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Automatic Control System of Brain Temperature by Air-Surface Cooling for Therapeutic Hypothermia*

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Abstract— **An automatic control system of brain temperature by air-surface cooling was developed for therapeutic hypothermia, which is increasingly recommended for hypoxic-ischemic encephalopathy after cardiac arrest and neonatal asphyxia in several guidelines pertinent to resuscitation.**

Currently, water-surface cooling is the most widespread cooling method in therapeutic hypothermia. However, it requires large electric power for precise control and also needs water-cooling blankets which have potential for compression of patients by its own weight and for water leakage in ICU. Air-surface cooling does not have such problems and is more suitable for clinical use than water-surface cooling, because air has lower specific heat and density as well as the impossibility of the contamination in ICU by its leakage.

In the present system, brain temperature of patients is automatically controlled by suitable adjustment of the temperature of the air blowing into the cooling blankets. This adjustment is carried out by the regulation of mixing cool and warm air using proportional control valves. The computer in the developed control apparatus suitably calculates the air temperature and rotation angle of the valves every sampling time on the basis of the optimal-adaptive control algorithm. Thus, the proposed system actualizes automatic control of brain temperature by the inputting only the clinically desired temperature of brain.

The control performance of the suggested system was verified by the examination using the mannequin in substitution for an adult patient. In the result, the control error of the head temperature of the mannequin was 0.12°C on average in spite of the lack of the production capacity of warm air after the re-warming period. Thus, this system serves as a model for the clinically applied system.

I. INTRODUCTION

Currently, therapeutic hypothermia is increasingly recommended for hypoxic-ischemic encephalopathy after cardiac arrest and neonatal asphyxia in several guidelines pertinent to resuscitation [1-5]. This therapy is intended to prevent the secondary death of brain cells by cooling brain tissue to 33 °C to 35 °C. Its clinical trials are variously ongoing not only for the forementioned diseases but also for cerebral infarction and cerebral trauma.

In clinical practice, brain tissue is cooled down mainly by surface cooling, blood cooling, or intravascular-cooling. Any method requires precise control of brain and body temperature because the side effects such as arrhythmia and infection are increasingly frequent with hypothermia [6].

In therapeutic hypothermia, water-surface cooling is the most widespread cooling method because of its non-invasive and easy operation. Thus, an automatic system of it was developed for not only precise control of brain temperature but also reduction of burden of clinical staff [7, 8]. This system has an automatic algorithm on the basis of control theories, by which the temperature of water-cooling blankets is suitably calculated and automatically adjusted for brain temperature control. Its performance was verified by its clinical applications in the three cases of venous and/or arterial cerebral infarction [9]. However, water-surface cooling requires large electric power for precise control by reason of large specific heat of water. This is one of the problems in clinical use because electric power is supplied only up to 1500VA at each bed. In addition, this cooling requires water-cooling blankets, which has potential not only of compression of patients by its own weight but also of water leakage in ICU.

Air-surface cooling does not have such problems and is more suitable for clinical use than water-surface cooling, because air has lower specific heat and density as well as the impossibility of the contamination in ICU by its leakage. In addition, it has already discussed that body and brain of a patient is cooled down more rapidly than water-surface cooling under blowing air to him/her more than 1.8m/s [10]. Thus, an automatic control system of brain temperature by air-surface cooling was developed for the basic performance examination of brain temperature control by using a mannequin [11]. This mannequin was developed for the simulation of thermal characteristics similar to an adult patient, including specific heat, metabolic rate distribution and blood flow distribution.

The developed system requires an enclosed box in which the mannequin is laid for reducing disturbances, and controls mannequin's head temperature by the adjustment of the air temperature in the box. However, this mechanism is not suitable for clinical use because of various difficulties in several medical cares, such as transfusion, artificial respiration, monitoring by electrocardiogram, and bed-bath. Therefore, in this study, a new automatic control system by air-surface cooling was developed in consideration of clinical use. And, its performance of brain temperature control was verified by using the above mannequin.

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II. DEVELOPMENT OF THE AUTOMATIC CONTROL SYSTEM

A. Mechanism of the control apparatus

Figure 1 shows the picture of the apparatus developed for the realization of the proposed system, and fig.2 represents its mechanism. In the system, a patient is covered by air-cooling blankets and this apparatus suitably adjusts the temperature of blowing air into the blankets by mixing cool and warm air. The blowing air leaks through lots of small holes on the surface of the blankets, and is released in the room. As just described, this mechanism does not intrinsically require the closed circulation of air. Therefore, the developed apparatus is simpler than apparatuses by water-surface cooling.

