# MODEL REFERENCE FUZZY CONTROL SYSTEM OF BRAIN TEMPERATURE FOR HYPOTHERMIA TREATMENT

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Abstract: Automatic control system of brain tissue temperature is theoretically studied for the brain hypothermia treatment. In order to realize human friendly control mechanism, an automatic temperature regulation system is constructed to simulate the brain hypothermia treatment, by introducing fuzzy algorithm for possible characteristic change of the patients. The brain temperature is successfully realized to follow up the desired temperature course automatically. 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 simulation experiments. 

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 brain-inflammatory patients from secondary brain damage (Hayashi, 1995, 2000; Obashi, *et al*., 1998).
It has been introduced into their clinical treatment using water-cooling blankets, in which expert nursing staffs manually regulate their water temperature to realize the appropriate thermal process prescribed by clinicians (Obashi, *et al*., 1998).

The hypothermia 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, the nursing staffs are incessantly forced to measure and control brain temperature deviation within 0.1 °C in every 20 min (Obashi, *et al*., 1998), 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 (Hayashi, 1995, 2000; Obashi, *et al*., 1998). Despite of such difficulties, the hypothermia treatment has gradually become more significant for clinical technique concerning brain death and resuscitation, in which necessary physiological information cannot be allowed to obtain from clinical experiments using patients.

In this connection, adaptive-optimal method has been applied automatically coping with time-varying and nonlinear characteristics inclusive of the differences of individual patients (Lu Gaohua and Wakamatsu, 2003; Wakamatsu and Lu Gaohua, 2003a, 2003b, 2004; Wakamatsu et al, 2004; Wakamatsu and Utsuki, 2004). 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 Water-cooling control system of brain temperature*

The automatic control of brain temperature is necessary not only for the effective clinic brain hypothermia treatment but also for the release from its complicated work. As illustrated by Fig.1, there are always some ambiguity 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 (Lu Gaohua and Wakamatsu, 2003; Wakamatsu and Lu Gaohua, 2002, 2003a, 2003b). Furthermore, there might be no guarantee to realize a human friendly thermal process, even though above problematic conditions were solved. Thus, conventional PID-regulations are not appropriate in the present case, because their design requires sufficiently well recognition of the biothermal characteristics of patients. In order to overcome such difficulties, one of the possible methods is automatic realization of the manual process of hypothermia treatment, for which adaptive control systems have been proposed by means of water-cooling methods (Lu Gaohua and Wakamatsu, 2004; Wakamatsu et al, 2004; Wakamatsu and Utsuki, 2004). Instead of such useful 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 degrees of freedom is proposed in this study.

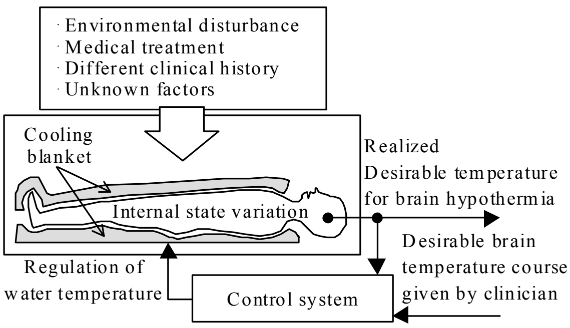



Fig. 1. Concept of brain temperature control in clinical hypothermia treatment process.

### *2.2 Basic concept of control system using characteristic model*

Figure2-(a) is a basic fuzzy control system often applied to various kinds of control. However, this unity feedback control system is not always enough on its control performance in order to cope with the undesirable effect of difference and characteristic change of individual patients, about which necessary information cannot be known practically beforehand. Those unknown effects must be dealt with precisely by the thermal control systems, even when metabolic change is possibly caused by shivering due to inadequate anesthesia for the life-support in clinical brain hypothermia treatment (Hayashi, 1995, 2000).

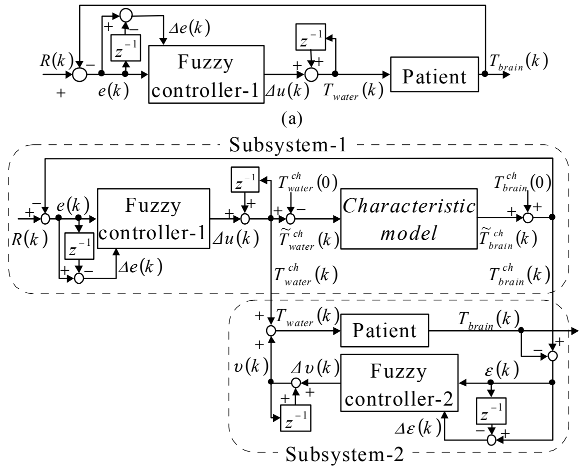



Fig. 2. (a)Unity feedback fuzzy control system and (b) proposed fuzzy control system consisting of two subsystems.

