Prevention of Airway Fires: Do Not Overlook the Expired Oxygen Concentration

Matthew Remz, Isaac Luria, BS, Michael Gravenstein, Scott D. Rice, Timothy E. Morey, MD, Nikolaus Gravenstein, and Mark J. Rice, MD

BACKGROUND: It is generally accepted that when an ignition source is used the inspired oxygen concentration (FIO2) should be <30% in the breathing circuit to help prevent airway fires. The time and conditions required to reduce a high O2% in the breathing circuit to <30% has not yet been systematically studied.

METHODS: We evaluated the inspired and expired circuit oxygen concentration response times of an Aestiva Avance S/5 anesthesia machine to reach an FIO2 of <30% from a starting FIO2 of 100% and 60% after reducing the FIO2 to 21%. The circuit was connected to a human patient which has a functional residual capacity of 2 L, total lung capacity of 2.8 L, an oxygen consumption of 200 mL/min, and respiratory quotient of 0.8. Fresh gas flow (FGF) inputs of 2 L/min and 5 L/min were chosen to represent a spectrum of typical clinical FGF rates. Minute ventilation was set at 4 L/min. Determining the requisite median time to reach an O2 concentration of <30% in the breathing circuit was the primary aim of the study.

RESULTS: The median times (1st–99th percent confidence interval) required to achieve inspiratory and expiratory oxygen concentrations of <30% with the extended circuit configuration when starting at 60% for 5 L FGFs were 35 (32–36) and 104 (88–122) seconds, respectively. With 2 L FGF, these median times increased to 303 (291–313) and 255 (232–278) seconds, respectively. A shortened circuit configuration (P = 0.006) and higher FGF flow rate (P < 0.0001) were noted to be factors decreasing the median time required to achieve an oxygen concentration of <30%.

CONCLUSIONS: Both inspired and expired circuit oxygen concentration may take minutes to decrease to <30% depending on circuit length, FGF rate, and starting circuit oxygen concentration. During the reduction in FIO2, the expiratory oxygen concentration may be >30% for a considerable time after the FIO2 is in a "safe" range. An increased expired oxygen concentration should also be considered an airway fire risk, and patient care protocols may need to be modified based on future studies. (Anesth Analg 2013;117:1172–6)

More than 600 so called “on patient” fires occur in the United States every year.1-4 Of the approximately dozen fires per week, about 21% occur in the airway despite reductions in inspired oxygen concentration (FIO2) to less than the recommended 30%.5 During general anesthesia, the FIO2 typically ranges from 40% to 100%. Therefore, initiation of laser or electrocautery in the airway dictates reduction in the airway oxygen concentration when clinically feasible. It is important to emphasize that even with a fully inflated endotracheal tube cuff, oxygen-enriched air can leak above the cuff, setting the stage for an airway fire in the pharynx. The time required to reduce a high FIO2 to <30% in the breathing circuit has not been systematically studied and may not be a simple time constant calculated from fresh gas flow (FGF) and circuit volume because the anesthesia machine is not a “single, well mixed compartment,” “…complicated anesthesia breathing system…”6 The breathing circuit is an intermediary between a laminar flow and complex mixing system that is influenced by factors such as the specific anesthesia machine, FGF rate, minute ventilation, and the volume of the breathing gas containing components. An understanding of the relationship between these factors provides clinical guidance and is critical to fire prevention. The American Society of Anesthesiologists (ASA) has issued a practice advisory that details the existing evidence for both prevention and management of operating room fires.7 Additionally, the Anesthesia Patient Safety Foundation has recently published a fire safety video that should be viewed by any practitioner who participates in cases with fire risk.8

The primary aim of the study was to determine the median times required for both the inspired and expired oxygen concentrations to reach an FIO2 of <30% when starting from an oxygen concentration of either 100% or 60% and to better characterize the interaction of the aforementioned factors. Although the FIO2 has been the classic focus of airway fire prevention, we wondered how the expired oxygen concentration behaved during a breathing circuit FIO2 reduction. Thus, the secondary aims of the study were to describe the interaction of the starting inspired oxygen concentration, FGF, and circuit volume and a description of the airway oxygen concentration (inspired and expired) over time.


**METHODS**

We evaluated the circuit oxygen concentration response times of an Aestiva Avance S/5 (GE Healthcare, Waukesha, WI) in reaching an \( \text{Fio}_2 \) of <30% from a starting \( \text{Fio}_2 \) of 100% and 60%. We varied breathing circuit volume, initial \( \text{Fio}_2 \) concentration, and FGFs. Total breathing circuit volume (inspiratory and expiratory limbs) of 1.67 L total volume (length = 0.190 m) or 5.3 L total volume (length = 0.532 m) were used to investigate the effects of circuit volume. Volumes of the limbs were determined using the fully extended and fully compressed lengths and determining the filling volume with water and a graduated cylinder.

