

Automatic Air-Cooling Incubating System for Brain Hypothermia Treatment

HIDETOSHI WAKAMATSU and LU GAOHUA

Summary. A new automatic air-cooling system is proposed using a cooling incubator to replace the manual water-cooling blanket, which has always been used for the cooling of the brain tissue temperature (BTT) in brain hypothermia treatment (BHT). This study concerns the feasibility of this system through its simulation as follows. First, an optimal-adaptive control algorithm is introduced into the proposed incubating system to realize automatic regulation of BTT, introducing the first-order lag system given as its basic *characteristic model*. Then, in order to verify this algorithm, a simulation is carried out where an *adult bio-thermal model* previously presented by the authors is introduced as a replacement for the hypothermic patient in the cooling incubator. It is shown from the simulation result that the BTT of the adult biothermal model is controlled by the optimal-adaptive control mechanism to follow a given reference temperature course, even if there exists a possible environmental change in the therapeutic cooling system including individual differences of patients and chronic conditional change. Thus, the present work ensures the possible development of the air-cooling adult-incubating system for the automatic regulation of BTT in intensive care unit application.

Key words. Brain hypothermia treatment, Brain tissue temperature, Incubator, Adult biothermal model, Automatic control

Introduction

In brain hypothermia treatment (BHT), brain tissue temperature (BTT) is kept in mild hypothermia to prevent the severely brain-injured patient from secondary brain damage [1,2]. It has been introduced into the clinical treatment of brain-injured adult patients using water-cooling blankets, in which expert nursing staff manually regulate the cooling-water temperature to realize the appropriate cooling process prescribed by clinicians. Hypothermia using the water-cooling blanket is a powerful and noninvasive method. However, clinicians are becoming more concerned with, for example, (a) the cooling effect of the water blanket depending largely on the blanketing technique, (b) insufficiency of peripheral

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circulation and its resultant decubitus partially due to the imperfect contact of heavy blankets with the patient's skin, and (c) sensitive change in BTT due to thermal conditions of the intensive care unit (ICU) in its open cooling situation. Thus, the clinicians always have to be engaged in an integrated operation of life support based on the temperature management of BHT in the ICU, in connection with anesthesia and heart-lung management inclusive of mechanical respiration.

On the other hand, the nursing staff are continuously forced to measure and control the temperature deviation in BTT to within 0.1°C every 20 min [1,3]. However, such manual control of water temperature imposes upon them a heavy mental and physical burden, which may make them keep a less accurate temperature regulation. Thus, the automatic control of BTT is necessary not only for the clinical effectiveness of BHT but also for the release of the staff from their laborious task.

Materials and Methods

The present study proposes a new automatic air-cooling incubating system including its feasibility to replace the conventional water-blanket system as a regulator of BTT. As shown in Fig. 1, an optimal-adaptive control mechanism is applied to the automatic regulation of BTT prescribed by clinicians. The present study ensures the development of an adult incubator for the actual clinical hypothermia application.

Optimal-Adaptive Control

There is always some ambiguity due to individual differences of patients, chronic change in physiological state, and disturbances caused by the clinical therapy and operation. To deal with these unknown factors, an adaptive mechanism is appropriate to realize an automatic incubating function similar to the one provided by the water-cooling system.

Wakamatsu and Lu Gaohua have precisely explained the relationship of the patient's BTT to the temperature of the surrounding water-cooling blanket in the therapeutic system, in

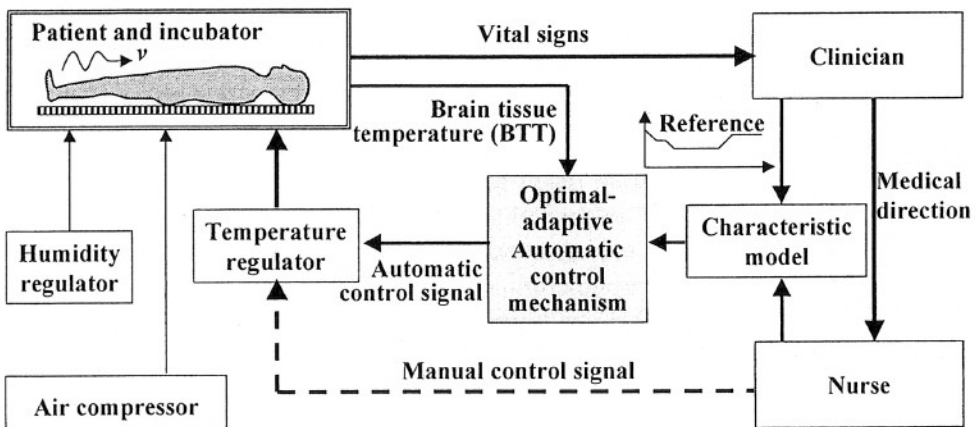


FIG. 1. Concept of automatic air-cooling incubating system. Clinicians prescribe the characteristic model for the automatic control mechanism. The loop of manual control indicated by the broken line is essential for the safety of patients in medical treatment. The characteristic model represents the basic characteristics of the patient and the water-cooling blanket used in the intensive care unit