In this apparatus, the air conditioner produces cool and warm air and blows out them to the mixing box. The dampers with stepping motors run as proportional controlling valves for the flow regulation depending on the signals from the computer. Each temperature of the cool air, the warm air and the blowing air is measured by platinum resistance temperature detectors, and their flow rate are respectively measured by hot-wire anemometers. The measurement signals are inputted into the computer through signal-converter or AD converter every its sampling time.

The computer automatically calculates the solution of the temperature of the blowing air based on the control algorithm described in the following section, and suitably operates the proportional controlling valve for the adjusting the temperature of cool and warm air. Thus, medical staff are able to control patients' brain temperature by only inputting clinically desired temperature of brain into this apparatus.

Clinically, inserting a temperature-measuring catheter to brain tissue is the most appropriate method to measure the brain temperature. However, this direct measurement is usually too invasive for therapeutic hypothermia because it requires drilling the skull of patients. In practice, core body temperature, such as tympanic temperature, nasal temperature, esophageal temperature, bladder temperature, rectum temperature and blood temperature, is often measured as a substitute for the brain tissue temperature. Thus, in this study, "brain temperature" represents not only brain tissue temperature but also core body temperature in consideration of clinical use.

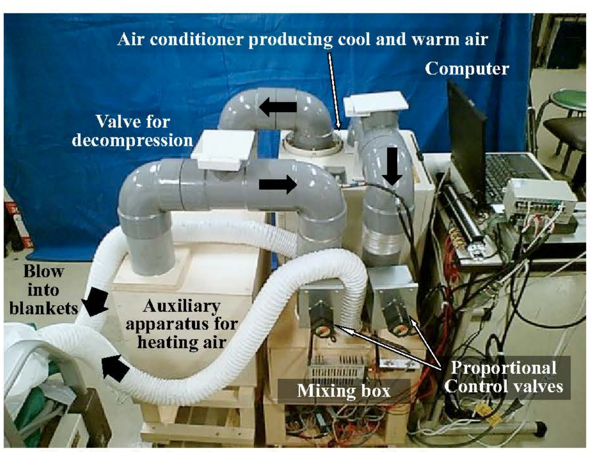

Fig.1 The developed control apparatus of brain temperature by air-surface cooling.

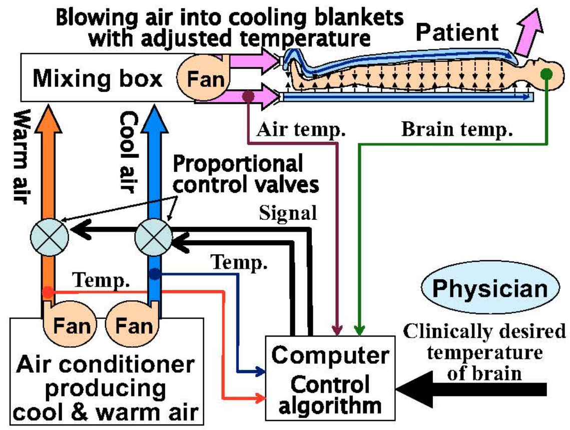

Fig.2 The mechanism of the developed apparatus for automatic control of brain temperature.

B. Algorithm of the control

Figure 3 represents the developed algorithm of brain temperature control by air-surface cooling. This algorithm consists of two feedback control loops similar to the automatic control system by water-surface cooling [7]. One is the optimal control loop regarding the characteristic model as controlled objects. This model represents typical thermal characteristics of patients as described hereinbelow. Thus, in this loop, the typical solution of the temperature of the blowing air is calculated. Another loop is the adaptive control loop for correcting the disturbance caused by individual differences and temporal changes of patients' characteristics.

The characteristic model is constructed as a first order lag system given by Eq. (1). A variable T with tilde indicates the difference from its initial value, and T_{brain}^{model} and T_{air}^{model} represent the brain temperature of patients and the temperature of the blowing air in the model. Developed algorithm is a discretized system and the number of sampling is represented by i.

$$\widetilde{T}_{brain}^{model}(i+1) = -a^{model}\widetilde{T}_{brain}^{model}(i) + b^{model}\widetilde{T}_{air}^{model}(i) \quad (1)$$

where a^{model} and b^{model} are the coefficients given by Eq.(2). Δt represents sampling time of brain temperature control, and K and τ indicate gain and time constant of the characteristic model.

$$a^{model} = -e^{-\frac{\Delta t}{\tau}}, \ b^{model} = K(1-e^{-\frac{\Delta t}{\tau}}) \quad (2)$$

$\widetilde{T}_{air}^{model}$ is given by Eq.(3) which represents the function of the optimal regulator.

$$\widetilde{T}_{air}^{model}(i) = h_1 \sum_{j=1}^{i} \left(\widetilde{R}(j) - \widetilde{T}_{brain}^{model}(j)\right) + h_2 \widetilde{T}_{brain}^{model}(i) \quad (3)$$

where R is the target value of brain temperature. h_1 and h_2 are coefficients of state feedback, and are obtained by solving the Riccati equation.