Initial oxygen concentrations were set to 100% or 60% and verified before experimentation using a calibrated rapid response paramagnetic oxygen sensor (Capnomac Ultima ULT-I.09.EN, Datex/GE Healthcare). Gas sampling (180 mL/min) was in the conventional location at the breathing circuit Y-piece. The circuit was connected to a human patient simulator (version B, software version 6.4, CAE Healthcare/Medical Education Technologies Inc., Sarasota, FL) using an 8.0-mm internal diameter cuffed endotracheal tube (Mallinckrodt™, Covidien, Mansfield, MA). FGF inputs of 2 and 5 L/min were chosen to represent a spectrum of typical clinical FGF rates. Each experimental run continued until the sampled inspired and expired gas concentrations reached the target of <30%. Each combination of breathing circuit volume, starting oxygen concentration, and FGF was individually tested 6 times.

The human patient simulator that we used has a functional residual capacity (FRC) of 2 L, total lung capacity of 2.8 L, an oxygen consumption of 200 mL/min, and respiratory quotient of 0.8. These variables were kept constant for all studies. The human patient simulator was ventilated as if under neuromuscular blockade using volume controlled mechanical ventilation of 400 mL per breath and 10 breaths per minute. The set 4 L minute ventilation was measured to be 3.7 L on average via the spirometry module sensor (Capnomac Ultima ULT-I.09.EN, Datex/GE Healthcare).

The FGF, initial \( \text{Fio}_2 \), and circuit length were verified before beginning data collection. Time was recorded, and \( t = 0 \) seconds was taken to be the time of gas composition adjustment from the initial \( \text{Fio}_2 \) (60% or 100%) to air (21% \( \text{O}_2 \)) when maintaining a consistent total FGF. The inspired and expired oxygen concentrations were recorded every 6 seconds (once per breath) from the side stream gas analyzer sampling at the circuit Y-piece. The time was recorded for at least 3 breaths past the point that \( \text{Fio}_2 \) was <30%.

**Statistical Analysis**

Data were analyzed for normality using Kolmogorov-Smirnov test with Lilliefors correction. Because the data were not normally distributed as is not infrequent for time data associated with anesthesia, central tendencies are reported as median values with dispersions as 1st to 99th percent 2-sided confidence intervals of the median after log transformation using IBM SPSS Statistics v21 (Chicago, IL). Calculations were performed using the student \( t \) distribution applied to the log times and then exponentials were taken. Inferential comparisons were performed with 3-way analysis of variance on log-transformed data (factors: [1] circuit configuration [extended or shortened], [2] flow rate [high or low], [3] circuit limb [inspiratory or expiratory]). A \( P \) value of <0.01 was considered statistically significant. If an overall \( P \) value of <0.01 was achieved, all pairwise comparisons were performed with Holm-Sidak corrections for multiple comparisons.

**RESULTS**

Examples of the time-course variations in oxygen concentrations from 60% to 21% at high and low FGF rates are shown in Figures 1 and 2, respectively. These data were used to calculate the summary data of the latency to observe an oxygen concentration of <30% (Table 1). For example, as noted in Table 1 and illustrated in Figures 1 and 2, the median times (1st–99th confidence intervals) to achieve inspiratory and expiratory oxygen concentrations of <30% with the extended circuit configuration when starting from 60% for 5 L FGF were 35 (32–36) and 104 (88–122) seconds, respectively. The median times required to achieve inspiratory- and expiratory oxygen concentrations of <30% with the extended circuit configuration when starting from 60% for 2 L FGF were 303 (291–313) and 255 (232–278) seconds, respectively. A shortened circuit configuration (\( P = 0.006 \)) and higher FGF rates (\( P < 0.0001 \)) were noted to be factors decreasing the time required to achieve an oxygen concentration of <30%. In addition, the median time required to achieve an oxygen concentration of <30% was shorter in the inspiratory limb of the breathing circuit compared with the expiratory limb (\( P < 0.0001 \)). Additional data and observed statistical differences are noted in Table 1.

