Nonrebreathing anesthetic systems in small animal practice

Phillip Lerche, BVSc; William W. Muir III, DVM, PhD, DACVA; Richard M. Bednarski, DVM, MS, DACVA

In a previous article, key issues (rebreathing, tidal volume, minute ventilation, and dead space volume) that are critical to understanding how anesthetic delivery systems work were discussed. The purpose of the review reported here was to discuss the nonrebreathing systems that are often selected for smaller, older, obese, or diseased patients.1-3

Design of Nonrebreathing Anesthetic Delivery Systems

Mapleson systems—In 1954, Mapleson classified breathing systems that use fresh-gas flow to wash out carbon dioxide into 5 types (A through E).4 A sixth type, type F, was added later as a modification of type E.5 The A, D, and F Mapleson systems are used in veterinary anesthetic practice, and the D and F systems are the most popular in North America.6

All Mapleson systems have the advantage of causing minimal resistance to gas flow, because they have no valves that the animal must displace in order to breathe (Appendix 1). They are relatively inexpensive to purchase and maintain, compared with other systems; the only moving part is the adjustable pressure-limiting valve (pop-off valve) present in some systems. Fresh-gas flow rates are adjusted to produce minimal or no rebreathing of exhaled gases, thereby ensuring that each breath taken by the patient is composed of almost entirely fresh gas. High fresh-gas flow rates facilitate carbon dioxide removal and also ensure that inspired anesthetic concentration closely reflects the percentage set on the vaporizer dial. Rapid changes in inspired anesthetic concentration and anesthetic depth result when the vaporizer setting is changed. Likewise, nitrous oxide may be used in concentrations as great as 70% with minimal risk of a hypoxic mixture developing. Nonrebreathing systems are usually made of lightweight materials, which reduces their total weight and equipment drag on the endotracheal tube. This prevents the weight of the breathing system from inadvertently extubating small patients or patients in which the endotracheal tube has not been properly secured. Mapleson systems are adaptable for use in a variety of surgical procedures and patient positions, and those with coaxial arrangements allow the surgeon easy access for dental, head, and neck procedures.

The necessity for high flow rates in conjunction with the expenditure of energy in humidifying and warming inhaled gases may cause substantial decreases in patient temperature, unless a humidifier-warmed is added to the system. Furthermore, high fresh-gas flow rates are uneconomical because large amounts of anesthetic and delivery gases (oxygen and nitrous oxide) are wasted. For example, a 30-kg (66-lb) dog connected to a nonrebreathing system requires a minimum fresh-gas flow of approximately 100 ml/kg (45 ml/lb) of body weight/min (total, 3,000 ml/min) and an isolauran vaporizer setting of 2%. One hour of anesthesia will use 18 ml of anesthetic liquid and cost $3.60 (assuming that 1 ml of isoflurane costs $0.20). If the same dog is anesthetized by use of a closed or semiclosed rebreathing system, in which the flow rate could be as low as 5 ml/kg (2.3 ml/lb)/min (total, 50 ml/min) with a vaporizer setting of 4% (the vaporizer setting is usually higher with closed-system anesthesia), 1 hour of anesthesia will cost $0.36, a saving of 90%. In addition to lost income, wasted anesthetic gases can result in increased operating room pollution if a waste gas scavenging system is not used or is inadequate. The release of inhalant anesthetics into the atmosphere contributes to the greenhouse effect and depletion of the ozone layer.7 Nitrous oxide is also deleterious to the ozone layer and adds to the greenhouse effect.7

Mapleson D system—The basic structure of the Mapleson D system is a T-shaped 3-way connector (T-piece; Fig 1A). One port delivers fresh gas, 1 port connects to the patient, and the third port directs exhaled gases away from the patient. In one common modification of the system, the third port is connected to a length of corrugated tubing, at the end of which are situated a pop-off valve and reservoir bag (Fig 1B). Fresh gas is continuously delivered to the patient during spontaneous breathing from the delivery limb and from the corrugated tube during inspiration (Fig 2A). As the patient exhales, fresh and expired gas flow together along the corrugated tube into the bag (Fig 2B). Expired gas contains mechanical and anatomic dead space gas in early exhalation and alveolar gas in late exhalation. When the bag is full, gas escapes through the pop-off valve (Fig 2C). Rebreathing is minimized by use of a fresh-gas flow rate of at least 1.5 to 2 times patient minute volume, or, alternatively, a value greater than inspiratory flow rate, which ensures that only fresh gas is breathed in from the corrugated tube (Appendix 2).8 The shorter the pause between breaths (as seen with increased respiratory rate), the more likely the gas inhaled from the corrugated tube during subsequent breaths will be alveolar gas and that some rebreathing will occur.

