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Intraoperative Air Entrainment with Ohio® Modulus™ Anesthesia Machine

WILLIAM L. LANIER, M.D.*

Mass spectrometry measurement of expiratory nitrogen (N_2) is beneficial in the detection[1] and quantitation[2] of venous air emboli in surgical patients. We recently have noticed intraoperative accumulations of expiratory N_2 in patients anesthetized in the sitting position in whom the ECG, blood pressure, expiratory CO_2, Doppler ultrasound, right atrial catheter aspiration, and inspection of the surgical site did not indicate evidence of air embolus. All patients had anesthesia administered through an Ohio® Modulus™ anesthesia machine using an Ohio® hanging-bellows ventilator and an Ohio® scavenging system, which employs a "waste gas scavenging interface valve." In each case, the reservoir bag on the anesthesia machine "waste gas scavenging interface valve" was completely deflated (fig. 1).

Expiratory nitrogen fraction (FE_{N_2}), which always was greater than inspiratory nitrogen fraction (FI_{N_2}), ranged from 0.02 to 0.03 with scavenger reservoir bag deflation. Upon adjusting the scavenging valve to allow proper inflation of the reservoir bag, or upon increasing anesthesia circuit fresh gas flow, expiratory N_2 decreased with time (though neither the source nor the mechanism of N_2 entrainment were identifiable). However, in two later cases, the mechanism of N_2 entrainment became apparent.

REPORT OF TWO CASES

Case 1: A 27-year-old woman, weighing 60 kg, presented for suboccipital craniotomy for tumor resection in the sitting position. General anesthesia was induced with thiopental and pancuronium iv, and maintained with fentanyl iv and isoflurane in N_2O and O_2. The trachea was intubated with a 7.0-mm OD cuffed wire spiral tube, and ventilation was controlled. Anesthesia circuit fresh gas flow was 3.0 $l \cdot min^{-1}$, and the ventilator was set to deliver a tidal volume of 650 ml at a rate of 11.5 breaths $\cdot min^{-1}$. Anesthesia proceeded uneventfully for 3 h, when the anesthetist noted an FI_{N_2} of 0.04 and an FE_{N_2} of 0.13. The surgeon and anesthesiologist were notified of a possible venous air embolus; however, careful evaluation of all monitoring devices and the surgical site failed to corroborate a diagnosis of venous air embolus. Anesthesia circuit fresh gas flow was increased to 4.0 $l \cdot min^{-1}$, and the scavenger reservoir (which was previously deflated) was adjusted to its properly inflated position. Over the next 5 min, FI_{N_2} decreased to 0.01 and FE_{N_2} decreased to 0.05. At this time, an endotracheal tube cuff leak, which had not previously been noted using continuous auscultation of an esophageal stethescope, appeared.

With inflation of the tube cuff, FI_{N_2} and FE_{N_2} decreased to 0.01. With the endotracheal tube cuff inflated, sequentially decreasing the fresh gas flow to 3.0 $l \cdot min^{-1}$ and adjusting the scavenging valve to allow reservoir bag deflation had no effect on FI_{N_2} and FE_{N_2}. However, with the scavenger reservoir bag deflated, the anesthesia circuit pressure (as measured by the carbon dioxide absorber cannister manometer) decreased to −3 cm H_2O in early expiration and gradually declined to −5 cm H_2O by late expiration. During the next 30 min, FI_{N_2} and FE_{N_2} did not vary from 0.01, regardless of the scavenging valve adjustment and reservoir bag position. The patient was hemodynamically stable throughout the anesthetic and awakened uneventfully from anesthesia. Retrospectively, venous embolus was not thought to have occurred at any time during the anesthetic. At the completion of the anesthetic, inspection of the anesthesia circle system revealed a leak of <250ml $\cdot min^{-1}$, as in the preanesthetic period.

