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Summary
The use of lasers during surgery in the airway of the horse bears various hazards of which airway combustion is the most severe. This risk is of particular concern in anesthetized animals breathing an oxygen-rich gas mixture. Though total intravenous anesthesia has been commonly advocated for laser procedures, laser surgery in the airway of the horse can be performed more safely under inhalation anesthesia, if the inspired oxygen concentration (FiO₂) is kept low. Use of a helium-oxygen (He/O₂) gas mixture and low FiO₂ (< 0.4) offers the advantage of significantly decreasing the risk of airway combustion while maintaining adequate arterial oxygenation in the majority of equine patients.

Introduction
Over the past decade the laser has become a standard tool for upper airway surgery in the horse [1,2]. While offering numerous advantages, the use of lasers in the airway is not without any risk. The potential hazards, particularly that of airway combustion, during laser surgery in the airway of the anesthetized horse have been reviewed in detail and evidence has been provided that the carrier gas used for inhalation anesthesia is important [3]. It is generally recommended to use the lowest concentration of inspired oxygen (FiO₂) that is compatible with adequate arterial blood oxygenation [4-6]. Usually a fraction of inspired O₂ of 40% or less (FiO₂ < 0.4) will achieve this goal, also in horses. Either nitrogen (N₂) or helium (He) may be used to dilute the oxygen [5]. A description of an inhalation anesthetic technique using a helium/oxygen carrier gas mixture (He/O₂) for horses undergoing airway laser surgery follows.

Rationale for Use of Helium versus Nitrogen or Air
Helium is an odorless, tasteless and inert gas, and offers some important advantages over N₂. Not only does He not support combustion, but due to its lower density, as compared to N₂, it also produces less turbulent gas flow, which may prove advantageous in a partially obstructed airway [7,8]. Furthermore, He compared to N₂, is characterized by a greater thermal conductivity and may thus act as a "heat sink" in the event of an airway fire [9]. In 1985, Pashayan and Gravenstein [10] demonstrated that 60% He retards polyvinyl chloride (PVC) tube ignition by CO₂ lasers significantly longer than 60% N₂. At the same time the authors confirmed an earlier report showing that an inspired O₂ concentration below 40% prevents tube fires [11]. Based on these results, an anesthetic protocol for laryngotracheal operations with CO₂ lasers was developed using an inspired He concentration of 60% or more and FIO₂ < 0.4 [12]. Pashayan et al., [12] did not report any incidence of airway fire or tracheal tube burns in 523 clinical patients treated with this "helium protocol". This finding coincided with an earlier report suggesting an inspired gas mixture of 30% O₂ in He as the safest for use in laser surgery of the airway [13]. Similarly, at the authors’ institution at the large animal hospital there have been no incidents of laser combustion of the endotracheal tube (ETT) or airway fire in more than 300 horses that underwent inhalation anesthesia with a He/O₂ gas mixture (FIO₂ < 0.4) for laser surgery in the airway. Thus, it is fair to conclude that use of He/O₂ avoids the necessity for employing shielded ETTs in anesthesia for airway laser surgery [6].

Technical Requirements for use of He/O₂ with Common Large Animal Anesthesia Machines
Helium/oxygen gas mixtures can be ordered from standard medical gas suppliers. At the authors’ institution, a gas mixture of 30% O₂ and balanced helium 70% (Heliox) is used. The Heliox gas mixture is supplied in "H" size tanks (about 7000 L gas volume) at a cost of approximately $70.00, with each tank lasting for about 15 - 25 surgeries dependent on the duration of the laser procedure and the Heliox gas flow. At the start of inhalant anesthesia, the authors usually choose a Heliox gas flow of about 5 - 6 L/min and an O₂ flow of about 1 - 2 L/min. If the inspired O₂ concentration exceeds 40%, the O₂ flow is gradually
reduced till a FiO2 < 0.4 is reached. The Heliox gas flow may later be reduced to lower flow rates of 3 - 4 L/min with appropriate reduction of the O2 flow to meet the goal of the lowest inspired O2 concentration necessary to ensure adequate oxygenation of the patient. Use of the Heliox gas mixture requires only minor technical modifications that can be carried out without great difficulty on most large animal anesthesia machines. Next, we briefly describe technical modifications made on a Dräger Large Animal Control Center (North American Dräger, Telford, PA) and a Mallard Model 2800 Large Animal Anesthesia Machine (Mallard Medical Inc., Redding, CA).

