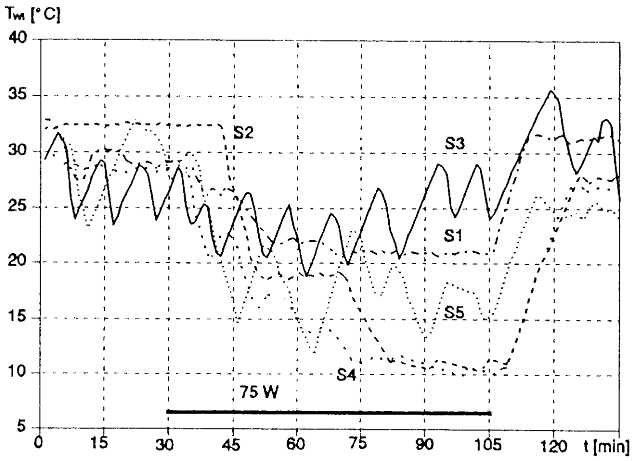

Fig. 3 Individual time courses of water inlet temperature T_{WI} during direct control by the subjects S1-S5.

The time period during which the subjective thermal sensation was voted "comfortable" normed to the whole experimental time period was defined to be the comfort level. Like the degree of the cooling this value exhibited a great span from 45.2 to 94.1 % (mean: 71.3 ± 18.8%). Three subjects were used for repeated experiments. The subject (S1) with the highest comfort level in the first experiment made one repetition three weeks later. Again his cooling strategy led to a very high comfort level (Fig.4), which was nearly maximal. The two subjects who started with the poorest comfort levels (S2 & S3) repeated the experiments three times, with one week intervals between the runs. S2 was able to increase his comfort level steadily with each experiment from 60% to 94%. Similiar to his first experiment he lowered the temperature in not more than three steps. The oscillating strategy of S3 was observed in the other experiments, too. Due to the large temperature changes which he evoked, his thermal sensation always alternated between the extreme ends of the scale. Nevertheless, he increased his comfort level with the exception of a transient fall in the third session.

II) Technical control of thermal comfort

An example for the time courses of the thermal sensation signal, the thermal comfort signal and the water inlet temperature is given in Fig.5. In order to

