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A CONTROL SYSTEM FOR OXYGEN THERAPY OF PREMATURE INFANTS

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Abstract- **A control system is proposed for oxygen therapy of premature infants. The control software consists of a stepwise as well as a PID control algorithm to provide fast and efficient response to changes in arterial oxygen saturation of the infant detected by pulse oximetry. The control system is tested by using a simulation model of the infant's respiratory system. The simulation results at different levels of hypoxia are evaluated and the robustness of the controller is assessed.**
Keywords- **Control, Oxygen, Infant, Simulation**

INTRODUCTION

Many infants, who are born prematurely, suffer from respiratory insufficiency and need supplemental oxygen treatment. This kind of therapy should provide sufficient oxygen to the infant in the incubator or under the hood, to prevent the damaging effects of hypoxia. At the same time, prolonged periods of hyperoxia have to be prevented to avoid retinopathy of prematurity, edema of the lungs, and other untoward effects of hyperoxia and oxygen toxicity. Several control systems have been proposed for oxygen treatment of newborn infants [1-4]. The system proposed in this paper uses a modified version of the technique presented in [4]. Compared to the systems developed previously, this new modified technique is designed to respond more quickly to very abrupt reductions in arterial oxygen saturation. This oxygen control system has the capability to respond safely and quickly to rapid disturbances in oxygen balance, as well as the ability to regulate arterial oxygen saturation of the infant under more stable and finely controlled clinical conditions.

METHODOLOGY

The block diagram of the system is shown in Figure 1. The arterial oxygen saturation of the infant, S_{amo2}, is detected by using pulse oximetry. This data is converted to digital and supplied to a microprocessor. The algorithm in this processor, which will be described later, is designed to control the input signal to a mixer regulator based on the arterial oxygen saturation level of the infant. This signal is converted to analog before being applied to the mixer regulator. The output of the mixer regulator controls the opening and closing of an electronic valve which allows the entry of oxygen into the oxygen air mixer. The output of this mixer is the oxygenated air which is supplied to the infant in the incubator, or under the hood treatment.

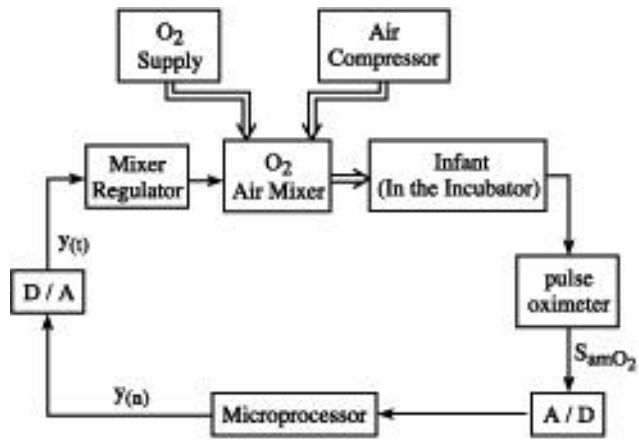

Fig 1. Block diagram of the system.

Figure 2 shows the flow chart of the steps performed by the control algorithm which is stored in the microprocessor. This algorithm uses a modified technique which incorporates two types of closed-loop controls to detect and correct hypoxia and hyperoxia in premature infants. As shown in Figure 2, at the beginning, the alarm signals are deactivated. Then the set-point for arterial partial pressure of oxygen is defined and the initial value of the inspired fraction of oxygen, F_{IO2}, is transmitted to the output port. In the next step, the threshold values for arterial oxygen saturation and arterial oxygen pressure are defined. In the step that follows, the main loop is started at A, and the data representing arterial oxygen saturation is read from the input port. This data is provided by using pulse oximetry. Next, the arterial oxygen pressure is calculated from the value of arterial oxygen saturation by using the following equation [5]:

$$P_{amO2} = -\ln [1- (S_{amO2})^{0.5}]/0.046 \qquad (1)$$

In this equation, P_{amO2}, is the partial pressure of oxygen in the mixed arterial blood, and S_{amO2} is the arterial oxygen saturation of the infant. In the step that follows, the arterial oxygen pressure is compared with a minimum threshold value to detect the possibility of an artifact. This possibility is detected if the calculated arterial oxygen pressure is less than the threshold value. In this case, an alarm signal is transmitted to an appropriate output port and control is returned to the beginning of the main loop at A. However, if the arterial partial pressure of oxygen is found to be higher than the minimum threshold value, in the step that follows, the arterial oxygen saturation is compared to a minimum safe level. If the measured value is less than or equal to the minimum safe value, the oxygen