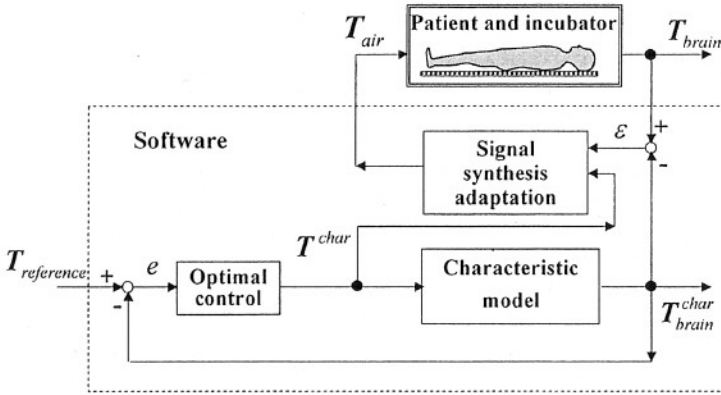


FIG. 2. Diagram of optimal-adaptive control. The output brain tissue temperature of the actual hypothermic patient (here, adult biothermal model) is adaptively controlled to follow up the characteristic model using the signal synthesis mechanism, which realizes the desired BTT reference given by clinicians. The subsystem indicated by the area surrounded by the dotted line corresponds to the control mechanism given by Fig. 1

which “actual patient thermal characteristics with water-cooling blanket” is given as a *characteristic model* [4,5].

As shown in Fig. 2, an optimal regulator is also introduced to produce effective input to the characteristic model and to the signal synthesis mechanism simultaneously. Then, the therapeutic air-cooling incubating system is optimally and adaptively controlled to follow up the output T_{brain} of the characteristic model by the pertinent input.

Characteristic Model and Therapeutic System

If the characteristic model is given by the first-order lag system, its discrete-time representation is

$$T_{brain}^{char}(i+1) = -a^{char}T_{brain}^{char}(i) + b^{char}T^{char}(i), \quad a^{char} = -e^{-\frac{\nu}{\tau}}, \quad b^{char} = k\left(1 - e^{-\frac{\nu}{\tau}}\right) \quad (1)$$

where the suffix *char* indicates the relevant parameters of the characteristic model. The time constant τ and the gain k are determined with sampling time ν according to the clinical experience on the “hypothermic patient and water-cooling blanket” [5,6].

Calculation of Optimal Input Signal

The optimal input T^{char} is calculated using the deviation e of output BTT of the characteristic model from the reference temperature $T_{reference}$ by introducing the following variables:

$$e(i) = T_{reference}(i) - T_{brain}^{char}(i), \quad \Delta e(i) = e(i) - e(i-1), \quad \Delta T_{brain}^{char}(i) = T_{brain}^{char}(i) - T_{brain}^{char}(i-1) \quad (2)$$

where Δe and ΔT_{brain}^{char} are calculated using the difference of the values at present and previous sampling time.

Equations (1) and (2) are summarized as represented by Eq. (3).

$$X(i+1) = AX(i) + G\Delta T^{char}(i) + G_R\Delta T_{reference}(i+1) \quad (3)$$

where $\Delta T_{reference}$, ΔT^{char} are calculated in the same way as Δe , ΔT_{brain}^{char}

$$\text{and } X(i) = \begin{bmatrix} e^{(i)} \\ \Delta T_{brain}^{char}(i) \end{bmatrix}, \quad A = \begin{bmatrix} 1 & a^{char} \\ 0 & -a^{char} \end{bmatrix}, \quad G = \begin{bmatrix} -b^{char} \\ b^{char} \end{bmatrix}, \quad G_R = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

Then, the optimal input to the characteristic model is calculated by using Eq. (4), provided that $T^{char}(0)$ and $T_{brain}^{char}(0)$ are given as initial conditions of the input and output temperatures of the estimated characteristic model.