Large animal anesthesia machines can be fitted with a separate Porter style flow meter (Fig. 1b) for controlling the flow of the He/O2 gas mixture. In the simplest case, such as the Dräger unit (Fig. 1a), one might only replace the flow tube from an already existing nitrous oxide flow meter with a flow tube calibrated for Heliox gas mixture (30% O2, balanced helium; Fig. 1b). The flow tube is commercially available from Dräger Medical, Inc. (formerly North American Dräger). Some large animal anesthesia machines like the Mallard unit (Fig. 1c) are not equipped with two flow meters and thus require the installation (potentially by the manufacturer) of a second flow meter with a flow tube calibrated for the He/O2 (70/30%) gas mixture. The tubing that originates at the Heliox flow meter joins tubing from the oxygen flow meter via a Y-piece connector (see Fig. 1d for gas tube assembly). This allows both the blending of the Heliox gas with 100% O2 to achieve in the breathing circuit a higher FiO2 to ensure adequate oxygenation of the individual patient. It also allows rapid return to 100% O2 as the sole carrier gas once the laser is not anymore in use. To supply the Heliox flow meter, an "H" tank of Heliox gas mixture is fitted with a pressure-reducing regulator (2000 psig [13.789MPa] reduced to 50 psig [345 kPa]) and then connected to the back of the anesthesia machine using a high pressure hose (100 psig [680 kPa] rating) and DISS (diameter index safety system) fitting designated for "special" mixed breathing gases.

In order to recognize delivery of a hypoxic gas mixture to the patient, a commercially available galvanic oxygen sensor (Fig. 2) should be mounted on the anesthesia machine, unless other multigas and anesthetic agent monitors with oxygen sensor function are available. These oxygen cells (also called FIO2 sensors) will allow continuous monitoring of the inspired O2 concentration. Since standard FIO2 sensors do not easily adapt to large animal anesthesia circuits, custom adaptations must be made to allow for accurate FIO2 measurement. The simplest solution is to drill a hole in the top of the inspiratory dome valve and glue on an appropriately sized PVC tube that matches the oxygen sensor to be used (Fig. 2 A-C). As a part of the anesthesia machine checkout, the FIO2 analyzer is calibrated first with room air (21% O2; Fig. 2D) and then with 100% O2. Once calibrated, the Heliox gas mixture is checked to ensure a fraction of 30% O2. When properly calibrated, these standard oxygen sensors are quite accurate, although a modest drift over time can occur in high humidity conditions.

Additional Monitoring Required for Safe use of Low O2 Gas Mixtures
During periods of low FIO2 inhalation anesthesia careful monitoring of the horse’s hemodynamic and respiratory functions is critical in order to detect signs of hypoxemia as early as possible and to respond appropriately. Besides FIO2 monitoring, continuous pulse oximetry and intermittent arterial blood gas analysis are important means to accurately evaluate the patient’s respiratory function and oxygenation status. A portable blood gas analyzer (e.g., AVL OPTI CCA, Roche Diagnostics, Indianapolis, IN; i-STAT system, Sensor Devices Inc., Waukesha, WI) stationed in or in close proximity to the operating
room facilitates immediate blood gas analysis if needed.

**Experiences with a Helium/oxygen Carrier Gas Mixture (He/O₂) in Inhalation Anesthesia for Horses Undergoing Airway Laser Surgery**

Based on extensive experience with He as the primary carrier gas in inhalation anesthesia for horses, the authors believe that an inhalant anesthetic protocol employing a He/O₂ gas mixture with low FiO₂ (< 0.4) offers a safe and potentially advantageous alternative to TIVA, which is generally more frequently advocated for upper airway laser surgery. Arterial blood gas results as well as hemodynamic data (Table 1 and 3) from more than 100 clinical patients anesthetized with volatile anesthetics (isoflurane; sevoflurane), under those conditions for various laser procedures in the upper airway, support this conclusion. Furthermore, in more than 10 years of routine practice of laser surgery in the airway of horses at the University of Pennsylvania’s Large Animal Hospital, no case of endotracheal tube combustion or any other incidence of airway fire has been reported, though incomplete punctures of endotracheal tubes by misdirected laser beams have been occasionally encountered.

