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〈原著〉

Human friendly control system of alveolar CO_2-concentration based on adaptive control theory

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Abstract The purpose of the present study is to construct a basic experimental system for automatic control of alveolar CO_2-concentration during controlled and assisted respiration. This system consists of a newly developed computer-controlled respirator and its controlling devices. In the present study, ventilation rate and alveolar CO_2-concentration are regarded as the input and output of the controlled object, respectively. The automatic control system of alveolar CO_2-concentration is designed using an adaptive pole-placement method. The proposed system is applied to clinically basic control experiments of alveolar CO_2-concentration both in controlled and assisted respiration. Furthermore, physiological experiments are made on healthy subjects during light exercise in order to ascertain the robustness of the system. Thus, the proposed system is confirmed to be useful for the control of alveolar CO_2-concentration taking into account characteristic differences of the respiratory regulation system due to chronic change and individuality.

Key Word : artificial respiration, respiratory regulation system, adaptive control, alveolar CO_2-concentration

Ⅰ. Introduction

A regulation system of an organic function is structured by some mutually related subsystems which have non-linear and time-varying characteristics dependent on its individuality. They function with appropriate controllers in order to maintain their homeostasis. Hence, it is not easy to control an organic function by some action from its external environment.

A respiratory regulation system with relatively well known characteristics is thought possible to control non-invasively in a real time by the appropriate choice of input and output owing to its anatomical structure. Various methods [1-2] have been proposed, including a trial by Frumin et al. to maintain a constant level of alveolar CO_2-concentration [3].

Wakamatsu et al. have developed computer controlled programmable respirators suitable for the various artificial control of respiration [4-8]. The control of artificial respiration using the programmable respirator based on the adaptive control method has been successful with healthy subjects at rest where their alveolar CO_2-concentration were accurately controlled.

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In the present study, the control system based on the adaptive pole-placement method is applied to the clinically basic control experiments of alveolar CO_2-concentration both in controlled and assisted respiration stages. That is, the physiological experiment is performed on healthy subjects during light exercise in order to ascertain its robustness. It is thus confirmed that the proposing system is generally useful for the control of alveolar CO_2-concentration even taking into account the non-linear and time-varying characteristics of a individual respiratory regulation system.

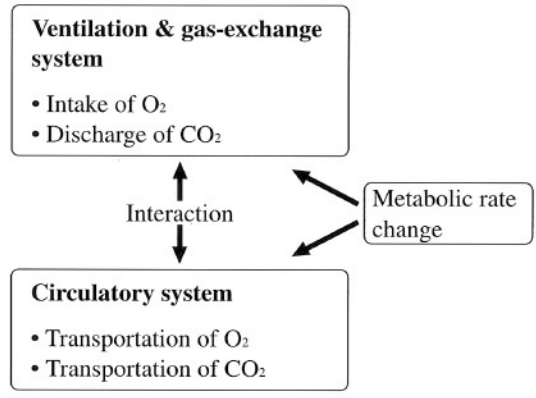

Fig.1 Respiratory regulation system

Ⅱ. Instrumentation and method

1. Respiratory regulation system

The regulatory mechanism of respiration is still not sufficiently understood. An attempt had been made to describe it using a mathematical model by Grodins et al.[9]. Then various kinds of models concerning respiratory rhythm and blood flow have been proposed [10]. Nevertheless, satisfactory models of respiratory regulation system have never been proposed representing its non-linearity, chronic change and differences of individuals which are remarkable in organisms.

The respiratory regulation system is widely regarded as the one composed of two subsystems; a ventilation and gas-exchange system, and a circulatory system as illustrated in Figure1.

In this study, only the essential functions concerning above subsystems including a circulatory system are described in the figure.

In the ventilation and gas-exchange system, ventilation amount ("controlling input") is determined by the respiratory center ("controller") monitoring the partial pressures of CO_2 and O_2 ($PaCO_2$ and PaO_2, respectively) in arterial blood ("controlled value") in order to maintain their proper levels ("desired values"). Ventilation and gas-exchange are performed by the activation of a diaphragm and intercostal muscles ("actuators"). $PaCO_2$ and PaO_2 are detected by central and peripheral chemosensitive areas. Then, the proper stimuli are transmitted to the respiratory center during this process, if their pressures are not appropriate.