$$T^{char}(i) = h_1 \sum_{k=1}^i e(k) + h_2 (T_{brain}^{char}(i) - T_{brain}^{char}(0)) + T^{char}(0) \tag{4}$$

The feedback coefficients h_1 and h_2 in Eq. (4) are described according to the optimal algorithm as follows:

$$H = [h_1 \quad h_2] = -[r + G^T P G]^{-1} G^T P A, \quad P = Q + A^T P A - A^T P G [r + G^T P G]^{-1} G^T P A \tag{5}$$

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

Mechanism of Input Signal Synthesis

The basic dynamics of adult patients with the incubator could be assumed by the first-order lag system given by Eq. (6), where \hat{a} and \hat{b} are the estimates during the adaptive process.

$$T_{brain}(i+1) = -\hat{a}(i)T_{brain}(i) + \hat{b}(i)T_{air}(i) \tag{6}$$

Then, the input T_{air} to the air-cooling incubating system is calculated by

$$T_{air}(i) = \frac{(h - a^{char})T_{brain}^{char}(i) + b^{char}T^{char} - (h - \hat{a}(i))T_{brain}(i)}{\hat{b}(i)} \tag{7}$$

where the output BTT T_{brain}^{char} and the input temperature T^{char} of the characteristic model are given by Eqs. (1) and (4). The parameters of \hat{a} and \hat{b} are estimated from Eq. (8), if the system state vector is $\phi(i) = [T_{air}(i) \quad T_{brain}(i)]^T$, and the system parameter vector $\hat{P}(i) = [\hat{b}(i) \quad h - \hat{a}(i)]^T$.

$$\hat{P}(i) = \hat{P}(i-1) + F(i-1)\phi(i-1)e^*(i) \tag{8}$$

where

$$e^*(i) = \frac{T_{brain}(i) + hT_{brain}(i-1) - \hat{P}(i-1)\phi(i-1)}{1 + \phi^T(i-1)F(i-1)\phi(i-1)}, \quad \lambda(i) = 1 - \frac{\|F(i-1)\phi(i)\|^2}{1 + \phi^T(i)F(i-1)\phi(i)} \cdot \frac{1}{\text{tr}F(0)},$$

$$F(i) = \frac{1}{\lambda(i)} \left(F(i-1) \frac{F(i-1)\phi(i-1)\phi^T(i-1)F(i-1)}{1 + \phi^T(i-1)F(i-1)\phi(i-1)} \right), \quad F(0) = \text{diag}[f_1 \quad f_2] \text{ and } h > 0.$$

Results

The *adult biothermal model*, which has been proposed by Wakamatsu and Lu [6], is applied to the simulation of automatic control of BTT instead of the therapeutic air-cooling incubating system in Fig. 1. Compared with the conventional water-cooling blanket, heat transfer is mainly enhanced by the speed of circulating air in the cooling incubator. Hence, the

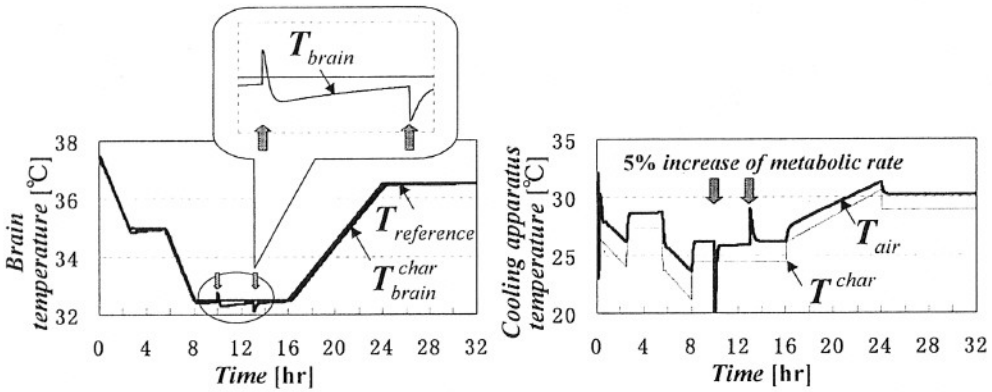


FIG. 3. Brain tissue temperature dynamics of the adult biothermal model using optimal-adaptive control. Temperature courses of the characteristic model and the adult biothermal model agree with the given BTT reference. Broad vertical arrows show the brain temperature dynamics due to a 5% metabolic rate increase in the adult biothermal model

air-cooling coefficient is calculated by $k = 7.2 + v^{0.67}$, which is based on the formula proposed by Shitzer and Eberhart [7].