Anesthesia was performed in all horses, whose data are presented in Table 1 and Table 3, following a routine inhalant anesthetic protocol with only minor adaptations mentioned below. Necessary technical modifications of the anesthesia machine that allows use of Heliox as the primary carrier gas have been already described. After premedication with either one or a combination of acepromazine, butorphanol, xylazine, and detomidine, anesthesia was induced with clinically common drug combinations of guaifenesin and/or diazepam plus ketamine or thiopental. Immediately following nasotracheal (most commonly) or orotracheal intubation, horses were placed in lateral (most frequently) or dorsal recumbency. The endotracheal tube was connected to an anesthetic rebreathing circuit, from which the animals were immediately breathing a He/O₂ gas mixture low in FiO₂. Anesthesia was maintained with either isoflurane or sevoflurane in helium and oxygen, using an initial total fresh gas flow (i.e., Heliox plus O₂) of 6 - 8 L/min that was changed to a lower total fresh gas flow rate of 4 - 6 L/min if the surgical procedure lasted longer than 30 - 45 min. Blending of Heliox with 100% O₂ was aimed to yield an initial FiO₂ of 0.3 - 0.4, as measured with the oxygen sensor built in the inspiratory limb of the anesthetic circuit. Standard instrumentation for monitoring of hemodynamic, respiratory and oxygenation parameters was applied to all patients and included ECG, pulse oximetry, FiO₂ and peak airway pressure recording, side-stream capnography, and invasive blood pressure and body temperature recording. Provided hemodynamic parameters were within acceptable range, intermittent positive pressure ventilation was instituted soon after completion of instrumentation or as soon as hemodynamic support therapy with IV fluids, inotropes (dobutamine or ephedrine), and occasionally vasopressors (phenylephrine) took effect. Previous experience indicated that mechanically ventilated horses were less likely to be hypoxic than those breathing spontaneously. Arterial blood samples for blood gas analysis were drawn after catheterization of an artery, i.e., usually before the first activation of the laser instrument. This allowed fine adjustment of both FiO₂ and mechanical ventilation prior to beginning the laser procedure, particularly in those cases in which blood gas data revealed hypoxemia and/or hypoventilation. Besides careful monitoring of the pulse oximeter signal, repeated blood gas analysis during the period of laser use was employed to detect changes in respiratory function, allowing for rapid corrective measures if needed. Following conclusion of the laser procedure, which lasted usually between 30 and 60 minutes, surgery proceeded with conventional techniques. At this time, the Heliox gas was turned off and inhalation anesthesia continued under low flow conditions (2.5 - 4 L/min) with 100% O₂ as the sole fresh gas source.

The anesthetic records of 108 normal size and 25 draft horses anesthetized between 1999 and 2003 for laser surgery in the upper airway were reviewed (Table 1 and Table 2). Results from arterial blood gas analyses in these isoflurane anesthetized and mechanically ventilated horses revealed that use of a He/O₂ gas mixture low in FiO₂ (< 0.4) allows adequate oxygenation in the majority of equine patients, at least for the limited time of Heliox application (usually no longer than 60 - 90 min). Nevertheless, arterial oxygen saturation (SaO₂) decreased in 2 out of 108 normal sized and 1 out of 25 draft horses below 90%, stressing the necessity for continuous monitoring for signs of oxygen desaturation.

As was to be expected, arterial partial pressures of oxygen (PₐO₂) were on average lower in draft as compared to normal sized horses, indicating that horses of the giant breeds are at an appreciably higher risk of developing hypoxemia during low FiO₂ anesthesia (Table 1 and Table 2).
Minute ventilation ($V_{\text{min}}$); inspired oxygen fraction ($FiO_2$); arterial partial pressures of oxygen ($PaO_2$) and carbon dioxide ($PaCO_2$); arterial oxygen saturation ($SaO_2$); arterial standard base excess (SBE). Data recorded during the laser procedure are from 91 male and 17 female horses of various non-draft breeds.

