Reducing Wastage of Inhalation Anesthetics Using Real-time Decision Support to Notify of Excessive Fresh Gas Flow

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ABSTRACT

Background: Reduced consumption of inhalation anesthetics can be safely achieved by reducing excess fresh gas flow (FGF). In this study the authors describe the use of a real-time decision support tool to reduce excess FGF to lower, less wasteful levels.

Method: The authors applied a decision support tool called the Smart Anesthesia Manager™ (University of Washington, Seattle, WA) that analyzes real-time data from an Anesthesia Information Management System to notify the anesthesia team if FGF exceeds 1 l/min. If sevoflurane consumption reached 2 minimum alveolar concentration-hour under low flow anesthesia (FGF < 2 l/min), a second message was generated to increase FGF to 2 l/min, to comply with Food and Drug Administration guidelines. To evaluate the tool, mean FGF between surgical incision and the end of procedure was compared in four phases: (1) a baseline period before instituting decision rules, (2) Intervention-1 when decision support to reduce FGF was applied, (3) Intervention-2 when the decision rule to reduce flow was deliberately inactivated, and (4) Intervention-3 when decision rules were reactivated.

Results: The mean ± SD FGF reduced from 2.10 ± 1.12 l/min (n = 1,714) during baseline to 1.60 ± 1.01 l/min (n = 2,232) when decision rules were instituted (P < 0.001). When the decision rule to reduce flow was inactivated, mean FGF increased to 1.87 ± 1.15 l/min (n = 1,732) (P < 0.001), with an increasing trend in FGF of 0.1 l/min/month (P = 0.02). On reactivating the decision rules, the mean FGF came down to 1.59 ± 1.02 l/min (n = 1,845). Through the Smart Anesthesia Messenger™ system, the authors saved 9.5 l of sevoflurane, 6.0 l of desflurane, and 0.8 l isoflurane per month, translating to an annual savings of $104,916.

Conclusions: Real-time notification is an effective way to reduce inhalation agent usage through decreased excess FGFs.

What We Already Know about This Topic

• Wasted anesthetic gases are expensive and can adversely affect the environment
• One way to reduce excess anesthetic use is by minimizing excessive fresh gas flows

What This Article Tells Us That Is New

• Real-time messages displayed by a decision support tool and the anesthesia information management system reduced the use of high fresh gas flows and anesthetic agents by anesthesia providers
• Cost savings were noted
Though such methods achieved moderate success in reducing FGF, sustained maintenance of low FGF could not be achieved because providers reverted to original behavior over time.\textsuperscript{5,10,15,14} In this study we describe the use of a real-time decision support tool to prompt practitioners to lower FGF to the lowest flow considered acceptable to the target users, consistent with the recommendations for reducing FGF. The decision support tool called Smart Anesthesia Manager\textsuperscript{™} (SAM), a custom software application developed at University of Washington, works in conjunction with an Anesthesia Information Management System (AIMS) to notify the anesthesia provider concerning issues related to quality of care, billing, and compliance in real time. SAM’s decision support rules were enhanced to add notifications for reducing FGF to the lowest levels considered acceptable to the target users during the maintenance phase of anesthesia.

The efficacy of real-time decision support to reduce and maintain FGF at the desired level was evaluated through a prospective study that used an interrupted time series approach. First, baseline data were collected for 2 months on FGF patterns immediately before any intervention. Then, the newly created SAM decision rules were activated for a period of 2.5 months. As a second intervention, to assess the true effect of decision support, the SAM messages to reduce FGF were inactivated for 2 months. In the third intervention, the rules were reactivated.

Materials and Methods
AIMS and Data Acquisition
In 2008, to improve clinical documentation, quality of care, and billing, our institution installed an AIMS system (Docusys/Merge AIMS; Merge Inc., Hartland, WI). The AIMS was configured to automatically acquire hemodynamic and ventilation parameters from the patient monitor and anesthesia machine every minute and record them as part of the anesthesia record. Minute-by-minute data acquisition of end-tidal inhalation agent concentration for the three anesthetic agents—sevoflurane, desflurane, and isoflurane; gas flows of oxygen, air, and nitrous oxide were included as part of this interface. By adding together the individual minute-by-minute gas flows, we could compute total FGF every minute. During our initial assessment phase before September 2010, not all anesthesia machines in our operating rooms (ORs) had the capability to measure gas flows. However, during July–September 2010, older anesthesia machines were progressively replaced by newer models that had the capability to measure gas flows. Starting September 1, 2010, all ORs had the capability to measure gas flows.