In the simulation experiment, $f_1 = f_2 = 100$, $h = a^{char}$ were first set for the adaptive algorithm, and $q_1 = q_2 = 0.01$, $r = 0.001$ for the optimal tracking algorithm. The sampling interval v was given as 30 s. k and τ of the characteristic model were set at 0.9 and 3.0 h, respectively, according to the clinical experience by the water-cooling blanket system [6]. The 5% increase in the metabolic rate was given in 3 h (10–13 h from the beginning), in the stable hypothermia phase of BHT, in order to simulate the possible undesirable effects during its control process.

In Fig. 3, both BTTs of the adult biothermal model and the characteristic model almost overlap the desired BTT reference during the simulation experiment. This means that both of the optimal and adaptive controls work sufficiently well to realize the given reference cooling process. It is, in particular, remarked that the temperature of circulating air in the adult biothermal model is actively given by the adaptive mechanism during 3-h metabolic change, in order to follow up the reference BTT 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. The adaptive algorithm is effective in dealing with such variation, as is illustrated by Fig. 3, even though any precise information about patients and their environment is practically never given beforehand.

The proposed combinatory control method with two mechanisms was confirmed to be useful in automatic regulation of BTT in following the desired cooling schedule of BHT. Eventually, it is expected to be used in clinical practice, if the similar control algorithms are applied to an actual therapeutic air-cooling incubating system.

Discussion

Brain hypothermia treatment has been mainly based on the water-cooling blanket, using manual regulation of temperature of circulating water to realize BTT scheduled by the clinicians. In the present study, an attempt has been made to use an automatic air-cooling incubator to replace not only the manual and but also the automatic water-cooling blanket methods, as there still exist clinically undesirable effects from their use in hypothermia.

For this purpose, the newly developed *biothermal model* of adult patients with blocked neural regulation mechanism of BHT has been precisely studied as well as its feasibility for its prospective clinical application. In addition, the *adult biothermal model* has been characterized by its environmental temperature [6] and partly applied to the development of its optimal control algorithm by the examination of its step response and feedback control [4].

Thereby, an optimal and adaptive control algorithm is confirmed to be useful for the realization of effective automatic regulation of BTT in the therapeutic air-cooling incubating system, if the first-order lag system substantially extracted from the basic characteristics of hypothermic patients by the water-cooling blanket system is taken into account. In the thermal control studied here, however, conventional PID-regulation is not appropriate, because its design requires sufficient recognition of the biothermal characteristics of the patients, who have ambiguity of their internal and external conditions including various uncertain factors such as interindividual differences and environmental and chronic change. To overcome such unknown factors the model reference adaptive control of BTT has been adopted for the air-cooling incubating system, which has commonly been applied to maintain the body temperature of premature infants [8], but has never been reported for the treatment of adult patients with severe brain injury.

For the calculation of optimal controlling input, BTT dynamics corresponding to the air temperature change have been given by the transfer function with the time constant set at shorter than 3 h with a gain of about 0.9 [5,6]. Thus, the combination of the optimal tracking control and model reference adaptive control has been successfully confirmed for the regulation of BHT, which will become a useful and powerful method. In addition, various problematic phenomena resulting from the water-cooling blanket have been solved by using the pertinent air-cooling incubating system. On the basis of precise and necessary clinical information gained beforehand from the pertinent simulation process of BTT, which can be freely prescribed or changed by the staff themselves, this system could thus provide clinicians and nurses with an appropriate method of therapy.

In the proposed air-cooling method, there still remain some inevitable mitigating factors for its clinical application, for instance, the velocity of circulating air, by which the temperature of the incubator is automatically controlled. Even if more precise experiments are required on its application, the present method will surely contribute to the frontier work on BHT in clinics in the near future.

From the simulation experiments, the automatic air-cooling incubator is confirmed as basically superior to the therapeutic water-cooling blanket system regarding possible avoidance of decubitus and bedsores during the patient's medical treatment and rehabilitation process. It also provides greater cooling efficiency with increased cost-benefit performance by easy system manipulation, and is convenient for keeping patients in sanitation with less environmental disturbance, inclusive of releasing them from physical and mental burdens.

It is concluded that the optimal-adaptive control mechanism using the proposed air-cooling incubating system ensures the subsequent control of the desired temperature course. In addition, the present work proposes development of an air-cooling adult-incubating system to replace the manual and/or automatic water-cooling blanket in BHT.

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