

ORIGINAL ARTICLE

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Comparison of fuzzy control systems for hypothermal brain temperature regulation

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Abstract The automatic control system for brain tissue temperature is studied theoretically for brain hypothermia treatment. In order to realize a human-friendly control mechanism, an automatic temperature regulation system is constructed to simulate brain hypothermia treatment by introducing a fuzzy algorithm for possible characteristic changes in patients. The brain temperature model is successfully realized to follow the desired temperature course automatically. The model reference fuzzy control of brain temperature based on water-cooling blankets is verified for clinical application to brain hypothermia treatments through various kinds of simulation experiment.

Key words Hypothermia · Brain temperature · Water-cooling · Fuzzy control system · Brain resuscitation

Introduction

In brain hypothermia treatment, the brain tissue temperature is kept in moderate hypothermia to prevent severely brain-injured or brain-inflamed patients from suffering secondary brain damage.^{1–3} This has been introduced into their clinical treatment using water-cooling blankets, in which expert nursing staff manually regulate the water temperature to realize the appropriate thermal process prescribed by clinicians.³

The hypothermia realized by the cooling blankets is a standard noninvasive method for brain hypothermia treatment. However, it has to be constantly monitored for accurate temperature control. Thus, the nursing staff are incessantly forced to measure and control brain tempera-

ture deviation within 0.1°C every 20 min,³ which imposes a heavy mental and physical burden if the brain temperature regulation mechanism not entirely accurate.

In addition, the staff are engaged in the integrated care of life-support systems based on the management of brain hypothermia treatment, as well as anesthesia and heart–lung management, including mechanical respiration.^{1–3} Despite such difficulties, hypothermia treatment has gradually become a significant clinical technique in sedation to brain death and resuscitation, although much essential physiological information cannot be obtained from clinical experiments using patients.

In this connection, an adaptive–optimal method has been applied for automatically coping with time-varying and nonlinear characteristics, including differences in individual patients.^{4–9} However, more useful methods are required for actual treatments which will apply the control algorithm to clinical knowledge. A fuzzy control system is proposed, which consists of a standard controller corresponding to the clinical experience of clinicians and a compensatory controller dealing with differences in individuals and environmental changes.

Synthesis of the fuzzy automatic control system

Water-cooling control system for brain temperature

The automatic control of brain temperature is necessary not only for effective clinical brain hypothermia treatment, but also for a release from its complications in practice. As illustrated in Fig. 1, there is always some ambiguity due to disturbances, differences between patients, changes in their physiological state, and unknown factors resulting from different environmental changes caused by the clinical therapy, the operation, and so on.^{4–6,10} Furthermore, it might not be possible to realize a human-friendly thermal process, even the problematic conditions listed above were solved. Thus, conventional PID-regulations are not appropriate in the present case, because their design requires a precise recognition of the biothermal characteristics of the patient. In

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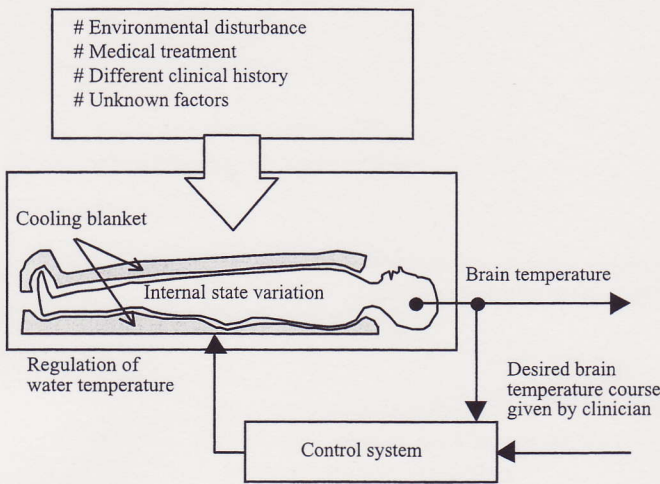


Fig. 1. Concept of brain temperature control in clinical hypothermia treatment processes

