Rate of change of oxygen concentration for a large animal circle anesthetic system

Adrian M. Solano, DVM; Robert J. Brosnan, DVM, PhD; Eugene P. Steffey, VMD, PhD

Objective—To describe the effects of changes in circuit volume and oxygen inflow rate on inspired oxygen concentration for a large animal circle anesthetic system.

Study Population—A large animal circle anesthetic system, a 10 L/min flowmeter, and 20- and 40-L breathing bags.

Procedure—Circuit volume was determined by a carbon dioxide dilution technique. Oxygen flow rates of 3, 6, and 10 L/min were delivered to the circuit with the large breathing bag, and a flow rate of 6 L/min was used with the small bag. Gas samples were collected during a 20-minute period. The time constant (τ) and half-time ($T_{1/2}$) were calculated and compared with measured values.

Results—Mean ± SEM volume of the breathing circuit with a 20- and 40-L breathing bag was 32.97 ± 0.91 L and 49.26 ± 0.58 L, respectively. The τ from measurements was 11.97, 6.10, and 3.60 minutes at oxygen flow rates of 3, 6, and 10 L/min, respectively, for the large breathing bag and 3.73 minutes at a flow rate of 6 L/min for the small breathing bag. The $T_{1/2}$ was 8.29, 4.22, and 2.49 minutes at oxygen flow rates of 3, 6, and 10 L/min, respectively, for the large breathing bag and 2.58 minutes for the small breathing bag.

Conclusions and Clinical Relevance—This study emphasizes that there are delays in the rate of increase in the inspired oxygen concentration that accompany use of conventional large animal circle anesthetic systems and low rates of inflow for fresh oxygen. (*Am J Vet Res* 2005;66:1675–1678)

The **inspired oxygen concentration** (C_IO_2) is a primary determinant of PaO_2. In a study[1] published in 1987, investigators describe the rate of increase of C_IO_2 and PaO_2 in horses during the early phase of inhalation anesthesia while breathing oxygen from a typical large animal circle anesthetic circuit. In that study, investigators documented that > 20 minutes of a constant inflow of oxygen at a rate of 6 L/min was necessary for the C_IO_2 to reach 90% (considered an acceptable reference value for oxygen-breathing horses). The use of low anesthetic delivery flow is a means of facilitating economy of especially expensive anesthetic gases.[2] However, such practices will, among other considerations, lower the rate of increase of C_IO_2 during periods of general inhalation anesthesia when the amount of inspired oxygen is diluted by other gases, such as nitrogen (eg, during early anesthesia or when, for various reasons, the anesthetic breathing circuit has been separated from the endotracheal tube and exposed to room air). Such delays may become clinically important during anesthesia of horses because the internal volume of the breathing circuit that is commonly used is large and can account for some variability in PaO_2 that commonly accompanies anesthetic management of horses. Accordingly, in the study reported here, we measured the impact of the rate of oxygen inflow on the change of C_IO_2 during simulated use of a large animal circle anesthetic system and compared the results obtained with predicted values. The study should provide information that will heighten the awareness of clinicians as to the C_IO_2 kinetics during anesthesia of horses.

Received November 11, 2004.
Accepted March 9, 2005.
From the Department of Surgical and Radiological Sciences, School of Veterinary Medicine, University of California, Davis, CA 95616 (Solano, Steffey); and the Department of Anesthesia and Perioperative Care, University of California, San Francisco, CA 94143 (Brosnan).
Address correspondence to Dr. Solano.

Materials and Methods

Equipment—A standard large animal circle anesthetic system[a] was used in the study. The system included a 10 L/min flowmeter,[b] 20-L (small)[c] and 40-L (large)[d] breathing bags, and two 120-cm-long delivery hoses attached to a plastic Y-piece (internal diameter, 5.1 cm). The open end of the Y-piece was sealed, and the circle system was tested to a peak circuit pressure of 30 cm H_2O before each study to ensure it would not leak. A simulated lung was prepared by use of a 10-L breathing bag placed in a barrel system powered by a positive-negative pressure–generating ventilator.[2,3,e] This arrangement was intended to simulate breathing and facilitate timely mixing of gases contained within the circuit. The bag-in-barrel apparatus was connected to the circuit Y-piece by a 40-cm-long piece of rigid tubing (**Figure 1**).

