Experimental Qualification of Fuzzy Control Systems for Brain Hypothermia Treatment Using Human Thermal Model

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Abstract Automatic control system of brain tissue temperature is experimentally studied for the brain hypothermia treatment. In order to realize human friendly control mechanism, an automatic temperature regulation system is constructed by fuzzy algorithm for possible environmental and characteristic change of patients. The brain temperature is successfully realized to follow up the desired temperature course automatically. Thus, the model reference fuzzy control of the brain temperature based on water-cooling blankets is verified for the clinical application to brain hypothermia treatment through the various kinds of experiments using a human thermal model.

Keywords: hypothermia, brain temperature, water-cooling, fuzzy control system, brain injury, brain inflammation, cerebral contusion, cerebral ischemia, brain resuscitation

1 Introduction

In brain hypothermia treatment, brain tissue temperature is kept in a moderate hypothermia to prevent severely brain-injured or inflammatory patients from secondary brain damage[1-3].

It has been introduced into their clinical treatment using water-cooling blankets, in which expert nursing staff manually regulate their water temperature to realize the appropriate thermal process prescribed by clinicians[3].

The surface control of brain temperature realized by the cooling blankets is a standard noninvasive method for brain hypothermia treatment. However, it has to be continuously much concerned with the accurate control of their temperature. Thus, nursing staff are incessantly forced to measure and control brain temperature deviation within 0.1 °C in every 20 min[3], which imposes them mentally and physically heavy burden with their less accurate brain temperature regulation.

In addition, they have to be engaged in an integrating care of life-support based on the management of brain hypothermia treatment, in connection with anesthesia and heart-lung management inclusive of mechanical respiration[1-3]. Despite of such difficulties, the hypothermia treatment has gradually become more significant for clinical technique concerning brain death and resuscitation.

In this connection, adaptive-optimal method has been applied automatically coping with time-varying and nonlinear characteristics inclusive of the differences of individual patients[4-11]. However, some more useful methods are required for the actual treatments to apply the control algorithm related to clinical knowledge.

The fuzzy control system is proposed, which consists of a standard controller corresponding to the clinical experience of clinicians and a compensatory controller dealing with difference of individuals and environmental change.

2 Synthesis of Fuzzy Automatic Control System

2.1 Basic concept of hypothermia treatment

The brain temperature is usually controlled as illustrated by Fig.1. However, there are always some ambiguous effect due to disturbance, difference of patients, change in their physiological state and unknown factors resulting from their different environmental change caused by the clinical therapy, operation and so on[4-7]. In order to overcome such difficulties, one of the possible methods was automatic hypothermia treatment by adaptive control methods[9-11]. Instead of above control systems, some other alternative systems are, however, required on the basis of actual treatments to utilize the control logic directly related to clinical knowledge. Thus, the fuzzy control system with 2-controllers was proposed and tested in the last studies. Actually, fuzzy control system for the thermal model and child-size mannequin was synthesized to examine its characteristics and usefulness for hypothermia[12, 13]. In the present study, accurate human adult thermal model with physiological characteristics is introduced considering the clinical preparation by fuzzy brain temperature control[13].

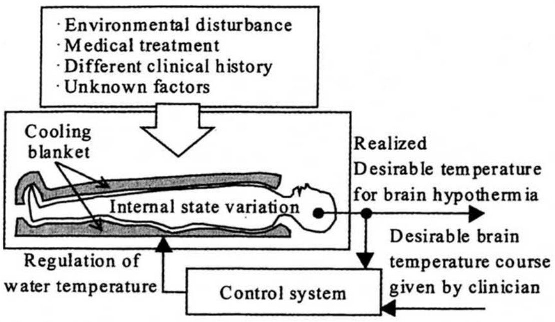


Fig.1 Concept of brain temperature control in clinical hypothermia treatment process