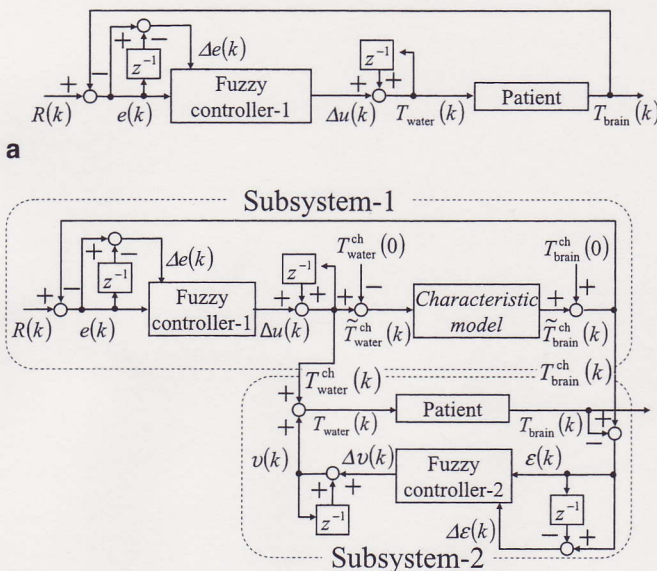


Fig. 2. a Unity feedback fuzzy control system, and b proposed fuzzy control system consisting of two subsystems

order to overcome such difficulties, one possible method is the automatic realization of the manual processes of hypothermia treatment, for which adaptive control systems have been proposed by means of water-cooling methods.^{8,9,11} Instead of such useful control systems, however, some alternative systems are required on the basis of actual treatments to utilize the control logic directly related to clinical knowledge. Therefore, a fuzzy control system with 2 degrees of freedom is proposed in this study.

Basic concept of the control system using a characteristic model

Figure 2a is a basic fuzzy control system often applied for various kinds of control. However, the control performance

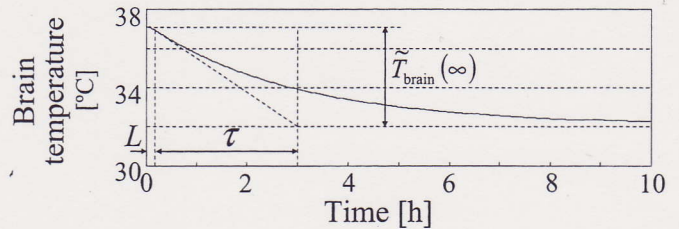


Fig. 3. Clinically typical response of the brain temperature to step changes in water temperature

of this unity feedback control system is not always enough to cope with the undesirable effects of differences and characteristic changes in individual patients, about which essential information cannot be known in advance. These unknown effects must be dealt with correctly by the thermal control systems, even when the metabolic change may be caused by shivering due to inadequate anesthesia for the life-support system in clinical brain hypothermia treatment.^{1,2}