During controlled inspiration (pop-off valve closed; Fig 2D), during which a larger tidal volume may be delivered compared with spontaneous ventilation, a larger volume of exhaled gas from the corrugated tube could contribute to the inspired volume. Thus, it is more likely that alveolar gas will be rebreathed.
during controlled ventilation. Adequate fresh-gas flow rates should push expired dead space and alveolar gases along the corrugated tubing and out of the pop-off valve during the inspiratory pause. Fresh-gas flow rates slightly higher than those used for spontaneous respiration may therefore be required during controlled breathing to prevent increased rebreathing of exhaled gases.

Before each use, system integrity is determined by occluding the patient end of the system, closing the pop-off valve, and pressurizing the system by either increasing the fresh-gas flow rate or pushing the oxygen flush button. The system should hold a pressure of at least 30 cm H2O. Opening the pop-off valve should cause the bag to deflate if the valve and scavenging systems are functioning properly.8

Modified Mapleson D system (Bain coaxial system)—The Bain modification of the Mapleson D system is a coaxial (tube within a tube) system in which the fresh-gas supply is delivered through the inner tube (Fig 1C). The Bain system may be attached to a bag mount that includes a port for attaching a breathing bag, a manometer to monitor airway pressure, and an automatic pressure-limiting valve (Fig 3). If a bag mount is not used, a hole located in the tail of a bag attached to the system (so-called mini-Bain; Fig 1D) conducts waste gas into the scavenging system. Theoretically, fresh-gas flow rates should be the same as those described for the classic Mapleson D (T-piece), however, flow rates of 100 to 130 ml/kg (45 to 60 ml/lb)/min cause minimal rebreathing during spontaneous breathing.9,10 Although rebreathing of exhaled gases can occur at a fresh-gas flow rate of 100 ml/kg/min, this flow rate is adequate to prevent hypercarbia during controlled ventilation when minute ventilation is adequate.9

It is important to inspect the Bain system prior to each use to ensure that the inner tube has not become disconnected or cracked. If the inner tube is cracked, the entire system contributes to equipment dead space, which increases the inspired fraction of carbon dioxide and drastically increases the volume of rebreathed gases. To test the system for a leak, a low flow of oxygen (approx 1 to 2 L/min) is delivered, and the inner tube is occluded with the barrel of a 3-ml syringe. If the tube is intact, the oxygen flowmeter indicator (rotameter) will fall, because backpressure will be directed to the flowmeter tube.11

Mapleson F system (Jackson-Rees modified T-piece system)—The Jackson-Rees modification of the T-piece is constructed by adding a bag to the corrugated tube attached to the exhalation port of the T-piece (Fig 1E). A pop-off valve is not used. The bag traditionally has a hole in the tail for the exit of waste gas, which makes scavenging difficult but possible. The absence of a pop-off valve reduces resistance to breathing, compared with the other nonrebreathing systems. A disadvantage of this system, however, is that the
small opening in the end of the bag may become occluded, which allows the system to overfill and results in dangerously high breathing system pressure and airway pressure. Recently developed Mapleson F systems have an attached scavenging device that may be open (spontaneous breathing), partially closed (to allow the bag to stay partially distended, or to facilitate controlled ventilation), or closed (in order to deliver a controlled breath). A further improvement is that the angle at which the fresh-gas delivery port enters the T-piece is more acute. This reduces mechanical dead space by facilitating washout of exhaled gases, which makes this breathing system ideal for small patients that weigh \(< 7 \text{ kg (15.4 lb)}\). Flow rates of 1 to 2 times minute volume as described for the Mapleson D are required to ensure that carbon dioxide is not rebreathed during spontaneous ventilation (Appendix 2).4