The proposed control system is composed of two control subsystems as shown in Fig.2-(b), using a *characteristic model* of standard biothermal characteristics of patients concerning 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 body with surrounding blanket (Wakamatsu and Lu Gaohua, 2003a, 2003c), the first-order lag system can be assigned to its estimated *characteristic model* relating to possible function of actual biothermal system of a patient based on the clinical experience.

Thus, its discrete-time representation is given by

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

neglecting relatively small dead time *L*, where $a^{ch} = -\exp(-\Delta t/\tau)$ , $b^{ch} = \kappa(1-\exp(-\Delta t/\tau))$ and relevant parameters are experimentally estimated. Hereby, the suffix *ch* indicates its concerning parameters and variables with sampling interval $\Delta t$, time constant $\tau$ and gain $\kappa$. $T$ with 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 hours and $\kappa$= 0.9.

The subsystem-1 is for the essential control, where its output is regarded as a reference of brain temperature in subsystem-2, which is for the accurate compensation of the

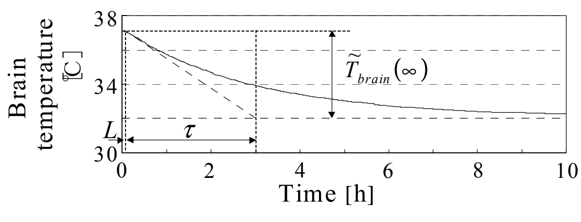



Fig. 3 Clinically typical response of the brain temperature to the step change of water temperature.

temperature deviation from the output of *characteristic model* caused by the environmental change and constitutional difference of patients. Thus, it is remarked that the temperature of circulating water is finally given by the both fuzzy signal synthesis mechanisms.

During clinical treatment of patients by doctors, that concept is analogous to their standard treatment based on the clinical data and 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.

### 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.4, if patient, $T_{water}(k)$ and $T_{brain}(k)$ are substituted by *characteristic model*, $T^{ch}_{water}(k)$ and $T^{ch}_{brain}(k)$, respectively. Thus, the mathematical relation is mentioned only in the case of the proposed control system consisting of two subsystems.

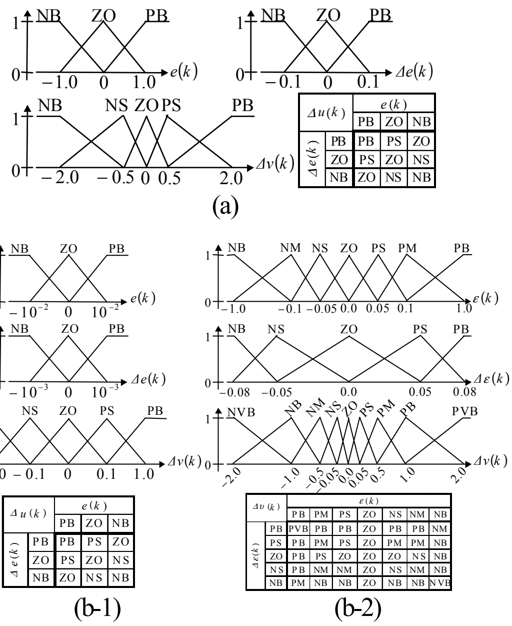
In the subsystem-1, the relatively rough determination of water temperature of blanket is characterized by the fuzzy controller-1 given by Eq. (2), for which the inputs are the deviation $e(k)$ and its derivative $\Delta e(k)$ of output $T^{ch}_{brain}(k)$ of *characteristic model* from the reference $R(k)$. The two inputs $e(k)$ and $\Delta e(k)$ are appropriately used, because the *characteristic model* has been represented by the first-order lag system. 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 fuzzy 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.4-(b-1), in which the antecedents are used in order to fuzzificate $e(k)$ and $\Delta e(k)$. The third illustration is for the consequent and the bottom table is the 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.4-(b-2) for the fuzzy controller-2. The two inputs $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are also appropriately used, because the *characteristic model* has been represented by the first-order lag system. $\Delta\upsilon(k)$ is calculated from the membership functions of the consequent and the fuzzy rule corresponding to the fuzzy controller-2, taking into account the resolution of measuring instruments of temperature in actual hypothermia treatment.