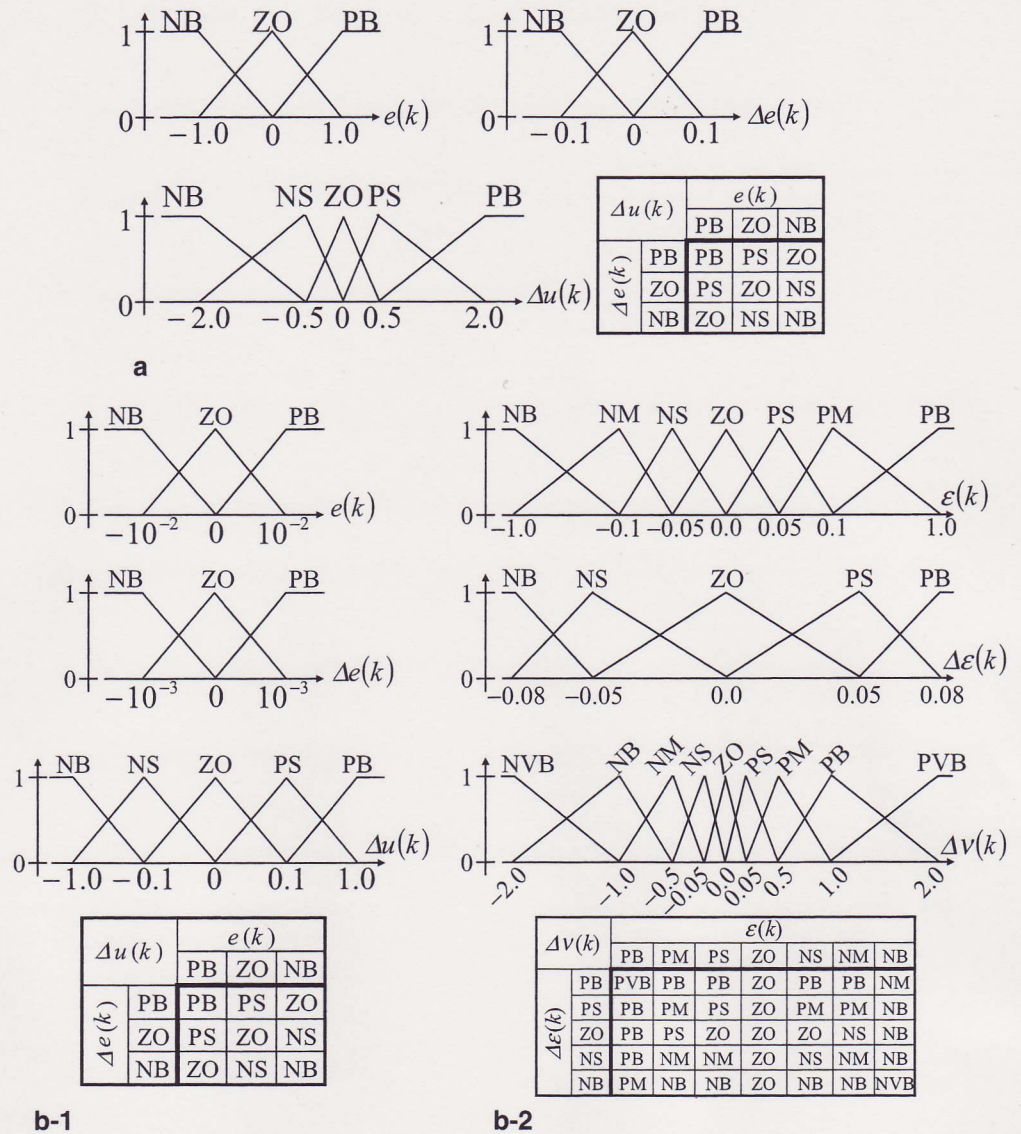
The proposed control system is composed of two control subsystems, as shown in Fig. 2b, using a *characteristic model* of the standard biothermal characteristics of patients undergoing brain hypothermia. Figure 3 shows the clinically typical response of the brain temperature of adult patients to the step-change of water temperature. Based on the precise heat transfer dynamics of a body with a surrounding blanket,^{5,12} the first-order lag system can be assigned to its estimated *characteristic model* relating to the possible function of the actual biothermal system of the patient based on clinical experience. Thus, its discrete-time representation is given by

$$\tilde{T}_{\text{brain}}^{\text{ch}}(i+1) = -a^{\text{ch}}\tilde{T}_{\text{brain}}^{\text{ch}}(i) + b^{\text{ch}}\tilde{T}_{\text{water}}^{\text{ch}}(i) \quad (1)$$

and neglecting the relatively small dead-time L , where $a^{\text{ch}} = -\exp(-\Delta t/\tau)$, $b^{\text{ch}} = \kappa(1 - \exp(-\Delta t/\tau))$, and the relevant parameters are estimated experimentally. Here, the suffix *ch* indicates the parameters concerned and the variables with a sampling interval Δt , time constant τ , and gain κ . T with a suffix indicates the brain or water temperature, and \tilde{T} denotes the temperature difference from its initial value. In this study, parameters for the *characteristic model* are estimated as $\tau = 3.0\text{h}$ and $\kappa = 0.9$.

Subsystem-1 is for essential control, and its output is regarded as a reference of brain temperature in subsystem-2, which is for accurate adjustment of the temperature deviation from the output of the *characteristic model* caused by environmental change and constitutional differences between patients. Thus, it is seen that the temperature of the circulating water is finally given by both the fuzzy signal synthesis mechanisms. During the clinical treatment of patients by doctors, that concept is analogous to their standard treatment based on clinical data and experience, and on specified precise management according to the medical history, idiosyncrasies, or allergic constitution of each patient. Thus, the merit of this control system is the so-called human-friendly control, physiologically and without

Fig. 4. a Fuzzy rule for the controller corresponding to Fig. 2a. **b-1** Fuzzy rules for controller-1 and **b-2** for controller-2 corresponding to Fig. 2b



any particular burden, in which controllers are not needed to re-design the system according to the differences and characteristic changes in patients.

