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ORIGINAL ARTICLE

Hidetoshi Wakamatsu · Tomohiko Utsuki

Development of a basic air-cooling fuzzy control system for hypothermia

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Abstract Surface cooling by an automatic control system using a water blanket ensures a bloodless method of accurate brain hypothermia for cerebral protection at various stages of medical treatment. The control of temperature without any effects from the outside environment means that medical staff have less need to use their special skills for the exact management of brain temperature in clinical application, although the method is based on an easily handled surface water-cooling system. However, water is not always an appropriate medium for clinical cooling, from the viewpoint of both patients and the medical staff, because of the maintenance of the system in an intensive care unit (ICU). In order to cope with such difficulties, air-cooling is proposed based on various simulation results. Here, the aim is to realize automatic temperature control based on a fuzzy algorithm as a clinical reflection of the medical staff's knowledge and experience. Experiments were carried out using a mannequin with human thermal characteristics in order to verify the utility of the basic automatic air-cooling control system for the treatment of brain hypothermia.

Key words Hypothermia · Brain temperature · Automatic control · Fuzzy control · Air-cooling · Surface cooling

1 Introduction

Surface water-cooling is one of the bloodless methods administered for brain hypothermia in order to prevent secondary cellular death after severe cerebral damage due to various kinds of trauma.[1–4] However, this is based on the cooling of the whole body, which is invasive to the immunological and/or circulatory system depending on the intensity of the cooling. Furthermore, the prognosis of the patient is considerably affected by temperature control in a long-term constitutional administration, which requires a lot of laborious work on the part of medical staff with special skills and experience.[3–5]

We have developed an automatic water-cooling control system by introducing optimal adaptive and fuzzy controls for the accurate management of brain temperature, and to reduce much of the burden on medical staff in intensive care units (ICUs).[6–18] However, effective cooling was difficult because heat transfer is dependent on the contact between the blanket and the skin, especially in the area of the axilla and the groin. In addition, a water blanket is problematic because of the danger of a water leak during medical treatment. Therefore it was necessary to develop a type of surface cooling by air around patients to control the brain temperature.

In this study, an automatic air-cooling temperature control system, including the experimental equipment, was developed for clinical use. This was believed to be an appropriate system on the basis of mathematical simulations.[19–22] A fuzzy algorithm was applied to control the system, based on the achievements of the water surface-cooling control system used in clinics.[23,24] In order to gain fundamental knowledge of air-cooling and its possibilities in clinical settings, a mannequin with human thermal characteristics was used to examine the proposed air-cooling system and the necessary equipment.

2 Automatic control of brain temperature

2.1 Air as a heat-transfer medium for the automatic control of brain temperature

Air-cooling has been applied to a limited extent in the clinical control of brain and body temperature, because it is much safer and easier to manipulate compared with water-cooling. Therefore, it has been used not only in brain hypothermia, but also for maintaining the body temperature under anesthesia.[25] It is usual to cover a patient by blankets over a jet nozzle pumping in air, or to lay a patient on an

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H. Wakamatsu (✉) · T. Utsuki
Department of Biophysical System Engineering, Graduate School of Health Care Sciences, Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113-8519, Japan
e-mail: wakamats.mtec@tmd.ac.jp

air mattress, in such a situation. However, the regulation of the air temperature relies only on manual manipulation by experienced medical staff, and there is no theoretical background supplying information about whether or not the air temperature is appropriately set to control brain and/or body temperature. Therefore, it should be possible to obtain an accurate brain temperature by air-cooling with automatic control, which would release the medical staff from their former physical and psychological burdens by doing much of the work for them.

2.2 To obtain basic knowledge of air-cooling

In order to understand the basic characteristics of air-cooling, the configuration of the proposed system was simplified so that the temperature of the head of the mannequin was enclosed in a chamber and reached a controlled value which was dependent on the convective heat flow. An air blanket with small holes was used to give a jet of air directly onto the object whose surface was being cooled. The administration of the air and control of the "brain" temperature was theoretically confirmed by a mathematical model to be little affected by environmental disturbance from any of the various simulations of air-cooling control systems.[21,22] Heat exchange by the air blanket was expected to be effective around the whole body compared with the water blanket method, and the merit of the light-weight equipment was that it gave very few problems of leakage of the heat exchange medium.