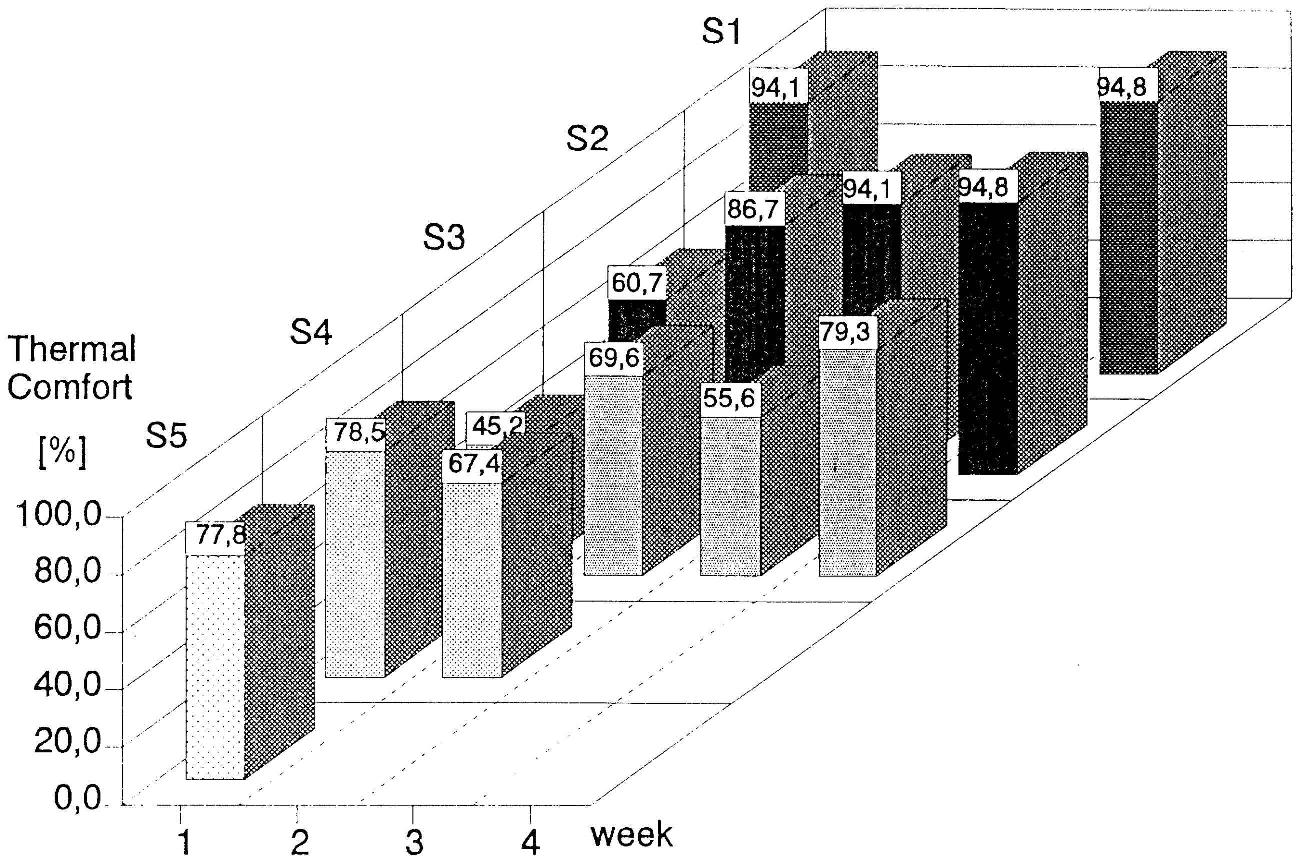

Fig. 4 Thermal comfort votes in all experiments using direct control by the subjects S1- S5.

achieve a thermal equilibrum, the subjects initially rested for an hour at a fixed inlet temperature of 29°C. The control algorithm was activated in the 60th minute (arrow) with the result that existing deviations from the neutral thermal sensation were corrected instantaneously. Looking at Fig. 5, it is evident that with the beginning of exercise, the increasing occurrence of warm sensa-

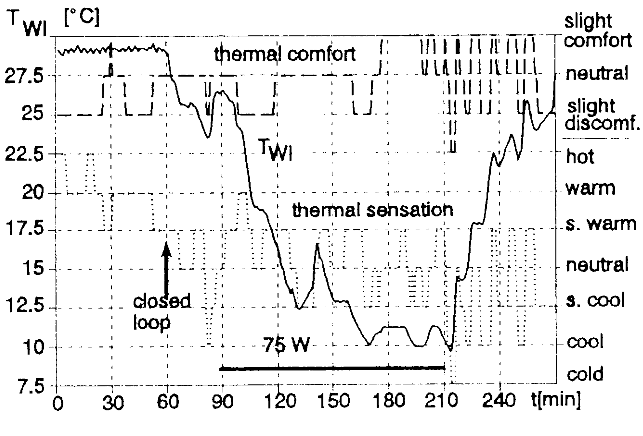

Fig. 5 Control behaviour of a single subject in the experiments using the technical control of the thermal sensation. "Closed loop" (arrow) was the time when the control loop was activated. T_{WI}: water inlet temperature.

tions led to lower water temperatures. However, this cannot be generalized for all subjects, as some of them preferred to perform their task at higher inlet temperatures as compared to the resting condition. In contrast, in other subjects the neutral thermal sensation was linked to such a strong cooling that sweat rate was close to zero towards the end of the exercise period. Fig. 6 illustrates this variability: The different heat removal rates of these two subjects led to totally different time courses in mean body temperatures, sweat rates and heart rates.

Discussion

In humans and other species thermal sensation and thermal comfort are the result of central integrative processes using the afferent information of thermal receptors. The thermal sensation correlates with the activity of the cutaneous temperature receptors and is nearly independent of the integrative thermal state (Hensel, 1982). That means that the same peripheral temperature stimulus elicites identical thermal sensations independently of the deep-body temperature. The thermal comfort, however, is the perceived result of the interaction of peripheral and deep-body temperature receptors. Any displacement of the body temperature

