AUTOMATIC MULTI-LOOP CONTROL OF COOLING GARMENTS

Martin Hexamer, Xiaojiang Xu and Jürgen Werner

Abt. Biokybernetik MA 4/59, Ruhr-Universität, 44780 Bochum, Germany

INTRODUCTION

In order to contribute to the optimization of construction and use of liquid cooling garments (LCG), several studies were undertaken to develop a concept for an automatically controlled multi-loop cooling system.

MATERIALS and METHODS

1) Physiological Measurements

As the methods for the physiological measurements are described in detail elsewhere (1) only a brief summary is given here. Skin temperatures were sensed with thermocouples at ten sites. Mean skin temperature was then calculated with weighting coefficients according to the Hardy/DuBois-formula (2). In the case of the multi-loop experiments a local mean skin temperature of each cooling compartment was calculated as the average of the local skin temperatures. Rectal temperature was measured 10 cm behind the anal sphincter (thermocouple; Ellab, Denmark). An open mask system was used to determine the standardized oxygen consumption and carbon dioxide production and finally the metabolic rate (STPD: standard temperature pressure and dry). Exercise was performed on an electrically braked cycle-ergometer. Metabolic heat production (MHP) was calculated as the difference between metabolic rate and exercise rate. With scaled turn-switches the subjects could indicate their thermal sensation and their thermal comfort independently for each cooling compartment. Heart rate was measured optically with an earclip registering the light transmission fluctuations due to the pulsatile nature of blood flow.

2) The Cooling Suits and Their Operation

2.1) The One-Compartment Multi-Loop Cooling Suit

The one-compartment LCG (ILC-Dover) was of the same type as used by the NASA during the Apollo missions (3). The suit covers the whole body excluding head, hands and feet. The cooling tubes (PVC, 91m, 1.6mm/3.2mm inner/outer diameter) are woven in a wide-meshed nylon layer. The starting point of the cooling loops 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 towards the extremities and nearly the same way back to the outlet manifold.

2.2) The Three-Compartment Multi-Loop Cooling Suit

The three-compartment LCG was a modified 'Webb-suit' with the diamond flow pattern (4). The modification was a subdivision of the original one-compartment suit in three independently perfusable parts (arms, trunk and legs). In both cases, an insulating overall was worn to protect the LCG from the environment.

2.3) Operation of the LCGs

Water flow to the LCG was supplied by a temperature control system located outside the climatic chamber. Temperature sensors were placed in the water stream just in front of the inlet manifolds (T_{WI}) and behind the outlet manifolds (T_{WO}). Volume flow of water (V) in each compartment was sensed by means of a flow rate transmitter. Flow rate was approximately 1.8 $l \cdot min^{-1}$ in the one-compartment LCG and 1.2 $l \cdot min^{-1}$ in each compartment of the three-compartment LCG. Heat removal rate (P_{suit}) was then calculated (ρ, c: density and specific heat of water):

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

Flow rate was constant throughout all experiments, while inlet temperature was changed by the closed-loop control algorithm. All experiments were carried out in a climatic chamber. Ambient conditions were 35°C, 40% relative humidity and a wind speed of 0.05 $m \cdot s^{-1}$. These conditions were considered to represent an average microclimate in the air layer between a LCG and an outer protective garment.

RESULTS

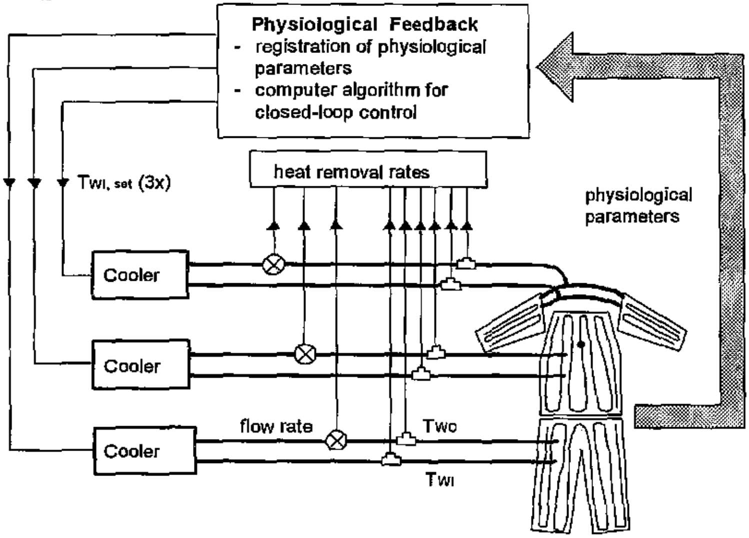

Fig. 1 Three-compartment cooling system with closed-loop control via the objective thermal state. ($T_{WI,set}$: setpoint of inlet temperature of the cooling units).

