Automatic Control of Physiological Function for Medical Treatment

Control of Brain Temperature

Biophysical System Engineering
Graduate School of Allied Health Sciences
Tokyo Medical and Dental University

Prof. Dr. H. Wakamatsu
Patient Confronting Death

Emergency, in and after Operation

(Unconsciousness Comatose State)

Brain contusion

Ischemia disorder

Serious respiratory illness

Control of

Intracranial Pressure, Respiration, Circulation, Anesthesia, Body temperature
Automatic control of patient’s state

Emergency lifesaving

Automatic control of medical equipment
  Respiratory-circulatory assist,
  oxygen inhalation, cough remedy

Intracranical: Osmotic pressure
  Intracranical osmotic control

$CO_2$, $O_2$-concentration: Respiration
  Control of respiratory system

Brain hypothermia: Body temperature
  Control of circulatory system

Anesthesia: Physiological state
  Control by respiratory-circulatory system
Control of Intracranial Osmotic Pressure

by administration of mannitol

(Biokinetic and chemical process)

Related to “Brain Temperature”
Schematic Representation of Brain

Extracellular fluid of body (except brain) $C_{ecf}$

Mannitol administration (input)

Mannitol excretion

Venous sinus

Blood flow to brain

Blood flow out of brain

CSF

Gray matter

White matter

Capillary $C_{cap}$

Capillary $C_{wm}$

Capillary $C_{gm}$

Capillary $C_{isf}$

Capillary $F_{cap}$

Capillary $F_{wm}$

Capillary $F_{gm}$

Capillary $F_{isf}$

Capillary $F_{meta}$

Capillary $F_{sec}$

Extracellular fluid of body (except brain) $C_{ecf}$

Mannitol excretion

Mannitol administration (input)
Intracranial Osmotic Pressure by Different Control Methods

Decrease of ICP by Less Amount of Mannitol in a Optimal Control Process

Administration of Mannitol
By PI-Control
Optimal Control
& Intermittent Control
Control of Anesthesia & Respiration

Respirator

Computer
(Adaptive control)

Cylinder / valve

Control

Arterial blood $S_{O2}$, $P_{CO2}$

Desirable $P_{O2}$, $P_{CO2}$ and anesthetic concentration in Alveolus

Input

order

Measurement

Ventilation, control of gas mixing rate
Respiratory Automatic Control System

Noninvasive Method
Control of Alveolar CO2
Improvement of hypoxia
Adaptive Control/ Fuzzy Control
Mechanical respirator
Adaptive Pole placement system

Mathematical Model

Ventilation Rate $u(k)$

Desired Value $u_r(k)$

Adaptation Mechanism

Determination

Respirator

Respiratory Regulation System

Timing Signal

$y(k)$

Alveolar $CO_2$-concentration

$K(k)$

$R^{-1}(k, z^{-1})$

$S(k, z^{-1})$
Controlled respiration

Examp. 1

Examp. 2

Sampling period 30sec (constant)
ventilatory frequency 14/min
Fuzzy control system with respect to difference of individuals

Decision mechanism of individual coefficient \( p \)

Disturbance (Metabolic rate \( m \))

Data of physical constitution

Desired value

Controlled deviation

Ventilation

Alveolar CO2 concentration

Controlled deviation

\[ u + \Delta u \]
Fuzzy control with different constitutional coefficients

(a) $p=0.5$

(b) $p=1.0$

(c) $p=1.25$

(d) $p=1.5$
Administration system of depth of anesthesia

in expectation of existence of biochemical material as an indicator of depth of anesthesia

Control of depth of anesthesia by respiration and circulation

Controlled system: plural subsystems

ventilation, gas exchange, circulation, nervous system
Comprehensive Monitoring System of Physiological State

Final Decision and Treatment

Indication by Simple Expression

Alarm

Inference, Decision, Description

Sum up Data

Physiological State

Blood Pressure • ECG • Blood Gas

Body, Rectal Temperature

Oxygen saturation

Blood transfusion

Medicament

Intravenous anesthesia

Urinary analysis

Artificial Respiration

Expiratory gas Analysis

Inspiratory anesthesia

Infusion

Anesthesiologist

Comprehensive Monitoring System of Physiological State
Automatic control system for brain temperature