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Abstract

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concentration, F_{IO2}, is increased stepwise and the additional oxygen is supplied to the O_2 air mixer. After 0.75 seconds, the routine is turned back to A and the arterial oxygen saturation is read from the input port. This loop continues until the arterial oxygen saturation is above the minimum safe level. At this point, a proportional, integral, derivative (PID) control loop is started at B. In this loop F_{IO2} is controlled according to a PID routine, and every 0.75 seconds the output is adjusted and the routine is turned back to A. If at any time during this operation, the arterial oxygen saturation falls below the minimum safe level, the stepwise control loop supersedes the PID loop to avoid any hazards of hypoxia.

The following is the system of equations describing the PID control loop:

$$Y(n) = a.E1(n) + b.E2(n) + c.E3(n) + D \quad (2)$$

Where

$$E1(n) = P_{amO2}\ (\text{set-point}) - P_{amO2} \quad (3)$$

$$E2(n) = E2(n-1) + K.E1(n) \quad (4)$$

$$E3(n) = (E1(n) - E1(n-1))/K \quad (5)$$

In these difference equations which are similar to the equations described in (4), P_{amO2} is the desired set-point value for the partial pressure of oxygen in the mixed arterial blood of the infant and E1(n) is the error signal. Also, K =0.75 seconds, a = $6.45X\ 10^{-5}$, b = $3.22X\ 10^{-5}$, c = $7.29X\ 10^{-6}$, and D = 0.21. Y(n) is the output of the PID control loop which is provided to the mixer regulator via a digital to analog converter.

In order to evaluate the response of the controller, the closed-loop system shown in the block diagram of Figure 1 was simulated on a digital computer. A detailed model of the infant respiratory system [6] was used in the simulation experiments. In this model, the effects of shunt in the lungs, a varying dead space, and prematurity of arterial receptors in infants are included. Lungs, brain, cerebrospinal fluid, and the body tissues are separate compartments. The respiratory controller in this model functions as a discrete system driven by Hering-Breuer type reflex signals, and the plant is a continuous system. The details of this model and its equations that constitute a 12th order system of non-linear equations are found in [6] and are not repeated here for brevity.

The O_2 air mixer and the effect of mixing in the incubator were represented by the following equation in the simulation experiments:

$$T.\ dF_{IO2}(t)/dt + F_{IO2}(t) = Y(t) \quad (6)$$

In this equation, T is the combined time constant of the O_2 air mixer and the incubator which was set at a typical value of 30 seconds.