Similar observations were made when the FGF oxygen concentration was abruptly decreased from 100% to 21% as noted in Table 2. The FGF rate (\( P < 0.0001 \)) affected the median time required for oxygen concentration to reduce to <30%, but the circuit configuration did not (\( P = 0.26 \)). The oxygen concentration decreased rapidly in the inspiratory limb compared with the expiratory limb (\( P < 0.0001 \)). Higher FGF

**Figure 1.** Time course of inspiratory and expiratory oxygen concentrations after an abrupt change of flowmeters to reduce the oxygen from 60% to 21% during higher fresh gas flows (5 L/min) and an extended circuit. The dashed, red reference line denotes 30% oxygen concentration, the maximal concentration recommended during laser ignition. Data shown are the median with 1st to 99th percent confidence intervals for 6 experiments.
Airway Fires: Expired Oxygen Concentration

rates caused more rapid decrements in oxygen concentration both for the inspiratory (P < 0.0001) and expiratory (P < 0.0001) limbs compared with lower FGF rates. Variation in inspired and expired oxygen concentrations was a significant factor in higher flow conditions (P < 0.0001), but not in lower conditions (P = 0.22).

**DISCUSSION**

Higher FGFs, shorter circuit lengths, and initially lower Fio2 all contributed to faster attainment of an acceptable Fio2 of <30%. Although not previously reported in detail, these are not surprising findings. We observed a steep and relatively fixed decrease in oxygen concentration after the reduction in Fio2 that was highly dependent on the initial oxygen concentration and FGF rate. Higher FGF rates allow much quicker oxygen concentration reduction to <30%. To optimize circuit conditions in the airway before using the laser or electrocautery, it is important to be familiar with these factors and with the time it can take to achieve the target circuit oxygen concentration.

Depending on the FGF rate, the circuit length, and the initial Fio2, it can take from just less than a minute to more than 5 minutes to attain circuit oxygen concentrations of <30%. This is especially true for the expired oxygen concentration wherein reduction to the targeted range takes significantly longer than does the inspired. A breach in the circuit or an underinflated cuff allowing oxygen leakage exposes the ignition source to expired as well as inspired oxygen concentrations. For this reason, clinicians should be mindful of both values. Although the inspired oxygen concentration decreases below 30% at high FGF (5 L/min) in approximately 40 seconds, it takes approximately an additional 60 seconds for the expired oxygen concentration to decrease below this safe metric. It is common practice for anesthesia providers to monitor the Fio2 carefully after they reduce the FGF oxygen concentration. However, the expired oxygen concentration can still be dangerously high and easily support combustion for a considerable time, as demonstrated in the figures.

During controlled ventilation with a normal I/E ratio of 1:2, 66% of the respiratory cycle is spent in exhalation. Thus, the expired oxygen concentration is an important variable and should be taken into consideration during cases when airway fires are possible. If apnea is not requested, a potential strategy to consider is using the laser or electrocautery during the inhalation phase of the respiratory cycle when the inspired oxygen may have a lower concentration than the expired.

![Figure 2. Time course of inspiratory and expiratory oxygen concentrations after an abrupt change of flowmeters to reduce the oxygen from 60% to 21% during lower fresh gas flows (2 L/min) and an extended circuit. The dashed, red reference line denotes 30% oxygen concentration, the maximal concentration recommended during laser ignition. Data shown are the median with 1st to 99th percent confidence intervals for 6 experiments.](image)

---

**Table 1. Median Time to Achieve a Measured Oxygen Concentration <30% in the Inspiratory or Expiratory Limbs of a Semiclosed Anesthetic Circuit After Reducing Fresh Gas Flow Oxygen Concentrations from 60% to 21% for a Given Circuit Configuration and Fresh Gas Flow**

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Circuit limb</th>
<th>Fresh gas flow (L/min)</th>
<th>Higher (5)</th>
<th>Lower (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended</td>
<td>Inspiratory</td>
<td>35 (32–36)</td>
<td>303 (291–313)</td>
<td>*†</td>
</tr>
<tr>
<td></td>
<td>Expiratory</td>
<td>104 (88–122)</td>
<td>255 (222–278)</td>
<td>†</td>
</tr>
<tr>
<td>Shortened</td>
<td>Inspiratory</td>
<td>24 (23–30)</td>
<td>264 (253–272)</td>
<td>*†</td>
</tr>
<tr>
<td></td>
<td>Expiratory</td>
<td>83 (70–122)</td>
<td>189 (176–194)</td>
<td>†</td>
</tr>
</tbody>
</table>

Data shown are median values with the 1st to 99th percent confidence intervals noted parenthetically for 6 experiments for each value. P < 0.01: *Inspiratory compared with expiratory for higher flow and same circuit configuration; †Higher compared with lower flow for same circuit configuration and circuit limb.