Initial Assessment of Inhalation Agent Usage
To begin with, we conducted a baseline analysis of the usage of inhalation agents in our institution. This allowed us to understand the existing pattern of inhalation agent usage and provide a basis to formulate future intervention steps to reduce wastage of inhalation agents. After Institutional Review Board (University of Washington, Seattle, WA) approval, data were extracted from the AIMS database for 2 months (July 1, 2010–August 31, 2010). Specifically, minute-by-minute end-tidal inhalation agent concentration and FGF data were extracted for cases in which both these parameters were measured (~50% of the total number of general anesthesia cases had gas flows measured during this period). Additionally, demographic data related to the surgery, such as procedure start time, procedure end time, procedure type, and description were also extracted. For each general anesthesia case, average FGF was computed by integrating minute-by-minute FGF between procedure start and end times, and dividing by the procedure duration. From the average FGF for each case, mean FGF across all general anesthesia cases was determined. In addition, cases were classified based on the type of inhalation agent used (sevoflurane, desflurane, and isoflurane) and the mean FGF among cases using the same inhalation agent was calculated. The minute-by-minute samples of FGF greater than 2 l/min were used to compute the number of minutes when FGF was set greater than 2 l/min for each case. The total time in minutes when FGFs were greater than 2 l/min between start and end of procedure were calculated for all cases and divided by the total procedure duration for all cases to determine the fraction of time when FGF was greater than 2 l/min. The initial assessment data are summarized in Table 1. The mean FGF for all cases in our institution was 2.27 l/min, with sevoflurane being the predominantly used agent (68%). Approximately 50% of the cases had a mean FGF of greater than 2.0 l/min, and FGF was set greater than 2.0 l/min 45% of the time in all cases. On the basis of this initial assessment, we formulated a proposal to reduce inhalation agent waste by reducing FGF. The baseline data were not included in the study because not all ORs had the capability to measure FGF during this phase.

Proposal to Reduce Inhalation Agent Waste
To reduce wastage of excess agents, we proposed the use of lower FGFs within the limits recommended by the Food and Drug Administration.\textsuperscript{**} Specifically, the Food and Drug Administration recommends that to minimize exposure to compound A, sevoflurane exposure should not exceed 2 minimum alveolar concentration (MAC)-\textsubscript{h} at flow rates of 1 to less than 2 l/min and that FGF rates less than 1 l/min are not recommended. Conversely, warnings have not been issued for desflurane and isoflurane usage. Considering these guidelines, we proposed a plan to use 1 l/min FGF during the maintenance phase of anesthesia for desflurane and isoflurane. For sevoflurane, we proposed using an FGF of 1 l/min.
Decision Support for Reducing Fresh Gas Flow

To introduce, enforce, and maintain the plan to reduce FGF, a real-time decision support tool, SAM, was used. SAM is a real-time decision support tool that works alongside the AIMS. SAM was internally developed by the University of Washington to improve quality of care, anesthesia professional services billing, and compliance.16,17 SAM acquires AIMS data in near real-time, processes it to identify clinical, billing, or compliance issues, and notifies the anesthesia provider. SAM was enhanced to add decision rules related to FGF. Specifically, SAM rules were created to remind the anesthesia provider to reduce FGF to 1 l/min after the start of surgical procedure (incision). For cases that used sevoflurane, once the usage has reached 2 MAC-h under low flow conditions (FGF < 2 l/min), a second reminder was generated to increase the flow to 2 l/min. To obtain low flow sevoflurane usage, MAC-adjusted expired sevoflurane fraction (expired % of sevoflurane/2.05) was integrated for those samples that had the corresponding FGF values less than 2 l/min. The messages were conveyed to the anesthesia provider via “pop-up” messages overlaid on top of the AIMS screen as shown in figure 1.

Evaluation of real-time decision support to reduce FGF was designed as a prospective study consisting of four phases. They include one baseline phase and three interventions phases. The evaluation was initiated after all ORs had the capability to measure FGF.

Preintervention Baseline (September 15, 2010–November 15, 2010)

Before introducing the new SAM messages, we chose 2 months (September 15, 2010–November 15, 2010) immediately before intervention to serve as a baseline period. All ORs of our hospital were configured to measure FGF before this period. A baseline period contiguous with the subsequent intervention phases was deliberately chosen to minimize the probability of any extraneous factors affecting the comparison of results obtained from the different phases.