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




(a), (b-1): $\Delta u(k)$

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

(b-2): $\Delta\upsilon(k)$

| $\Delta\varepsilon(k)$ \ $\varepsilon(k)$ | PB | PM | PS | ZO | NS | NM | NB |
|---|---|---|---|---|---|---|---|
| PB | PVB | PB | PB | ZO | PB | PB | NM |
| PS | PB | PM | PS | ZO | PM | PM | NB |
| ZO | PB | PS | ZO | ZO | ZO | NS | NB |
| NS | PB | NM | NM | ZO | NS | NM | NB |
| NB | PM | NB | NB | ZO | NB | NB | NVB |

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

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 (Xu Haoyuan et al., 1996), in proportion to the deviation and derivative of brain temperature caused by the disturbance and difference of individual patients and water temperature.

Thus, the membership functions are designed as shown in Fig4-(a), (b-2). Thus, for the greater environmental change, the output is not only easily controlled back to the desired value, but also 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 as in the case of adaptive control.

Hereby, product-sum-gravity method is used for fuzzy-inference, in which fuzzy variables are defuzzificated. The theoretical water-cooling system is finally controlled by the input $T_{water}(k)$ using signal

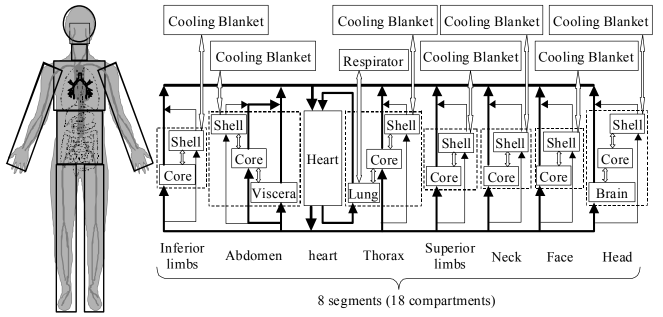



Fig. 5. Human biothermal model consisting of eight segments and relating 18 compartments.

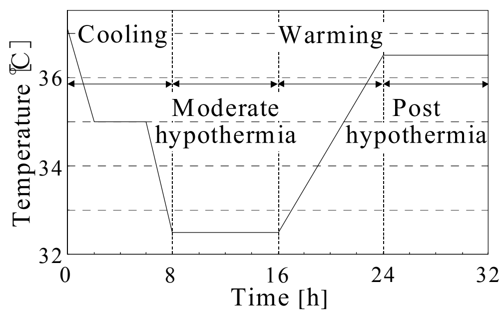



Fig. 6. Assumed schematic reference temperature for brain hypothermic treatment

Table 1 The parameters for human biothermal model Illustrated by Fig.5.

| Segments | Compartments | Length segment [mm] | Outer radius compartment [mm] | Thermal conductance [W/m/℃] | Density [kg/m$^3$] | Heat capacitance [J/kg/℃] | Blood perfusion rate [$\times 10^{-3}$1/s] | Metabolic heat production [W/m$^3$] |
|---|---|---|---|---|---|---|---|---|
| | Brain | | 86 | 0.49 | 1080 | 3850 | 10.13 | 13400 |
| ***Head*** | 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 | 98 | 78 | 0.34 | 900 | 2652 | 2.36 | 123 |
| ***Neck*** | Core | 84 | 55 | 0.42 | 1118 | 3464 | 0.47 | 601 |
| | Shell | 84 | 57 | 0.34 | 974 | 3112 | 3.60 | 221 |
| ***Superior limbs*** | Core | 1609 | 34 | 0.42 | 1139 | 3278 | 0.43 | 549 |
| | Shell | 1609 | 42 | 0.34 | 907 | 2703 | 0.27 | 134 |
| | Lungs | 306 | 77 | 0.28 | 550 | 3718 | 14.32 | 600 |
| ***Thorax*** | Core | 306 | 123 | 0.42 | 1143 | 3247 | 0.42 | 539 |
| | Shell | 306 | 129 | 0.34 | 944 | 2932 | 0.63 | 181 |
| ***Heart*** | | | | | | 3550 | | 7.19[W] |
| | Viscera | 552 | 79 | 0.53 | 1000 | 3697 | 4.31 | 4100 |
| ***Abdomen*** | Core | 552 | 109 | 0.42 | 1123 | 3421 | 0.46 | 589 |
| | Shell | 552 | 126 | 0.34 | 874 | 2472 | 0.15 | 89 |
| ***Inferior limbs*** | Core | 169 | 48 | 0.42 | 1142 | 3252 | 0.42 | 540 |
| | Shell | 169 | 55 | 0.34 | 918 | 2770 | 0.30 | 147 |

synthesis mechanism to follow up the output $T_{brain}^{ch}$ 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*

