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Systemic Arterial Blood pH Servocontrol of Mechanical Ventilation

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Servocontrol of mechanical ventilation using systemic arterial blood *p*H, measured by a dual-function *p*H/P_{CO_2} intra-arterial sensor, as the controlled variable was carried out in 30 dogs anesthetized with pentobarbital, 30 mg/kg. The control loop consisted of the animal, an intra-arterial dual-function *p*H/P_{CO_2} sensor and sensor amplifier, a controller, and a Siemans-Elema 900 servoventilator. The system responded appropriately to changes in set-point *p*H from 7.30 to 7.50, as well as to infusions of lactic acid, which, with the control loop open, decreased systemic arterial blood *p*H 0.1 to 0.2 *p*H units. Long-term (16 hr) ventilation of one dog with the systemic arterial blood *p*H servocontrol ventilator was shown to be feasible. (Key words: Acid–base equilibrium, *p*H; Ventilation, mechanical, controlled.)

In 1957, Frumin[1] and Frumin and co-authors[2] described a method for ventilating the lungs of patients using end-tidal P_{CO_2} servocontrol of ventilation. A variation of this technique was described by Mitamura *et al.*[3] These investigators used a ventilator that was servocontrolled in response to changes in CO_2 output. More recently, Schulz *et al.*[4] used a single-function intra-arterial P_{CO_2} sensor to control a servoventilator. Recently, a dual-function *p*H/P_{CO_2} intra-arterial sensor (General Electric Co., Milwaukee, Wisconsin) has been described.[5,6] The purpose of this study was to use systemic arterial blood *p*H, as measured by the sensor, to servocontrol a Siemens-Elema servoventilator 900.

Methods

The dual-function *p*H/P_{CO_2} sensor consists of a miniature P_{CO_2} electrode covered with a membrane that, in addition to being permeable to CO_2, is hydrogen ion (H^+)-permselective, containing specific H^+ carriers.[6] When such a membrane is placed between two solutions containing different H^+ ion concentrations, H^+ ion exchange across the two membrane–solution boundaries occurs, similar to that which occurs with H^+-sensitive glass electrodes. Also similar to glass electrodes, the actual inward flux of H^+ is only transient and small in magnitude, since the electrical potential that results from flux of ions across the membrane opposes further ion migration,[7] thus producing a negligible effect on P_{CO_2} measurement. For *p*H measurement an external reference electrode is necessary. The sensor is connected to high-impedance DC amplifiers with digital displays.

For this study, dogs weighing 15–30 kg were anesthetized with sodium pentobarbital, 30 mg/kg, the tracheas were intubated, and the lungs were ventilated with a Siemens-Elema 900 servoventilator. The dual-function *p*H/P_{CO_2} sensor§ was placed percutaneously into a femoral artery through a 16-gauge catheter. A silver–silver chloride General Electric Daisy electrode was used as a reference electrode. After placement, the sensor was calibrated to agree with discrete blood samples drawn from an arterial catheter in the contralateral femoral artery and analyzed on a bench instrument. When the sensor showed drift or low *p*H sensitivity, the sensor was replaced and the calibration procedure repeated. The ventilator was then adjusted to produce a systemic arterial blood *p*H of 7.40 and the control loop was closed. The control loop consisted of the controller, ventilator, animal, sensor, and sensor amplifier (fig. 1). A dial on the controller, calibrated in *p*H units, was used to set the desired *p*H value. The difference between the desired and the actual *p*H values as measured by the sensor system, was the error signal that was the input to the controller. The control unit was equipped with gain elements, a differentiator, an integrator, and a summer.

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§ The General Electric Company sensor used for this study is no longer commercially available. However, a sensor based on the same principles as the G. E. Sensor is presently in production and will soon be commercially available through Biochem International, Inc., 11311 W. Locust St., Wauwatosa, Wisconsin 53222.

