Automatic Optimal-Adaptive Control of Brain Temperature by Water-Cooling System

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Abstract Automatic control system of brain tissue temperature (BTT) is synthesized to replace its conventional manual regulation system for brain hypothermia treatment (BHT). In order to verify the optimal-adaptive control mechanism previously proposed by the authors, a mechanical automatic temperature regulation system is constructed to simulate the clinic BHT, by introducing a mannequin model with possible characteristic change instead of the patients in ICU. Electric heater and heat exchanger are used to regulate the water temperature circulating in the cooling blanket according to the optimal-adaptive control mechanism. The representative temperature of the mannequin's head (hereafter, brain temperature) is successfully realized to follow up the desired temperature course automatically. The adaptive control of the mannequin's brain temperature with the optimal control of the cooling blanket is verified from the various kinds of simulation experiments. Then, the proposed combinatory control mechanism is confirmed valid and available for the clinical application to BHT.

Keywords: hypothermia, brain temperature, water-cooling, optimal-adaptive control

1 Introduction

In brain hypothermia treatment, brain tissue temperature is kept in a mild hypothermia to prevent severely brain-injured patient from secondary brain damage[1-3]. It has been introduced into its clinical treatment using water-cooling blankets, in which expert nursing staffs manually regulate the water temperature to realize the appropriate cooling process prescribed by clinicians[3]. The hypothermia realized by the cooling blanket is a powerful and noninvasive method for BHT. However, they have to be much concerned with the followings: (a) cooling effect of the water blanket depending largely on the blanketing technique; (b) insufficiency of peripheral circulation and its resultant decubitus partially due to the contact of heavy blankets with the patient's skin; and (c) sensitive change in BTT to thermal condition of ICU due to its open cooling circumstance, and so on[1-3]. Thus, they have to be engaged in an integrated operation of life-support based on the temperature management of BHT, in connection with anesthesia and heart-lung management inclusive of mechanical respiration[1-3]. On the other hand, the nursing staffs are continuously forced to measure and control BTT deviation within 0.1 ℃ in every 20 min[3], which mentally and physically imposes them heavy burden, making them keep less accurate brain temperature regulation.

2 Automatic Water-Cooling System

The automatic control of BTT is necessary not only for the clinical effectiveness of BHT but also for the release from their laborious work. The present study proposes an automatic water cooling system including its feasibility to replace the conventional water blanket system. In the present case, conventional PID-regulations are not appropriate, because its design requires sufficiently well recognition of the biothermal characteristics of the patients, which have ambiguity in their internal and external conditions including various uncertain factors such as their difference of individuals and environmental change[4-5]. Furthermore, there might be no guarantee to realize an optimal cooling process, even though above problematic conditions were solved[5-7].

The output BTT of the hypothermic patient is

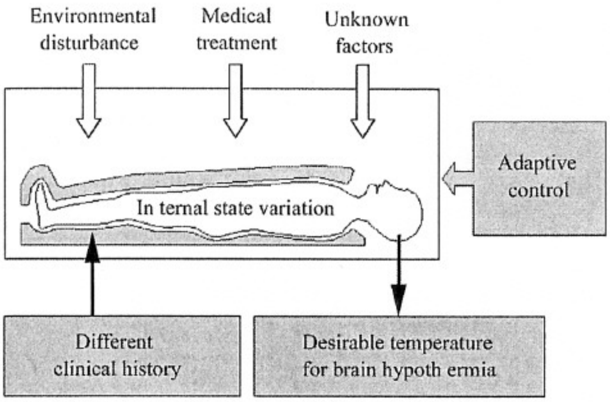

Fig. 1 Concept of adaptive control in clinical BHT process

adaptively controlled to follow up BTT of *a characteristic model* using the signal synthesis mechanism, which realizes the desired brain temperature course given by clinicians.

There are always some ambiguity due to individual differences of patients, chronic change in physiological state and disturbances caused by the clinical therapy and operation. In order to deal with these uncertain factors, an adaptive mechanism is appropriate to realize the automatic water-cooling system consistent with the function of the conventional blanket cooling system, based on the thermal *characteristic model* of the patients with the water-cooling blanket[4-5].