2.3 Need for the method to be independent of environmental change

For the accurate control of brain temperature, the differences in individual patients mean that time-varying, thermal, and nonlinear characteristics must be coped with or overcome during the whole thermal control process. Such problems are normally dealt with by the clinical knowledge and experience of the medical staff. In effect, their conventional skills in actual clinical processes mean that the brain temperature is controlled by the fuzzy mechanism of a water-cooling system.[8,9] The applied algorithms have been confirmed to be effective by simulations in various experimental environments[8–22] and in clinical applications,[23,24] including their usefulness in the domain of biological engineering, such as a respiratory control system.[26–31] Therefore, in this case a fuzzy algorithm was applied to the air-cooling control system.

2.4 Control mechanism

The control system was synthesized as described in Fig. 1 according to a control mechanism based on previous studies of fuzzy water-cooling systems.[14–18,23,24] The control system consists of two subsystems: subsystem-1 controls a model of the thermal characteristics of patients commonly observed and experienced by medical staff, and subsystem-2 maintains precise control to compensate for the effects due to the differences between the characteristics in the model and real individual patients, including environmental changes.

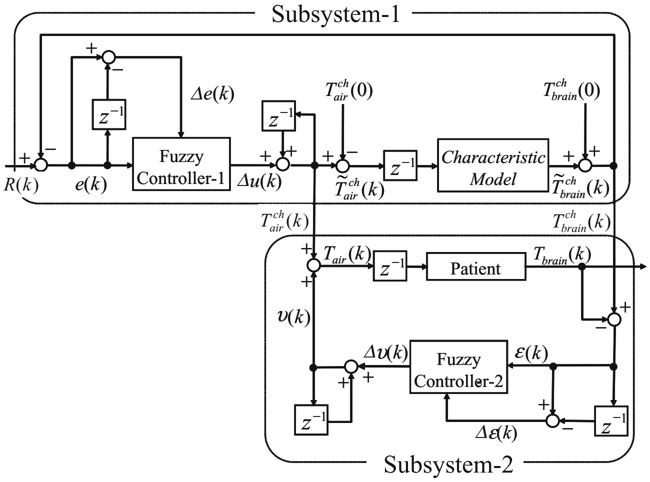


Fig. 1. Block diagram of the two-degrees-of-freedom fuzzy control system

Table 1. Designation of the variables in Fig. 1

Variables	Interpretation
$R(k)$	Desired brain temperature
$T^{ch}_{brain}(k)$	Brain temperature of the characteristic model
$T^{ch}_{air}(k)$	Air temperature of the surface of the characteristic model
$T_{air}(k)$	Air temperature around the surface of the patient
$T_{brain}(k)$	Brain temperature of the patient
$\upsilon(k)$	Compensatory value of $T^{ch}_{air}(k)$
$e(k)$	Compensatory deviation between $R(k)$ and $T^{ch}_{brain}(k)$
$\Delta e(k)$	Difference in the controlled deviation of $e(k)$
$\Delta u(k)$	Difference in the operated value of $T^{ch}_{air}(k)$
$\varepsilon(k)$	Controlled deviation between $T^{ch}_{brain}(k)$ and $T_{brain}(k)$
$\Delta\varepsilon(k)$	Difference in the controlled deviation of $\varepsilon(k)$
$\Delta\upsilon(k)$	Difference in the operated value of $\upsilon(k)$

The controllers are based on fuzzy logic in two subsystems, as shown in Fig. 1. The symbols in the figure are explained in Table 1, where k denotes the sampling number, ~ is a deviation from the initial value of the temperature, and z^{-1} is a backward difference operator of the digital signal concerned.