Fuzzy rules and membership functions

The unity feedback system shown in Fig. 2a is the same as subsystem-1 in Fig. 2b, excluding the fuzzy rules shown in Fig. 4, if the patient, $T_{\text{water}}(k)$, and $T_{\text{brain}}(k)$ are substituted by *characteristic model*, $T_{\text{water}}^{\text{ch}}(k)$, and $T_{\text{brain}}^{\text{ch}}(k)$, respectively. Thus, the mathematical relation is mentioned only in the case of a proposed control system consisting of two subsystems.

In subsystem-1, the relatively rough determination of the water temperature of the blanket is characterized by fuzzy controller-1 given by Eq. 2, for which the inputs are the deviation $e(k)$ and its derivative $\Delta e(k)$ of output $T_{\text{brain}}^{\text{ch}}(k)$ of the *characteristic model* from reference $R(k)$. The two inputs

$e(k)$ and $\Delta e(k)$ are used appropriately, because the *characteristic model* has been represented by the first-order lag system. The input $T_{\text{water}}^{\text{ch}}(k)$ to the *characteristic model* is given by $T_{\text{water}}^{\text{ch}}(k-1)$ and the water temperature derivative $\Delta u(k)$, where the latter is calculated from the membership functions of the consequent rule and the fuzzy rule corresponding to fuzzy controller-1.

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

The membership functions are given as shown in Fig. 4b-1, in which the antecedents are used in order to fuzzificate $e(k)$ and $\Delta e(k)$. The third illustration is for the consequent rule, and the bottom table is the fuzzy rule for subsystem-1.

In subsystem-2, the water temperature of the blanket is regulated by $T_{\text{water}}^{\text{ch}}(k)$, with a compensatory value of water temperature $v(k)$ described by Eq. 3. The brain tempera-

ture deviation $\varepsilon(k)$ and its derivative $\Delta\varepsilon(k)$ are obtained from the output $T_{\text{water}}^{\text{ch}}(k)$ of the *characteristic model* and brain temperature $T_{\text{brain}}(k)$ of the patient. $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are fuzzified based on the membership functions of the antecedents given by Fig. 4b-2 for fuzzy controller-2. The two inputs $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are also used appropriately, because the *characteristic model* has been represented by the first-order lag system. $\Delta v(k)$ is calculated from the membership functions of the consequent rule and the fuzzy rule corresponding to fuzzy controller-2, taking into account the resolution of the instruments measuring temperature in actual hypothermia treatment.

$$\begin{aligned} \varepsilon(k) &= T_{\text{brain}}^{\text{ch}}(k) - T_{\text{brain}}(k) \\ \Delta\varepsilon(k) &= \varepsilon(k) - \varepsilon(k-1) \\ v(k) &= \Delta v(k) + v(k-1) \\ T_{\text{water}}(k) &= v(k) + T_{\text{water}}^{\text{ch}}(k) \end{aligned} \tag{3}$$

Note that the range of fuzzy variables increases in the antecedents and the consequent change in a sufficiently well-performing system dynamics¹³ in proportion to the deviation and derivative of the brain temperature caused by the disturbances and differences in individual patients and water temperatures.

Thus, the membership functions were designed as shown in Fig.4a, b-2. For greater environmental changes, the output is not only easily controlled back to the desired value, but also accurately controlled to eliminate any small deviation in brain temperature $T_{\text{brain}}(k)$.

This hypothermia control system works appropriately for patients for whom precise information about their environment is not available beforehand, as in the case of adaptive control. Note that the product-sum-gravity method is used for fuzzy inference, in which fuzzy variables are defuzzified. The theoretical water-cooling system is finally controlled by the input temperature $T_{\text{water}}(k)$ using a signal synthesis mechanism to follow up the output $T_{\text{water}}^{\text{ch}}$ of the *characteristic model*. That is, the input is given by two regulators which consequently realize the desired brain temperature course given by clinicians.