The non-linear and time-varying characteristics depending on individualities in a respiratory regulation system can be found, for instance, in the transportation of O_2 and CO_2 according to their dissociation curves which are modified by physiological state depending on pH, $PaCO_2$, body temperature and 2, 3-DPG. In addition, the transportation of the gases is affected by blood flow depending on metabolic rate change. Hence, it is not easy to seize the accurate dynamic characteristics of such a respiratory regulation system with much variable characteristics.

2. Control of respiratory regulation system based on adaptive control theory

The purpose of respiration is an intake of O_2 for oxidation in the body and a discharge of side-products of CO_2, which are closely related to the level of hydrogen ion concentration. It is, therefore, appropriate to design the control system of artificial respiration with $PaCO_2$ i.e. alveolar CO_2-concentration as a physiological indicator for its significant control.

In order to synthesize a control system, some description of a controlled object is necessary. However, it is not easy to represent a respiratory regulation system by mathematical models because of its non-linear characteristics as well as individual differences and chronic change as mentioned previously. Thus, it is not too much to say in present situation that by an artificial respiration the gas-exchange and circulatory systems cannot be controlled but only insufficiency of ventilation can be compensated.

By the way, an adaptive control method is effective in the case of controlled objects whose characteristic change cannot be well recognized. Actually, this method has ever been adopted to the control of alveolar CO_2-concentration [4-8].

In the present study, a deviation from an equilibrium point of alveolar CO_2-concentration is regarded as the output $y(k)$ of the controlled object. And a deviation from ventilation rate giving the equilibrium point is regarded as its input $u(k)$. The following linear auto-regressive moving average (ARMA) model is used as a mathematical model of the controlled object.

$$A(z^{-1})\, y(k) = B(z^{-1})\, u(k) \tag{1}$$

where

$$A(z^{-1}) = 1+\sum_{i=1}^{n_a} a_i z^{-i},\ B(z^{-1}) = \sum_{j=d}^{n_b} b_j z^{-j}$$

Here, parameters a and b are interpreted as the respective influence of past input and/or output series with their finite memories on the present output value.

A mathematical model is given by

$$\begin{aligned} y_M(k) &= -\sum_{i=1}^{n_a} \hat{a}_i(k)\, y(k-i) + \sum_{j=d}^{n_b} \hat{b}_j u(k-j) \\ &= \hat{\theta}^T(k)\, \zeta(k) \end{aligned} \tag{2}$$

where

$$\hat{\theta}^T(k) = [\hat{a}_1(k), \cdots, \hat{a}_{n_a}(k), \hat{b}_d(k), \cdots, \hat{b}_{n_b}(k)]$$

$$\zeta^T(k) = [y(k-1), \cdots, y(k-n_a), u(k-d), \cdots, u(k-n_b)]$$

The adaptive law is given by

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \Gamma(k-1)\zeta(k)\varepsilon(k) \tag{3}$$

$$\varepsilon(k) = \frac{y(k) - \hat{\theta}^T(k-1)\zeta(k)}{1 + \zeta^T(k)\Gamma(k-1)\zeta(k)} \tag{4}$$

$$\Gamma(k) = (1/\lambda(k))\Gamma'(k) \tag{5}$$

$$\Gamma'(k) = \Gamma'(k-1) + \frac{\Gamma(k-1)\zeta(k)\zeta^T(k)\Gamma(k-1)}{1 + \zeta^T(k)\Gamma(k-1)\zeta(k)} \tag{6}$$

$$\lambda(k) = tr\Gamma'(k)/tr\Gamma'(0),\ tr\Gamma(0) > 0 \tag{7}$$

Here, $\Gamma(k)$ is a gain matrix to lead the estimated parameters converge to their true values.

The mathematical model is innovated by the adaptive law, monitoring the ventilation rate and alveolar CO_2-concentration. Thus, the non-linearity of the respiratory regulation system and its characteristic changes are regarded as deviations of the parameters of the mathematical model [11, 12].

The adaptive pole-placement method allows the poles of the whole control system assigned to the required values in advance.