It is thereby remarked that the temperature of circulating water is actively given by the adaptive mechanism during possible metabolic change, in order to make BTT follow up the reference given by the clinicians. It is obvious that such an increase in metabolic rate is often caused by shivering due to inadequate anesthesia of the integrated life-support in clinical BHT[1-2]. The adaptive algorithm is effective under such circumstances that any precise information about patients and their

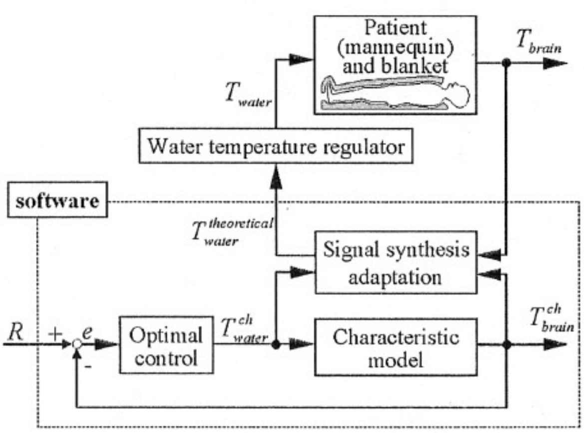

Fig. 2 Optimal-adaptive control of brain temperature

environment are practically never given beforehand.

In addition, the optimal regulator is introduced to produce the effective input to the *characteristic model* and to the signal synthesis mechanism simultaneously. Then, the output BTT of the actual water-cooling system is adaptively controlled using the signal synthesis mechanism to follow up the output T_{brain}^{ch} from the *characteristic model* for the input given by the regulator, which is consequently to realize the desired brain temperature course given by clinicians.

3 Characteristic Model for Optimal Input Signal

Based on the relation of BTT to the temperature of surrounding blanket, precisely explained by Wakamatsu and Lu Gaohua[5,8], a first-order lag system has been adopted for its estimated *characteristic model* related to possible structure of actual biothermal system. Thus, its discrete-time representation is given by

$$T_{brain}^{ch}(i+1) = -a^{ch}T_{brain}^{ch}(i) + b^{ch}T_{water}^{ch}(i) \quad (1)$$

where $a^{ch} = -e^{-\frac{v}{\tau}}$, $b^{ch} = k(1-e^{-\frac{v}{\tau}})$, indicating *ch* the concerning parameters of the estimated *characteristic model* with sampling time v, time constant τ and gain k.

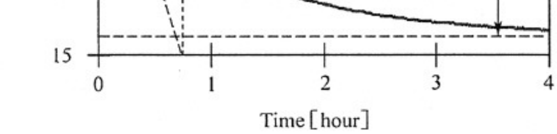

Fig. 3 Thermal characteristics of mannequin with the controller of metabolic heat and its transfer by water circulation

The optimal input, water temperature T_{water}^{ch} into the *characteristic model* is calculated using the tracking error e of the its output BTT from the reference temperature R by introducing the following variables:

$$e(i) = R(i) - T_{brain}^{ch}(i) \quad (2)$$

$$\Delta e(i+1) = e(i+1) - e(i) \quad (3)$$

$$\Delta T_{brain}^{ch}(i) = T_{brain}^{ch}(i) - T_{brain}^{ch}(i-1) \quad (4)$$

Using the above variables, Eq. (1) - (4) are summarized as follows:

$$X(i+1) = AX(i) + G\Delta T_{water}^{ch}(i) + G_R \Delta R(i+1) \quad (5)$$

where

$$X(i) = \begin{bmatrix} e(i) \\ \Delta T_{brain}^{ch}(i) \end{bmatrix}, A = \begin{bmatrix} 1 & a^{ch} \\ 0 & -a^{ch} \end{bmatrix},$$

$$G = \begin{bmatrix} -b^{ch} \\ b^{ch} \end{bmatrix}, G_R = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

Hereby, the optimal input to the *characteristic model* is calculated by using Eq.(6), provided that T_{brain}^{ch} (0) and T_{water}^{ch} (0) are initial conditions of the brain and water temperatures.

$$T_{water}^{ch}(i) = h_1 \sum_{k=1}^{i} e(k) + h_2[T_{brain}^{ch}(i) - T_{brain}^{ch}(0)] + T_{water}^{ch}(0) \quad (6)$$