Control by body surface cooling
- Noninvasive measurement and control
- Whole body, cervix and head cooling

Adaptive control/ Fuzzy control
Hypothermia Protection of Brain Tissue

Treatment in the acute stage of irreversible brain damage
Cooling brain for the protection of its secondary damage

Surface cooling method
Wash out metabolic heat of brain by cooled blood flow supplied from the circulation

Dilemma by surface cooling
Constitutional effects caused by biochemical environment
Seriously physiological invasion

Water
Blanket
Patient
Measurement of Temperature in Hypothermia

Brain Tissue Temperature

Alternative Temperature

Tympanic, Nasopharyngeal, Esophageal, Rectal etc.
Automatic Control of Brain Temperature

Physiological state

Manual regulation

Medical staffs

Patient & cooling apparatus

Blanket (Air box)

Temperature of water-blanket (Circulating Air)

Actuator

Signal for regulation

Automatic Control

Characteristic system & Desired brain temperature

Brain temperature
Damage of brain cell caused by energy insufficiency

Symptom
Head injury
Cerebrovascular disorder
Neonatal asphyxia
Insufficiency of heart & lung

Cerebral Ischemia & Energy Insufficiency

Brain cell damage
Precocious nerve cell damage
Delayed nerve cell damage
Damage of brain cells caused by hypersecretion of neurohormone

Hypothalamus-Pituitary-Adrenal System Hyperfunction

Excessive secretion of catecholamines

Cardiac hypofunction due to disorder of heart muscle in diastolic phase
Insulin resistance hyperglycemia due to glycogenolysis
Decrement of erythrocyte DPG → disorder of O₂ – dissociation from Hb

Recovery obstruction of trauma brain cell
Protection of brain cells by brain hypothermia

Suppression of Damage caused by Energy insufficiency

- Improvement homeostasis of Ca$^{2+}$
- Suppression of oxidation by free radicals
- Activation of antiapoptosis substance
- Suppression of dopamine A10 neural groups

Suppression of Hyperfunction of Endocrine system

- Suppression of hypersecretion of catecholamines
Damage of brain cells caused by hypothermia less than 32 °C

Energy metabolic insufficiency
imperfect circulation

- Shortage of ATP for brain cell recovery
- Decrement of brain blood flow amount

Deprivation of Recovering damaged brain cells
Necessity of precise and accurate control of brain temperature!

Trade off in Hypothermia

Protection of brain Tissue

Biological reaction

Demerit in hypothermia
Mild Hypothermia

Cooling | Stable | Warming | Hypothermia

37.0°C | 35.0°C | 32.0°C

Adaptive zone

Dangerous zone

ca 36.0°C

h: hour
d: day
w: week

2~3h | 2~6d | 4~6d | 3~6w
Concept of Adaptive Control Engineering

Different regulation
Various kinds of medical treatment
Change in external environment

Change in internal environment
- Circulatory change
- Metabolic change etc.

Unknown thermal characteristics

Patient under the brain hypothermia treatment

Blood circulatory change
Tympanic temperature
Cooling blanket

Adaptive control
Realization of desired brain temperature
Overview of Experimental Equipment for infantile brain hypothermia
Outlook of cooling system for infantile brain hypothermia
Automatic control system of brain temperature

- Patient & water cooling blanket
- Storage tank
- Heating
- Control of Heating
- Cold water making system
- Cooling
- Characteristic Identification
- Brain temperature
- Water temperature
- Computer
- Adaptive control
- Fuzzy control
- Opening & shutting of valve
- Time course of brain temperature
Influential Factors on Brain Temperature Control

Environmental change
- Room temperature, Direct sunshine, and Covering of Blanket

Patient’s state change
- Blood amount in circulation
- Metabolic rate (esp. in brain)

Control of brain temperature

affection

affection
(1) Optimal Adaptive Control

Temperature of water-blanket (Cooling Air) → Patient & Cooling

Adaptive control

Characteristic system

Optimal regulator

Theoretical optimal solution

Brain temperature of characteristic system

Brain temperature

Reference brain temperature

\( T_{brain} \)

\( e \)

\( R \)
Tracking of brain temperature for desired brain temperature schedule
In the case of increase of metabolic rate in the head
Opening the door