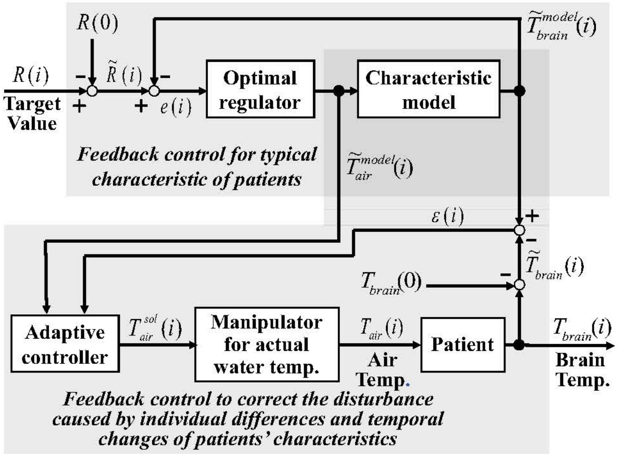

Fig.3 The applied algorithm of automatic control of brain temperature.

$\widetilde{T}^{sol}_{air}$, the solution of the temperature of the blowing air, is given by Eq.(4) which represents the function of the adaptive controller.

$$\widetilde{T}^{sol}_{air}(i) = \frac{1}{\hat{b}(i)}\Big[\left(g - a^{model}\right)\widetilde{T}^{model}_{brain}(i) + b^{model}\widetilde{T}_{air}(i) - \left(g - \hat{a}(i)\right)\widetilde{T}_{brain}(i)\Big] \tag{4}$$

where T_{brain} and T_{air} are actual temperature of patient's brain and air blowing into cooling blankets. $\hat{a}(i)$ and $\hat{b}(i)$ are the adaptively identified coefficients correspond to a^{model} and b^{model}. In addition, g is a parameter concerned with convergence speed in adaptation process and its absolute value is within 1. These coefficients are given in the adaptation process using the fixed trace method.

Therefore, T_{brain} automatically follows R by the precise adjustment of T_{air} to $\widetilde{T}^{sol}_{air}$ in the proposed system.

C. *Algorithm of the air temperature adjustment*

The developed apparatus automatically adjusts T_{air} to $\widetilde{T}^{sol}_{air}$ according to the proportional control algorithm, which is represented by Fig.4. The mixing flow of cool and warm air is regulated by the proportional control valves, of which the rotation angle is calculated as the product of the proportional gain, kp, and the difference between T^{sol}_{air} and T_{air}.

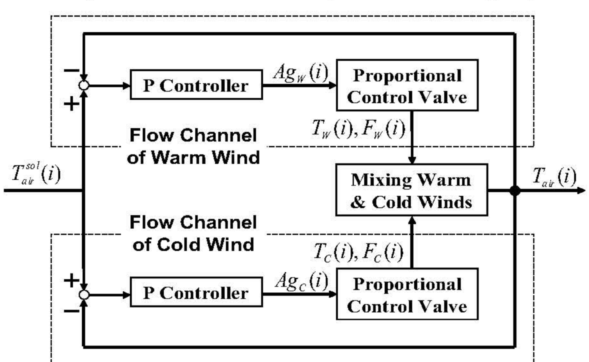

Fig.4 The developed algorithm for adjusting the temperature of blowing air into cooling blankets. T_c and T_w represent the temperature of the cool and warm air. F_c and F_w indicate the flow of them. Ag_c and Ag_w represent the rotation angle of each proportional control valve.

In this algorithm, the efficiency of adjusting T_{air} per the mixing air flow physically alters due to increase or decrease of T^{sol}_{air}. Thus, for the stabilization of the control performance, kp is given as the variable by Eq.(5), where KP is a criterial parameter corresponding to kp in the case that T_{air} is equal to T_c or T_w, and CK is a parameter indicating the gain of the adjustment of kp.

$$kp = \frac{(\mathrm{CK}-1)\times \mathrm{KP}\times\left|T^{sol}_{air} - \frac{T_W + T_C}{2}\right|}{\mathrm{CK}\times\left(T_W - T_C\right)} + \frac{\mathrm{KP}}{\mathrm{CK}} \tag{5}$$

III. Performance Examination of the System

The basic performance of brain temperature control by the developed system was examined using a mannequin [8] in substitution for a patient because of ethical concerns in clinical investigation. This mannequin consists of hydrous gel and has same specific heat as an adult. And, it represents the metabolic rate distribution similar to a patient by using electrical heaters. Moreover, the mannequin has tubes and sheets in its each part, and represents the blood flow distribution similar to a patient due to the water circulation produced by a pump outside of mannequin's body. Thus, this mannequin sufficiently simulates response characteristics of brain temperature to body surface temperature. In this examination, the head temperature of the mannequin was regarded as brain temperature and was measured by platinum resistance temperature detectors.

