Volatile anesthetic agents act as greenhouse gases. Low-flow anesthesia techniques (≤1 L/min) are associated with lower costs. Decreasing volatile anesthetic delivery provides safe and effective strategies for anesthesia providers to decrease costs and reduce environmental pollution. This evidence-based project aimed to estimate cost savings and reduction in the environmental release of anesthetic gases, under simulated lower fresh gas flow (FGF) practices. For each surgical case, the exhaled anesthetic gas percent and FGF data were used to calculate the volume of fluid volatile anesthetic. The fluid volatile anesthetic for each case was then estimated using simulated FGFs. Changes in volatile agent cost and environmental release of anesthetic gases were predicted.

Sevoflurane was the most commonly used volatile agent. The mean FGF for cases using sevoflurane was 2.5 L/min. The simulated FGF of 1 L/min FGF across all agents predicted a 48% ($50,892) reduction in costs of volatile anesthetics and a 42% (33 metric tons of carbon dioxide equivalent) decrease in carbon emissions. Simulated low-flow anesthesia demonstrated cost savings and environmental conservation. Project findings align with current literature showing that lowering FGFs represents an area of cost containment and an opportunity to lessen the environmental impact of anesthesia.

Keywords: Closed-circuit, compound A, inhalation anesthesia, low-flow anesthesia.
The purpose of this analysis was to use an evidence-based approach to understand how changing FGF could have an impact on the total volume of liquid anesthetic used. The project aimed to report subsequent potential savings and environmental benefits by lowering FGF.

Methods

This evidence-based project was classified as exempt research by the local institutional review board. Surgical cases measuring expired volatile agents (desflurane, isoflurane, and sevoflurane) from a tertiary medical center in the Pacific Northwest were included. Pediatric procedures involving children less than 10 years of age were excluded, avoiding case data from inhalation inductions requiring high flows. Cases in which multiple volatile anesthetic agents were used were also excluded from the analysis. Deidentified data for general anesthesia cases in 2017 were extracted and manipulated in a server database (SQL Server database, Microsoft Corp) and in a spreadsheet (Excel, Microsoft Corp).

For every minute of each case a volatile agent was recorded, the FGF rate (liters per minute) and the percentage of expired anesthetic gas were compiled. The exhaled anesthetic gas percent and the FGF data were used to calculate the milliliters of fluid volatile anesthetic (FVA) used in each minute interval (Figure 1).

\[
\text{Fluid Volatile Agent} = \frac{\text{FG flow (ml/min)} \times \text{VA conc. (Vol%)} \times \text{Anesthesia duration (min)} \times \text{Saturated vapor volume (ml/ml)} \times 100 (\text{Vol%})}{\text{ml}}
\]

Figure 1. Biro Equation to Calculate Volume of Liquid Anesthetic Consumed

Abbreviations: FG, fresh gas; VA conc., volatile anesthetic concentration; Vol, volume.

The minute interval FVAs were summed for each case. Appropriate vapor-to-liquid constants for the 3 inhaled anesthetic gases were used.

Using the Biro equation, the FVA for each case was then predicted by substituting actual flow rates with simulated FGFs. Also used was the average end-tidal volatile agent percentage and the total duration with a volatile agent expired percent (not minute-by-minute). The predicted FVAs at each simulated FGF were then summed to demonstrate the difference in total FVA had each case instead employed the simulated FGF (Figure 2).

\[
\text{Fluid Volatile Agent} = \frac{\text{Simulated FGF (ml/min)} \times \text{Average VA conc. (Vol%)} \times \text{Duration (min)} \times \text{SVV (ml/ml)} \times 100 (\text{Vol%})}{\text{SVV (ml/ml)} \times 100 (\text{Vol%})}
\]

Figure 2. Equation Used to Predict Liquid Volatile Agent Volume With Simulated FGFs

Abbreviations: FGF, fresh gas flow; VA conc., volatile anesthetic concentration; Vol, volume.

A correction factor was applied to each total predicted FVA because the use of average FGFs and average volatile agent concentration yields less accurate data. The correction factor was obtained for each agent by comparing the actual FVA (summed from minute-to-minute calculations) to the FVA using average expired agent, average FGF, and total minutes with expired volatile agent. The FVA calculated using averages was larger than the actual FVA for all 3 agents. For this reason, the actual FVA was divided by the FVA using averages to establish a correction factor (percent difference) that was then applied to each predicted FVA at given FGFs. The correction factors were established to be 0.89 (sevoflurane), 0.98 (isoflurane), and 0.79 (desflurane).