The pole of whole control system seen from reference input $u_r(k)$ to output $y(k)$ is given by the following equation:

$$C(z^{-1})\, y(k) = KB(z^{-1})u_r(k) \tag{8}$$

Here, $C(z^{-1})$ is a polynomial that provides desirable poles and K is a gain to make a controlled deviation zero.

The controlling input is determined by

$$R(z^{-1})\, u(k) = Ku_r(k) - S(z^{-1})\, y(k) \tag{9}$$

where

$$R(z^{-1}) = 1 + \sum_{i=1}^{n_r} r_i z^{-i},\ S(z^{-1}) = \sum_{j=0}^{n_s} s_j z^{-j}$$

Polynomials $R(z^{-1})$ and $S(z^{-1})$ are determined so that they may satisfy

$$C(z^{-1}) = A(z^{-1})\, R(z^{-1}) + B(z^{-1})\, S(z^{-1}) \tag{10}$$

Hence, the proposed system ensures a stable control of alveolar CO_2-concentration coping with the differences of individuals and chronic change of the respiratory regulation system. The block diagram of the whole control system is shown in Figure 2.

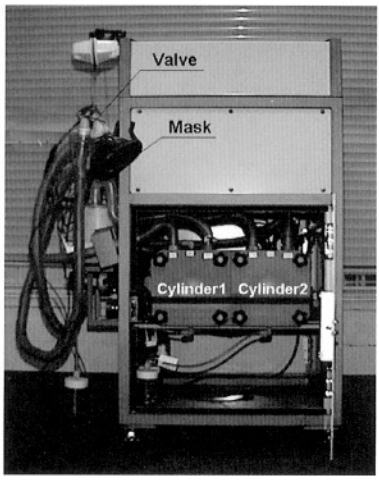

Fig.3 External view of the respirator

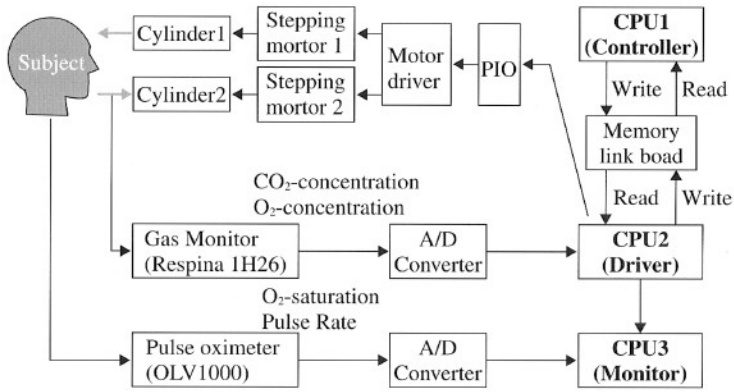

Fig.4 Outline of the experimental system

the control system of the present physiological experiments.

The hardware control system is supported by three computers (BP386SX, WACOM) for controlling alveolar CO_2-concentration, driving pistons, detecting fault and processing experimental data. The intermixture of inspiratory and expiratory air is avoided by a valve mounted on an air mask which moves with synchronization of respiration so that alveolar CO_2-concentration can be measured accurately. The whole control system of alveolar CO_2-concentration including the respirator and the measuring instruments are illustrated in Figure 4.

Respina 1H26 (NEC SAN-EI) is used as an expired gas analyzer and Pulse-oximeter OLV-1000 (NIHON KODEN) as measuring instrument of O_2-saturation of peripheral arterial blood.

Ⅲ. Experiments and results

The control of alveolar CO_2-concentration was performed on 9 healthy subjects (7 male and 2 female, age 27-38 years) using the control system of the respiration.

The proposed system was first supplied for the physiological experiment using healthy subjects at rest in 30 [min], where the frequency of the ventilation was chosen 16 [times/min] and the sampling interval 30 [sec]. Secondly, in order to ascertain its robustness, alveolar CO_2-concentration of a subject during light exercise using an ergometer was controlled in 10 [min], where the frequency of the ventilation was chosen 22 [times/min]. The subjects were instructed to breathe with not own respiratory rhythm but the rhythm of the respirator. Thirdly, as the basic experiment for the control of alveolar CO_2-concentration in an assisted respiration, the frequency of ventilation was changed at random from 14 to 18 [times/min]. Hereby, experimental data were acquired at every 7 ventilatory period with the sampling intervals varied from 23.3 to 30.0 [sec]. The desired value of alveolar CO_2-concentration was given in all cases by a step-like function with decrement by 1.0 [Vol%] at 10 [min] after the start of the control experiments.