The feedback coefficients h_1 and h_2 in Eq. (6) are described according to the optimal algorithm as follows:

$$H = [h_1\ h_2] = -[r + G^T PG]^{-1} G^T PA \quad (7)$$

$$P = Q + A^T PA - A^T PG[r + G^T PG]^{-1} G^T PA \quad (8)$$

where

$$Q = \text{diag}[q_1 \quad q_2], r > 0.$$

4 Input Signal Synthesis Mechanism

The basic dynamics of patients inclusive of water-cooling blanket has been assumed by first-order lag system given by Eq.(9), where unknown parameters of $\hat{a}$ and $\hat{b}$ are estimated in the adaptive process.

$$T_{brain}(i+1) = -\hat{a}(i) T_{brain}(i) + \hat{b}(i) T_{water}^{theoretical}(i) \quad (9)$$

Then, the input $T_{water}^{theoretical}$ to the therapeutic system is calculated by

$$T_{water}^{theoretical}(i) = \frac{(g - a^{ch}) T_{brain}^{ch} + b^{ch} T_{water}^{ch}(i) - [g - \tilde{a}(i)] T_{brain}(i)}{\hat{b}(i)} \quad (10)$$

where the output brain temperature T_{brain}^{ch} and the input blanket temperature T_{water}^{ch} to the *characteristic model* are given by Eqs.(1) and (6). The parameters of $\hat{a}$ and $\hat{b}$ are given by Eq.(11), when the state variable vector is

$$\varphi(i) = \begin{bmatrix} T_{water}^{theoretical}(i) \\ T_{brain}(i) \end{bmatrix}$$

and the system parameter vector is

$$\hat{P}(i) = \begin{bmatrix} \hat{b}(i) \\ g - \hat{a}(i) \end{bmatrix}$$

$$\hat{P}(i) = \hat{P}(i-1) + F(i-1)\varphi(i-1)e^*(i) \quad (11)$$

where

$$e^*(i) = \frac{T_{braim}(i) + gT_{brain}(i-1) - \hat{P}^T(i-1)\varphi(i-1)}{1 + \varphi^T(i-1)F(i-1)\varphi(i-1)} \quad (12)$$

$$F(i) = \frac{1}{\lambda(i)} \left\{ F(i-1) - \frac{F(i-1)\varphi(i-1)\varphi^T(i-1)F(i-1)}{1 + \varphi^T(i-1)F(i-1)\varphi(i-1)} \right\} \quad (13)$$

$$\lambda(i) = 1 - \frac{\| F(i-1)\varphi(i) \|^2}{1 + \varphi^T(i)F(i-1)\varphi(i)} \cdot \frac{1}{trF(0)} \quad (14)$$

and $F(0) = \text{diag}[f_1 \quad f_2], g > 0$.

5 Experimental Result of Hypothermia

5.1 Equipment and condition

The reference temperature course, by which the mannequin's brain temperature is controlled, is schematically simplified on the basis of clinical experiences as given by Figure 4. Owing to the previously mentioned method, the brain hypothermia experiment is performed using the experimental system illustrated by Figure 5.

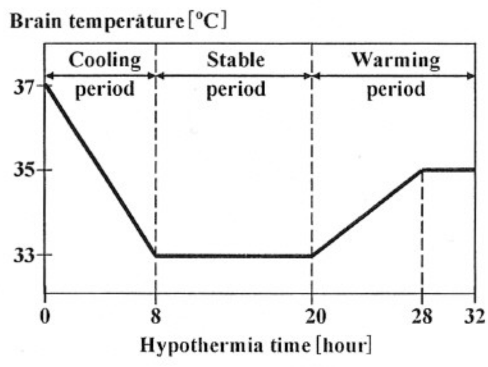

Fig.4 Schematic reference of brain temperature for brain hypothermic treatment assumed in the present study

The mannequin is made, so that heaters are immersed into its four extremities and body, in which metabolic rate change are given by electric heating. The circulatory blood is simulated by water circulation, which transfers metabolic heat to the mannequin's brain by using a mechanical pump.