Experimental result and discussion

Human biothermal model used for a patient

Figure 5 shows a human biothermal model consisting of 8 segments and 18 compartments with cooling blankets.⁶ The respirator, denoted by the square box, represents respiratory control in brain hypothermia treatment. Blood flow into the lung compartment is equal to the total blood flow into other compartments brought together into the same square box by the dotted line. The double-headed open arrows represent direct heat exchange between the two compartments. Solid arrows represent convective heat exchange due to blood perfusion. The important parameters of the standard biothermal model are summarized in Table 1.¹⁴⁻¹⁶

Note that the various kinds of simulation experiment substantially confirmed that the present human biothermal model is an appropriate description of the actual thermal dynamics. Thus, a macroscopic step response is given by the first-order lag system, with a clinically obtained time constant and gain, including the characteristics of the main parts of the body, on the measurement of brain temperature by tympanic temperature.¹⁷ However, the temperature distribution in each compartment was not considered and the heat transfer dynamics were not taken into account, because their time constants mean that they can be ignored. The blood-flow change, including heartbeat and blood CO₂ concentration, was not physiologically considered as a function of body temperature, but the metabolic rate change was taken into account by the introduction of its relevant coefficients. Thus, the heat radiation ability per unit area is theoretically included in the order: face > head > neck > inferior extremities > chest > abdomen > superior extremities. Furthermore, the cooling efficiency of the hypothermia treatment is suggested to be in the order: abdomen > superior extremities > chest > head > face > inferior extremities > neck, which is useful knowledge for the construction of a human-friendly brain-temperature control system.

Fig. 5. Human biothermal model consisting of eight segments and 18 related compartments

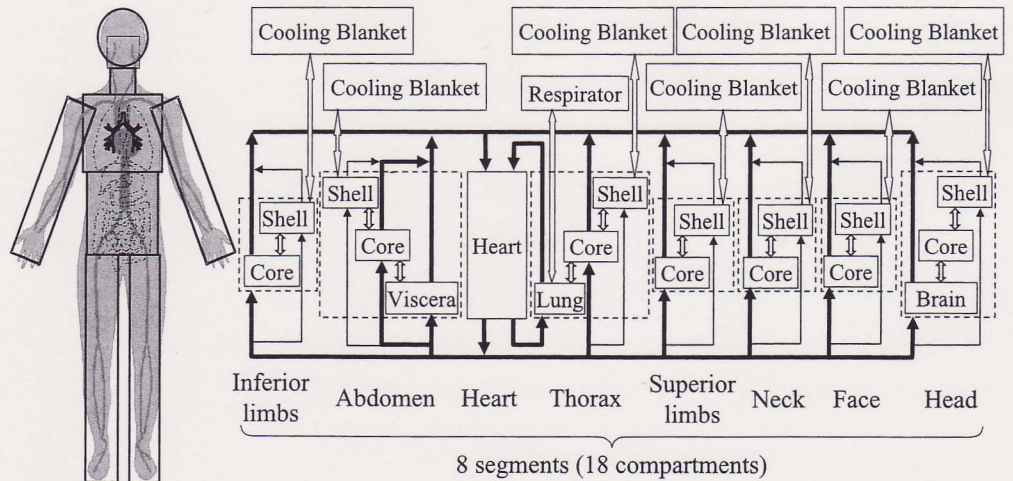
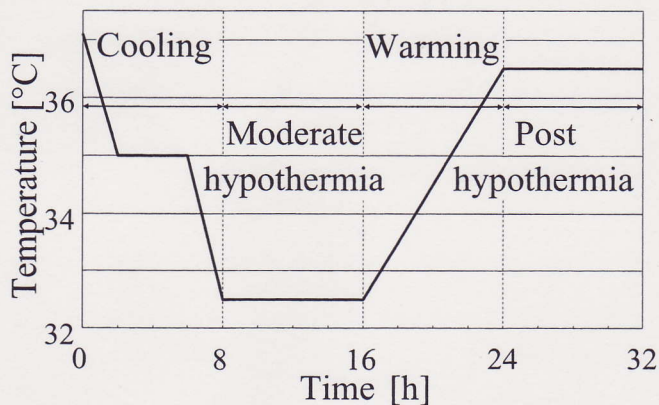