Case 2: A 62-year-old, 65-kg woman was anesthetized for lumbar laminectomy in the prone position. General anesthesia was induced with thiopental, lidocaine, and vecuronium iv, and maintained with diazepam and fentanyl iv and N_2O. The trachea was intubated with a 7.0-mm OD cuffed wire spiral tube, and ventilation was controlled. Circuit fresh gas flow was 3.0 $l \cdot min^{-1}$, and the ventilator was set to deliver a tidal volume of 800 ml at a rate of 11 breaths $\cdot min^{-1}$. Thirty minutes after surgical incision, with the scavenger reservoir properly inflated, FI_{N_2} and FE_{N_2} were stable at 0.01. The scavenging valve was adjusted electively to produce reservoir deflation to test the effects of this intervention on circuit N_2. Six minutes later, FI_{N_2} and FE_{N_2} were unchanged; however, the anesthesia circuit manometer, which previously had registered zero expiratory pressure, now noted an expiratory pressure of −3 cm H_2O. To test if this pressure gradient was sufficient to allow air entrainment in the presence of a system leak, the endotracheal tube cuff was deflated. The anesthetist acknowledged the presence of inspiratory esophageal stethoscope sounds suggestive of a cuff leak superimposed on apparently unchanged lung ventilation. Two minutes after cuff deflation, FI_{N_2} and FE_{N_2} had increased to 0.28 and 0.38, respectively. The test promptly was terminated by inflating the endotracheal tube cuff. One minute later, FI_{N_2} was 0.03 and FE_{N_2} was 0.05. These values gradually declined and stabilized at 0.01 over the ensuing 13 min.

To see if air entrainment could occur with proper scavenging valve adjustment, the endotracheal tube cuff balloon was deflated while the scavenger valve was adjusted to allow proper inflation of the scavenger reservoir bag. Anesthesia circuit pressure, which was zero, decreased to −3 cm H_2O early in each expiratory cycle. Over the next 3 min, FI_{N_2} increased from 0.00 to 0.01, and FE_{N_2} increased from 0.01 to 0.18. Two minutes later (with FI_{N_2} and FE_{N_2} at 0.02 and 0.21, respectively) the endotracheal tube cuff was reinflated. Circuit pressure returned to zero, and FI_{N_2} and FE_{N_2} declined to 0.00 and 0.01, respectively. Airway pressure and nitrogen remained at these levels for the next 2 h. Throughout the study, the ventilator continued to cycle without activation of the low pressure alarm. At the completion of the

* Senior Associate Consultant in Anesthesiology, Mayo Clinic; Assistant Professor of Anesthesiology, Mayo Medical School.

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Address reprint requests to Dr. William L. Lanier.

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anesthetic, the anesthesia circuit was assessed for a leak, which was <250 ml · min^{-1}.

SURVEY OF SCAVENGER SYSTEM USAGE

The adjustment of anesthesia scavenging valves was surveyed during regular use at weekly intervals in the six Ohio® Modulus™ anesthesia machines used in our neurosurgical corridor. Scavenging valve adjustments were assigned to one of three categories: 1) overinflation: reservoir bag maximally expanded throughout the respiratory cycle and positive expiratory circuit pressure noted on the circuit manometer; 2) underinflated: reservoir collapsed throughout the respiratory cycle, resulting in negative expiratory circuit pressure; and 3) normal: zero expiratory circuit pressure, regardless of reservoir inflation.

All manometers registered zero when exposed to atmospheric pressure. In 18 machine operation examinations, scavenger reservoir overinflation resulting in +1 to +3 cm H_2O expiratory circuit pressure occurred in two (11%), normal inflation was noted in five (28%), and underinflation resulting in negative expiratory pressure of ≤4 cm H_2O occurred in 11 (61%). One of the reservoirs listed as normal was totally deflated throughout the respiratory cycle, although a negative circuit pressure did not develop.