2.2 Control system using characteristic model

A first-order lag system, *characteristic model* given by Eq. (1) is taken into account, which is clinically based on the typical response of the brain temperature to the step change of water temperature. It represents standard biothermal characteristics concerning brain hypothermia based on the precise heat transfer dynamics of human being of an adult with surrounding blanket [6, 7]. Their relevant parameters are estimated as time constant $\tau = 3.0$ hours and gain $\kappa = 0.9$ neglecting relatively small dead time in the present case of mannequin instead of human being of an adult.

$$\begin{aligned} \tilde{T}^{ch}_{brain}(k+1) &= -a^{ch}\tilde{T}^{ch}_{brain}(k) + b^{ch}\tilde{T}^{ch}_{water}(k) \\ a^{ch} &= -\exp(-\Delta t/\tau) \\ b^{ch} &= K\{1 - e(-\Delta t/\tau)\} \end{aligned} \tag{1}$$

The concerning variables of the brain and water temperature T with sampling interval Δt are given as $T_{brain}(k)$, $T_{water}(k)$, $T^{ch}_{brain}(k)$ and $T^{ch}_{water}(k)$ with indication of *characteristic model* by suffix *ch*. $\tilde{T}$ denotes the temperature difference from its initial value.

The control system composed of two control subsystems is shown in Fig.2(b), in which subsystem-1 is for the essential control, where its output from *characteristic model* is regarded as a reference in subsystem-2 for the accurate compensation of the temperature deviation from the reference output caused by the environmental change and constitutional difference of patients.

Hereby, the basic fuzzy control system is given in Fig.2(a) in order to qualify the 2-controller system in Fig.2(b). It is remarked that the temperature of circulating water is finally given by the both fuzzy signal synthesis mechanisms. Such concept is analogous to the standard treatment based on the clinical experience and on the specified precise management according to the medical history, and idiosyncrasy or allergic constitution of patients. Thus, the merit of this control system is so called human friendly control, physiologically without any particular burden, in which controllers are not necessary to design according to the difference and characteristic change of patients.

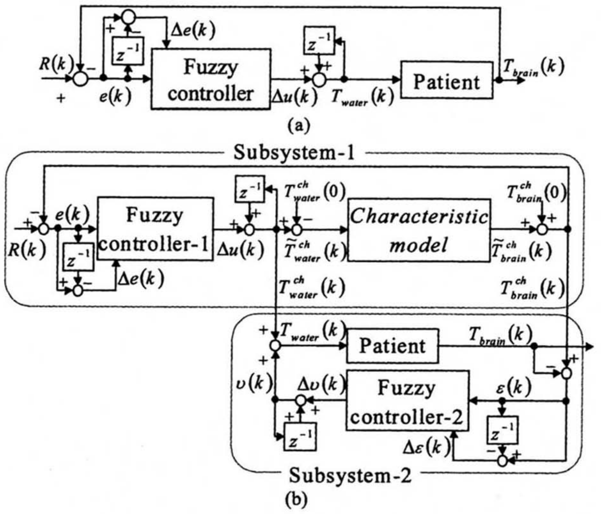


Fig. 2 (a)Unity feedback fuzzy control system and (b) proposed fuzzy control system consisting of two subsystems

2.3 Fuzzy rules and membership functions

The unity feedback system given by Fig.2(a) is the same as the subsystem-1 in Fig.2(b), excluding fuzzy rules given by Fig.3, if patient is substituted by *characteristic model*. Thus, the mathematical relation is mentioned only in the case of the 2-controller system.

In the subsystem-1, the relatively rough determination of water temperature of blanket is characterized by the fuzzy controller-1 given by Eq. (2), for which the inputs are the deviation $e(k)$ and its derivative $\Delta e(k)$ of output $T^{ch}_{brain}(k)$ of *characteristic model* from the reference $R(k)$. The input $T^{ch}_{water}(k)$ to the *characteristic model* is given by $T^{ch}_{water}(k-1)$ and the water temperature derivative $\Delta u(k)$, where the latter is calculated from the membership functions of the consequent and the fuzzy rule corresponding to the controller-1.

$$\begin{aligned} e(k) &= R(k) - T^{ch}_{brain}(k) \\ \Delta e(k) &= e(k) - e(k-1) \\ T^{ch}_{water}(k) &= \Delta u(k) + T^{ch}_{water}(k-1) \end{aligned} \tag{2}$$

The membership functions are given according to Fig.3 (a),(b),(c),(d), in which the antecedents are used in order to fuzzificate $e(k)$ and $\Delta e(k)$. The illustration (c) is for the consequent and table (d) is fuzzy rule for the subsystem-1.