Table 1. Initial Assessment Summary (July 1, 2010–August 31, 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean FGF</td>
<td>2.27 l/min</td>
</tr>
<tr>
<td>All cases</td>
<td>2.34 l/min</td>
</tr>
<tr>
<td>Sevoflurane cases</td>
<td>1.59 l/min</td>
</tr>
<tr>
<td>Desflurane cases</td>
<td>2.33 l/min</td>
</tr>
<tr>
<td>Inhalation agent usage</td>
<td></td>
</tr>
<tr>
<td>Sevoflurane cases</td>
<td>68%</td>
</tr>
<tr>
<td>Desflurane cases</td>
<td>25%</td>
</tr>
<tr>
<td>Isoflurane cases</td>
<td>7%</td>
</tr>
<tr>
<td>FGF &gt; 2 l/min</td>
<td></td>
</tr>
<tr>
<td>Number of cases with mean FGF &gt; 2 l/min</td>
<td>47%</td>
</tr>
<tr>
<td>Percentage time when FGF &gt; 2 l/min</td>
<td>45%</td>
</tr>
</tbody>
</table>

A total of 2,826 cases were analyzed, of which 2,455 used general anesthesia. Of the 2,455 general anesthesia cases FGF could be measured only in 1,338 cases. The 1,338 cases were classified based on the inhalation agent that was used. In case of multiple agent usage, the agents that was used for the most duration was used to classify the case.

FGF = fresh gas flow.

Fig. 1. SAM message to reduce FGF overlaid on top of AIMS (anesthesia information management system) screen. The FGF value is computed by adding individual flows of oxygen, air, and nitrous oxide. FGF = fresh gas flow; SAM = Smart Anesthesia Manager™, University of Washington Medical Center, Seattle, WA.
Initial Go-live of SAM Rules and Their Refinement (November 17, 2010–November 30, 2010)

Without any additional training, the anesthesia providers were notified of the new SAM rules via an e-mail message and an announcement during a departmental conference. Subsequently, the newly added decision rules on FGF were activated. Messages were generated every 6 min just after the start of the surgical procedure (incision) until the end of surgery (closing), based on the decision logic described previously. The system was closely monitored to make sure that the messages were generated accurately. We noticed that with a messaging frequency of once every 6 min, a high frequency of messages (three to four messages/case to reduce flow) was generated, which was distracting to the users. Also, the first message was sent immediately after the start of the procedure when the anesthesia provider was busy making the final adjustments toward the maintenance phase of anesthesia. On the basis of these observations and user feedback from the anesthesia providers, the notification strategy was refined to reduce information overload, exclude nonapplicable periods or cases, and remind users to increase flow in case the FGF is set significantly below the recommended level. The final set of rules is outlined in table 2. In the final set of rules, the first message to reduce FGF was generated 10 min after the start of surgical procedure (incision), to give a buffer period during which the anesthesia provider can make final adjustments to FGF in preparation for the maintenance phase of anesthesia. In addition, we established a documentation feature that allowed the provider to record whether FGF could not be reduced for a medical reason (e.g., nitric oxide being used). If there is documentation that FGF could not be reduced for a specific reason, the decision support to reduce FGF is disabled for that case.

Intervention-1: Activation of SAM Messages (December 1, 2010–February 14, 2011)

The refined SAM decision rules were activated on December 1, 2010, with no further announcement to the anesthesia providers. The decision rules and the associated messages were kept constant and continued for 2.5 months.

Intervention-2: Inactivation of Some SAM Messages (February 15, 2011–April 14, 2011)

To independently evaluate the impact of the SAM messages, the message to reduce FGF was deliberately turned off without notifying the anesthesia providers. However, the other messages related to FGF (messages FGF2 and FGF3) continued to be active during this period. Intervention-2 was applied for 2 months.

Intervention-3: Reactivation of All SAM Messages (April 15, 2011–June 14, 2011)

At the end of the previous intervention, the inactive SAM message was reactivated so that the exact same messages generated during Intervention-1 were restored. Similar to the previous intervention, no notification or announcement was issued before this intervention as well.