A predictive analysis of waste emissions and cost savings associated with simulated average FGFs was completed. Estimated cost changes (in US dollars) and estimates of environmental impact were calculated for simulated alterations in FGF practices. The approximate purchasing costs (due to the proprietary nature of specific purchasing costs) of individual bottles of the inhaled anesthetics were obtained from the medical center. Carbon dioxide equivalents (CO\textsubscript{2e}) were used to report the environmental impact of volatile agents. To determine the CO\textsubscript{2e}, one multiplies the weight (in kilo-
grams) of each gas by its GWP. For example, desflurane's GWP is 2,540 units. One kilogram of desflurane is equal to 2,540 kg of CO$_2$. Twenty kilograms of desflurane is equal to 50,800 kg CO$_2$.

The specific gravity of each agent was used to convert calculated case volume of liquid anesthetic to weight (kilograms), to report CO$_2$e comparisons (Figure 3).

Furthermore, a greenhouse gas equivalency calculator aided in converting CO$_2$e of the volatile agents used in our cases to equivalency vehicles driven for a year.

**Results**

A total of 14,977 cases were analyzed. The total calculated FVA consumption was 256,735 mL (1,027 bottles) of sevoflurane; 23,190 mL (93 bottles) of isoflurane; and 27,413 mL (114 bottles) of desflurane (Table 1). The highest mean FGFs were observed in cases using sevoflurane, whereas the lowest mean FGFs were observed in cases using desflurane. Although desflurane is the most expensive agent, larger quantities of sevoflurane were used and thus represented the highest overall cost. The total amount spent on volatile agents for cases in the project was estimated at $96,960 (see Table 1).

In the predictive simulation analysis, the estimated consumption of liquid anesthetic varied by average simulated FGF (Table 2). The actual average FGF for cases using sevoflurane was 2.5 L/min. If cases using sevoflurane employed average FGFs of 2 L/min (the US Food and Drug Administration [FDA] recommendation), an estimated 128 fewer bottles would have been consumed. Additionally, had all cases using any inhalational agent used an average of 1 L/min FGF, an estimated total of 660 bottles of volatile agents could have been conserved (see Table 2).

Estimated potential cost savings with various FGFs were substantial (Table 3). As an example, the total cost of sevoflurane in 2017 was calculated to be $78,561. If every case in 2017 that used sevoflurane had instead used an average of 2 L/min FGF, the cost savings would have been $9,830. More drastic savings are demonstrated using simulated lower FGFs. Savings between $5,700 and $10,960 would have been realized had anesthesia providers using desflurane decreased average FGFs to between 0.5 and 1 L/min. Using average simulated flows of 1 L/min for all 3 inhalation agents demonstrated an estimated overall projected cost savings of $50,892.

Carbon dioxide equivalents were calculated and simulated using various FGFs (Table 4). Although over 9

### Table 1. Results of Volatile Anesthetic Use and Calculated Mean Fresh Gas Flow

<table>
<thead>
<tr>
<th>Agent</th>
<th>FVA, mL</th>
<th>Mean FGF (SD), L/min</th>
<th>Bottles of FVA</th>
<th>Cost/bottle, $</th>
<th>Cost/y, $</th>
<th>mtCO$_2$e/bottle</th>
<th>mtCO$_2$e/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sevoflurane</td>
<td>256,735</td>
<td>2.5 (1.1)</td>
<td>1,027</td>
<td>76.5</td>
<td>78,561</td>
<td>0.0214</td>
<td>22</td>
</tr>
<tr>
<td>Isoflurane</td>
<td>23,190</td>
<td>2.0 (1.1)</td>
<td>93</td>
<td>23.5</td>
<td>2,180</td>
<td>0.0852</td>
<td>8</td>
</tr>
<tr>
<td>Desflurane</td>
<td>27,413</td>
<td>1.8 (0.9)</td>
<td>114</td>
<td>142.0</td>
<td>16,220</td>
<td>0.4161</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>307,338</td>
<td></td>
<td>1,234</td>
<td></td>
<td>96,960</td>
<td></td>
<td>77</td>
</tr>
</tbody>
</table>

Abbreviations: FGF, fresh gas flow; FVA, fluid volatile anesthetic; mtCO$_2$e, metric tons carbon dioxide equivalent.

**GWP, 100-year global warming potential where CO$_2$=1.**

Specific gravities: sevoflurane, 1.522; isoflurane, 1.496; desflurane, 1.465.

