STRATEGIES FOR AUTOMATIC CONTROL OF COOLING GARMENTS

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INTRODUCTION

The benefits of artificial cooling during work in stressful environments by means of a liquid cooled garment (LCG) are well known. Several proposals for automatic control of the water temperature have been made in the past. Depending on the author, inlet temperatur was controlled by the metabolic rate (1), heat removal rate (1,2), sweat rate (3) or skin temperature (4). In order to contribute to the solution of the closed control-loop problem, some other approaches have been studied.

EXPERIMENTAL SETUP

The subjects wore a LCG while exercising in a warm environment (35°C, 40% r.h.) on a cycle ergometer. Exercise rate was 75 W at a minimum. The LCG (Apollo-type) covered the whole body, excluding head, feet and hands. An additional isolating overall diminished the heat transfer between the LCG and the environment. The measured parameters necessary to assess the thermal state were metabolic rate (corrected to standard conditions), exercise rate, heat removal by the suit, heart rate, sweat rate (ventilated sweat capsule), ten local skin temperatures and rectal temperature (thermocouples). Thermal sensation and thermal comfort of the subjects were registered separately by means of scaled turn switches. All data were sampled each minute by a computer and, in the case of automatic control, the inlet temperature was calculated by a control algorithm.

RESULTS OF COOLING CONTROL STRATEGIES

a) In a first series of experiments the subjects could choose the inlet temperature directly by means of an unscaled temperature selector. They used different strategies, ranging from gradual changes to oscillations of the suit temperature (5). This was accompanied by great differences in the chosen inlet temperature and the comfort level attained. However, comfort level could be increased by training.

b) A technical 'comfort' controller changed the inlet temperature of the suit in the right direction as long as the personal assessment of thermal sensation differed from the neutral state. The subjects 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. The mean values of the inlet temperature during exercise ranged from 12°C up to 30°C. Two subjects had problems with their heat balance expressed by the fact that their rectal temperature did not reach a steady state. This was accompanied by the biggest weight losses and a continuous increase of the heart rate after the work induced step, reflecting the strain on the circulatory system. Two other subjects preferred such a strong cooling that sweating was below the detectable level at the end of the exercise period. The other subjects chose inlet temperatures between the described extremes followed by moderate reactions of the thermoregulatory system.

c) In order to prevent body heat storage, mean body temperature (T_{body}) was controlled to the pre-exercise level. To ensure this, each rise in rectal temperature above the resting level must be compensated by a lowering of skin temperature. With

$$T_{body}(t) = a \cdot T_{rect}(t) + b \cdot T_{skin}(t) \tag{1}$$

(T_{rect}: rectal temperature, T_{skin}: skin temperature) and the demand that

$$\Delta T_{body}(t) = T_{body}(t) - T_{body,rest} \doteq 0 \tag{2}$$

(subscript rest: resting values) one can calculate the appropriate value of T_{skin} leveling out the rise of T_{rect}:

$$T_{skin,set}(t) = T_{skin,rest} - \frac{a}{b} \cdot (T_{rect}(t) - T_{rect,rest}) \tag{3}$$