In the subsystem-2, the water temperature of blanket is regulated by $T^{ch}_{water}(k)$ with the compensatory value of water temperature $\upsilon(k)$ described by Eq.(3). The brain temperature deviation $\varepsilon(k)$ and its derivative $\Delta\varepsilon(k)$ are obtained from the output $T^{ch}_{brain}(k)$ of *characteristic model* and brain temperature $T_{brain}(k)$ of the patient. $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are fuzzificated based on the membership functions of the antecedents given by Fig.3-(e),(f) for the fuzzy controller-2. The two inputs $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are also appropriately used, so that $\Delta v(k)$ is calculated from the membership functions of the conseguent and the fuzzy rule corresponding to the fuzzy controner-2, taking into account the resolution of measuring instruments of temperature in actual hypothermia treatment.

$$\begin{aligned}
&\varepsilon(k)=T^{ch}_{brain}(k)-T_{brain}(k)\\
&\Delta\varepsilon(k)=\varepsilon(k)-\varepsilon(k-1)\\
&\upsilon(k)=\Delta\upsilon(k)+\upsilon(k-1)\\
&T_{water}(k)=\upsilon(k)+T^{ch}_{water}(k)
\end{aligned}\qquad(3)$$

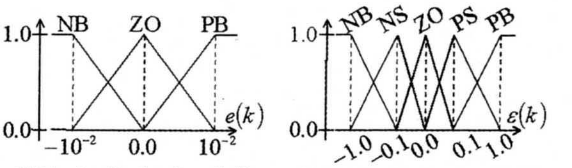
It is hereby remarked that the range of fuzzy variables increases in the antecedents and the consequent change for the sufficiently well performance of the system dynamics, in proportion to the deviation and derivative of brain temperature caused by the disturbance and difference of individual patients and water temperature change.

Thus, the membership functions are designed as shown in Fig3. For the greater environmental change, the output is easily controlled back to the desired value and accurately controlled to eliminate its smaller deviation of brain temperature $T_{brain}(k)$. Then, the hypothermia control system appropriately works, for which any precise information about patients and their environment are practically not obtained beforehand. Hereby, product-sum-gravity method is used for fuzzy-inference, in which fuzzy variables are defuzzificated. The water-cooling system is finally controlled by the input signal synthesis mechanism using $T_{water}(k)$ to follow up the output T^{ch}_{brain} of *characteristic model.* That is, the input is given by the two regulators, which consequently realize the desired brain temperature course given by clinicians.

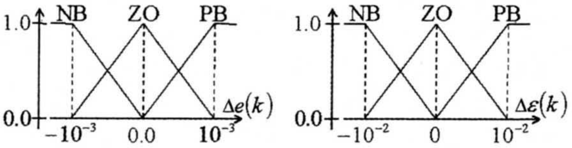
3 Experimental Result and Discussion

3.1 Human biothermal model used for patient

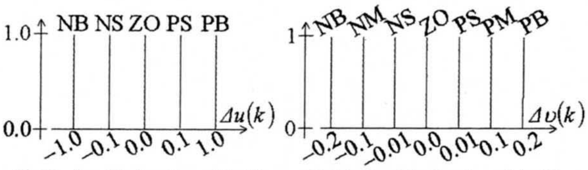
In the case of such basic research, the clinical experiment is ethically not allowed. Thus, the mannequin representing bone structure, specific heat, metabolic heat, blood circulation of a patient as much as possible is introduced as shown by Fig.4(a). The mannequin has height of 2m, weight of 100kg which are characterized by parameters of head, neck, thorax, chest, abdomen, superior and inferior limbs given by Table 1. The concerning materials are skins of pig and deer for its surface and water contented gel or hydrogel (Sekisui Plastics Co. Ltd) for the tissue.