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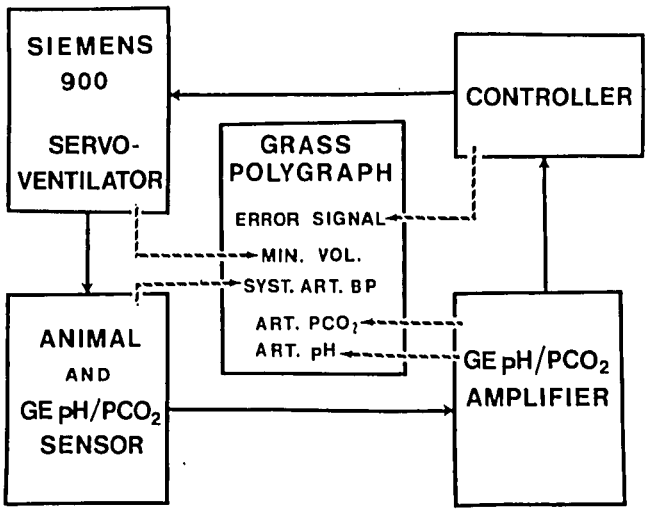

FIG. 1. Block diagram of the control loop and variables measured.

By appropriate adjustment of the gain elements any linear combination of proportional, differential, and integral control could be tested. With proportional control the error signal is multiplied by the gain of the controller. However, with proportional control some residual error signal must exist to maintain an output control voltage to the ventilator. When differential control is used the deviations of the error signal with respect to time are multiplied by the gain of the controller. Differential control is used to produce a predictive control system that anticipates and corrects for future error signal deviations. With integral control the integral of the error signal with respect to time is multiplied by the gain of the controller. Thus, the output of the controller is determined by past misalignments, or with respect to past error signal deviation. The use of integral control in combination with proportional control produces a system in which the residual error is minimized or eliminated altogether. Studies were conducted to determine a control system that produced a rapid, stable response with a minimum of steady-state error. Proportional control gain was studied alone and in combination with differential and integral control. The output signal of the control unit adjusted the tidal volume of the ventilator. The relationship between ventilator output and input control voltage was quasilinear over the ventilation range from 0 to 25 l/min. The slope of the relationship was approximately (−) 4.4 l/min/volt. With a control voltage of zero, the ventilator output could be set by the ventilator minute volume control. The controller then operated about this minute volume value. The frequency of the ventilator was set independently and remained constant. Thus, alterations in minute ventilation drove the arterial blood *p*H value in a direction that minimized its difference from the set-point *p*H.

Systemic arterial blood *p*H and P_{CO_2} values, as measured by the sensor, the error signal, ventilator minute volume, and arterial blood pressure, were recorded on a Grass Model 5 polygraph.

Arterial blood *p*H servocontrol of ventilation has been used on 30 dogs. Twenty animals were used to develop the control system. Perturbations in the system were produced in 19 animals by changing set-point *p*H. In two of these animals lactic acid was infused using a Harvard perfusion pump. Infusion was at a rate (0.6 to 2.2 ml/min of a 1 to 4 dilution of 85 per cent lactic acid, Fisher Scientific, in physiologic saline solution) sufficient to produce a 0.1 to 0.2 *p*H unit reduction in systemic arterial blood *p*H in 3 to 5 min with the control loop open. This dose of lactic acid was repeated with the control loop closed. In one animal, long-term (16 hr) *p*H servocontrol of ventilation was carried out. The control system was then