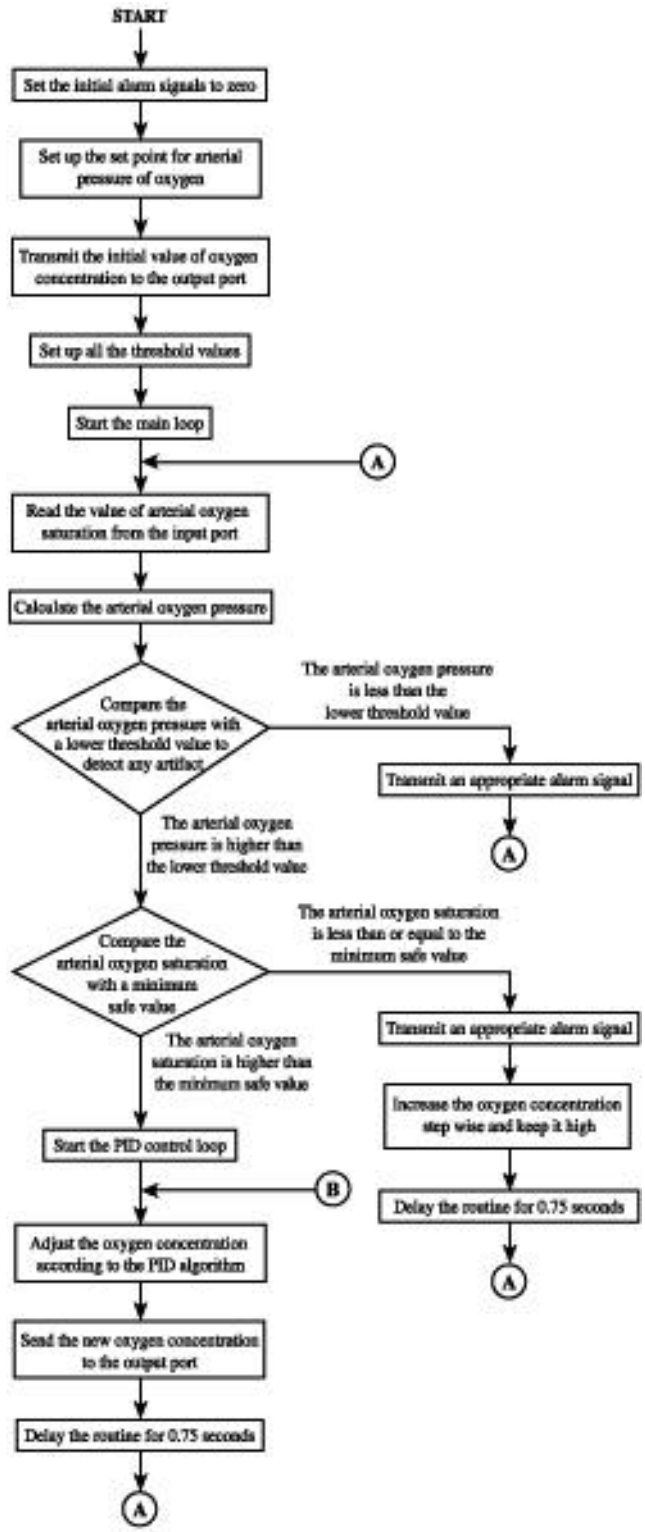

Figure 2. Flow chart of the control algorithm

RESULTS AND DISCUSSION

The performance of the controller was examined at different levels of hypoxia by using simulation experiments. Of particular interest in these tests, were the duration of hypoxia and the effectiveness of the controller in correcting the hypoxic conditions. Two examples of the transient responses of the system to hypoxia are shown in Figures 3 and 4.

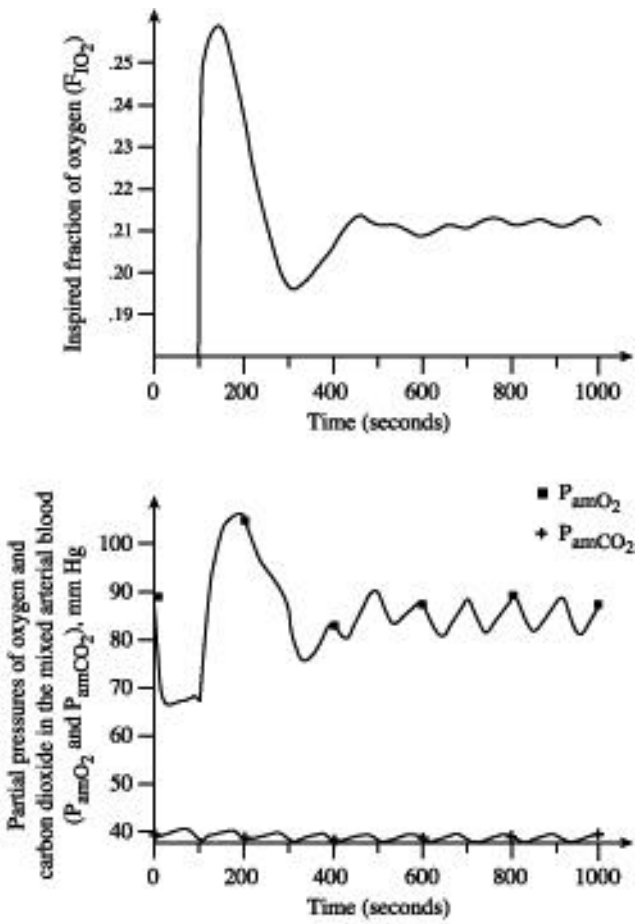

Fig 3. Transient responses of the control system to 100 seconds of 18% oxygen breathing. The lung shunt ratio is 0.1 and the alveolo-arterial oxygen difference of the infant is 20 mm Hg.

In Figure 3, hypoxia is induced by 18% oxygen breathing during the first 100 seconds of simulation time. The lung shunt ratio of the infant is 10%, the alveolar-arterial oxygen difference is 20 mm Hg and the maturity factor of the arterial receptors of the infant is 80% of the normal value. The transient responses of partial pressures of oxygen and carbon dioxide in the mixed arterial blood of the infant (P_{amO2} and P_{amCO2}) as well as the F_{IO2} response are shown in this figure. As is seen, P_{amO2} falls to about 68 mm Hg at the end of the first 100 seconds. At this point the oxygen controller is turned on. As a result, F_{IO2} rises to about 0.255 during the first 20 seconds of control and P_{amO2} rises to above 100 mm Hg. Then a few oscillations in F_{IO2} and P_{amO2} are observed and F_{IO2} returns to slightly higher than 0.21 and P_{amO2} reaches to about 87 mm Hg in approximately 5.5 minutes. As expected, there are no disturbances in the P_{amCO2} response in this experiment.