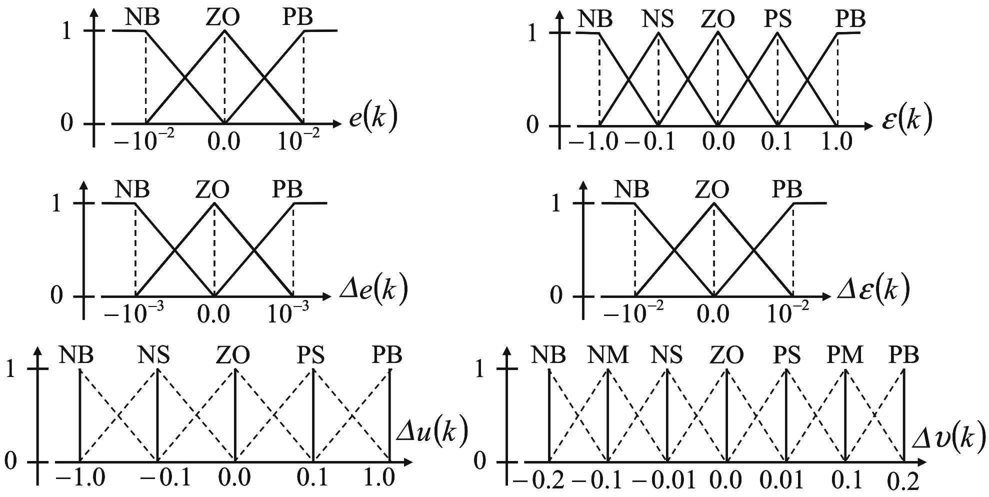
2.5 Characteristic model

The characteristics model applied is represented by a mathematical model of a first-order lag system, which was identified from theoretical or clinical data,[19,22–24] and which is further described by a discrete time system as

$$\tilde{T}^{ch}_{brain}(k) = -a\tilde{T}^{ch}_{brain}(k-1) + b\tilde{T}^{ch}_{air}(k-1) \qquad (1)$$

where $a = -\exp(-v/\tau)$, $b = K\{1 - \exp(-v/\tau)\}$, K is the gain, τ is a time constant, and v is the sampling period. In this system, a control object is assumed to be in equilibrium at the initial time. Therefore, the initial value of the brain temperature and the surface temperature of a patient are set as

Fig. 2. Membership function and fuzzy rules. *Left* Fuzzy controller-1, *right* Fuzzy controller-2



$\Delta u(k)$		$e(k)$		
		PB	ZO	NB
$\Delta e(k)$	PB	PB	PS	ZO
	ZO	PS	ZO	NS
	NB	ZO	NS	NB

$\Delta\upsilon(k)$		$\varepsilon(k)$				
		PB	PS	ZO	NS	NB
$\Delta\varepsilon(k)$	PB	PB	PB	PB	PB	PM
	ZO	PM	PS	ZO	NS	NM
	NB	NM	NB	NB	NB	NB

$$T^{ch}_{brain}(0)=T_{brain}(0)=R(0),\quad T^{ch}_{air}(0)=T_{air}(0) \tag{2}$$

2.6 Design of fuzzy controller

As the characteristic model is a first-order lag system, an input to fuzzy controller-1 is given by the combination of $e(k)$ and $\Delta e(k)$ described by Eq. 3. Its output $\Delta u(k)$ is given by $T^{ch}_{air}(k)$ as a controlling input for subsystem-1 as Eq. 4.

$$\begin{cases} e(k)=R(k)-T^{ch}_{brain}(k) \\ \Delta e(k)=e(k)-e(k-1) \end{cases} \tag{3}$$

$$T^{ch}_{air}(k)=\Delta u(k)+T^{ch}_{air}(k-1) \tag{4}$$

On the other hand, fuzzy controller-2 is synthesized with its input of $\varepsilon(k)$ and $\Delta\varepsilon(k)$ by Eq. 5, and its output $T_{air}(k)$ is given by Eq. 6 using $\Delta\upsilon(k)$.

$$\begin{cases} \varepsilon(k)=T^{ch}_{brain}(k)-T_{brain}(k) \\ \Delta\varepsilon(k)=\varepsilon(k)-\varepsilon(k-1) \\ \upsilon(k)=\Delta\upsilon(k)+\upsilon(k-1) \end{cases} \tag{5}$$

$$T_{air}(k)=\upsilon(k)+T^{ch}_{air}(k) \tag{6}$$

$\Delta u(k)$ and $\Delta v(k)$ are calculated from fuzzy controller-1 and -2, respectively, based on the membership functions and fuzzy rules given by Fig. 2.