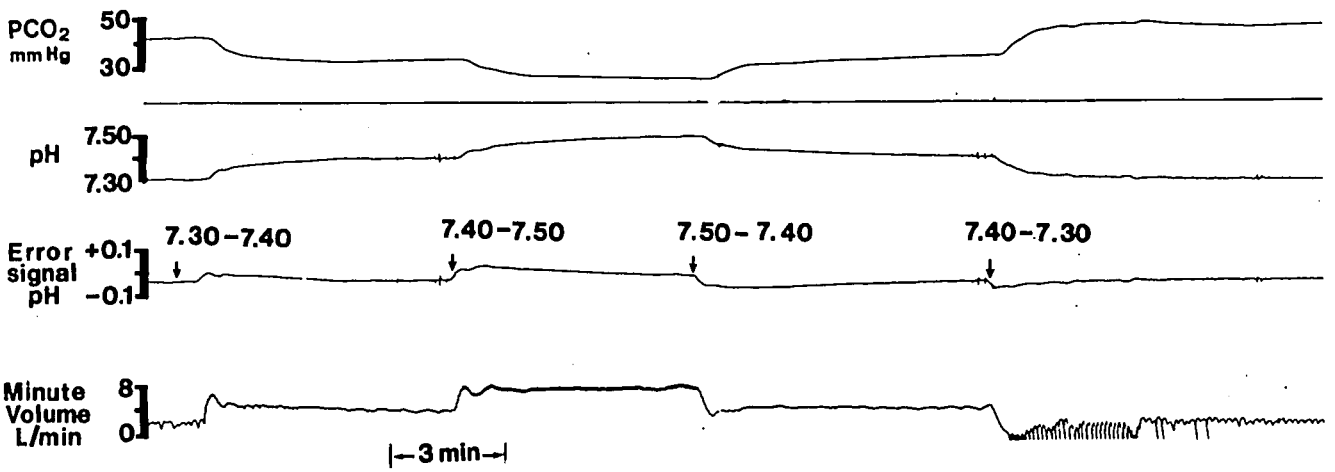

FIG. 2. Response of the system to changes in set-point *p*H. Changes in the set-point of 0.1 *p*H caused a deflection in the error signal, the controller produced the appropriate increase or decrease in minute volume, and as systemic arterial blood *p*H approached the new set-point *p*H the error signal returned toward zero.

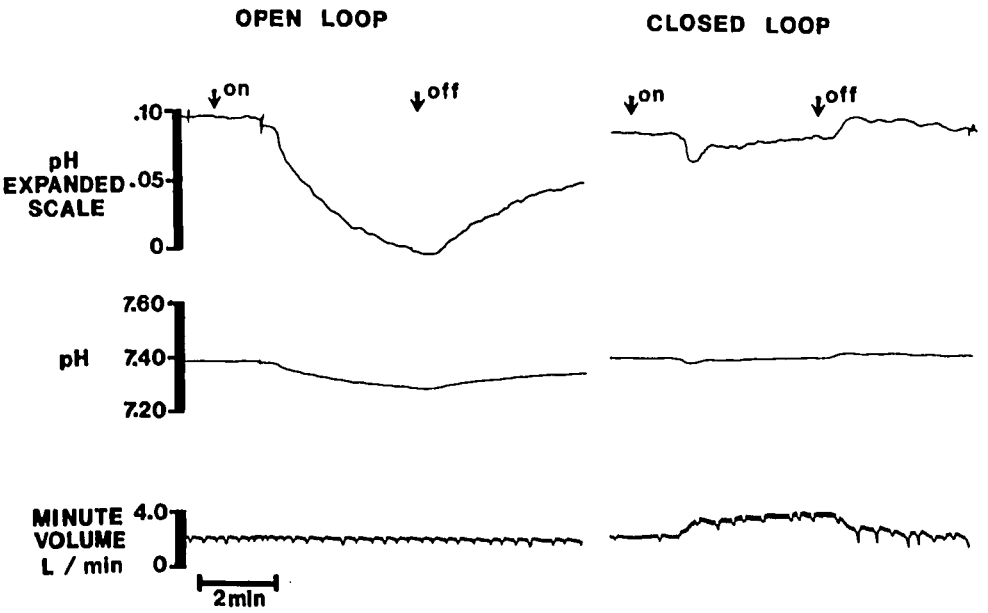

FIG. 3. Comparison of the effect of lactic acid infusion on systemic arterial blood *p*H with the control loop open and the effect of a similar infusion of lactic acid with the control loop closed (lactic acid, 17 per cent, infused at 0.56 ml/min).

used on ten additional animals as part of another study in which precise control of systemic arterial blood *p*H in the presence of changes in ventilatory dead space was essential.

Results

Changes in set-point *p*H produced corresponding changes in minute ventilation (fig. 2). At each step, the error signal (the desired minus the actual *p*H) increased and then decreased as the *p*H approached the new level. At each step, P_{CO_2} also changed appropriately. The minute ventilation showed an initial overshoot and then gradually approached the new level. Of the three types of control studied (proportional, proportional plus differential, and proportional plus integral), proportional plus integral control (proportional gain = 30–50 and integral gain = 0.2–0.6) produced the most stable system with the least residual or steady-state error. The steady-state error in most experiments using this system was consistently less than ± 0.01 *p*H unit. However, in some experiments oscillations in the system still occurred. The combination of proportional plus differential control produced a rapidly responding but unstable system.