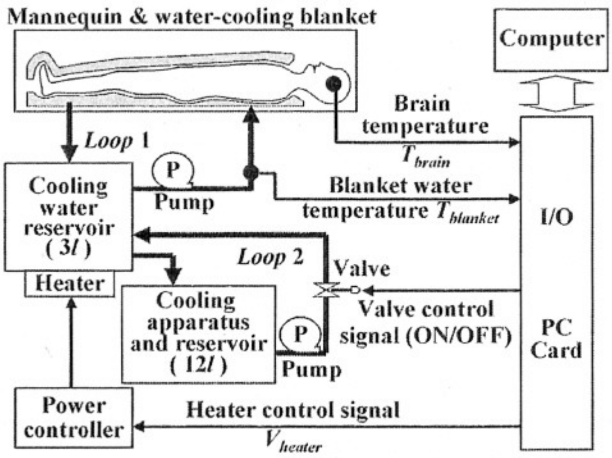

Fig.5 Mechanism of automatic control system of brain temperature

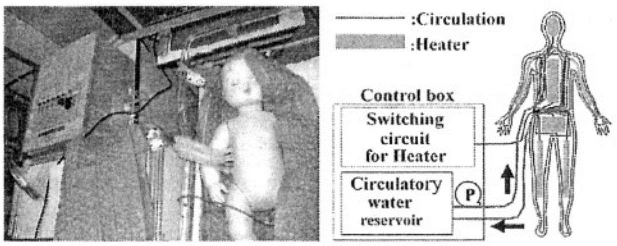

Fig.6 Mannequin with variable metabolic heat and its heat transfer by water circulation

5.2 Experimental result

Figure 7 is a long-term display of the brain, body, water and room temperatures with given reference brain temperature in 32-hour experiment. It presents the whole experimental procedure with various kinds of environmental change internally and externally, in which the brain temperature has been nevertheless kept within an appropriate range of values.

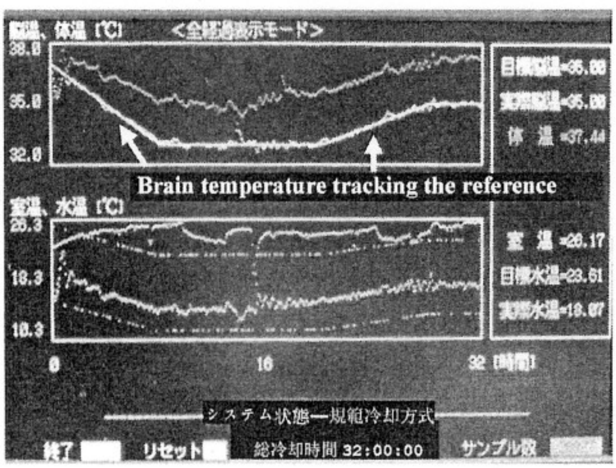

Fig.7 The whole experimental procedure of brain, body, water and room temperatures (32h)

As shown in Figure 8, the brain temperature well followed up the reference one given by Figure 4, even though the room temperature climbed down about 8 ℃, because ofthe cold wind from the outdoor. The brain temperature incidentally climbed downin about 15 min with body temperature change, which might be concerned with some fatal damage to the patients life in clinical therapy. However, by water temperature increase, the brain temperature is kept around 33.0 ℃ within a permissible range of its deviation.

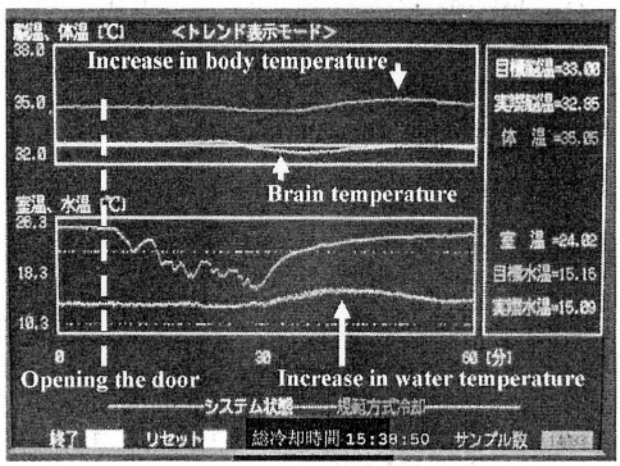

Fig.8 Dynamics of brain, body, water and room temperatures (60min) due to room temperature change

Figure 9 shows the dynamic change of the brain, body, water and room temperatures with the given reference temperature due to the inadequate contact of the blanket with the mannequin's skin, when the upper cover blanket is partly removed. In 5 minutes after removal of the blanket, water temperature is controlled lower by 1.3 ℃ in order to reduce the effect of smaller contact area