**Mapleson A system (Magill system)**—The Magill system consists of a corrugated tube with a compliant reservoir bag at one end and an endotracheal tube connection port at the other (Fig 1F). The unique characteristic of the Magill system is the low fresh-gas flow rate that is required (100 to 150 ml/kg [45 to 68 ml/lb])/min.4 Fresh gas (oxygen, nitrous oxide, and inhalant anesthetic) enters at the end where the breathing bag attaches. A pop-off valve is situated near the patient. The Magill system is less commonly used in North America than in the United Kingdom, where, because of relatively low fresh-gas flow rates used during spontaneous ventilation, the system is used in medium to large (body weight, 15 to 59 kg [33 to 130 lb]) dogs as well as smaller (body weight, 10 to 15 kg [22 to 33 lb]) dogs.4

During spontaneous ventilation (Figs 4A-D), the valve is kept in the fully open position. The patient inhales fresh gas from the system, and the breathing bag collapses (Fig 4A). As the patient exhales, dead space gas followed by alveolar gas flows down the tube toward the bag. Simultaneously, fresh gas fills the bag from the opposite end of the system (Fig 4B). When the bag is full, the pressure in the system rises, opening the pop-off valve. The continuous flow of fresh gas during the inspiratory pause forces the exhaled gas out of the valve and into the scavenging system (Fig 4C). The first gas to exit the valve is the alveolar gas, followed by dead space gas, and then fresh gas (Fig 4D). This preferential exit of alveolar gas results in a rela-
tively low fresh-gas flow rate requirement to prevent rebreathing, compared with other systems. Mapleson calculated that a flow rate that is at least equal to minute ventilation is required to prevent rebreathing with the Magill system.4

During controlled or manual ventilation (Figs 4E-H) the pop-off valve is adjusted to a partially closed position during inspiration while the bag is squeezed. Typically, the valve is closed to the point that a pressure of 15 to 20 cm H$_2$O is required for the pop-off valve to open. The inspiratory force thus generated inflates the lungs and causes some of the gas to be vented out of the pop-off valve (Fig 4E). The reservoir bag is, therefore, partially collapsed at the end of inspiration. During expiration, a large portion of the corrugated tube and possibly some of the bag fills with expired dead space and alveolar gas from the patient and fresh gas from the anesthetic machine (Fig 4F). Pressure in the system then builds, and gas is flushed out of the pop-off valve into the scavenging system. This may result in some of the expired alveolar gas being retained in the tube (Fig 4G). Rebreathing of this alveolar gas will occur at the initiation of the next and subsequent manually delivered breaths (Fig 4H).

Rebreathing during controlled ventilation can be overcome by using higher fresh-gas flow rates, similar to that used in the Mapleson D system. Therefore, it is not advisable to use a Magill system for controlled ventilation because of the requirement for high fresh-gas flow rate and the possibility for rebreathing to occur. In addition, the position of the pop-off valve (near the patient and away from the bag) makes it awkward to use for controlled ventilation. This system is leak-tested as described for the Mapleson D system.

Modified Mapleson A system (Lack system)—The Lack modification of the Mapleson A system has an added expiratory limb that places the pop-off valve away from the patient end of the system and closer to the breathing bag. This type of nonrebreathing system can be formed by 2 tubes (the parallel Lack system) or by placing a tube within a tube (the coaxial Lack system; Fig 1G).8 Because exhalation occurs through the inner tube of a coaxial Lack system, the diameter of the inner tube must be large enough to minimize resistance during expiration. The dynamics of gas flow are similar to those described for the Magill system. The fresh-gas flow rate required to prevent rebreathing during spontaneous ventilation when using the Lack system is 0.7 to 1 times minute ventilation in dogs, suggesting a more efficient use of fresh gas that is similar to that of the Magill system (as much as 30% less fresh gas required).12 Like the Magill system, the Lack nonrebreathing system promotes excessive rebreathing when controlled ventilation is used. Lack systems are leak-tested as described for the Magill system. Additionally, the coaxial Lack system can be tested for leaks in the inner (expiratory) limb by connecting an endotracheal tube to the system and blowing through it with the pop-off valve closed. If there is a leak between the inspiratory and expiratory tubes the reservoir bag will expand.13