Figure 5 shows two experimental results taken out as examples from the ones on subjects at rest in a controlled respiration. These show that alveolar CO_2-concentration was satisfactorily controlled to follow up the given desired value.

Figure 6 shows two experimental results taking into account the metabolic rate change caused by the light exercise using an ergometer where subjects pedaled in 40 [rpm] with 30 and 50[W]. It shows

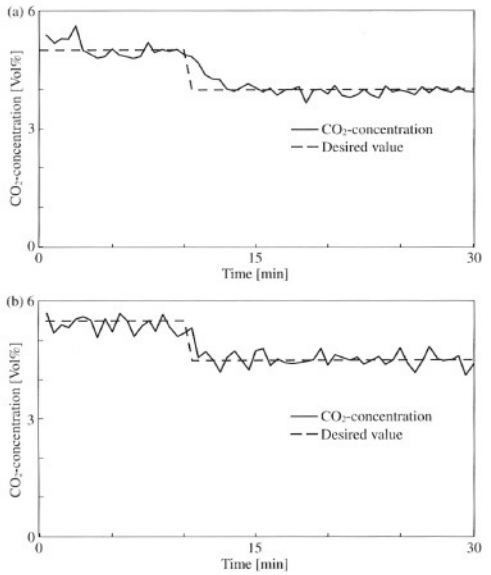

Fig.5 Experimental result in controlled respiration

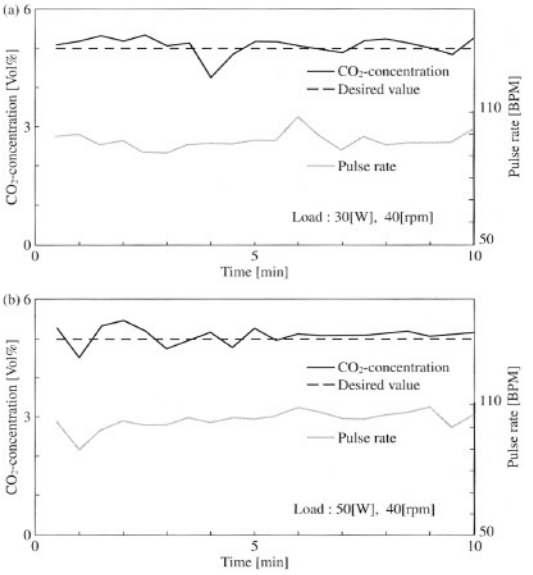

Fig.6 Experimental result taking into account irregular metabolic rate change

that alveolar CO_2-concentration can be controlled irrespective of metabolic rate change.

Figure 7 shows two experimental results in an assisted respiration under the previously mentioned sampling intervals. These show that proposed system can control alveolar CO_2-concentration even in an assisted respiration.

Controlled deviations were relatively large only in a few steps from the beginning of the control or on the change in a desired value. They became smaller in accordance with proper adaptation of the control system which yielded a considerable accurate control of alveolar CO_2-concentration as illustrated in Figures 5, 6 and 7.

The evaluation is given by the average of the following normalized error concerning 9 subjects:

$$\frac{u_r(k) - y(k)}{u_r(k)} \times 100\ [\%] \qquad (11)$$

The averages of normalized error are -0.871 [%] in the controlled respiration, -1.688 [%] with metabolic rate changes and 0.275 [%] in the assisted respiration, respectively.

Ⅳ. Conclusions

A computer-based control system of the artificial respiration by the adaptive pole-placement method was proposed. It was experimentally confirmed to follow up a desired value satisfactorily irrespective of metabolic rate change and difference of individual subjects.

The proposed system is applicable to patients whose respiratory dynamic characteristics cannot be completely seized because of their individual differences and chronic changes etc., being automatically adapted to their environmental characteristic change. This is the reason why such a proposing "adaptive control system" is useful.