2.7 Experimental equipment

In order to investigate the possibility of this air-cooling method, a chamber is used so that the heat exchange for the replacement of the air-blanket may be discussed simply. Figure 3a shows schematically the automatic air-cooling

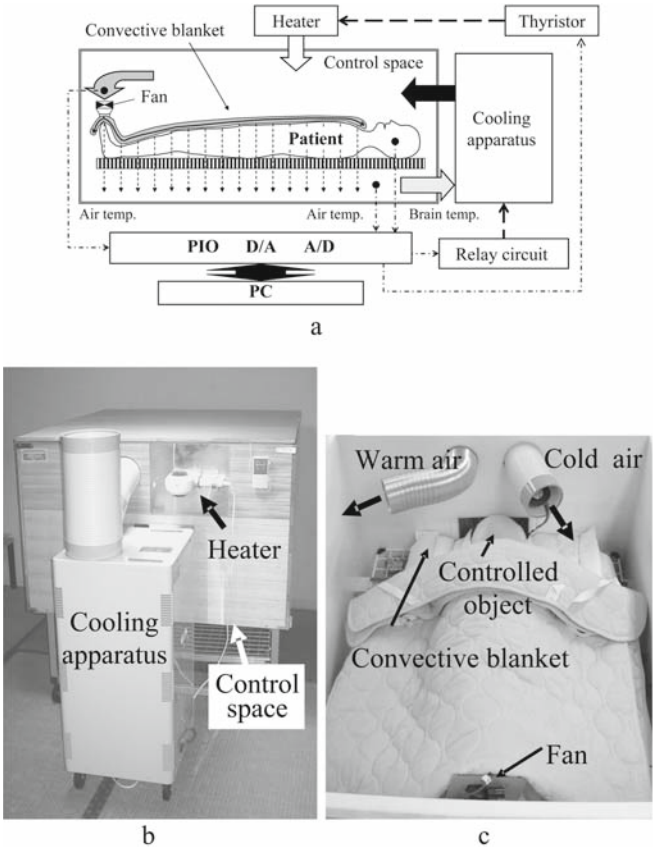


Fig. 3. Equipment for automatic air-cooling control of brain temperature. **a** Outline of the controlled system. **b** View of all equipment. **c** Inner view of a controlled system (chamber) with a controlled object (mannequin)

control of the brain temperature, together with the necessary experimental equipment. This is to realize the air temperature in the chamber by regulating the mixing rate of warm and cold air from the relevant apparatus, so that the brain temperature may quickly reach the desired value. The control system is composed of a chamber and a controlled object (mannequin) set on a plastic net support with a covering blanket (Graseby Medical, SW-2002). The places where the blanket contacts the surface of the mannequin are used to send air to the controlled object. The convective heat transferred to the surface of the mannequin results in a uniform distribution of heat around the whole body. The inner temperatures of the chamber and the brain are measured by platinum thermal sensors (CHINO R040-32). The temperature data are acquired by the main processor (NEC PC9821V200, OS, Microsoft MS-DOS 6.2; application programming language, Microsoft MS-C 6.0) through an A/D converter (CONTEC, DA 12-8/2(98)) after their conversion into a voltage signal by a measuring converter (M-SYSTEM, KRS-34-B/K).

In addition, the signal from a thyristor (CHINO, JA-2030N), using a signal converted by a DC input converter (M-SYSTEM, KVS-4A-B/K) through an D/A converter (CONTEC, ADA 12-8/2(98)), regulates the apparatus producing warm air (TESCOM,NB1901; Hitachi, DR-727), and the relay is driven by a parallel signal from the computer to an ON/OFF switch controlling the apparatus producing cold air (NAKATOMI, SPC-407). The size of the chamber, with accessories, is 1076 × 1750 × 1098 mm, as shown in Fig. 3b and c.

3 Controlled thermal object

In this research, direct clinical examination is not ethically allowed. For that reason the mannequin was used for the basic confirmation of the utility of our newly developed simple type of thermal control system.

This type of mannequin has very similar thermal characteristics[13] to those of a human adult. The structure and materials used for the mannequin are shown in Fig. 4, and the mannequin had been used in a series of experiments into surface water-cooling thermal control systems before its clinical application.[12,13]

Table 2 describes each compartment of the mannequin with its size and parameters, and its metabolism and blood circulation were simulated by a heater and water circulation, respectively.

Figure 5 shows the step response of the brain temperature when the air temperature around the body falls from 29.0° to 20.0°. The brain temperature initially falls from its initial value of 37.4° to 32.9°. Therefore, the characteristics of a controlled object are represented by a first-order lag