A long-lasting design process resulted in a three-compartment cooling system (fig. 1) with an independent cooling control of the legs, the trunk and the arms. A basic part of our automatic cooling control was a controller for mean skin temperature. The controller included both a proportional and an integral path, attempting to compensate all load errors in this control loop with the feature of a close match between the setpoint and the actual value of mean skin temperature ($T_{SKIN,set}$ and $T_{SKIN,act}$). This was proven in an experimental series with the one-compartment LCG where four subjects had to work at three different exercise rates (rest, 75W, 125W) and a fixed $T_{SKIN,set}$ of 32°C. By changing T_{WI} and thereby P_{suit}, all load errors had been compensated especially by the integral part of the controller. The result was a close match between the setpoint and the actual skin temperature. 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 .

As heart rate (HR) is a good indicator of metabolic rate, this parameter was taken to adapt the setpoint of a skin temperature controller to the level of work rate:

$$T_{skin,set}(t) = T_{skin,rest} - k_{HR} \cdot (HR'(t) - 60\ min^{-1}) \qquad (2)$$

At rest, when heart rate was about 60 min^{-1}, the setpoint for skin temperature was $T_{skin,rest}$ (=34°C). Cooling intensity is influenced by k_{HR}, which should 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. 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. 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). Compared to the experiments with a fixed setpoint, the heat removal rate was increased in all cases (n=4) with the result of lower sweating and less discomfort. However, it became obvious from these experiments that with the one-compartment LCG some regions of the body were overcooled while others were undercooled. Ignoring local cooling requirements resulted in great differences of local skin temperatures (fig. 2), which can be avoided if different regions are cooled independently

Therefore we took these experiments as the basis of a multi-loop automatic control (fig. 1). Each compartment of the multi-loop cooling suit was provided with an own controller with its local skin temperature as the controlled variable. The setpoints of these local controllers were all adapted to exercise rate according to eq. 2, the only difference being different values for $k_{HR,local}$ (arms,trunk: 0.02..0.035; legs: 0.05..0.08) and $T_{skin,rest,local}$ (arms,trunk: 34..35°C; legs: 32°C). From the following experiments it became obvious that this multi-loop cooling concept exhibited a closer match to the physiological requirements as the thermal sensation was more homogenous (slightly cool, neutral, slightly warm) and a higher comfort level was attained (trunk: 1.7±3.3 % uncomfortable; legs: 0 % uncomfortable).

These effects were accompanied by the small levels of thermal sweating (body weight loss: 0.145±0.035 kg/h) which had been due to the high P_{suit} (>0.7 MHP).

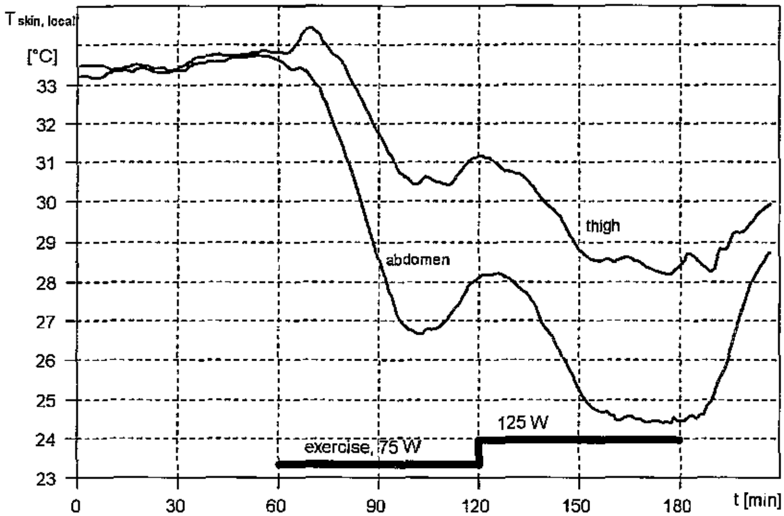

Fig. 2 Skin temperature gradient underneath the one-compartment suit.

CONCLUSIONS

Heat removal rate should be adapted to the local requirements of the working body by means of an independent multi-loop cooling control. This will result in a more physiological profile of local skin temperatures such leading to a higher comfort level. Additionally smaller body weight losses can be attained diminishing the risc of an early dehydration. These positive effects are the justification for the higher technical expenditure.

REFERENCES

1) Hexamer M and Werner J (1995) Control of liquid cooling garments: Subjective versus technical control of thermal comfort. Appl Human Sci 14(6):271-278
2) Hardy JD and DuBois EF (1937 The technique of measuring radiation and convection. J.Nutr. 15: 461-475
3) Nunneley SA (1970) Water cooled garments: A Review. Space Life Sciences 2: 335-360
4) Webb P, Annis JF and Troutman SJ (1972) Human calorimetry with a water-cooled garment. J Appl Physiol 32(3): 412-418