Table 1. The parameters for the human biothermal model illustrated in Fig. 5

Segments	Compartments	Segment length (mm)	Outer radius of compartment (mm)	Thermal conductance (W/m ² /°C)	Density (kg/m ³)	Heat capacitance (J/kg/°C)	Blood perfusion rate (×10 ⁻³ l/s)	Metabolic heat production (W/m ³)
Head	Brain		86	0.49	1080	3850	10.13	13400
	Core		101	1.16	1500	1591	0	0
	Shell		104	0.34	986	3180	3.18	237
Face	Core	98	68	0.42	1258	2351	0.20	250
	Shell		78	0.34	900	2652	2.36	123
Neck	Core	84	55	0.42	1118	3464	0.47	601
	Shell		57	0.34	974	3112	3.60	221
Superior limbs	Core	1609	34	0.42	1139	3278	0.43	549
	Shell		42	0.34	907	2703	0.27	134
Thorax	Lungs	306	77	0.28	550	3718	14.32	600
	Core		123	0.42	1143	3247	0.42	539
	Shell		129	0.34	944	2932	0.63	181
Heart						3550		7.19 (W)
Abdomen	Viscera	552	79	0.53	1000	3697	4.31	4100
	Core		109	0.42	1123	3421	0.46	589
	Shell		126	0.34	874	2472	0.15	89
Inferior limbs	Core	169	48	0.42	1142	3252	0.42	540
	Shell		55	0.34	918	2770	0.30	147

**Fig. 6.** Assumed schematic reference temperature for brain hypothermic treatment

Experimental conditions and various possible types of procedure

Simulation experiments based on mathematical conditions are necessary under circumstance where new clinical methods can not ethically be applied directly to the treatment of critical patients. Thus, when there were some phenomena which were inconsistent with the ones given by the standard human thermal system, this was appropriately revised after various clinical verifications, including, i.e., compensation for any metabolic rate increase by the use of the coefficient $\alpha = 1.5$ during a body temperature fall under anesthesia.⁶

Despite such limits in clinical discussion, this brain hypothermia experiment was performed with a sampling interval of 1 min according to the previously mentioned method, using the biothermal model in Fig. 5 and Table 1 for the patient's details. The resulting reference temperature course

is given schematically in Fig. 6 on the basis of clinical experiences.

Figure 7 shows a long-term display of brain and water temperatures with the given reference brain temperature, including a controlled error. The seven graphic representations show the whole 32-h experimental procedure under different control and physical conditions. One group is concerned with the unity feedback system with (a) a standard biothermal model and (b) a smaller body size with a different metabolic rate. The proposed control system is assessed with (c) a standard body size, (d) a smaller body size, and (e) a different metabolic rate. The modified biothermal model measures the effect of changes in water temperature on (f) the change in metabolic rate, and (g) the changes in blood perfusion rate during 11–14h from the start of the experiment.

Figure 7e–g show the whole experimental procedure under the three different kinds of environmental and condition changes during 11–14h from the beginning of the thermal process. Figure 7e shows that the brain temperature changed by 0.1°C and returned to its original level about 9 min after a step-like water temperature increase of 2°C. In Fig. 7f, the controlled dynamics are given in the case of a 10% metabolic rate increase. Figure 7g gives the results when the blood perfusion rate decreases by 10% on average in the whole body.

It is obvious that the controlled error in the brain temperature compared with the given reference is smaller using the proposed control system than using the unity feedback system (Fig. 7a,c and Fig. 7b,d). In addition, it is confirmed that the brain temperature follows the given reference temperature to within 0.1°C, even if an environmental or conditional change occurs in the patient, which may be concerned with some fatal danger to the patient's life in clinical therapy.