Figure 5 shows the human biothermal model consisting of 8 segments and 18 compartments with cooling blankets (Wakamatsu and Lu Gaohua, 2003b). 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 others brought together into the same square box by dotted line. Double-headed hollow arrow represents direct heat exchange between the next two compartments. Solid arrow represents convective heat exchange due to blood perfusion. The concerning parameters of the standard biothermal model are summarized in Table 1 (Werner and Webb, 1993; Lou and Yang, 1990; Fiala, et al., 2001).

It is remarked that the various kinds of simulation experiments substantially confirmed the present human biothermal model appropriate for the description of actual thermal dynamics. Thus, macroscopic step response is given by the first-order lag system with clinically obtained time constant and gain, including the characteristics of main parts of body on the measurement of brain temperature by tympanic temperature (Plattner et al., 1997). However, the temperature distribution was not considered in each compartment and the heat transfer dynamics were not taken into account, as they can be ignored considering their time constants. The blood flow change including heartbeat and blood $CO_2$-concentration was not physiologically considered as a function of body temperature, nevertheless the metabolic rate change is taken into account by the introduction of its relevant coefficients. Thus, the heat radiation ability per unit area, is theoretically mentioned as in turn larger as Face > Head > Neck > Inferior extremities > Chest > Abdomen > Superior extremities. Furthermore, the cooling efficiency for the hypothermia treatment can be suggested using the following superiority as Abdomen > Superior extremities > Chest > Head > Face > Inferior extremities > Neck, which is a useful knowledge for the construction of human friendly brain temperature control system.

*3.2 Experimental condition and various types of possible procedure*

The simulation experiment based on the mathematical conditions are necessary under the circumstance that new clinical methods are not ethically allowed to apply directly to such a treatment of critical patients. Thus, when there were some inconsistent phenomena with the ones given by the present human thermal system, it was appropriately revised by various clinical verifications, including i.e. compensation of metabolic rate increase by use of coefficient $\alpha$ =1.5 during the body temperature fall in anesthesia (Wakamatsu and Lu Gaohua, 2003b) .

Despite of such limits in clinical discussion, the brain hypothermia experiment was here performed with sampling interval of 1 minute according to the previously mentioned method, regarding biothermal model in Fig.5 and Table1 as a patient. Thereby, the reference temperature course was schematically given by Fig.6 on the basis of clinical experiences.

Figure 7 is a long-term display of the brain and water temperatures with the given reference brain temperature including controlled error. Seven graphic representations show the whole 32-hour experimental procedure under different control and physical conditions. One group is concerned with standard biothermal model (a) by the unity feedback system and (c) by the proposed control system, the others are concerning modified biothermal model by the 80% size of standard one with basic metabolism 25% increase, (b) by unity feedback system and (d) by the proposed control system.

Figure7-(e),(f),(g) show the whole experimental procedure under the three different kinds of environmental and conditional change during 11-14 hours from the beginning of the thermal process. Figure7-(e) shows that brain temperature changed within 0.1 ℃ and came back to original state in about 9 minutes after the step-like water temperature increase by 2 ℃. In Fig.7-(f), the controlled dynamics are given in the case of 10% metabolic rate increase. Figure7-(g) gives the result when the blood perfusion rate decreases 10% in average in the whole body.

It is obvious that the controlled error of brain temperature from the given reference is smaller by the proposed control system than by the unity feedback one, comparing Fig.7-(a),(c) with Fig.7-(b),(d).

In addition, the dynamics of the brain temperature following-up the given reference within 0.1℃ deviation is confirmed, even if there occurs the environmental and conditional change of patients, which may be concerned with some fatal damage to the patient's life in clinical therapy.

Those suggest us that the proposed fuzzy control system with two controllers is much friendly to patients in comparison with the unity feedback system and the adaptive-optimal system previously discussed (Lu Gaohua and Wakamatsu, 2003; Wakamatsu and Lu Gaohua 2003a, 2003b, 2004; Wakamatsu et al, 2004; Wakamatsu and Utsuki, 2004).