However, a desired value of alveolar CO_2-concentration still has to be set within a physiologically appropriate range depending on the state of patients, for which a proper method such an artificial intelligence is clinically required. It is remarked that conventional respirators can be substituted in the control system, although only 2-cylindrical respirator has been taken into account in the present experiments.

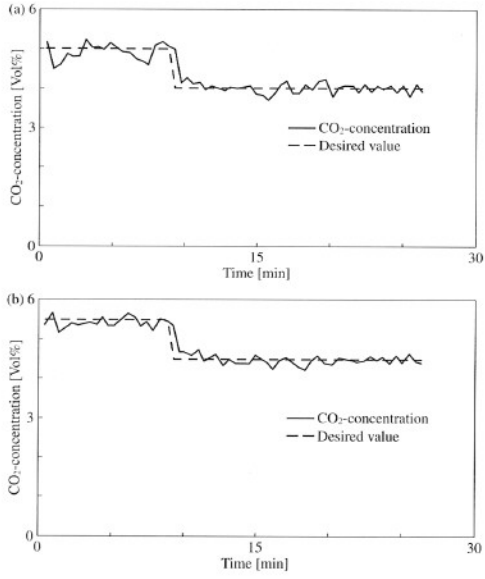

Fig.7 Experimental result in assisted respiration

The present control system of artificial respiration in principle will become available not only clinically but also even at home e.g. to muscular dystrophy patients who need an assisted respiration by a smaller respiratory equipment without any requirement of peculiar medical knowledge. Therefore, the further study is necessary from the methodological viewpoint to make the system smaller with simplified operation for its easier application.

In addition, as the present method ensures the objective description of the change in individual characteristics, it is applicable to various kinds of medical fields. Thus, this method will be directly applied to the control of the depth of anesthesia in the progressive process of the present study concerning the control of respiratory gas concentration, provided that appropriate indicators of the depth of anesthesia are clarified.

References

1) G H Holloman, H T Milhorn, T G Coleman: A sampled-data regulator for maintaining a constant alveolar CO_2 . J Appl Physiol 1968 ; 25 : 463-468.

2) M H Giard, F O Bertrand, D Robert, J Pernier: An algorithm for automatic control of O_2 and CO_2 in artificial ventilation. IEEE Trans Biomed Eng 1985 ; 32 : 658-667.

3) M J Frumin, N A Berman, D A Holaday: Carbon dioxide and oxygen blood levels with a carbon dioxide controlled artificial respirator. Anesthesiology 1959 ; 20 : 313-320.

4) H Wakamatsu: Nonlinear adaptive control of human respiration using newly developed respirator with variable respiratory rhythm. Proc IFAC 11th World Congr, Biomed Control 1990 ; 1 : 1-6.

5) H Wakamatsu: Comparison of control performances in artificial respiration by different adaptive methods using programmable respirator. Proc IFAC 12th World Congr, Biomed Control 1993 ; 201-206.

6) K Takahara, H Wakamatsu: Control of artificial respiration by adaptive pole-placement method. Trans. IEICE (D-Ⅱ), J76-D-Ⅱ 1993 ; 9 : 2126-2132.

7) K Takahara, H Wakamatsu, I Miyazato, A Ishida: Automatic control of alveolar CO_2-concentration using programmable respirator. Jap J Med Electron Biol Eng 1994 ; 32 : 173-179.

8) K Takahara: Automatic control system of alveolar CO_2-concentration coping with individuality and chronic change of respiratory regulation system. Jap J Appl Physiol 1997 ; 27 : 9-16.

9) F S Grodins, J S Gray, K R Schroeder, A L Norins, R W Jones: Respiratory responses to CO_2 inhalation, A theoretical study of nonlinear biological regulator. J Appl Physiol 1954 ; 7 : 260-276.

10) W F Finch, F T Tehrani: A mathematical model of the human respiratory system. J Biomed Eng 1983 ; 5 : 125-133.

11) H Wakamatsu, T Kitamori: Design of respiratory control system using Volterra series on basis of partial model matching technique. Trans. Soc. Instrum. & Control. Eng. 1985 ; 21 : 1231-1238.

12) H Wakamatsu: Control of respiratory system using Volterra series. Biomed. Meas. Inform. Control 1988 ; 2 : 25-35.