Hazards of the Nonrebreathing Systems

Nonrebreathing systems have low compliance in comparison to circle rebreathing systems. This, in conjunction with the higher fresh-gas flow rates, increases the risk of barotrauma if the path of expired and waste gases becomes occluded. Examples of such occlusion are inadvertently leaving the pop-off valve closed, occluding the end of an open-tailed reservoir bag, and incompatibility of monitoring equipment placed between the breathing system and the endotracheal tube connector.1416 A modification to prevent pressure...
from building up within a nonrebreathing system has been described. In one instance of incompatible equipment, however, the occlusion was proximal to the pop-out valve, and gas was not able to escape, resulting in patient injury.

Selecting an Anesthetic System

Factors to consider when choosing an anesthetic system have been discussed in a previous article. A rebreathing system may cause increased resistance to breathing in small patients (body weight, < 7 kg), compared with the Mapleson systems. When deciding which type of anesthetic breathing system to use, patient body composition is as important as body weight in making this determination; for example, an 8-kg (17.5-lb) overweight Toy Poodle is technically large enough to be placed on a rebreathing system. However, adipose tissue within the lungs may decrease lung compliance, resulting in lower tidal and minute volumes. Such a patient may, therefore, benefit from the reduced resistance and lower mechanical dead space of a nonrebreathing system. Patients with moderate to severe respiratory tract disease that causes increased resistance to breathing may also benefit from being placed on a nonrebreathing system.

References


Appendix 1

Advantages and disadvantages of nonrebreathing anesthetic systems

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>* Decreased resistance to breathing</td>
<td>* Potential for rebreathing expired gases unless high fresh-gas flow rates are used</td>
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<tr>
<td>* Small equipment dead space</td>
<td>* Minimal conservation of heat and moisture</td>
</tr>
<tr>
<td>* Light-weight equipment reduces anesthetic equipment drag on endotracheal tube</td>
<td>* Uneconomical high fresh-gas flow rates waste oxygen, nitrous oxide, and inhalant anesthetic</td>
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<tr>
<td>* Percentage inhalant anesthetic indicated on vaporizer dial approximates percentage inhalant anesthetic inspired by patient</td>
<td>* Large amount of waste anesthetic and delivery gases results in increased operating room and atmospheric pollution, requiring effective scavenging system</td>
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<tr>
<td>* Allows rapid changes in percentage inhalant anesthetic inspired and anesthetic depth</td>
<td>* * Special considerations during controlled breathing</td>
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<td>* Nitrous oxide can be used safely at inspired concentrations as great as 70%</td>
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<tr>
<td>* Adaptable to a variety of patient positions</td>
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<td>* Inexpensive to purchase and maintain</td>
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Appendix 2

Recommended flow rates (ml/kg [mg/lb] of body weight/min) for nonrebreathing anesthetic breathing systems

<table>
<thead>
<tr>
<th>System type</th>
<th>Flow rate for spontaneous ventilation</th>
<th>Flow rate for controlled ventilation (IPPV)</th>
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<tbody>
<tr>
<td>Magill (Mapleson A)</td>
<td>≥ 200 (80)</td>
<td>≥1.0 X minute ventilation</td>
</tr>
<tr>
<td>Lack (modified Mapleson A)</td>
<td>120–200 (55–90)</td>
<td>0.7–1.0 X minute ventilation</td>
</tr>
<tr>
<td>Bain (modified Mapleson D)</td>
<td>100–200 (45–90)</td>
<td>2.5–3.0 X minute ventilation required in theory; clinically, lower flows prevent rebreathing</td>
</tr>
<tr>
<td>Jackson-Rees modified Ayre’s T-piece (Mapleson F)</td>
<td>300–400 (135–180)</td>
<td>Similar to flow rate required for spontaneous ventilation</td>
</tr>
</tbody>
</table>

IPPV = Intermittent positive-pressure ventilation. NA = Not applicable.