### Table 2. Predicted Number of Bottles Saved at Varying FGFs

<table>
<thead>
<tr>
<th>Agent</th>
<th>0.5 L/min</th>
<th>1 L/min</th>
<th>1.5 L/min</th>
<th>2 L/min</th>
<th>3 L/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sevoflurane</td>
<td>802</td>
<td>578</td>
<td>353</td>
<td>128</td>
<td>(+) 321</td>
</tr>
<tr>
<td>Isoflurane</td>
<td>68</td>
<td>42</td>
<td>17</td>
<td>(+)8</td>
<td>(+)58</td>
</tr>
<tr>
<td>Desflurane</td>
<td>77</td>
<td>40</td>
<td>3</td>
<td>(+)34</td>
<td>(+)108</td>
</tr>
<tr>
<td>Total</td>
<td>947</td>
<td>660</td>
<td>373</td>
<td>87</td>
<td>(+)487</td>
</tr>
</tbody>
</table>

Abbreviations: FGF, fresh gas flow; (+), additional bottles that would have been used had all cases employed the given average FGF.

In cases using desflurane. Although desflurane is the most expensive agent, larger quantities of sevoflurane were used and thus represented the highest overall cost. The total amount spent on volatile agents for cases in the project was estimated at $96,960 (see Table 1).

In the predictive simulation analysis, the estimated consumption of liquid anesthetic varied by average simulated FGF (Table 2). The actual average FGF for cases using sevoflurane was 2.5 L/min. If cases using sevoflurane employed average FGFs of 2 L/min (the US Food and Drug Administration [FDA] recommendation), an estimated 128 fewer bottles would have been consumed. Additionally, had all cases using any inhalational agent used an average of 1 L/min FGF, an estimated total of 660 bottles of volatile agents could have been conserved (see Table 2).

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Carbon dioxide equivalents were calculated and simulated using various FGFs (Table 4). Although over 9
times more liquid sevoflurane was used compared with desflurane (256,735 mL sevoflurane vs 27,413 mL desflurane), the CO$_2$e of desflurane use was twice that of sevoflurane (48 metric tons CO$_2$e [mtCO$_2$e] desflurane vs 22 mtCO$_2$e sevoflurane). When FGFs were simulated at an average of 1.5 L/min or less, there was a decrease in CO$_2$e emissions for each volatile agent. A subanalysis of cases using sevoflurane for less than 2 hours was conducted to illustrate potential savings in line with FDA flow recommendations (Table 5). In the inclusion criteria, 12,605 cases used sevoflurane. More than half of these cases (7,827) measured sevoflurane for less than 2 hours. The cases included in the subanalysis accounted for 40% of the bottles consumed (417 of 1,027 total). Had all cases using sevoflurane for less than 2 hours decreased FGFs to between 1 and 2 L/min, $6,977 to $19,424 could have been saved.

**Discussion**

Low-flow anesthesia techniques are an environmentally conservative and fiscally responsible mode of anesthesia delivery across many surgical populations.\(^{23}\) The project estimated the use, cost savings, and reduced metric ton equivalents of CO$_2$ at various simulated rates of FGFs. The project demonstrated facility-specific areas where altering FGF practice may improve the financial performance of the anesthesia department and decrease the environmental impact of excessive anesthetic agent use.

Based on the findings from this evidence-based project and consistent with current research evidence, simulated LFA demonstrated cost savings and environmental conservation. Sevoflurane was the most commonly used volatile agent at the medical center in 2017 and accounted for the majority of volatile agent expenditures. In cases using sevoflurane, average FGF was 2.5 L/min. If the institution adopted the FDA-recommended 2 L/min FGF rate, annual savings of greater than $9,000 would have been achieved. For cases lasting less than 2 hours using sevoflurane, between $6,977 and $19,424 could have been conserved by the anesthesia provider decreasing to literature-supported flows of 1 to 2 L/min. Desflurane had the lowest average FGF rate of 1.8 L/min; however, due to its significantly larger GWP, the estimated contribution of mtCO$_2$e was greater than for sevoflurane and isoflurane combined (48 mtCO$_2$e desflurane vs 22 mtCO$_2$e sevoflurane and 8 mtCO$_2$e isoflurane). Furthermore, by aiming to decrease average FGFs to literature-supported flows of 0.5 to 1 L/min during use of desflurane, $5,700 to $10,960 could have been saved. Lowering FGFs represents an immediate method to decrease the cost associated with anesthesia at the project facility.