(a) Membership function of $e(k)$ (e) Membership function of $\varepsilon(k)$



(b) Membership function of $\Delta e(k)$ (f) Membership function of $\Delta\varepsilon(k)$



(c) Membership function of $\Delta u(k)$ (g) Membership function of $\Delta\upsilon(k)$

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

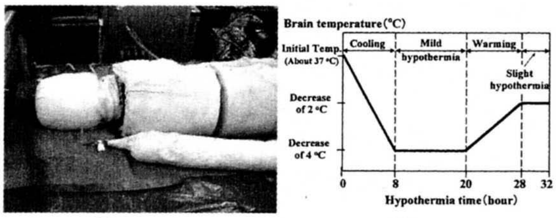
(d) Fuzzy rule of controller-1

$\Delta\upsilon(k)$		$\varepsilon(k)$				
		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

(h) Fuzzy rule of controller-2

Fig.3 Fuzzy rules (a)-(d), (e)-(h) are for the controller-1 and for the controller-2, respectively, corresponding to Fig.2(b); Fuzzy rule (e)-(h) is also for the unity control system corresponding to Fig.2(a)

Thus, the specific heat of the mannequin is set between 3.0 and 4.0 J/g/K, comparable to the human parameters. In order to simulate metabolic rate and blood circulation, the warming heater of body and flow tubes of water (mannequin's blood) are arranged in corresponding organs and tissues. The heating through controlling water flow is regulated by pump. The metabolic heat production in abdominal organs are given by direct heating of circulatory water in vinyl chloride cylinder of about 3 *l* set in abdomen, where much blood amount is taken into account. The heat production rate in every tissue or organ and amount of circulation are adjusted manually according to Table 1, which are physiologically appropriate considering the parameters of adult males[9].



(a) (b)

Fig. 4 Human biothermal model consisting of 7 segments and their relating 17 compartments, and schematic reference temperature for brain hypothermic treatment

3.2 Manipulator

The newly developed automatic control system consists of main part, a cold water supply with built-in water pump 2 (Shibata Scientific Technology Ltd, C-761). Pump 3 (Sanso Electric Co. Ltd, PMD521A 6DK) is for the warm water supply. The temperature of both water supplies are manually set, mechanics of which is depicted by Fig.5. Cold and warm water of respective constant temperatures from supplies are mixed by main reservoir to obtain water of actual temperature $T_{water}(k)$ for the control of brain temperature. The necessary water is supplied by flow control system, which consists of flow meters 1 and 2 (Buerker, Ty8071), proportional magnet valve (Buerkert, Ty6022) and flow controlling unit (Buerkert, Ty8623-2). Valve 1 and 2 (CKD, FWB5187O2 CB3) are controlled for the mixing of additional cooling and warming water. The same amount of used cold and warm water for mixing are back to the corresponding sub reservoir by Pumps 4 and 5 (Sanso Electric Co. Ltd, PMD121B1B and MD0411B6B, respectively). The room and water temperatures are measured by platinum sensor (Nikkato Co.Ltd, R040-32 and Buerkert, YP100) and are acquired through A/D converting system (PC recorder: M-System, R1 M-J3) and RS-232C into computer (NEC, PC9821Nw150).