Decrease in room temperature

Brain temperature

Body temperature

Water temperature of blanket
In the case of partly uncovering blanket

Brain temperature change within ±0.15

Deviation

Water temperature falling down
In the case increment of metabolic rate in the whole body

- Brain temperature change within $\pm 0.15^\circ$C
- Switch-ON of heaters in whole body
- Water temperature falling down
(2) Introduction of Fuzzy method

Optimal-adaptive control not always match with commonly understood knowledge of medical staffs

Control system based on clinical experience

- Human friendly control of brain temperature

Its realization? Fuzzy Control
Fuzzy Control System of Brain Temperature

Rational Control According to Common Characteristics of Patients

Fuzzy Controller-1

Water Temperature to Model

Characteristic Model

Patient

Fuzzy Controller-2

Desired Value

Suitable Control to Environment, State & Individual Difference

Rational change in Bain Temperature

Patient Bain Temperature

Actual water temperature

Compensating water temperature
Membership Functions and Fuzzy Rule

For fuzzy controller-1

<table>
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<th>$\Delta u(k)$</th>
<th>$e(k)$</th>
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<tr>
<td>PB</td>
<td>ZO</td>
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<tr>
<td>ZO</td>
<td>PS</td>
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<tr>
<td>NB</td>
<td>ZO</td>
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The antecedent

The consequent

The antecedent

$e(k)$

$\Delta e(k)$

$\Delta u(k)$
## Membership Functions and Fuzzy Rule

For fuzzy controller-2

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<tr>
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<td>PM</td>
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</table>

The antecedent

The consequent

![Graph showing membership functions and fuzzy rule](image)
Experimental Result during Cooling and Stable Period

- Suspension of blood (water) flow in 2 Minutes
- Warm up the head by heating in 30 Second

- Desired Brain Temperature
- Water Temp. to Characteristic Model
- Brain Temp. of Characteristic Model
- Objective Water Temp. to Mannequin
- Brain Temp. of Mannequin
- Actual Water Temp.
Experimental result

Environmental change
Change of metabolism in brain (2)

Heater in the brain switches on in 30sec
Clinical Control System of Brain Temperature

Adaptive Control & Fuzzy Control
Apparatus for heating and cooling of water
Reservoir for warm water

Reservoir for warm water
Control System of Brain Temperature
Brain Hypothermia Treatment (image)
Experimental brain hypothermia 5-channel water cooling suits (image)
Control of Brain Temperature by Air-Cooling System
Air-cooling Incubating System

- Transparent air-cooling box
- Fan
- Mannequin
- Radiator
- Peltier module
- Control mechanism
- Electric power supply
- A/D
- D/A
- Air temperature
- Brain temperature
- Air speed
Prospective
Administration system of whole physiological state
Parallel measuring system of physiological data
Control system of depth of anesthesia
Comprehensive Control System

Manual control of whole body

Overall View of Physical Constitution
  Monitoring • Decision • Action
  Treatment with Experience & Intuition

Supplementary Administrative System for monitoring constitutional physiology
  Routine work treatment
  Treatment based on calculation of systematic description

Information
  Execution

Communication

Examination
  Order

Automatic Control
  Integrated Monitoring
Comprehensive Monitoring of Physiological State

- **Respiratory Control**
  - Artificial Respiration
  - Respiratory Sound
  - Expired gas analysis

- **EEG**
- **Intracranial Pressure**
- **Decision of Warming Time**

- **Control of Anesthesia**
- **Control of Metabolism**

- **Control of Circulation**

- **Infusion, Fluid Replacement**
- **Intravenous Anesthesia**

- **Urine**

- **Temperature Control**
  - Body Temperature (Brain T., Tympanic Membrane T., Internal Juglar vein blood T., Peripheral cutaneous T.)

- **Blood Pressure**
- **Blood gas analysis**

- **Control of Metabolism**
Evaluation and Alarming System

Various Physiological Data Monitored from Patients

Fuzzy Logic

Estimation of Physiological State

Display & Alarm if necessary
Acquisition system of various kinds of physiological data
Various physiological data acquisition and information processing
Cooperative teams for clinical test

Tokyo Medical and Dental University
Integrated pulmonology, Neurosurgery, Anesthesiology, Critical care medicine

National Hospital Tokyo Disaster Medical Center
Critical care center, Neurosurgery