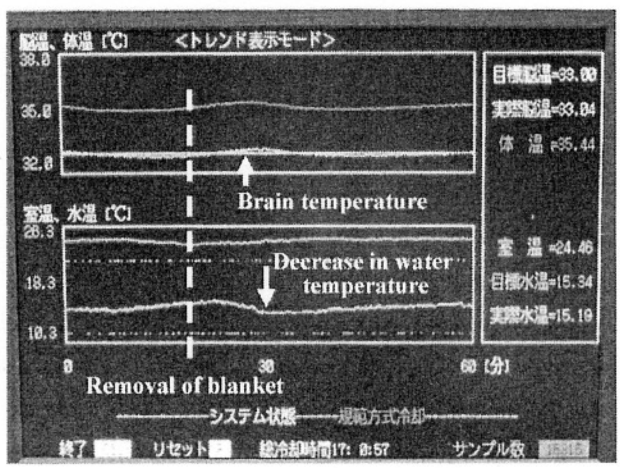

Fig.9 Dynamics of brain, body, water and room temperatures (60min) due to the inadequate state change of water blanket

of the blanket. Consequently brain temperature has bee kept within 0.15 ℃ deviation.

In the case of the metabolic rate increase in the brain by heating the head as an additional important factor, the brain, body, water and room temperatures are presented in Figure 10. The change in brain temperature of mannequin is also adaptively controlled to follow up the reference temperature. However, the thermal inertia of mannequin is relatively smaller (time constant; $\tau = 0.8$ h) in comparison with the patient's one ($\tau = 3.0$ h)[5,8], there are expected some problems in actual clinical BHT with a larger thermal inertia, which will impose us more technical difficulty in the response time and control accuracy of the brain hypothermia by the proposed method.

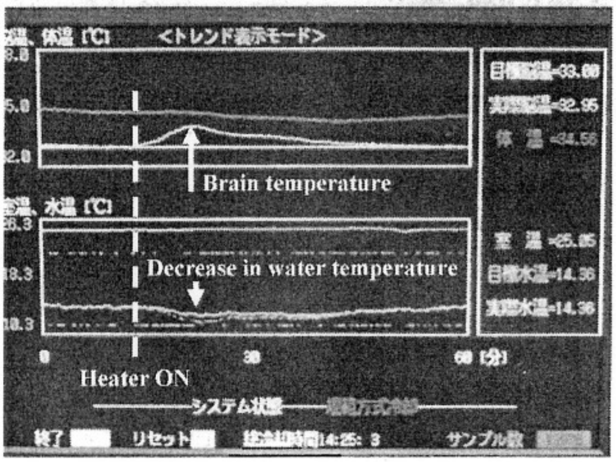

Fig.10 Dynamics of brain, body, water and room temperatures (60 min) due to heating of the head

6 Conclusion

The proposed combinatory optimal-adaptive control mechanism was confirmed useful in automatic regulation of BTT, although it has been mainly based on the water-cooling blanket by the manual regulation of temperature of circulating water to realize BTT scheduled by the clinicians. The automatic BTT control, overcoming possible difficulties, was realized successfully in BHT, as one of the useful and powerful methods. Thereby, the control algorithm is confirmed useful for the realization of effective automatic regulation of BTT, if taken into account the first-order lag *characteristic model* substantially extracted from the basic characteristics of hypothermic patients with water-cooling blanket system. At the same time, some problems in the manual regulation are incidentally overcome by the proposed optimal-adaptive control mechanism, although there still exist its clinically undesirable effects in hypothermia. In addition, it could provide the clinicians and nurses appropriate ways on the basis of precise and necessary clinical information beforehand from the pertinent simulation process of BHT, as the thermal process can be freely changed by themselves. It is thus concluded that the optimal-adaptive control of the proposed therapeutic water-cooling system ensures the following-up control of the desired temperature course. In addition, the present work encourages us to develop an automatic water-cooling system to replace the manual water-cooling blanket in BHT. It is thus expected useful in clinical practice, if the similar adaptive control algorithms are applied to actual therapeutic air-cooling system[9].

It is further remarked that the present study provides us a significant medical method, which overcomes the individual characteristic difference of patients and existing possible environmental change in some therapeutic systems.

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