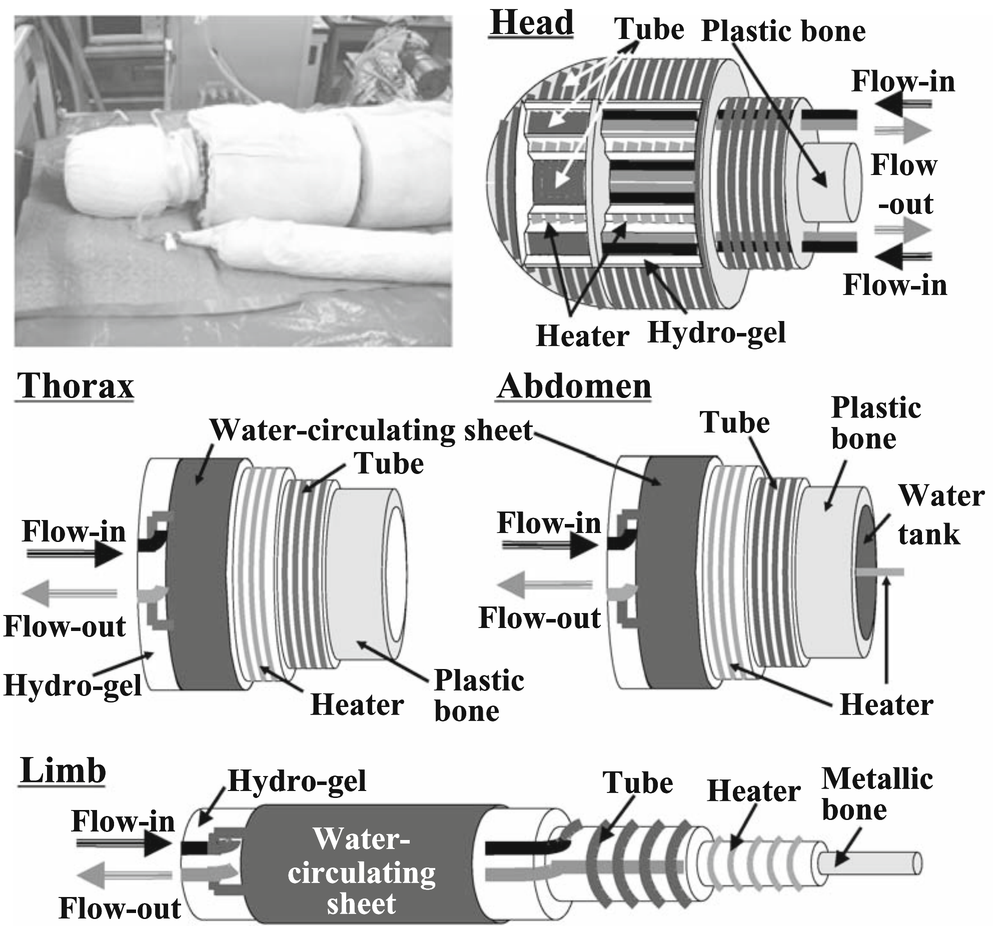


Fig. 4. Overview and mechanical structure of the mannequin

Table 2. Parameters of the mannequin

Part in body	Tissue in each part	Form	Length (mm)	Radius (mm)	Volume (ml)	Heat production (W/m^3)	Blood perfusion rate (ml/min)
Head	Skin	Hemisphere		104	204	0.0	39
	Skull			101	826	0.0	0
	Brain			86	1331	18.0	809
Face	Surface	Column	100	80	1224	0.4	64
	Spine			50	785	0.0	0
Neck	Surface	Column	85	60	721	0.5	13
	Spine			30	240	0.0	0
Thorax	Skin	Column	300	130	1453	4.0	31
	Muscle			124	8840	0.0	223
	Heart and lung			80	5697	0.0	4864
Abdomen	Skin	Column	550	130	6924	0.0	62
	Muscle			109	9776	6.0	270
	Viscera			80	10817	50.0	2797
Superior limbs	Surface	Column	800	45	4330	0.0	49
	Core			34	5844	3.5	151
Inferior limbs	Surface	Column	850	60	7569	0.0	65
	Core			47	11648	4.5	291
Whole body		Column			78228	87.4	4864

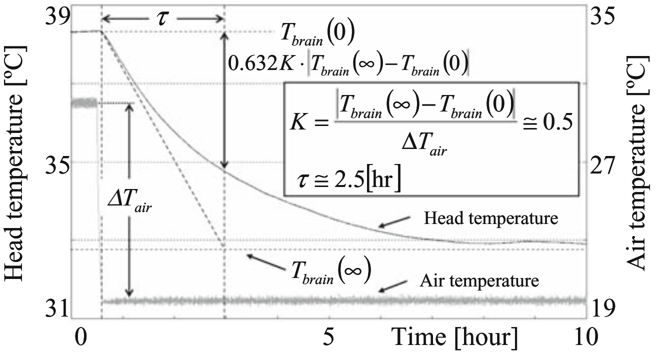


Fig. 5. Response of head temperature to the step changes in surface temperature of the mannequin under air-cooling