When lactic acid was infused during ventilation of the animal with the control loop open, systemic arterial blood *p*H decreased 0.1 to 0.2 *p*H units while minute-ventilation remained constant. After the infusion was stopped, systemic arterial blood *p*H returned toward the preinfusion level (fig. 3). During closed-loop servoventilation, *p*H decreased slightly initially, then ventilation increased to compensate for the

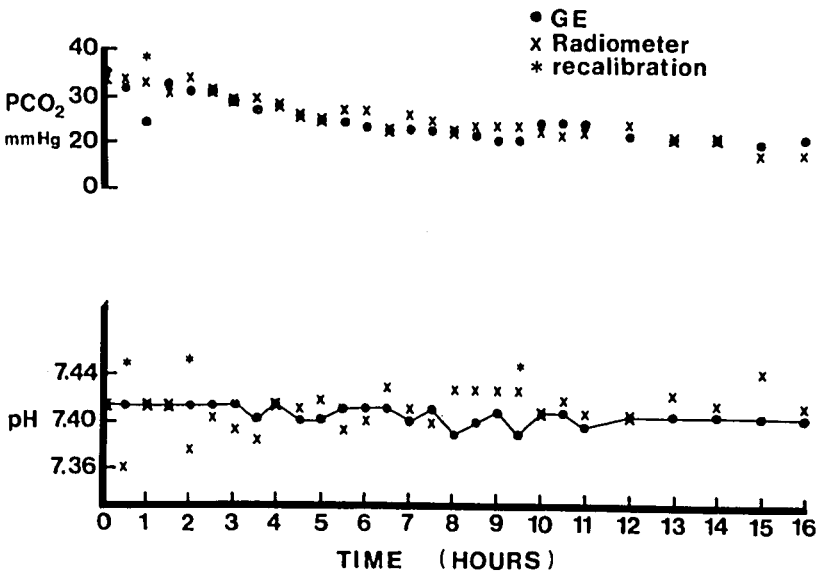

FIG. 4. Comparison of bench instrument and sensor measurements of systemic arterial blood P_{CO_2} and *p*H during long-term systemic arterial blood *p*H servocontrol of mechanical ventilation.

induced metabolic acidosis. After the infusion was stopped, ventilation remained slightly higher than the pre-infusion value and a slight overshoot in arterial blood *p*H occurred.

During ventilation of the lungs of one dog for 16 hr with the *p*H servocontrol ventilator, the sensor was recalibrated only once for P_{CO_2} and three times for *p*H. Except at the first recalibration point for *p*H, the maximum differences between the sensor and the bench instrument were 3 torr for P_{CO_2} and 0.04 *p*H units for *p*H (fig. 4). Although the animal was given sodium biocarbonate, 30 mEq, between one and two hours, metabolic acidosis developed and was present throughout the remainder of the experiment.

Discussion

Of the three types of control studied, proportional plus integral produced the most stable system with the least residual or steady-state error. However, some oscillations in the system still occurred under certain conditions. Stability of this type of system is strongly affected by system gain, time delays, and slow time responses. An increase in any of these values may decrease stability. Loop gain is affected by sensor sensitivity, controller gain, the nonlinear relationship between controller output and tidal volume, and the animal's *p*H response to ventilation, which alters with changes in metabolic state, buffering systems and physiologic dead space. The longest delays in the system are of biological origin. These can be assessed by observing the time course of the *p*H response to a step change in ventilation. To ensure stability under various biological conditions the controller gain must be kept moderate. The resulting steady-state error can be decreased to zero by the use of a small amount of integral control.

The present study demonstrates that systemic arterial blood *p*H servocontrol of mechanical ventilation, using the dual-function sensor, is feasible. This servocontrol system has several advantages. The more rapid response of the arterial blood *p*H sensor compared with the P_{CO_2} sensor allows it to track and monitor rapid fluctuations in *p*H. Instantaneous information of the controlled variable allows the control system to respond more rapidly and with greater stability. Using arterial blood *p*H as the controlled variable also allows for compensation of metabolic acidosis through increased ventilation.

It is premature to suggest the use of the present *p*H servocontrol system in clinical practice. However, after further animal testing this type of servocontrol ventilation may be useful either in long-term patient ventilation or in short-term cases such as neurosurgery where a low but not excessively low systemic arterial blood P_{CO_2} may be desired.[8] The systemic arterial blood *p*H servocontrol of mechanical ventilation may also have two additional uses, which became apparent in the development of this system. First, this could be a unique piece of teaching equipment in respiratory physiology and respiratory therapy for demonstrating the dynamics of changes in blood gases and *p*H that result from changes in ventilation. Second, the transient responses produced by these changes in ventilation and blood-gas and *p*H values may be of value in studying the dynamics of the cardiopulmonary system.

The 900 servoventilator was supplied to us for use in this study by the Siemens Corporation.

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