Data recorded during the laser procedure are from 21 male and 4 female draft horses of various breeds.
Table 3. Hemodynamic, respiratory, and arterial blood gas and acid base variables in horses anesthetized with sevoflurane in He/O2 for airway laser surgery.

<table>
<thead>
<tr>
<th>Physiological parameter</th>
<th>Post induction</th>
<th>During laser procedure</th>
<th>Post laser procedure</th>
</tr>
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<tbody>
<tr>
<td>HR (per min)</td>
<td>37 +/- 3</td>
<td>37 +/- 2</td>
<td>37 +/- 3</td>
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<tr>
<td>SAP (mm Hg)</td>
<td>104 +/- 10</td>
<td>101 +/- 8</td>
<td>114 +/- 7</td>
</tr>
<tr>
<td>DAP (mm Hg)</td>
<td>57 +/- 4</td>
<td>57 +/- 8</td>
<td>68 +/- 11</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>74 +/- 6</td>
<td>73 +/- 9</td>
<td>86 +/- 11</td>
</tr>
<tr>
<td>CO (L/min)</td>
<td>34.6 +/- 6.6</td>
<td>32.9 +/- 6.9</td>
<td>34.9 +/- 4.4</td>
</tr>
<tr>
<td>CI (L/min/m²)</td>
<td>5.31 +/- 0.81</td>
<td>5.03 +/- 0.77</td>
<td>5.39 +/- 0.72</td>
</tr>
<tr>
<td>He/O2 gas flow (L/min)</td>
<td>6.8 +/- 1.1</td>
<td>5.5 +/- 0.9</td>
<td>2.8 +/- 0.4</td>
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<tr>
<td>FiO2</td>
<td>0.26 +/- 0.04</td>
<td>0.28 +/- 0.04</td>
<td>0.57 +/- 0.07</td>
</tr>
<tr>
<td>SEVOET (%)</td>
<td>2.4 +/- 0.4</td>
<td>2.5 +/- 0.2</td>
<td>2.6 +/- 0.3</td>
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<tr>
<td>Vmin (mL/kg/min)</td>
<td>87 +/- 8</td>
<td>80 +/- 9</td>
<td>80 +/- 11</td>
</tr>
<tr>
<td>Peak PAW (cm H2O)</td>
<td>27 +/- 4</td>
<td>28 +/- 3</td>
<td>29 +/- 3</td>
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<tr>
<td>PETCO2 (mmHg)</td>
<td>43 +/- 10</td>
<td>36 +/- 5</td>
<td>36 +/- 4</td>
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<tr>
<td>pHa</td>
<td>7.40 +/- 0.05</td>
<td>7.46 +/- 0.04</td>
<td>7.45 +/- 0.05</td>
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<tr>
<td>PaCO2 (mmHg)</td>
<td>51 +/- 6</td>
<td>43 +/- 4</td>
<td>44 +/- 6</td>
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<tr>
<td>PaO2 (mmHg)</td>
<td>104 +/- 29</td>
<td>113 +/- 18</td>
<td>266 +/- 72</td>
</tr>
<tr>
<td>HCO3- (mmol/L)</td>
<td>31 +/- 3</td>
<td>31 +/- 2</td>
<td>32 +/- 2</td>
</tr>
<tr>
<td>SBE (mmol/L)</td>
<td>6.3 +/- 2.9</td>
<td>6.8 +/- 1.8</td>
<td>8.0 +/- 2.1</td>
</tr>
<tr>
<td>SaO2 (%)</td>
<td>98 +/- 2</td>
<td>99 +/- 1</td>
<td>100 +/- 0</td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td>0.7 +/- 0.2</td>
<td>0.7 +/- 0.1</td>
<td>0.7 +/- 0.2</td>
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Heart rate (HR); systolic (SAP), diastolic (DAP), and mean arterial pressure (MAP); cardiac output (CO); cardiac index (CI); He/O2 gas flow representing combined flow from Heliox and O2 flow meters; inspired oxygen fraction (FiO2); end-tidal concentration of sevoflurane (SEVOET) and carbon dioxide (PETCO2); minute ventilation (Vmin); peak airway pressure (PAW); arterial partial pressures of oxygen (PaO2) and carbon dioxide (PaCO2); arterial bicarbonate concentration (HCO3-); standard base excess (SBE); and arterial oxygen saturation (SaO2). Values are means +/- SD of 6 Thoroughbred horses (4 +/- 2 years; 517 +/- 56 kg), premedicated with IV acepromazine 0.02 mg/kg, butorphanol 0.03 mg/kg, and xylazine 0.3 mg/kg, and then anesthesia induced with IV guaifenesin 0.04 mg/kg, diazepam 0.1 mg/kg, and ketamine 2.0 mg/kg.