Procedure—Calibration of the oxygen flowmeter and volume of only the circle system, including the delivery hoses and small and large breathing bags, were determined by use of a dilution technique for carbon dioxide gas with measurements made at ambient conditions of pressure at approximately sea level.[4,5] Briefly, the flowmeter was set at each of 4 flow rates, and gas was collected during a 1-minute period into an initially empty collecting bag (20-L breathing bag). The volume was determined by adding a known volume and concentration of carbon dioxide to the collecting bag and measuring the concentration of carbon dioxide after 10 minutes of equilibration. In the same manner, the volume of the circle system was determined. The ventilator was set to cycle at a rate of 5 cycles/min. The internal volume of the circle circuit–simulated lung assembly (ie, the system) was initially flushed with compressed air with the circuit pop-off valve in open position until the simulated lung was fully inflated during inspiration. At end expiration, the simulated lung was fully or almost fully collapsed. After a time necessary for adequate mixing of gases within the system, the inflow of air was stopped, the pop-

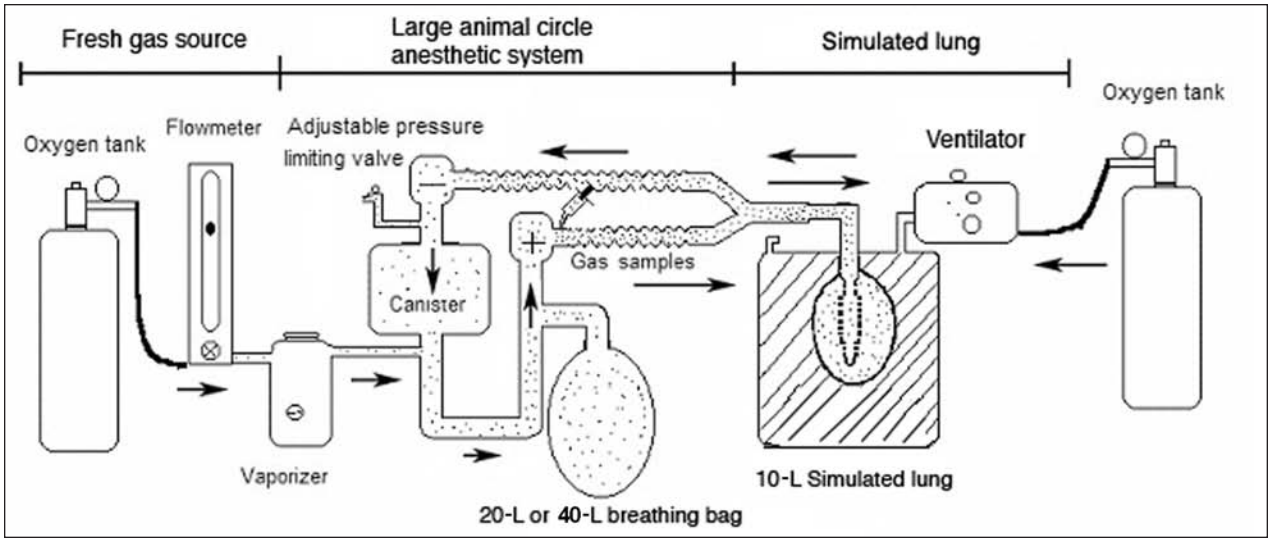

Figure 1—Diagram of the large animal circle anesthetic system used to evaluate the rate of increase in oxygen concentration. The inlet for fresh gas is located at the base of the canister, and a gas sampling port is located at the level of the inspired limb of the system beyond the 1-way inspiratory valve (+).

off valve was closed, a known volume and concentration of carbon dioxide was added, and volume of the system was determined. Peak system pressure was maintained within 0 ± 2 cm H_2O to achieve the same compliance among experiments.

Volume of the circle system was measured by use of the 20- and 40-L breathing bags. After 10 minutes of mixing equilibration, the carbon dioxide concentration within the system was measured. Volume was derived by use of the following equation:

$$V2 = (V1 \times [C1 - C2])/C2,$$

where V2 is the volume after equilibration, V1 is the initial volume of gas, C1 is the initial carbon dioxide concentration, and C2 is the carbon dioxide concentration after equilibration. The same principle was applied for flowmeter calibration.

Carbon dioxide concentrations were measured by use of an infrared gas analysis technique.[f] All of the analyzer values were corrected by use of a curve calculated for 8 carbon dioxide standards[g] whose concentrations extended just beyond the range of measurements.