DISCUSSION

Intraoperative air entrainment into the anesthesia circuit can cause deleterious alterations in patient management. Since expiratory N_2 can be used to identify[1] and possibly quantitate[2] the volume of venous air emboli, intraoperative air entrainment into the anesthesia circuit from nonsurgical sites can lead to the false diagnosis of venous air embolism. Such a false diagnosis was made in case 1. If a closed or semiclosed anesthesia circuit is used, air entrainment from the inspiratory or expiratory circuit limb may accidentally cause a dilution of inspiratory anesthetic gases and oxygen. Waters[3] and Bookallil[4] have documented intraoperative awareness secondary to air entrainment into the anesthesia circuit. Dilution of inspiratory oxygen with air introduces the potential for arterial hypoxemia. Theoretically, the development of hypoxemia due to air entrainment would be greatest in patients requiring high F_{IO_2} values. Thus, if air (F_{IO_2} = 0.21) was mixed with inspiratory gases having a low F_{IO_2} (*e.g.*, F_{IO_2} = 0.30), there would only be a small decrease in F_{IO_2}, regardless of the volume of air entrained. However, if air is mixed with inspiratory gases having a large F_{IO_2} (*e.g.*, F_{IO_2} = 1.00), the potential exists for large decreases in delivered F_{IO_2}.

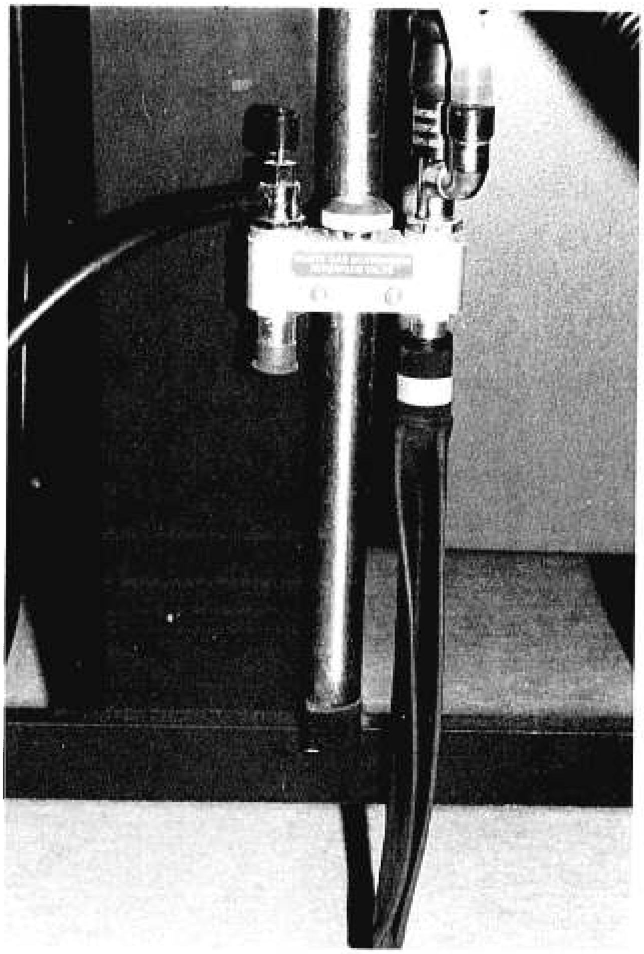

FIG. 1. Waste gas scavenging interface valve adjustment resulting in collapse of the reservoir bag throughout the ventilatory cycle. Adjustment of the valve in this manner resulted in a potential for negative expiratory anesthesia circuit pressure.

Intraoperative air entrainment in the cases we reported are assumed to be related to the design of the Ohio® Modulus™ anesthesia machine. This machine scavenges waste gases by employing a closed system "waste gas scavenging interface valve." The use of a closed scavenging system theoretically decreases the risk for operating room pollution and, thus, the potential for harm to operating room personnel by exposure to anesthetic gases.[5] However, closing the scavenging system introduces the potential for creating negative airway pressure, resulting in barotrauma.[6] To prevent excessive pressure accumulation, the Ohio® scavenger uses a system of valves designed to limit pressure that may develop within the system to ≤ +5 cm H_2O and ≤ −0.05 cm H_2O.*

* Operation Maintenance Manual, Ohio® Modulus™ Anesthesia Gas Machine, Ohio Medical Products, Madison, Wisconsin.