Figure 4 shows another set of the simulation responses of the control system to hypoxia induced by 14% oxygen breathing for 100 seconds. In this test, alveolar-arterial oxygen difference is 25 mm Hg, lung shunt ratio is 20%, and the maturity factor of arterial receptors is 80% of the normal value.

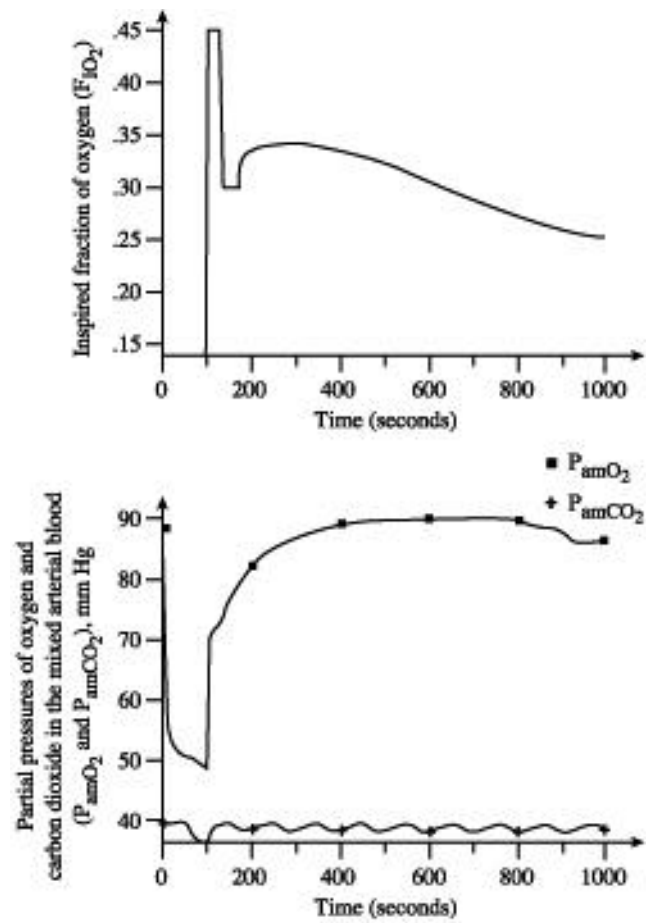

Figure 4. Responses of the control system to hypoxia induced initially by 14% oxygen breathing for 100 seconds. Alveolo-arterial oxygen difference is 25 mm Hg and lung shunt ratio is 0.2.

As can be seen in this figure, during the first 100 seconds that the oxygen controller is off, P_{amO2} falls below 50 mm Hg. Since arterial oxygen saturation goes below the minimum safe level, F_{IO2} rises stepwise to 0.45 at the time that the feedback oxygen controller is turned on. Consequently, it is seen that P_{amO2} increases to about 70 mm Hg during the first several minutes of

control. F_{IO2} remains at 0.45 for less than 20 seconds, and then it decreases stepwise to 0.3 as a result of the increase in S_{amO2}. Thereafter, F_{IO2} remains at 0.3 level for about 30 seconds and then after a slight overshoot to about 0.34, it gradually decreases and reaches about 0.25 in approximately 17 minutes. P_{amO2} reaches safe levels in less than 10 seconds after the oxygen controller is turned on in this experiment and gets to about 90 mm Hg in less than 5.5 minutes. The P_{amCO2} values are not affected by hypoxia as expected.

It is seen in the simulation experiments that the oxygen controller is quite robust and effective in response to hypoxia. The hypoxic conditions are corrected within 5-7 seconds while prolongation of high levels of oxygen breathing are prevented.

CONCLUSION

A new oxygen control system has been proposed to detect and correct hypoxia and hyperoxia by using the non-invasive measurement technique of pulse oximetry. Two different closed-loop mechanisms are incorporated in this system. One of them is provided to respond instantly to rapid changes in oxygen balance, and the other one provides fine control of the inspired oxygen concentration of the infant. This controller has been successfully tested by using computer simulation. Clinical experiments are needed to further assess the effectiveness of the proposed control system.

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