Characterization of the rate of increase of C_IO_2—Flow rates for fresh oxygen (3, 6, and 10 L/min) were delivered into the system with the large breathing bag, whereas a flow rate of 6 L/min was used for the system with the small breathing bag. The spring-loaded pop-off valve was set to maintain a full breathing bag at end expiration (ie, collapsed simulated lung and circuit pressure were 0 ± 2 cm H_2O) during each experiment. The system was flushed with room air between experiments. Gas samples were manually collected in glass syringes at 0, 15, and 30 seconds and 1, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 15, and 20 minutes. Time 0 was designated as the start of inflow of fresh oxygen. The C_IO_2 was measured by use of a calibrated polarographic oxygen sensor.[h] All analyzer values were corrected by use of a curve for 6 oxygen standards[i] whose concentrations extended beyond the range of measurements. At least 3 experiments were conducted at each flow rate and for each breathing bag.

Data analyses—Values were grouped and expressed as mean ± SEM. The mean C_IO_2 for each flow rate and breathing bag was plotted against time. The influence of the fresh oxygen inflow on the rate of increase of C_IO_2 in the system was predicted by use of the following equation:

$$C_IO_2 = 100 \times (1 - e^{-(t/\tau)}),$$

where e is the base of the natural logarithm, t is time in minutes, and τ is equal to a time constant (ie, circuit volume divided by inflow rate of fresh gas). The predicted and measured results were plotted on linear axes for visual comparison. The percentage difference was calculated between measured values for τ obtained here and predicted values for τ. The time required for the circuit C_IO_2 to reach 50% (ie, **half-time** [$T_{1/2}$]) was also calculated by use of the following equation[6]:

$$T_{1/2} = 0.693 \times \tau.$$

Results

Volume was determined for the large animal circle anesthetic system used in the study reported here. Mean ± SEM volume was 32.97 ± 0.91 L and 49.26 ± 0.58 L for the 20- and 40-L breathing bags, respectively.

Measured and predicted values of the C_IO_2 within the inspired limb of the circle circuit for continuous flow rates of 3, 6, and 10 L/min with the large breathing bag were plotted (**Figure 2**). Similarly, C_IO_2 within the inspired limb of the circle circuit for a continuous flow rate of 6 L/min with the small breathing bag was plotted (**Figure 3**).

Values of τ obtained from measurements with the large breathing bag were 11.97, 6.10, and 3.60 minutes for flow rates of fresh gas of 3, 6, and 10 L/min, respectively. The associated percentage difference from predicted values was 30.10%, 27.53%, and 30.14% at flow rates of 3, 6, and 10 L/min, respectively. For the system with the small breathing bag at a flow rate of 6 L/min, the value for τ was 3.73 minutes and the percentage difference from the predicted value was 33.77%. The $T_{1/2}$ was 8.29, 4.22, and 2.49 minutes for the system with the large breathing bag at flow rates of 3, 6, and 10 L/min, respectively. For the system with the small breathing bag at a flow rate of 6 L/min, $T_{1/2}$ was 2.58 minutes.

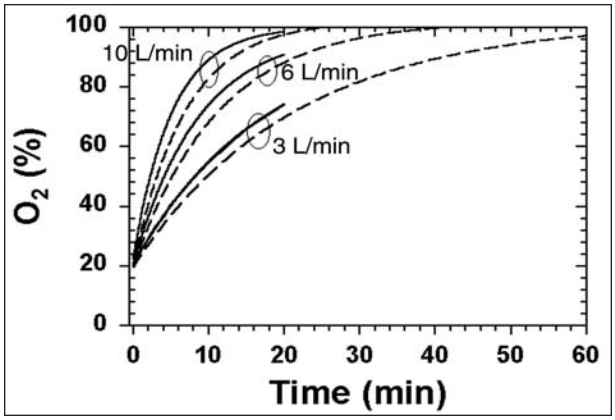

Figure 2—Measured (solid line) and predicted (dotted line) rate of increase in oxygen (O_2) concentration for a large animal circle anesthetic system with a 40-L breathing bag and inflow of fresh O_2 at rates of 3, 6, and 10 L/min. Time 0 = Start of inflow of fresh O_2.