In our experience, the positive pressure pop-off valves functioned as designed, and airway pressure ≤ +5 cm H_2O was recorded with scavenger reservoir bag overinflation. However, adjusting the scavenging valve to allow total deflation of the scavenger reservoir bag often resulted in expiratory airway pressures of −2 to −4 cm H_2O. The accumulation of negative expiratory circuit pressure in this setting probably is related to the use of a hanging bellows ventilator with the Ohio® Modulus™ machine. Bellows expansion is produced by the expiratory inflow of gases and the effects of gravity. If the volume of expiratory gas or rate of its flow is insufficient to fill the descending ventilator bellows, a potential exists for development of a negative pressure in the anesthesia circuit.[1] This condition was demonstrated in case 2, when inspiratory loss of gases from the patient–circuit unit occurred following deflation of the endotracheal tube cuff. Similarly, depletion of volume from the circuit (and not direct generation of negative pressure by the scavenger valve) probably accounts for the generation of negative pressure by the hanging bellows ventilator in the presence of an "underinflated" scavenger reservoir bag. Thus, the greatest expiratory air entrainment occurs with the Ohio® Modulus™ machine during periods in which volume is simultaneously removed from the circuit by an inspiratory circuit leak and scavenger valve adjustment resulting in "underinflation" of the scavenger reservoir bag. This was demonstrated in both cases reported. The potential for negative pressure accumulation and air entrainment should further increase by decreasing fresh gas flow, increasing tidal volume, and increasing the weight of the bellows.

If negative anesthesia circuit pressure develops from any source, air entrainment occurs in the presence of a circuit leak. This complication has been reported with the Ohio® Modulus™ machine following a user-induced anesthesia circuit leak.[7] As in that report, the source of the circuit leak was obvious in the two cases we reported; however, we have experienced intraoperative air entrainment, resulting in small increases in FE_{N_2} in many patients in whom the source of the circuit leak was not apparent. Our circuits are tested daily to ensure that outboard system leaks remain small (*e.g.*, ≤250 ml · min^{-1} during positive airway pressure). The introduction of negative airway pressure can convert allowable outboard leaks into small inboard leaks. This probably represents the source of small intraoperative increases in FE_{N_2} we have observed using the Ohio® Modulus™ system in patients in whom no obvious sources of increased FE_{N_2} were found.

Although large leaks in the anesthesia system should be detected by low pressure ventilator alarms, this is not the case with the Ohio® hanging bellows ventilator.[8] The Ohio® ventilator alarm is designed to "trigger if a pressure of 10 cm H_2O has not been obtained for a period of 15 consecutive seconds."† These criteria were not met in either of the cases reported, and the ventilators continued to cycle without alarm detonation and deliver a mixture of entrained air and anesthetic gases.

To ensure prevention of intraoperative air entrainment with the Ohio® Modulus™ system, the following criteria should be met: 1) the circuit–patient unit should be as free of leaks as possible; 2) the "waste gas scavenging interface valve" must be adjusted properly for each patient; 3) fresh gas flow rates and descension of the ventilator bellows must be coordinated to prevent negative pressure generation by the hanging bellows; and 4) the system should be monitored continuously for negative circuit pressure. If others share in our pattern of misuse of the Ohio® Modulus™ "waste gas scavenging interface valve" (as seen in our survey), the potential for intraoperative air entrainment exists with a majority of patients. When we consider the additional, independent potential for air entrainment with the hanging bellows ventilator, almost all patients are at risk for air entrainment when using the Ohio® Modulus™ anesthesia machine in the presence of a moderate circuit leak.

† Operation Maintenance Manual, Ohio® Anesthesia Ventilator, Ohio Medical Products, Madison, Wisconsin.

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