Table 1 The parameters for human biothermal model

Part in body	Tissue in each part	Form	Length (mm)	Radius (mm)	Volume (ml)	Heat production (W)	Blood perfusion (ml/min)
Head	Skin	Hemisphere		104	204	0	39
	Skull	Hemisphere		101	826	0	0
	Brain	Hemisphere		86	1331	18.0	809
Face	Surface	Column	100	80	1224	0.4	64
	Spine	Column		50	785	0	0
Neck	Surface	Column	85	60	721	0.5	13
	Spine	Column		30	240	0	0
Thorax	Skin	Column	300	130	1453	4.0	31
	Muscle	Column		124	8840		223
	Heart & lung	Column		80	5697	0	4864 #
Abdomen	Skin	Column	550	130	6924	6.5	62
	Muscle	Column		109	9776		270
	Viscera	Column		80	10817	50.0	2797
Superior limbs	Surface	Column	800	45	4330	3.5	49
	Core	Column		34	5844		151
Inferior limbs	Surface	Column	850	60	7569	4.5	65
	Core	Column		47	11648		291
Whole body					78228	87.4	4864

3.3 Experimental condition and operations

The temperature of blanket water is kept 30 °C and heat is given to the mannequin by heaters until its brain and blood temperatures hold their equilibrium. Then, the brain temperature is controlled using unity fuzzy control system and 2-controller system according to the desired brain temperature illustrated by Fig.4(b).

In order to examine effect of difference of individual thermal characteristics on the control performance by both control systems, the newly developed thermal mannequin model as a controlled object e.g. without superior and inferior limbs are taken into account for the check of control performance by the two methods. The gain and time constant of characteristic model are set as κ=0.5 and τ=3.6 hour with the sampling period of 12 sec. Room temperature is kept between 26 °C and 28 °C except for the experiment by changing room temperature.

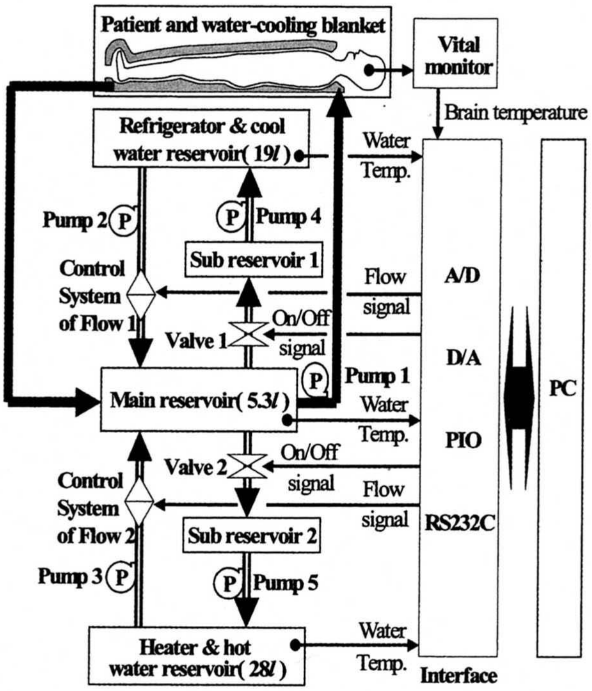


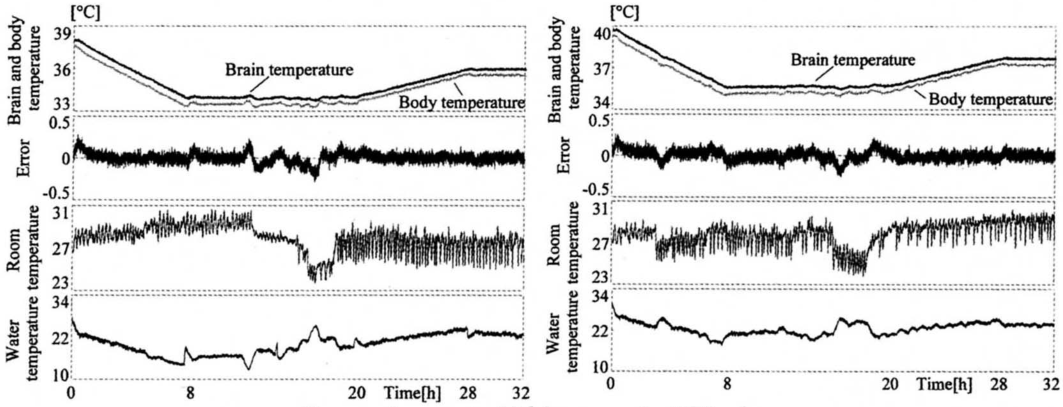
Fig.5 Automatic control mechanism of brain temperature experiment by changing room temperature