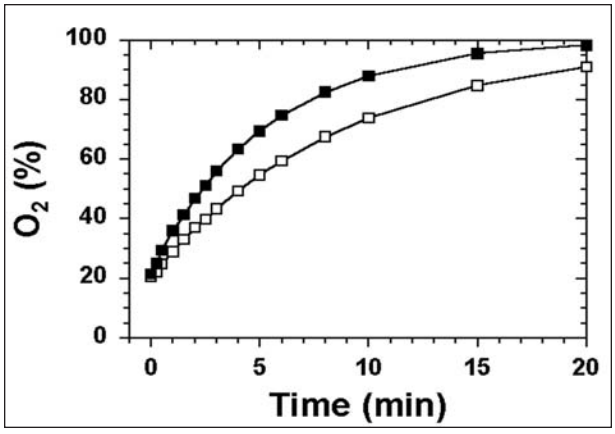

Figure 3—Rate of increase in O_2 concentration at an inflow rate for fresh O_2 of 6 L/min for a large animal circle anesthetic system with a 40-L breathing bag (white squares) or a 20-L breathing bag (black squares).

Discussion

The resident gas volume within an anesthetic breathing circuit dilutes the inflowing fresh gases. Fresh gas flowing into the circuit must wash out the circuit to establish and maintain desired gas concentrations for inspiration. This applies both to inspired oxygen and inhalation anesthetics.[2] We chose to focus the study reported here on the rate of change of oxygen concentration in the inspired limb of circuits commonly used in the anesthetic management of animals that weigh > 200 kg. We reasoned that this was necessary because, in our experience, anesthetist trainees and clinicians not commonly involved in anesthetic management of large animals rarely consider changes in circuit oxygen concentrations and therefore the C_IO_2. The reason usually expressed is that because the anesthetic carrier gas is typically virtually pure oxygen, the C_IO_2 is assumed to be close to 100%. Of course, this is inaccurate and may contribute, in certain circumstances, to patient morbidity or even death.

Considering only the anesthetic breathing circuit (ie, no animal is attached to the circuit), 3 factors govern the rate of change of oxygen concentration in the circuit and therefore the C_IO_2. These factors are the gas volume within a gas-tight circuit, inflow rate of fresh gas, and loss of oxygen to the circuit (ie, absorption by circuit components). For our purposes in the study reported here, loss of oxygen to the circuit components was considered negligible. Our breathing circuit was used with 2 volumes of breathing bags (ie, 20- and 40-L breathing bags). We measured a circuit volume of 33.0 and 49.3 L with the small and large breathing bags, respectively. We considered the difference between each of the measurements for each of the breathing bags (ie, approx 4 L) to be within the range of likely variability of differences in the actual volumes of each breathing bag.

Predictably, C_IO_2 increases directly in relation to the magnitude of fresh oxygen inflow to the breathing circuit and inversely to the overall size or internal volume of the circuit (Figures 2 and 3). In the study reported here, measured C_IO_2 appeared to increase faster than the predicted change, especially early in each measurement period. In addition, there was a greater difference in measured C_IO_2, compared with the predicted concentration, early in the course of experiments. For example, soon after starting inflow of fresh oxygen at the rate of 10 L/min to the circuit containing the large breathing bag, there was a difference of approximately 30% in τ, whereas at an inflow rate of 3 L/min, τ was reduced to 4%. The difference between observed and predicted C_IO_2 values and the variability of calculated τ were not surprising because the predicted values were generated assuming instantaneous mixing of the gases within the total volume of the circuit, whereas there likely was a time delay in mixing in the system because of the low breath rate used in the study and the circuit's large volume. With time, there was mixing of gases, and the variability in measured C_IO_2 and the differences between the measured and predicted curves lessened and eventually disappeared.

In the circuit of our study, positioning of the inlet for the entry of fresh gas was upstream from the inspired limb of the circuit. This circuit arrangement would be expected to facilitate a faster change in C_IO_2 then positioning that inlet in the expired limb of the circuit. However, similar oxygen kinetics will not necessarily be found for other commercially available types of large animal circle anesthetic systems because positioning of circuit components differs.

We always began our experiments on the rate of increase of C_IO_2 after the breathing circuit was flushed with air to mimic clinical use in which a circuit that has been idle for some time (eg, overnight) is put into service without modification; this is commonly observed in large animal clinical practice. By use of this technique, analysis of our results indicated the time for the circuit to reach a C_IO_2 of at least a desirable concentration of 90% would be in the range of 10 to 11 minutes with a flow of 10 L/min and a large breathing bag or by use of the small breathing bag and a flow of 6 L/min. At an inflow of 6 L/min and use of the large breathing bag, the time for C_IO_2 to reach 90% would be at least twice the time required with an inflow of 10 L/min (Figure 3).