The weighting coefficients for the calculation of T_{body} were $a = 0.83$ and $b = 0.17$, meaning that an 1°C increase of T_{rect} would be answered by a 5°C decrease of T_{skin}. The whole control system consisted of two parts, an inner controller for mean skin temperature and an outer one, calculating the setpoint of the skin temperature $T_{skin,\,set}$, as described above. Skin temperature control included both a proportional and an integral path, attempting to compensate all load errors in this inner control loop with the result of a close matching between the setpoint and the actual T_{skin}. The experiments confirmed that mean body temperature can be clamped to the resting level thereby preventing heat storage. Although exercise rate (75 W, 2h) was the same for all subjects, differences in the level of heat strain expressed by different rises in rectal temperature could be observed. Due to the nature of control, this was fully projected to the skin temperature and the cooling level - the lower the rise in rectal temperature the lower the amount of cooling. In some cases this was accompanied by heavy sweating and warm discomfort. Another source of discomfort were delays, or paradoxical time courses of rectal temperature at the start and end of exercise, being responsible for a slow onset of cooling or heating. The repetition of the experiments pointed out, that the latter effects can be avoided by a faster physiological signal in the control loop. To ensure an undelayed reaction, the metabolic rate signal, which is directly related to the internal heat production was added to the control loop. Each increase above the resting level of the metabolic rate enforced a decrease of suit temperature. As it was not the aim to compensate the heat production completely in this way, the controller for the mean body temperature was still active. A slight delay (time constant = 3 min) was added to the supplementary control path to diminish the potential risk of vasoconstriction at work onset. As the results showed, comfort level was increased in transient phases with the help of this fast signal in the control loop. For further improvement, one might consider the weighting factors a and b in Eq. 1 and their adjustment to the individual physiological characteristics of the subjects.

d) As heart rate is a good indicator of metabolic rate, this parameter was taken to adapt the setpoint of a skin temperature controller to changing levels of work rate. In preceding experiments the skin temperature controller described above confirmed the capability to react to different levels of heat production. There the setpoint for skin temperature was fixed at 32°C for different exercise rates (75 W, 125 W). If heat transfer from core to skin was changing, skin temperature tended to deviate from the chosen setpoint thus producing a load error in the control loop. By changing the inlet temperature and thereby the heat removal rate, this load error was completely eliminated, especially by the integral part of the controller. However, these experiments pointed out that only one setpoint for different levels of exercise could not satisfy entirely, since the gap between heat production and heat removal of the suit increased with an increasing work rate. Therefore a simple adjustment to the actual work rate was made by means of the heart rate signal (HR):

$$T_{skin,set}(t) = 34^{\circ}C - k_{HR} \cdot (HR'(t) - 60 \text{ min}^{-1}) \tag{4}$$

To reduce the risk of vasoconstriction at the onset of cooling, a smoothed version HR'(t) (time constant = 10 min) of the original heart rate HR(t) was used in the calculation above. At rest, when heart rate was about 60 min^{-1}, the setpoint for skin temperature was 34 °C. Cooling intensity is influenced by k_{HR}, which may be adapted to the physical fitness. Here k_{HR} was 0.1 °C·min, so that the setpoint was lowered by 1°C per 10 min^{-1} increase of heart rate. The calculated skin temperatures in the experiments were about 31°C for the lower exercise level (75 W) and 29°C for the higher level (125 W). Heat removal rate was increased in all cases with the result of lower sweating and less discomfort.

CONCLUSION

Skin temperature control to a fixed setpoint with a controller including an integral path is able to react adequately to different levels of heat production. Further adjustments to different levels of heat production can be made by use of a second physiological signal, such as metabolic or heart rate. In the case of heat storage control rectal temperature determined the setpoint. Although heat storage was prevented, different levels of rise of rectal temperature were observed. Simpler measurement and a closer relationship between exercise level and heart rate favours the last strategy, using heart rate to adjust the skin temperature controller.

1. Webb P., Annis J.F. and Troutman S.J. 1970, Automatic Cooling in water cooled space suits. *Aerospace Med* 41(3), 269-277

2. Kuznetz, L.H. 1980, Automatic control of human thermal comfort by a liquid-cooled garment, *ASME J. Biomech. Eng* (102), 155-161

3. Chambers, A. and Blackaby J. 1972, A liquid cooled garment temperature controller based on sweat rate, in *Second Conference on Portable Life Support Systems* NASA SP-302, 283-294

4. Starr J.B. 1970, Fluidic temperature control for liquid-cooled flight suits, in *Portable Life Support Systems* NASA-SP-234, 179-189

5. Hexamer, M. and Werner J. 1992, Control of the temperature of a cooling garment by the subject, in W.A. Lotens and G. Havenith (eds) *Environmental Ergonomics V*, 230-231