In order to observe the time course of thermal dynamics and external change of environment in 6 hours long between 12 to 18hours from the start of the experiment, the following operations (1), (2) and (3) are given after confirmation of keeping almost steady temperature of brain:

(1) Upper cover blanket unveiled in 30 minutes
(2) Heat production of whole body except for head with increment of 20% in 60 minutes
(3) Room temperature lowered by 3 °C down by air conditioner in 150 minutes

3.4 Experimental result

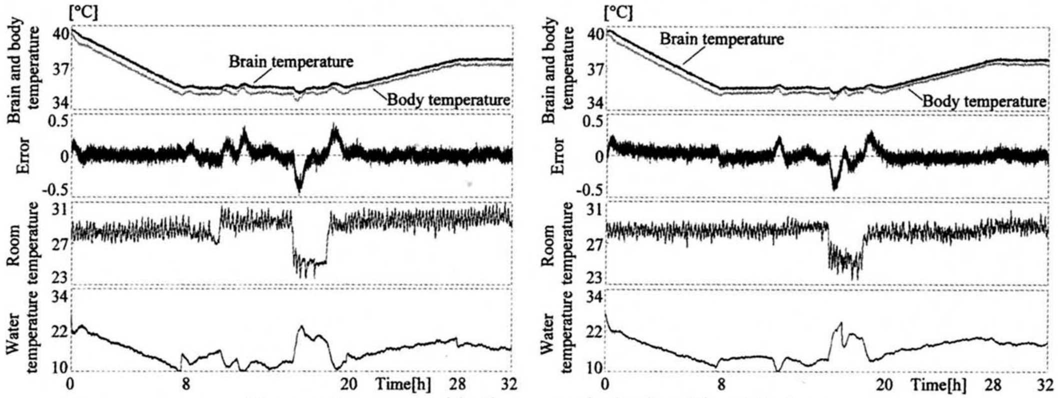
Figure 6 represents the time course of temperatures of brain and body of mannequin, room and blanket water. In the present figure, (a) and (b) are concerned with the mannequin with a full body. (a) is by the 2-controller system and (b) is by the unity feedback system. Figures (c) and (d) are the results concerning with the mannequin without superior and inferior limbs. (c) is by the 2-controller system and (d) is by the unity feedback system. Figures (a) to (d) indicate that brain temperature is well controlled to follow up desired value from the viewpoint of clinical application. Hereby, it is emphasized that the systems cope with frequent large temperature change of manipulating water for above mentioned (1), (2) and (3) operations, comparing the adaptive-optimal system previously discussed[4, 6, 9-11]. As for controlled deviation