The data reported here directly impact principles of anesthetic management of large animals such as

horses, a species known for inefficiencies in oxygenation during general anesthesia.[7,8] Analysis of our results emphasizes that there are delays in the rate of increase in C_IO_2 accompanying use of the voluminous, conventional large animal circle anesthetic system and low inflow rates of fresh gas. Such circuit volume–gas flow delays are substantially out of proportion with those commonly associated with the anesthetic management of smaller species, such as dogs and cats, for which clinicians use circle circuits of about one tenth the size of the large animal circle anesthetic system or nonrebreathing circuits. Analysis of our results also implies that anesthetists must consider appropriate steps to rapidly achieve the desired C_IO_2, especially during clinical circumstances when a high C_IO_2 is necessary to maintain an adequate PaO_2 (a circumstance seen in the anesthetic management of horses). Common circumstances in which such conditions may prevail include during the early phase of inhalation anesthesia or during anesthetic maintenance whenever the continuity of the breathing circuit is broken and air is introduced.

In the study reported here, the rate of change in C_IO_2 in a conventional large animal circle anesthetic system was determined for various conditions that simulated common use in clinical practice. Use of 2 sizes of breathing bags and various inflow rates of fresh gas (ie, oxygen) enabled us to plot graphs of the rates of increase of C_IO_2 and compare measured values with predicted values. Not surprisingly, the smaller circuit volume and largest gas inflow rate were necessary to achieve a rapid change in C_IO_2. This information is clinically applicable whenever the gas volume of the anesthetic breathing circuit is exposed to air for prolonged periods or a high C_IO_2 is vital to sustaining an adequate PaO_2 in anesthetized large animals.

a. Large animal anesthesia machine, North American Drager, Telford, Pa.
b. 10-L oxygen flowmeter, Porter Instrument Co, Hatfield, Pa.
c. 20-L breathing bag, Con-Rob-Consultant Ltd, Oxford, UK.
d. 40-L breathing bag, Con-Rob-Consultant Ltd, Oxford, UK.
e. Bird Mark 9 ventilator, Bird Corp, Palm Springs, Calif.
f. LB2, Sensormedics Corp, Anaheim, Calif.
g. CO_2 calibration gases (Vol %: 0.02, 2.81, 3.41, 5.45, 7.6, 9.97, and 13.19), Matheson Tri-Gas, Newark, Calif.
h. OM-11, Sensormedics Corp, Anaheim, Calif.
i. O_2 calibration gases (Vol %: 11.00, 15.3, 20.9, 39.6, 59.5, 78.00, and 97.2), Matheson Tri-Gas, Newark, Calif.

References

1. Grandy JL, Steffey EP, Miller M. Arterial blood PO_2 and PCO_2 in horses during early halothane oxygen anaesthesia. *Equine Vet J* 1987;19:314–318.

2. Steffey EP, Howland DJ. The rate of change of halothane concentration in a large animal circle anesthetic system. *Am J Vet Res* 1977;38:1993–1996.

3. Steffey EP, Berry JD. Flow rates for an intermittent positive pressure breathing-anesthetic delivery apparatus for horses. *Am J Vet Res* 1977;38:685–687.

4. Comroe JH. Lung volumes. In: Comroe JH, ed. *The lung: clinical physiology and pulmonary function test*. 2nd ed. Chicago: Year Book Medical Publishers, 1967;7–23.

5. West JB. Ventilation. In: West JB, ed. *Pulmonary pathophysiology: the essentials*. 6th ed. Philadelphia: Lippincott Williams & Wilkins, 2000;11–19.

6. Meakin GH. Time constant or half time of a breathing system? *Anaesthesia* 2003;58:386–387.

7. Hall LW, Gillespie JR, Tyler WS. Alveolar-arterial oxygen tension differences in anesthetized horses. *Br J Anaesth* 1968;40:560–568.

8. Gillespie JR, Tyler WS, Hall LW. Cardiopulmonary dysfunction in anesthetized, laterally recumbent horses. *Am J Vet Res* 1969;30:61–72.