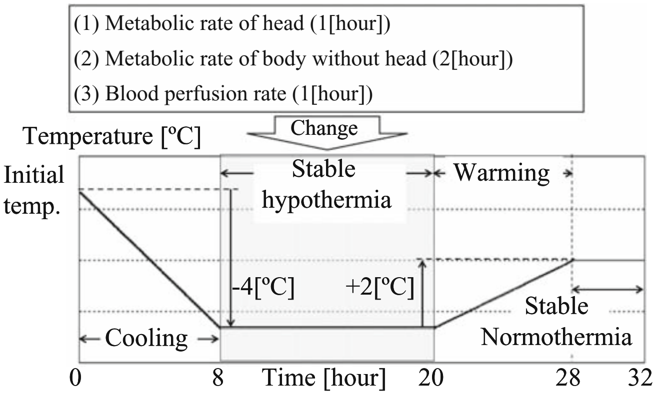


Fig. 6. Experimental schedule of hypothermia using a mannequin

system with a gain K of about 0.5 and a time-constant τ of about 2.5 h. These parameters are almost comparable with the surface water-cooling of a patient,[20,32] except that this is about half the gain of a healthy human adult. It is quite usual for the system to be hard to control if the gain of the controlled object is small with a larger time-constant. This means that it is easier to control the brain temperature in the case of an actual patient than in a mannequin, and the air-cooling is more effective than water-cooling because its gain is 0.5 with a time-constant of about 4 h.

4 Experimental conditions and results

In order to investigate the performance of the constructed system, the mannequin described above was used for the control experiment. For the actual temperature measurements, the brain and body temperatures were replaced by head and surface temperatures, respectively. The surface temperatures were measured at the inlet and outlet of air to the chamber with a velocity of 1.4 m^3/min, and they were averaged to find their representative values with a sampling period of 12 s. The total duration of the experiment was 32 h. The desired temperature of the head was adopted by referring to four scheduled terms,[3,4] i.e., the clinically used periods of cooling, stable hypothermia, rewarming, and stable normothermia, as shown in Fig. 6.

To simulate an actual clinical situation in the present system, the responses of the controlled object were observed for any deviation of its inner and outer thermal characteristics with inner and outer environmental changes during stable hypothermia. The time used was set as 10 h after the beginning of the experiment. A 20% increase in the heat production of the head during 1 h was set for case 1. For case 2, we set a 20% increase in the heat production of the whole body, excluding the head, during 2 h, at 13 h after the start of the experiment. For case 3, we set a 5% decrease in the circulatory water (blood) flow around the whole body, during 1 h, at 17 h after the beginning of the experiment.

Figure 7 shows an experimental result from this study. The head temperature was realized within an error of 0.2°C from the desired time-course of the temperature. The head temperature changed as the result of heat being generated

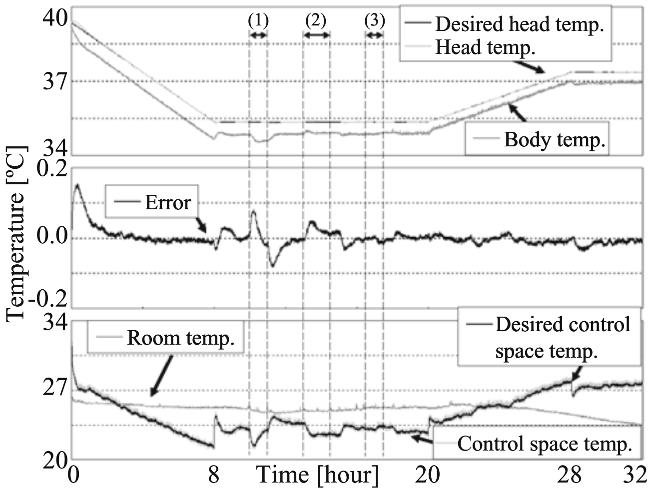


Fig. 7. Result from the experiment using a mannequin in a chamber

externally and internally in the head, constitutional circulatory changes, and the general status and environmental changes around the mannequin. In these experiments, the procedures in cases 1, 2, and 3 involved rapid environmental changes which would not be experienced in real clinical cases. The thermal control system reacted to the changes in air temperature to realize an appropriate surface air temperature, and consequently to control the head temperature with sufficient accuracy.