Although isoflurane, sevoflurane, desflurane, and nitrous oxide all act as greenhouse gases, isoflurane and nitrous oxide are the 2 inhalational agents that contribute...
to ozone depletion. Desflurane requires the administration of 3 to 6 times the quantity of sevoflurane and isoflurane, respectively, to achieve the same level of anesthesia. Desflurane also lasts up to 14 years in the atmosphere compared with 1.1 years for sevoflurane and 3.2 years for isoflurane. On an hourly basis, the greenhouse gas impact of desflurane is more than 20 times higher than isoflurane and sevoflurane. Vollmer et al measured and calculated global atmospheric levels of volatile anesthetic gases and reported that the combined release of volatile anesthetic gases was about 3.1 million metric tons of CO$_2$-e, 80% of which was attributed to desflurane.

Release of volatile anesthetic gases translates to the equivalent of the CO$_2$ emissions of approximately 650,000 passenger vehicles. Other findings compare global anesthetic emissions to the emissions from 1 coal-fired power plant or approximately 1 million cars. Evidence exists indicating that pollution from inhaled anesthetic gases has a negative environmental impact.

**Patient Safety.** Providers interested in adopting a low-flow anesthesia technique, first and foremost, should consider patient safety. There are specific practices the anesthesia professional must follow to ensure patient safety while delivering anesthetic gases using LFA techniques. Since the 1850s, anesthesia practice has evolved to include rebreathing systems with CO$_2$ absorption as well as intricate monitoring systems. As technology and anesthetic techniques have developed and improved, safer and more cost-effective ways to deliver anesthesia have been implemented. Education and understanding of best practice when performing low-flow anesthesia is paramount.

Low flow is considered to be 0.5 to 1 L/min, minimal flow is 0.25 to 0.5 L/min, and metabolic flows are considered to range from 0.25 to 0.3 L/min. Meeting minimal metabolic requirements for the patient is a physiologic necessity. Exploring flows below 0.25 L/min would be detrimental to a patient’s safety and could carry severe repercussions. Patients’ oxygen requirements can vary greatly, even among patients with similar ages and weights. It is therefore important to understand that minimal flow varies from person to person. If flows less than 1 L/min are desirable, a calculation of minimal oxygen consumption should be quickly carried out. A complex formula by Brody could be conducted; however, a linear approximation of predicted oxygen consumption (VO$_2$) is $[2.5 \times \text{Weight (kg)} + 67.5] = \text{mL/min oxygen demand}$. Another calculation for VO$_2$ can be completed by subtracting the end-tidal oxygen (ETO$_2$, eg, 0.46) percentage from the fraction of inspired oxygen (FiO$_2$, eg, 0.5) percentage measurement and then calculating this as a proportion of the minute ventilation (MV), in milliliters: $[(\text{FiO}_2 - \text{ETO}_2) \times \text{MV}] = \text{mL/min oxygen demand}$. This number represents an estimation of the patient’s oxygen consumption and is the minimal amount of oxygen needing to be delivered using low-flow anesthesia. The provider must also account for a small loss in volume to the gas analyzer via the sampling line, which varies by machine.

Another factor to be considered with LFA is the rebreathing of CO$_2$. During times when FGFs are low, the patient will be rebreathing at least 50% of the exhaled volume; thus, the removal of CO$_2$ is vital. When LFA is performed, there is not enough FGF to wash out the exhaled CO$_2$ from the circuit. Carbon dioxide is toxic at high levels, and concentrations in the ventilation system can greatly rise without a working CO$_2$ absorber. An early assessment showed that with minimal-flow anesthesia, the rate of soda lime consumption increased 2- to 4-fold. However, a more recent study showed the cost savings from decreased volatile agent consumption with LFA outweighed the cost of purchasing additional CO$_2$ absorbent. Awareness of the type of absorber being used and its level of freshness can alleviate the risk of CO$_2$ rebreathing, ensuring continued patient safety with LFA.

