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. Thus, in an oxygen-volatile agent technique, the rate of O₂ 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 spirometric bellows such as that in the Air-Shields 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 O₂ and volatile agent delivery, we predicted that automated control would also be of some interest. The purpose of this project, therefore, was to implement an automatic control system for O₂ 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 circuit was used with an Air-Shields Ventilator. 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 set sent an infrared light beam through a phototransistor, and the resulting photocurrent was proportional to the reflected light intensity. The phototransistor's output was connected to the Air-Shields ventilator. 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. The Exorset 30A had a 16-bit RISC processor, 64 k bytes of memory, a keyboard and CRT display, and dual flexible diskette drives. The Exorset was programmed to control O₂ delivery to the breathing circuit based on a proportional-integral-derivative (PID) control algorithm and to display data including the patient's O₂ 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 O₂ 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 normocapnia. Following denitrogenation, the high-flow O₂ was discontinued, and the oxygen control system started. To verify the validity of the dog's calculated O₂ consumption, all gas delivery was stopped for a period of one minute 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 O₂ consumption.

Results. The anesthesia machine had a leak of only 20 ml/minute when pressurized to 40 cm H₂O. The mass flow controller could be set with an accuracy of ±5 ml throughout its range of 0-1400 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 O₂ concentration was measured to be 95%, and it remained stable during the 30 minutes of the experiment. The dog's temperature was measured to be 38°C and his PaCO₂ was measured to be 40 torr on ventilator settings of VT = 400 ml and f = 10/minute. Peak inspiratory pressure measured 15 cm H₂O. Commanaced by the Exorset, the 6801 set the flow controller accurately as verified by rotameter readings. The Exorset controlled and displaced 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 O₂ 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 O₂ consumption (10X dog mass in kg⁴/₄) derived from Brody's equation was 130 ml/minute. Both the O₂ 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 O₂ 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 closer than ±50 ml of its end expiratory set point. When given simulated bellows position and O₂ 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 O₂ consumption exactly. The initial settling time and steep response of the real controller agreed well with the simulation despite the position variability. Refinement of the Exorset 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 O₂ uptake, and by automatically adjusting O₂ flow, it would free the anesthesiologist for other aspects of patient care.

References.