5 Discussion

5.1 Assumed experimental condition

The mannequin used for this study was a thermal model whose tissue volume, specific heat capacity, metabolic heat production, and blood circulation are almost within the range of the average values of a healthy human adult. The model does not contain an autonomous temperature regulatory function by the hypothalamus and the medulla oblongata, which is suppressed by anesthesia in the case of actual medical treatment. Except for the gain, our mannequin basically represents the thermal characteristics which correspond to the parameters of an actual patient. The smaller gain of heat convection when controlling the head temperature is more difficult in a mannequin than in the average human adult. Therefore, the engineering and physiology is much more appropriate and meaningful in an actual case than in this kind of automatic air-cooling experiment using a mannequin.

Nevertheless, the method based on an air-blanket and/or an air-mattress may be unduly affected by changes in the room temperature, and therefore the present experiment was based on the control of the head temperature by setting the mannequin in a chamber, which can give rise to problems in the diagnosis and treatment of a real patient. In other words, this is an impractical method for use in clinics. However, our method is very little affected by such external changes, as is shown in the experimental results. Therefore, the experimental results from this system will be a good reference point for a comparison with the performance of the next new system to be developed for clinical practice, in terms of the effect of changes in room temperature and various other disturbances.

5.2 Environmental change and control accuracy

In these hypothermia experiments, there were circulatory decreases of 5% and metabolic rate increases of 20% in rapid step-like changes in two cases. However, it was satisfactorily confirmed that the control system could cope with a change in head temperature. In other words, our system can overcome rapid changes in the thermal characteristics of a patient, and consequently it is sure to work sufficiently well for gradual changes in thermal characteristics.

In clinics, the highly accurate control of head temperature is clinically essential, i.e., within an error of ± 0.1°C during the re-warming period.[1–4] In our case, the error was sometimes more than ± 0.1°C, as indicated by Fig. 7. However, the maximum error was only observed soon after the beginning of the experiment and during the re-warming period of 20–28 h from the beginning of the experiment. Therefore, it would be able to administer an accurate brain temperature because the experimental results under various conditions are almost comparable with the ones obtained by the surface water-cooling fuzzy control system.[14–18] That is, the surface air-cooling system is almost fully confirmed as the next useful clinical application.

5.3 Wind velocity and consuming energy

Our control system can surely be used in clinics despite the changes in the thermal characteristics of a patient. The wind velocity around the mannequin from the blast volume and the area of air flow was calculated as 0.02 m/s on average. This means that it is almost calm, so its power may be classed as zero on the Beaufort wind scale. If the wind speed is any greater, the transpiration over the body surface may negatively affect the state of the patient. Therefore, an appropriate wind speed must be determined for clinical applications. In practice, there might be a small physiological invasion of the patient by a slight movement of air in order to establish effective heat exchange, although this must be measured precisely and taken into consideration.

The nominal total electric power consumption in the surface water-cooling control system was 3.6 kW, which was mainly due to the production of warm and cool water.[12,13] In our air-cooling system, the total nominal power used to provide the warm and cold wind apparatus was 2.4 kW. A lower energy consumption is expected in future because a larger surface of heat exchange can be ensured compared with water-cooling, and because the specific heat coefficient of air is smaller than that of water. Thus, our system could deliver lower energy consumption than a water-cooling system, and a more appropriate structure for the apparatus will be sought in future studies.

6 Conclusion

An automatic air-cooling control system for head temperatures based on fuzzy theory was examined. This air-cooling system was confirmed as offering an effective cooling method for brain hypothermia, and ensuring almost the same accuracy as a water-cooling system by the use of the fuzzy control law.

The experimental equipment was constructed, and using a mannequin with similar thermal characteristics to those of an adult patient, its control system was confirmed to be useful. This result shows the highly accurate automatic control of brain temperature and the strong possibility that the system will be suitable for clinical applications.

Nevertheless, in order to supply a system which can be used at the bed-side, it will have to be considerably improved. These improvements concern the present equipment for the control system, finding an appropriate algorithm, and avoiding any drying of the patient's skin due to the transpiration effect.

Our final remark is that this kind of system can be applied to any syndrome requiring body temperature control, not only in hypothermia but also in heat stroke.

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