Anesthesia in the horse is known to be accompanied by derangements of pulmonary gas exchange leading to impaired arterial blood oxygenation, despite animals breathing oxygen-rich gas mixtures (FiO2 > 0.8) [14-16]. The most important change regarding arterial oxygenation is the development of a large right-to-left intrapulmonary vascular shunt, with blood perfusing unventilated areas of the lung [17]. Therefore significant concern existed whether horses breathing a He/O2 gas mixture low in FiO2 would be able to maintain adequate arterial blood oxygenation. However, the retrospective analysis of blood gas data
obtained in this large population of clinical patients anesthetized with a He/O2 gas mixture does not seem to support this concern. In fact, previous studies in anesthetized human patients demonstrated that if the use of 100% O2 is avoided during inhalation anesthesia and the FiO2 is maintained at moderately low levels (e.g., 0.4), no or very little atelectasis is produced [18]. Furthermore, changing the inspired gas mixture from room air to 100% O2 in patients showing significant regional ventilation-perfusion (V/Q) mismatching has been shown not to improve blood oxygenation but instead to worsen it due to aggravation of right-to-left shunting [19]. It is thought that the increase in shunt fraction during anesthesia is due to a phenomenon described as absorption atelectasis, which progressively converts poorly ventilated areas of the lung (i.e., units with low V/Q ratio) into atelectatic foci by rapid and complete O2 uptake from those units, which are no longer being ventilated [19]. In humans, atelectatic shunting is effectively reduced during breathing of gas mixtures composed largely of inert gases (e.g., N2 or He), which are minimally absorbed and therefore keep small airways and alveoli open even if underventilated. The same reasons may explain why horses can maintain a reasonably good blood oxygenation while breathing a He/O2 gas mixture with low FiO2.

To further substantiate our conclusion that inhalant anesthesia using a He/O2 gas mixture with low FiO2 (< 0.4) can be safely administered in the horse for at least a limited period of time, we conducted also a small prospective study, in which the inspired O2 concentration during sevoflurane in He/O2 anesthesia was kept below 30% (Table 3).

To further substantiate our conclusion that inhalant anesthesia using a He/O2 gas mixture with low FiO2 (< 0.4) can be safely administered in the horse for at least a limited period of time, we conducted also a small prospective study, in which the inspired O2 concentration during sevoflurane in He/O2 anesthesia was kept below 30 %. Arterial blood gas and acid base data obtained in this group of horses support the idea that it might be feasible to reduce FiO2 even further below the threshold of 30% of O2 (FiO2 > 0.3), above which the risk of ETT combustion significantly rises [20-22]. Hemodynamic data, including cardiac output (as measured by the lithium dilution technique [23]), showed no clinically significant difference whether measured during periods of low or high FiO2, thus indicating that a lower inspired oxygen concentration is not associated with compromised cardiovascular function.

Admittedly, horses undergoing laser surgery in their upper airway are commonly relatively young and systemically healthy animals. Hence, conclusions as to the safety of an inhalant anesthetic protocol employing a He/O2 gas mixture with low FiO2 (< 0.4) may not apply to a much older or otherwise compromised patient population.

References