Temperature control in the case of a full body

(a) System with two controllers

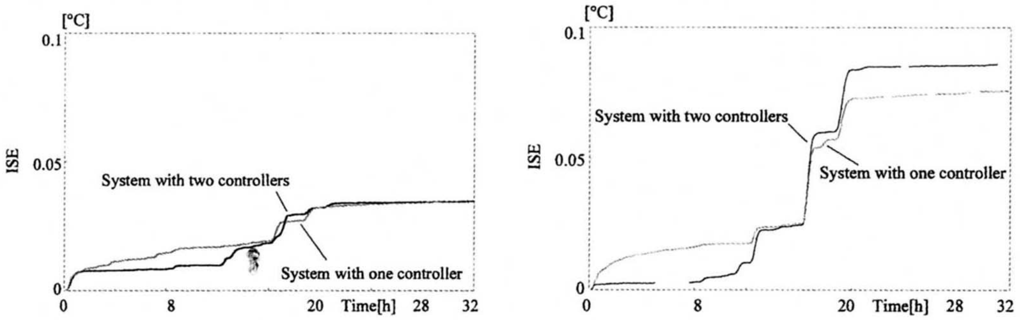
(b) Unity feedback control system



Temperature control in the case of a body without limbs

(c) Control system with two controllers

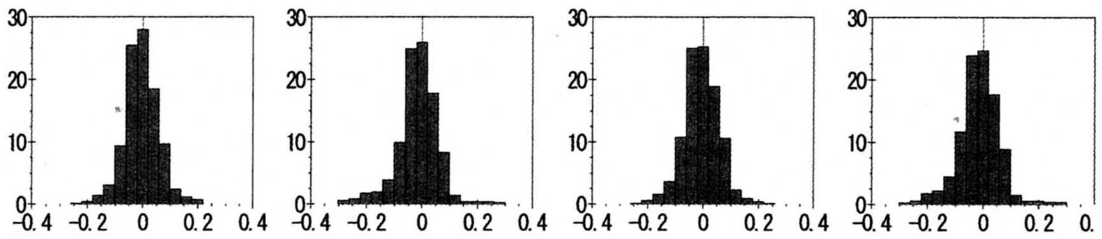
(d) Unity feedback control system



Integrals of squared error in temperature control

(e) System with two controllers

(f) Unity feedback control system



1) System with two controllers in the case of a full body

2) System with two controllers in the case of a body without limbs

3) Unity feedback control system in the case of a full body

4) Unity feedback control system in the case of a body without limbs

(g) Distribution of control error in each case and comparison with a normal distribution

Fig. 6 Controlled dynamics of brain and water temperatures, control error, room temperature

(e) and (f) are concerned, integration of squared error given by the 2-controller system and by the unity feedback system, respectively. From (e), (f) and (g) the 2-controller system is superior to the unity feedback system as for the capability of following up control.

In the present study feedforward function has been systematically considered for the set up of changing desired value to calculate blanket water temperature beforehand. The integration of squared controlled deviation is much greater observed in 18 hours after the start of experiment. However, they cannot be directly compared due to the operation (3) under the big difference of room temperature change between two experiments. Then, integrals of squared error due to normalized change by room temperature are compared, in which there seems practically no obvious difference in both cases. (g) represents the error distribution of each case of controls. In the case of controlling whole body, there is no difference between two methods, giving approximate normal distribution with mean 0.0086, 0.0105, standard deviation 0.0613, 0.0618 (within ±0.2 °C), kurtosis -0.1655, 0.0040, skewness 4.1616, 3.7635, respectively. In the case of deficit of all the extremities, mean 0.0163, 0.0146, standard deviation 0.0843, 0.0789 within ±0.2 °C, kurtosis -0.5150, -0.7089, skewness 8.2838, 7.258, respectively. The error distribution spreads toward the bottom with more pixy shape, which shows that integral of error is larger in the case of (f) than in the case of (e). The difference of distribution is due to smaller thermal inertia from deficit of limbs, which causes quick response of brain temperature to the temperature change of blanket water. That is, control was easy with smaller controlled deviation, as brain temperature responds to smaller change in blanket water temperature. However, the big change of water temperature often causes big change with big control error due to fuzzy inference.

4 Conclusion

The proposed system can cope with external change of environment, physiological state change and difference of individuals observed in actual hypothermal treatment. The fuzzy control process is easier to understand intuitively and more patient-friendly than in the case of optimal-adaptive method. The proposed system with 2-controller is superior to the unity feedback system concerning with following up of desired value. It was also confirmed useful to apply the first-order lag *characteristic model* substantially obtained from clinical experience to the brain temperature control. Consequently, many problems in the manual regulation such as mental and physical burden of clinicians will be incidentally overcome by the automatic fuzzy control system, so that the general management of respiration, circulation and anesthesia in connection with brain hypothermia treatment may be in the same way ensured. In addition, it would provide the medical staff with appropriate ways of hypothermia treatment on the basis of precise and necessary clinical information *a priori* from its experimental process, as they could freely try to change its thermal desired process.

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