NEONATAL WORKSTATION FOR INSPIRED OXYGEN CONTROL AND CLINICAL MONITORING
Yao Sun MD, Isaac Kohane MD, PhD
Children's Hospital, Harvard University Medical School, Boston, MA

Introduction
The regulation of oxygen delivery to acutely ill infants requiring mechanical ventilation is a vital process in neonatal intensive care medicine. We have designed a microcomputer based system to automatically and continuously control the inspired oxygen concentration (FIO2) delivered mechanically ventilated newborn infants. In addition, we will utilize this computer platform to collect and analyze clinical data (such as heart rate, respiratory rate, arterial blood pressure, and oxygen saturation) in newborn infants with pulmonary disease.

Background
Oxygen toxicity plays a role in the development of chronic lung disease in newborn infants requiring mechanical ventilation. (12,16,17) In premature infants, oxygen toxicity is also implicated in the development of retinopathy of prematurity. (1,7,8) Therefore, minimizing oxygen exposure of ventilated newborn infants has become a priority in neonatal intensive care.

By constantly monitoring the signals from cardiac and pulse oximetry monitors and correlating these signals, a computer system has been designed to control the inspired oxygen concentration (FIO2) delivered to mechanically ventilated newborn infants. This computer-controlled FIO2 delivery system can continuously adjust oxygen delivery to the minimum amount needed to achieve a target oxygen saturation.

physiological data received by the computer from a patient monitoring system is readily available for selective storage and analysis. These data could be utilized in several ways. The information for an individual patient could be analyzed and plotted to detect trends in clinical improvement or deterioration. By comparing data from many neonates, we might also elucidate physiological trends and patterns associated with particular pulmonary diseases. Displaying the data in a selective and informative way will also benefit the clinician by facilitating the analysis of enormous quantities of raw information.

Investigation into computer-controlled or computer-assisted mechanical ventilation is expanding. One form of computer assistance is an “expert system” designed to advise clinicians about ventilator management. Some recent examples include: VentPlan, a ventilator management advisor that interprets patient data within a physiological model to predict the effect of proposed ventilator changes; (11) ESTER, a program which assesses the patient’s pathophysiological state using modified APACHE-II criteria, then offers suggestions for weaning from intermittent mandatory ventilation; (6) WEANPRO, a program designed to help wean postoperative patients from ventilators; (15) and KUSIVAR, a program which describes a comprehensive system for respiratory management during all phases of pulmonary disease. (10) Although many such expert systems have been described, few have been tested in clinical patient care.

Other investigators have studied direct computer control of specialized aspects of ventilator management. (14,18) For example, studies of computer-controlled optimization of positive end-expiratory pressure, and computerized protocols for management of adult respiratory distress syndrome have been explored by East. (3,4) A computerized ventilator weaning system for post-operative patients has been tested by Strickland. (13)

Experience in computer controlled ventilation in infants, however, is limited. In one of the few reports available in the literature, Morozoff and Evans showed that a computerized FIO2 controller could maintain the oxygen saturation of a ventilated newborn infant at least as well, and sometimes better than manual FIO2 control. (9) They described their FIO2 controller as a “differential-feedback” controller. This description matches the general class of controllers known as “proportional integral derivative” (PID) controllers. For best response, most PID controllers need to be optimized for the system that they will be used in. This may lead to degradation of performance if the system changes.

Clinical monitoring systems have also been described previously. Examples include Guardian, a “proof of concept” of an intelligent agent designed to coordinate a range of reasoning tasks in intensive care monitoring, (5) and Simon, a series of semi-independent modules designed to collect and analyze clinical data while interpreting patient status.
and predicting the evolution of monitored parameters. (2)

The present system incorporates a new FIO2 controller in the context of a system designed to collect, store, and display the physiological monitored data for mechanically ventilated newborn infants.