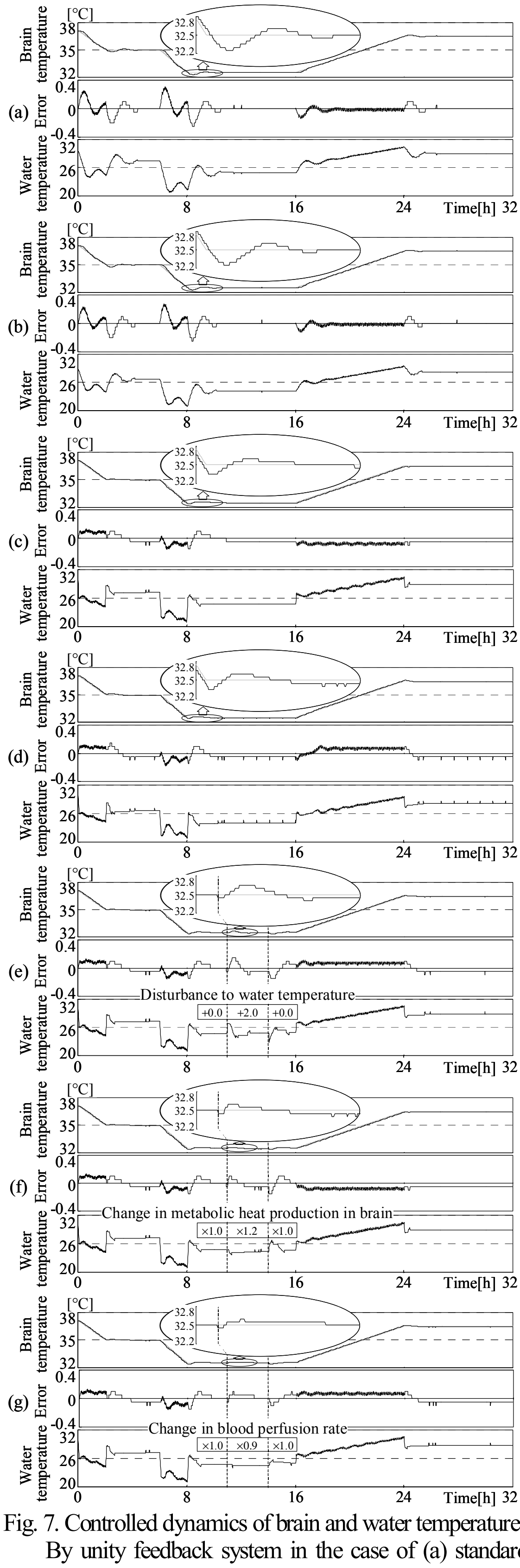



Fig. 7. Controlled dynamics of brain and water temperatures, By unity feedback system in the case of (a) standard body size and (b) smaller body size with different metabolic rate; By proposed control system in the case of (c) standard body size and (d) smaller body size with different metabolic rate; (e) On water temperature change, (f) on metabolic rate change and (g) on blood perfusion rate change, respectively, during 11-14hours from the beginning of experiment.

However, in the case of such larger biothermal inertia of patient (Wakamatsu and Lu Gaohua, 2003a, 2003c), some problems may be still expected in actual clinical brain hypothermia treatment, which will impose us some technical difficulties in the necessity of quick response and control accuracy of the brain temperature.

Nevertheless, the proposed combinatory fuzzy control mechanism by water-cooling was confirmed useful in automatic regulation to realize brain temperature scheduled 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, which would be one of the useful and powerful methods in medicine.

## 4. CONCLUSION

Fuzzy control algorithm was applied to the therapeutic water-cooling blanket system to realize automatically desirable brain temperature scheduled by the clinicians.

The control system consisting of two control subsystems were shown appropriate to cope with possible environmental and conditional change of patients, which are unavoidable in actual brain hypothermia treatments.

It was confirmed useful to apply the first-order lag *characteristic model* substantially obtained from clinical experience to the brain temperature control of hypothermic patients.

Thus, the proposed model reference fuzzy control system was basically confirmed successful for the realization of effective and human friendly regulation of brain temperature.

At the same time, it was guaranteed that as well as adaptive control systems the present fuzzy control system was clinically applicable, in order to overcome the individual characteristic difference of patients and possible environmental and conditional change in some therapeutic system.

Consequently, many problems in the manual regulation such as mental and physical burden of clinicians will be incidentally 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 staffs with appropriate ways of hypothermia treatment on the basis of precise and necessary clinical information *a priori* from its pertinent simulation process, as they could freely change its thermal desired process.

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