**Table 2. Median Times to Achieve a Measured Oxygen Concentrations <30% in the Inspiratory or Expiratory Limbs of a Semiclosed Anesthetic Circuit After Reducing Fresh Gas Flow Oxygen Concentrations from 100% to 21% for a Given Circuit Configuration and Fresh Gas Flow**

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Circuit limb</th>
<th>Fresh gas flow (L/min)</th>
<th>Higher (5)</th>
<th>Lower (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended</td>
<td>Inspiratory</td>
<td>48 (39–50)</td>
<td>498 (464–520)</td>
<td>*†</td>
</tr>
<tr>
<td></td>
<td>Expiratory</td>
<td>163 (127–197)</td>
<td>432 (411–447)</td>
<td>†</td>
</tr>
<tr>
<td>Shortened</td>
<td>Inspiratory</td>
<td>30 (28–34)</td>
<td>450 (431–467)</td>
<td>*†</td>
</tr>
<tr>
<td></td>
<td>Expiratory</td>
<td>143 (109–185)</td>
<td>363 (346–384)</td>
<td>†</td>
</tr>
</tbody>
</table>

Data shown are median values with the 1st to 99th percent confidence intervals noted parenthetically for 6 experiments for each value. P < 0.01: *Inspiratory compared with expiratory for higher flow and same circuit configuration; †Higher compared with lower flow for same circuit configuration and circuit limb.
The anesthesia machine may be useful. 13 The Emergency Care Research Institute recommends: “…immediately and simultaneously disconnect the breathing circuit from the tracheal tube and remove the tube.”5 The ASA Practice Advisory calls for removal of the tracheal tube followed by discontinuation of all airway gases.7 Because the FRC provides an oxygen reservoir, which now has been demonstrated as flame supporting, we believe immediately pulling the tube and not disconnecting the airflow may actually be the wisest course of immediate action to limit patient injury.

We have extrapolated from our expiratory oxygen concentration data that this may be a cause of some airway fires. However, in this study, we did not measure the oxygen concentration in the endotracheal tube. Also, we studied only a single anesthesia machine. Other machines may yield slightly different results.

In conclusion, we have shown that depending on circuit length, FGF rate, and starting circuit oxygen concentration, the reduction of the (inspired and expired) circuit oxygen concentration may take minutes to reach a “safe” level of <30%. Furthermore, the expiratory oxygen concentration may still be >30%, even with safe levels of inspired oxygen. We suggest that an alarm be set for an expired oxygen concentration >30% and that documentation of expired oxygen concentration <30% appear in the anesthetic record before use of airway cautery or laser. Finally, high levels of oxygen in the FRC may be the cause of the delay in the decrease of the expired oxygen concentration. The teaching of first turning off the FGF instead of first removing the breathing tube during an airway fire should be reconsidered. Based on these data, Table 3 includes suggested revised steps to avoid and treat an airway fire.

Table 3. Suggested Revised Steps to Prevent and Treat an Airway Fire

To help prevent airway fires:

- Begin with lower Fio2
- Use high fresh gas flows when decreasing Fio2
- Use a shorter circuit, if possible

In addition to monitoring the inspired concentration, carefully observe the expired oxygen concentration after reduction in the Fio2

In the event of an airway fire:
- First, pull the endotracheal tube—the expired oxygen concentration may be higher than the inspired concentration!
- Extinguish the fire

Fio2 = inspired oxygen concentration.

**DISCLOSURES**

Name: Matthew Remz.
Contribution: This author helped design and conduct the study, analyze the data, and write the manuscript.
Attestation: Matthew Remz approved the final manuscript.
Name: Isaac Luria, BS.
Contribution: This author helped conduct the study and analyze the data.
Attestation: Isaac Luria approved the final manuscript.
Name: Michael Gravenstein.
Contribution: This author helped conduct the study and analyze the data.
Attestation: Michael Gravenstein approved the final manuscript.
Name: Scott D. Rice.
Contribution: This author helped conduct the study and analyze the data.
Attestation: Scott D. Rice approved the final manuscript.
Name: Timothy E. Morey, MD.
Contribution: This author helped design and conduct the study, analyze the data, and write the manuscript.
Attestation: Timothy E. Morey approved the final manuscript.
Name: Nikolaus Gravenstein, MD.
Contribution: This author helped design and conduct the study, analyze the data, and write the manuscript.
Attestation: Nikolaus Gravenstein approved the final manuscript.
Name: Mark J. Rice, MD.
Contribution: This author helped design and conduct the study, analyze the data, and write the manuscript.
Attestation: Mark J. Rice approved the final manuscript.

This manuscript was handled by: Sorin J. Brull, MD, FCARCSI.
REFERENCES