

**Title:** AUTOMATED OXYGEN DELIVERY INTO A CLOSED CIRCUIT

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**Introduction.** The technique of closed circuit anesthesia involves the delivery of oxygen and anesthetic agents to a patient in a controlled and quantitative fashion depending on the patient's individual rates of uptake<sup>1</sup>. Thus, in an oxygen-volatile agent technique, the rate of O<sub>2</sub> delivery to the breathing circuit is adjusted so that the end expiratory circuit volume remains constant. The circuit volume can be determined from the position of an upright spirometer bellows such as that in the Air-Shields Ventimeter ventilator. The volatile agent is infused in liquid form into the circuit so that its end expiratory concentration remains at a predetermined level. Given the simplicity of the manual control procedures for O<sub>2</sub> and volatile agent delivery, we predicted that automated control would also be feasible. The purpose of this project, therefore, was to implement an automatic control system for O<sub>2</sub> delivery into a closed circuit leaving the volatile agent infusion under manual control for the present.

**Method.** The system was based on a North American Dräger Narkomed II anesthesia machine equipped with a standard oxygen flow meter and made leak free. A standard circle absorber system was used with an Air-Shields Ventimeter ventilator attached. A Tylan mass flow controller for oxygen was added with its output piped through a rotameter and then into the Narkomed common outlet. Outside the Air-Shields spirometer cannister, a bellows position sensor was mounted. This consisted of a vertical stack of 80 infrared light-emitting diode and phototransistor pairs. Each LED activated its corresponding phototransistor by reflecting light off a small aluminum reflector mounted on the top of the spirometer bellows. The flow controller and position sensor were interfaced to a Motorola MC6801 microprocessor which was programmed to set the flow controller and track the spirometer bellows. The 6801 was in turn interfaced to a Motorola Exorset 30A system consisting of an MC6809 processor, 64 k bytes of memory, a keyboard and CRT display, and dual flexible diskette drives. The Exorset was programmed to control O<sub>2</sub> delivery to the breathing circuit based on a proportional-integral-derivative (PID) control algorithm and to display data including the patient's O<sub>2</sub> consumption on the CRT. The software was implemented in BASIC and assembly language. To test the system a dog weighing 30 kg was anesthetized on multiple occasions with pentobarbital 35 mg/kg. Following orotracheal intubation, the dog was connected to the anesthesia machine and his ventilation controlled by the Air-Shields ventilator. Denitrogenation was accomplished by allowing the dog to breathe O<sub>2</sub> delivered at 6 liters/minute for 20 minutes. The dog's temperature and arterial blood gases were measured, and he was maintained at normothermia and normocarbia. Following denitrogenation, the high-flow O<sub>2</sub> was discontinued, and the oxygen control system started. To verify the validity of the dog's calculated O<sub>2</sub> consumption, all gas delivery was stopped for a period of two minutes and the change in end expiratory bellows position measured. Finally the step response of the automatic controller was measured by setting the manual oxygen flow meter to ~ 50 ml/minute

simulating a step decrease in O<sub>2</sub> consumption.

**Results.** The anesthesia machine had a leak of only 20 ml/minute when pressurized to 40 cm H<sub>2</sub>O. The mass flow controller could be set with an accuracy of ± 5 ml throughout its range of 0-500 ml. The position sensor measured the bellows position with a precision of ± 17 ml through its range of 0-1400 ml. Following denitrogenation of the dog, the circuit O<sub>2</sub> concentration was 90%, and it remained stable during the 30 minutes of the experiment. The dog's temperature was 38°C and his PaCO<sub>2</sub> was 40 torr on ventilator settings of V<sub>T</sub> = 400 ml and f = 10/minutes. Peak inspiratory pressure measured 15 cm H<sub>2</sub>O. Commanded by the Exorset, the 6801 set the flow controller accurately as verified by rotameter readings. The 6801 calculated end expiratory bellows position to within ± 50 ml. The PID controller program was able to keep the end expiratory bellows position within ± 50 ml of its set point following an initial offset of 200 ml and a settling time of 3 minutes. The dog's calculated oxygen consumption was 140 ± 15 ml/minute. A measurement of 120 ml/minute was obtained from a bellows drop of 240 ml over a 2 minute period with all gas flows off. Following the step addition of O<sub>2</sub> to the circuit, the controller required 2 minutes to return the bellows to within ± 50 ml of the end expiratory set point.

**Discussion.** The predicted O<sub>2</sub> consumption (10 X dog mass in Kg<sup>3/4</sup>) derived from Brody<sup>2</sup> was 130 ml/minute. Both the O<sub>2</sub> consumption calculated by the controller and that measured from the bellows drop were within 10% of this value. Since gas leak was demonstrated to be minimal and the mass flow controller performed accurately, the main source of variability in the calculated O<sub>2</sub> consumption was probably due to variation in the end expiratory bellows position measured by the 6801. This latter variability also accounts for the inability of the PID controller to keep the bellows nearer than ± 50 ml of its end expiratory set point. When given simulated bellows position and O<sub>2</sub> consumption data without this variability, the controller kept the bellows within ± 1 ml of the set point after a 4 minute settling time, and calculated the simulated O<sub>2</sub> consumption exactly. The initial settling time and step response of the real controller agreed well with the simulation despite the position variability. Refinement of the 6801's software should decrease the variability of the calculated end expiratory bellows position.

This device could benefit practitioners of closed circuit anesthesia in two ways. It would provide a continuous measurement of patient O<sub>2</sub> uptake, and by automatically adjusting O<sub>2</sub> flow, it would free the anesthesiologist for other aspects of patient care.

#### References.

1. Lowe HJ and Ernst EA: *The Quantitative Practice of Anesthesia - Use of Closed Circuit*. Baltimore: Williams and Wilkins, 1981. Pp. 163-205.
2. Brody S: *Bioenergetics and Growth*. New York: Reinhold, 1945. Pp. 307-13, 368-74, 932-7.