A key concern in using low-flow anesthesia is to minimize the risk to the patient from the accumulation of byproducts of anesthetic gases reacting with the CO$_2$ absorber. One byproduct of concern with low-flow sevoflurane use is compound A. Sevoflurane is degraded to compound A by CO$_2$ absorbents containing a strong base, such as potassium hydroxide. Compound A formation is more likely to occur with LFA, increased temperature in the breathing circuit, desiccated absorbers, the use of halalyme/potassium hydroxide as an absorbent, and a high sevoflurane concentration. Because of the risk of compound A–induced kidney injury, the FDA recommends sevoflurane exposure should not exceed 2 MAC (minimum alveolar concentration)-hours at flow rates of 1 to less than 2 L/min. Flow rates below 1 L/min are also not recommended in the United States. However, there is no flow restriction with sevoflurane in the European Common Market, where LFA has been safely employed for decades. Anesthesia providers list fear of compound A exposure as a barrier to implementing LFA, yet clinically significant compound A–related kidney injury in humans has not been demonstrated. A 2017 meta-analysis of randomized clinical trials analyzing the overall effect of sevoflurane, compound A, and renal dysfunction, compared kidney function of patients at 24 and 72 hours after anesthesia. The results of this meta-analysis demonstrated that creatinine changes from baseline among patients receiving either low or high-flow sevoflurane did not statistically differ from those with low-flow isoflurane.

Low-flow anesthesia techniques have been employed for many different patient populations. Pediatric patients are one of the special populations in which providers may be reticent to use LFA. The safety of LFA in pediatric patients is demonstrated in several case series.
Additionally, in a prospective, randomized trial examining low-flow (1 L/min) desflurane and sevoflurane in healthy pediatric patients between the ages of 5 to 15 years (n=80), no adverse effects on hepatic or renal function were found. Larger randomized controlled trials in the pediatric population would provide further support to adoption of a low-flow anesthesia practice.

Another population in which to consider using low-flow anesthesia is patients with preexisting kidney disease. Sevoflurane is metabolized in the liver to inorganic fluoride, which is then removed by the kidneys, so there is a concern for renal damage with sevoflurane use in patients with preexisting renal disease. Two randomized trials have not demonstrated a difference in renal function after anesthesia with either low-flow sevoflurane or low-flow sevoflurane in patients with chronic renal impairment (FGF ≤ 1 L/min). 41,42

• Limitations. The findings of this project should be considered within its limitations. Because of the proprietary nature of contractual purchasing agreements, costs per bottle of VAs were based on a range of values instead of actual costs and thus may vary from institution to institution. This project may have underreported estimated savings due to a large number of omitted cases based on study-specific exclusion criteria. For data extraction, only expiratory percentage of volatile agent was available and analyzed. Inspiratory volatile agent percentage yields a more specific estimation; however, these data were unavailable for extraction from the electronic health record. Additionally, when carrying out the predictive analysis, the average, instead of minute-to-minute, expired volatile agent percentage and FGF were used. This was deemed necessary as using more precise minute-to-minute calculations for simulated flow analysis would not have been readily translatable to clinical practice. It is not realistic for every minute in a case to have the same low FGF, so trends were analyzed and presented. To mitigate this limitation, a correction factor (percent) was applied to the predicted FVA volumes at various FGFs. This was done by using the difference between actual calculated fluid volatile agent use and volatile agent use when averaged (FGF, expired volatile agent percent). Although not designed to be generalizable to other institutions, a large and clinically representative sample of cases from a tertiary medical center was used to estimate cost savings and environmental impact under simulated FGFs.

• Recommendations. The current FGF practices at the project facility were examined, and this project offered specific examples of the impact of lowering FGF. Specifically, cases using sevoflurane for less than 2 MAC-hours should aim for an FGF rate of 1 L/min, for an estimated annual costs savings of $19,424 and more than 5 mtCO₂e. For cases using desflurane, anesthesia providers should aim for FGF of 0.5 L/min, for an estimated annual costs savings of $10,960 and 32 mtCO₂e. For cases using isoflurane, providers should aim for FGF less than 1 L/min, for an estimated annual costs savings of $997 and 4 mtCO₂e. The greatest financial savings could be achieved by decreasing FGF with sevoflurane. The greatest environmental savings involve decreasing FGF with use of desflurane. Although savings with isoflurane could be achieved, they are dwarfed by those of the other gases.

The findings align with the current literature showing that low FGFs represent an area of cost containment in anesthesia, as well as a decrease in the environmental impact of anesthesia. Further research on this subject could include an education project to anesthesia providers with pre- and post-FGF analysis. Ongoing reports of FGF, cost, and environmental impact in anesthesia, potentially on a provider-specific level, could also be shared. This project served as a starting point for this facility to track volatile agent use and FGF, in an ongoing effort to provide safe, cost-effective, and environmentally responsible care.

REFERENCES


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DISCLOSURES
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