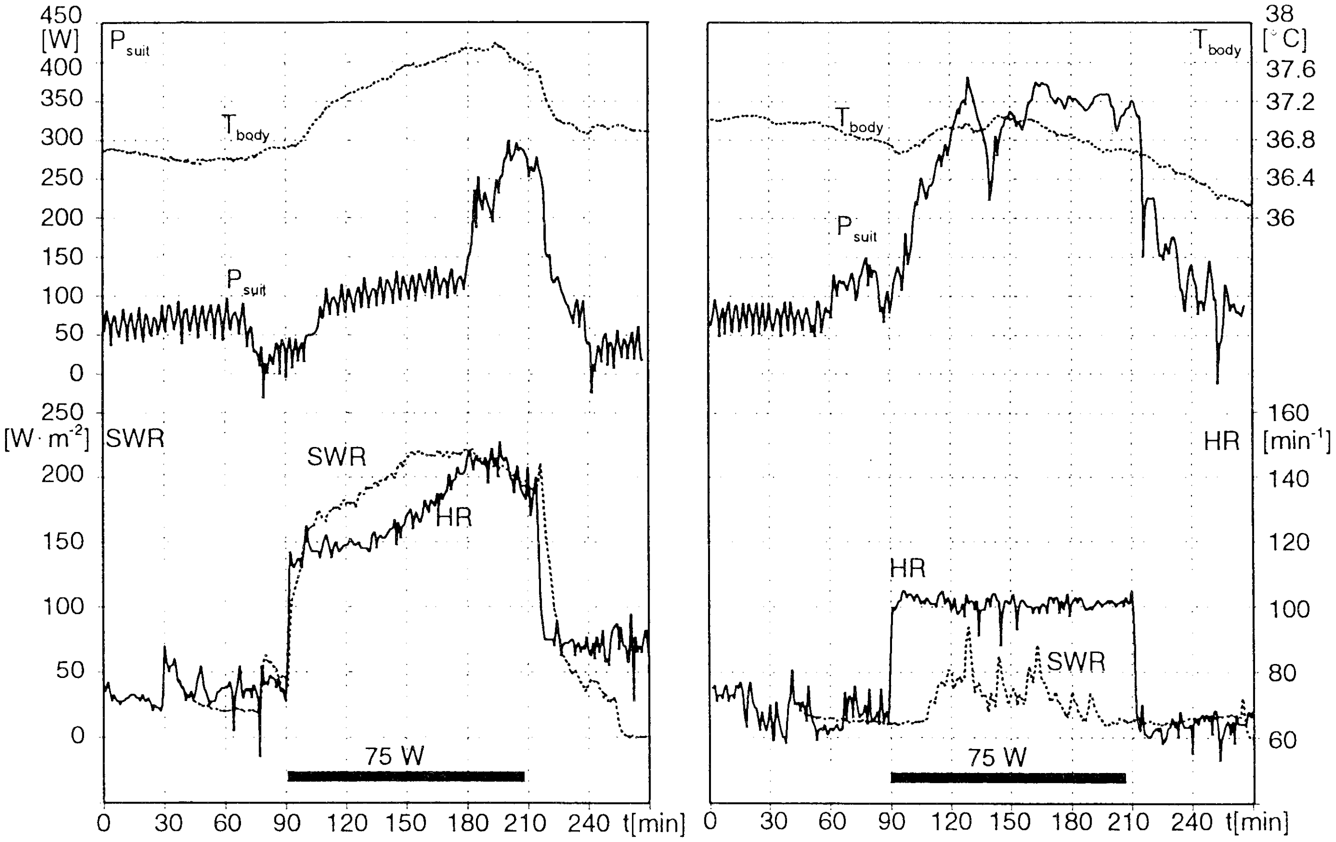

Fig. 6 Comparison of subjects with weak cooling (left) and strong cooling (right). T_{body}: mean body temperature ($=0.83 \cdot T_{rect} + 0.17 \cdot T_{skin}$); P_{suit}: heat removal rate by the cooling suit; SWR: sweat rate at chest; HR: heart rate.

from the setpoint leads to thermal discomfort thereby stimulating behavourial temperature regulation. In such a situation, any peripheral temperature stimulus which helps to eliminate or to minimize the temperature deviation will be perceived as "comfortable". Of course, this natural principle could also be observed in our experiments using artifical cooling. Regarding the mentioned trend ($T_{WI,m} = 30.17\text{-}20.14 \cdot \Delta T_{rect}$, $r=-0.85$ $p<0.1$), it is obvious that the chosen peripheral temperature stimulus was stronger when core temperature was higher, with the result that the 'load error' was adequately counteracted.

So, at first sight, we may conclude that the human controller works adequately. At a second glance, however, control concepts based on subjective votes must be criticized:

1) Neither from a technical nor from a physiological point of view, is there any reason to accept the oscillatory control behaviour (especially when the exercise load is constant).

2) After work had started and initial cooling had been to strong, subjects repeatedly reported a strange feeling which was due too an uncomfortably hot body core in conjunction with an uncomfortably cool skin.

3) In the series using the thermal sensation as the controlled variable, some subjects did not succeed in cooling adequately with the result that their rectal temperature increased throughout the exercise period.

Compatible results had been obtained by other authors. Kuznetz (1980) reported that even astronauts, although being well trained in handling such a cooling system, sometimes did not cool efficiently. Burton (1966) observed a great variability of the chosen inlet temperatures (5.6°C..31.1°C) in his experiments, where the subjects rested in a hot environment (45°C). Webb et al. (1970), a very experienced team in that field of research, summarized their observations on manual control as follows: *'man is a poor judge of his own thermal state'.*

So our findings together with those of other researchers, call for an automatic control of the cooling system using objective physiological parameters as input signals. Additionally, such an approach has the advantage that the operator's attention may focus exclusively on the main task. In a further report, we shall present adequate strategies of automatic control of the objective physiological state.

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References

Allan JR (1988) The development of personal conditioning in military aviation. Ergonomics 31(7): 1031-1040

Burton DR (1966) Performance of water conditioned suits. Aerospace Med May 1966: 500-504

Hensel H (1982) Thermal sensations and thermoreceptors in man. Charles C. Thomas Publisher, Springfield, Illinois

Kuznetz LH (1980) Automatic control of human thermal comfort by a liquid-cooled garment. ASME J Biomech Eng (102): 155-161

Nunneley SA (1970) Water cooled garments: a review. Space Life Sciences 2: 335-360

Webb P (1971) Measuring the physiological effects of cooling. Human Factors 13(1): 65-78

Webb P, Annis JF, Troutman SJ (1970) Automatic cooling in water cooled space suits. Aerospace Med 41(3): 269-277

Webb P, Annis JF, Troutman SJ (1972) Human calorimetry with a water-cooled garment. J Appl Physiol 32(3): 412-418

Werner J (1993) Temperature regulation during exercise. In Gisolfi CV, Lamb DR & Nadel ER eds. Exercise, Heat and Thermoregulation.. Brown & Benchmark, Dubuque, 49-84

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