**System description**

The system consists of a microcomputer, a ventilator with electronic signal outputs, a clinical monitor with signal outputs, and the patient. Software currently exists that enable clinical monitors to accept input signals from a ventilator indicating ventilator parameters such as the FIO2. The clinical monitor also collects patient physiological data such as heart rate, respiratory rate, and oxygen saturation. Using these data inputs from the clinical monitor, the computer will execute an algorithm to make changes in the FIO2 to achieve a target oxygen saturation. The computer will also continuously record the clinical data input for later retrieval and analysis.

Currently, the system is designed to operate by displaying suggested FIO2 changes to the clinician, rather than to control the ventilator directly. This ensures medical safety until the system is fully tested for clinical efficacy.

The algorithm to be tested in this system has two features that differ from a standard PID controller. First, changes in the FIO2 will be based on the hemoglobin-oxygen dissociation curve. This builds in a “predictive” component to the controller based on the expected changes in oxygen saturation for given changes in partial pressure of oxygen. As patient oxygen saturation values are collected by the system, these values are mapped to a corresponding portion of the hemoglobin-oxygen dissociation curve. If the oxygen saturation maps to a steeper portion of the curve, smaller changes in FIO2 will occur for flatter portions of the curve (i.e. at high oxygen saturation values).

Secondly, the algorithm will dynamically adjust the magnitude of the changes in FIO2 depending on the individual patient’s responses. This will compensate for changes in a patient’s clinical condition over time, and also allow the system to be used with different patients without the need to modify the system for each patient. The adjustment algorithm works by examining the patient’s past response to FIO2 change and regulating the magnitude of subsequent FIO2 changes based on that response.

The system's user interface allows the clinician to enter identifying patient information and critical alarms limits for the oxygen saturation, heartrate, mean blood pressure and respiratory rate. The clinician also sets the target oxygen saturation for the system to maintain.

Although it is currently the only active control function, the FIO2 controller is incorporated in a processing loop that includes data collection, diagnostic analysis, and data storage. This general architecture will enable expansion of the system to accommodate future diagnostic and therapeutic options, such as the implementation of total ventilator control and diagnosis of pulmonary disease.

**System Testing**

The system has been tested on the data set of patient physiological information provided for this symposium. For the purposes of FIO2 control, the only data that need processing are the oxygen saturation, the "arterial heartrate", the ECG (cardiovascular monitor) heartrate, and the FIO2. The other patient information is gathered and stored.

Since the data set represents static information, it did not test the FIO2 controller's response to a dynamically changing system. The system performs the following actions correctly for the data set:

1) For the target oxygen saturation set by the clinician, the controller will suggest FIO2 changes in the appropriate direction (higher or lower) with appropriate adjustments in the magnitude of FIO2 changes based on the difference between the measured oxygen saturation and the target.

2) Validation of the oxygen saturation is performed by comparing the "arterial heartrate" with the ECG heartrate. The arterial saturation is presumed to be an artifact if the two heart rates do not correlate within 5 beats/minute.

3) The system correctly displays alarm messages when the physiological information represents values outside the limits set by the clinician.

4) All the patient data is stored in a file for later retrieval and analysis.

Subsequent clinical trials of the FIO2 control system will test the effectiveness of the controller in maintaining patient oxygen saturations. Data will be analyzed to compare the oxygen exposure of patients during "open loop" computer control vs.
during manual FIO2 control. If the data analysis reveals that the computer FIO2 control system provides lower patient oxygen exposure without compromise in tissue oxygenation, a clinical trial of direct computer control of ventilator FIO2 will be conducted.

Summary
The implementation of this system to control FIO2 in mechanically ventilated newborns may have important clinical implications for reducing the development of chronic lung disease and retinopathy of prematurity. In addition, the data collection functions of the system will allow analysis of physiological variables in multiple ways. As the system evolves, concurrent selective display of realtime data will also enable clinicians to assimilate and process raw information in an efficient manner.

Current testing with static clinical data verifies that the FIO2 control algorithms will produce appropriate recommendations to increase or decrease the FIO2 while observing the alarms and limits imposed by the clinician user. Further dynamic testing in the neonatal intensive care setting will evaluate the ability to respond to changing patient clinical conditions.

REFERENCES