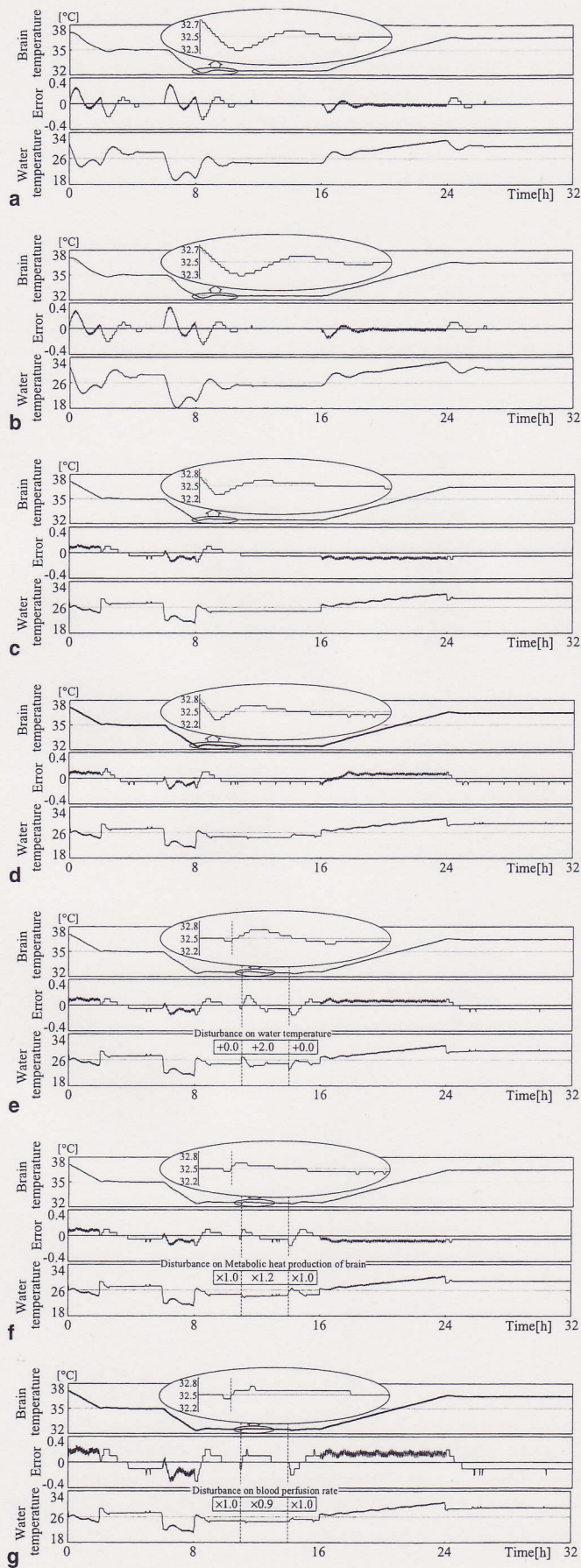


Fig. 7. The controlled dynamics of the brain and water temperatures. The unity feedback system is assessed on **a** a standard body size, and **b** a smaller body size with a different metabolic rate. The proposed control system is assessed on **c** a standard body size, **d** a smaller body size, and **e** a different metabolic rate. The modified biothermal model measures the effect of changes in water temperature on **f** the metabolic rate change, and **g** the blood perfusion rate change during 11–14 h from the beginning of the experiment

These results suggest to us that the proposed fuzzy control system with two controllers is much friendlier to patients than the unity feedback system or the adaptive-optimal system discussed previously.^{4–9} However, in the case of large biothermal inertia in the patient,^{5,12} some problems may be still expected in actual clinical brain hypothermia treatment. These will impose some technical difficulties in terms of a quick response and accurate control of the brain temperature.

Nevertheless, the proposed combinatory fuzzy control mechanism for water-cooling was confirmed as a useful automatic regulatory system to realize the brain temperature needed by the clinicians. Thus, the present work encourages us to develop an automatic clinical water-cooling system to replace the conventional manual water-cooling system in brain hypothermia treatment.

Conclusion

A fuzzy control algorithm was applied to a therapeutic water-cooling blanket system to automatically realize the desirable brain temperature scheduled by the clinicians. The control system, consisting of two control subsystems, was shown to be appropriate for coping with possible environmental and conditional change in patients, which are unavoidable in actual brain hypothermia treatments.

It was found to be useful to apply the first-order lag characteristic model, substantially obtained from clinical experience, to brain temperature control for hypothermic patients. Thus, the proposed model reference fuzzy control system was basically confirmed as being successful for the realization of effective and human-friendly regulation of brain temperature. At the same time, it was shown that as well as adaptive control systems, the present fuzzy control system was clinically applicable in overcoming the individual characteristics of patients, and any possible environmental and conditional changes in some therapeutic systems.

Consequently, many problems which arise in manual regulation, such as the mental and physical burden of clinicians, will also be overcome by the automatic control system, so that the general management of respiration, circulation, and anesthesia in connection with brain hypothermia treatment may be satisfactorily ensured. In addition, it would provide the medical staff with appropriate ways of using hypothermia treatment on the basis of precise and necessary clinical information a priori from its pertinent simulation process, as they could freely change the thermal process desired.

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