Figure 5 shows the time course of the automatic control of mannequin's head temperature in the case that K, τ, h_1, h_2, g, KP, CK and Δt were set to 0.90, 12600s, 10, 10, 0.80, 6.0, 3.0 and 30s. In this examination for 30 hours, following operations were additionally carried out during the hypothermic period in order to verify the control performance in the presence of control disturbances and characteristic changes of patients.

1. Stopping the pump of the mannequin for 10 minutes.
2. 20% increase in heating of the mannequin except its head for 5 minutes.
3. Maintaining the preset room temperature of air conditioner at 22°C for 20 minutes, after its decrease from 27°C.
4. 20% increase in heating of mannequin's head for 3 minutes.
5. Maintaining the state that the upper cooling blanket was removed for 10 minutes.

The flow rate of the air blowing into the cooling blankets was up to 200*l*/min, and the flow velocity of air around the mannequin was 0.45m/s on average during the whole period of this examination.

In the case with the exception of the effect caused by above additional operations, the error of the head temperature control ranges from -0.14°C to 0.27°C, and its root-mean-square was 0.12°C. This error is sufficiently-small for clinical application and probably gets lower by the refinement of the air temperature adjustment.

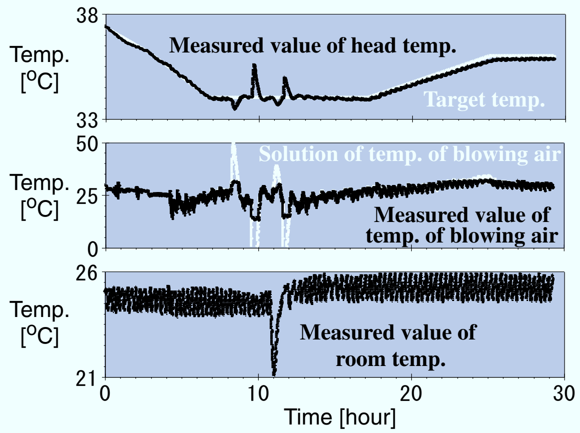

Fig.5 The results of the performance examination of controlling mannequin's head temperature. In the upper illustration, the white line and the black one represent the target temperature and the mannequin's head temperature. In the middle, the white and black represent the solution and the measured value of the temperature of the blowing air. In the bottom, the line represents the room temperature.

The deviation from the target temperature was observed during the period after re-warming, and its average was -0.17°C. In the case with the exception of the data during this period, the range of the control error decreased in -0.14°C to 0.18°C, and its root-mean-square also decreased in 0.073°C. This result suggests lack of the productive capacity of the warm air.

The responses to the foregoing operations during the hypothermic period are listed below.

Responses to the operation 1: The head temperature of the mannequin went down by 0.50°C, followed by its recovery to the target temperature in 45 minutes. The temperature of the blowing air formed a peak of 6.15°C in 20 minutes.

Responses to the operation 2: The head temperature converged within ±0.05°C around the target temperature in 55 minutes, after its increase and decrease. The temperature of the blowing air went down by 7.83°C in 10 minutes and, after that, returned to 13.8°C in 45 minutes.

Responses to the operation 3: The room temperature went down by 3.65°C in 20 minutes, followed by its return to the prior level in 20 minutes after that. The temperature of the blowing air formed a peak of 7.74°C in 35 minutes, and the head temperature recovered to the target temperature in 35 minutes after its decrease of 0.30°C.

Responses to the operation 4: The head temperature went up by 0.70°C in 5 minutes and, after that, converged within ±0.05°C around the target temperature in 35 minutes. The temperature of the blowing air went down by 4.69°C in 20 minutes and went up by 8.22°C in 20 minutes after that.

Responses to the operation 5: The head temperature did not change significantly, however the air temperature formed a bottom of 2.51°C in 10 minutes.

These responses indicate that the developed system runs sensibly in the presence of control disturbances and changes of patient's characteristics, because the additional operations in this examination are superabundant so as to be impossible to occur in practice.

IV. Conclusion

A new automatic control system of brain temperature by air-surface cooling was developed in consideration of clinical use. And, its sufficient performance was verified by the examination using the mannequin in substitution for an adult patient. The developed system serves as a model for a clinically applied system, because of its sufficient performance and suitable mechanism for clinical use. Currently, the commercial realization of the proposed system is in process in collaboration with a medical equipment manufacture in order to improve the chain of survival by facilitation of therapeutic hypothermia. For this, it is required to investigate the suitable flow velocity of the air around patients and the transpiration rate from the body surface during air-surface cooling.

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