Table 2. Final Set of FGF Decision Rules in SAM

<table>
<thead>
<tr>
<th>Rule Code</th>
<th>Rule</th>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGF1</td>
<td>If current FGF &gt; 1.0 l/min notify users to reduce FGF to 1 l/min</td>
<td>Rule triggered only if • FGF is measured • Inhalation agent is used • 10 min after procedure start</td>
<td>Rule not triggered if • Closing or procedure end events have occurred • Low flow (FGF &lt; 2 l/min) sevoflurane consumption is &gt; 1.8 MAC • Documentation that low FGF cannot be maintained due to a medical reason</td>
</tr>
<tr>
<td>FGF2</td>
<td>If current FGF &lt; 2.0 l/min notify users to increase FGF to 2 l/min</td>
<td>Rule triggered only if • FGF is measured • Inhalation agent is used • Current agent is sevoflurane • Low flow (FGF &lt; 2 l/min) sevoflurane consumption is &gt; 1.8 MAC</td>
<td>None</td>
</tr>
<tr>
<td>FGF3</td>
<td>If current FGF &lt; 1 l/min for sevoflurane agent, notify users to increase FGF to 1 l/min</td>
<td>Rule triggered only if • FGF is measured • Inhalation agent is used • Current agent is sevoflurane • Current expired sevoflurane concentration is &gt; 0.5 % (not TIVA cases)</td>
<td>Rule not triggered if • Closing or procedure end events have occurred • Rule FGF2 is not triggered</td>
</tr>
</tbody>
</table>

When comparing FGF to specified limits, a tolerance of 0.2 l/min was used. Rules were executed every 12 min. The rule codes were used internally in the decision rules engine of SAM.

FGF = fresh gas flow; MAC = minimum alveolar concentration; SAM = Smart Anesthesia Manager™ (University of Washington, Seattle, WA); TIVA = total intravenous anesthesia.
Data Preparation

After obtaining Institutional Review Board approval, minute-by-minute FGF and end-tidal inhalation agent concentration values, surgical procedure start time (incision time) and surgical procedure end time were extracted from the AIMS database for the baseline and intervention periods. Mean FGF and duration of each anesthetic agent usage between procedure start and end times were computed. Moreover, surgery-related information such as date of surgery, type, and duration of surgical procedure, and OR location were also extracted from the AIMS database. In addition to the data extracted from the AIMS database, an audit of the inhalation agents’ stock was performed by the Department of Pharmacy. Specifically, at the start and end of a new intervention, the current stock of agent bottles in all the ORs and satellite pharmacy was audited. To calculate the agent consumption during an intervention, the agent stock at the end of the intervention was subtracted from the sum of the agents purchased and the OR/Pharmacy stock at the start of the intervention. However, for the baseline period, we did not perform the aforementioned audit as the study has not been initiated. Hence, the baseline consumption was obtained from the Department of Pharmacy, which keeps information on agent purchase and average consumption of inhalation agents.

Statistical Analysis

Descriptive statistics for the procedure variables were calculated for each of the four phases to verify that the phases were matched with respect to these variables. These variables include the proportion of cases by different anesthetic agents, the proportion of cases by procedure type, and the mean ± SD of the procedure duration. Differences between pairs of phases in these variables were tested by the two-sided chi-square test and by the two-sided two-sample t test with unequal variances. To compare different phases, the mean and standard variation of the primary variable – FGF were computed for each phase. Mean FGF was compared between pairs of phases by the two-sided two-sample t test with unequal variances. The difference in mean FGF between pairs of phases and the 95% CI for the difference were calculated. This comparison was done for all cases as well as separately for sevoflurane, desflurane, and isoflurane cases.

Temporal trend in mean FGF across the four phases was visualized by plotting the procedure date against the mean FGF. Loess smoother was fit separately for each period to estimate the temporal trend within that period. The smoothing parameter α was set to 1.2 for all four phases. For the intermediate, trial period between baseline and Intervention-1 period α was set to 2. We tested for a monotonous trend within each phase using linear regression of the mean FGF against the procedure date. The slope of the trend was expressed in terms of a change in FGF per month.

Results

For each of the four phases of the study, the number of cases, distribution of case types, distribution of inhalation agents used, and the mean procedure duration were similar (table 3).

The comparison of mean FGF values for the four phases of the study is shown in table 4. The mean ± SD of FGF for all cases reduced from a baseline value of 2.10 ± 1.12 l/min to 1.60 ± 1.01 l/min (P < 0.001) when SAM decision rules were activated during Intervention-1. However, when the messages to reduce flow were inactivated in Intervention-2, the mean ± SD of FGF increased to 1.87 ± 1.15 l/min (P < 0.001). When the messages to reduce flow were reactivated, the mean ± SD of FGF reduced to 1.59 ± 1.02 l/min, a value similar to Intervention-1 (mean Intervention-1 FGF vs. mean Intervention-3 FGF: P = 0.7). Sevoflurane and isoflurane cases showed a similar pattern for all the four phases. However, for desflurane cases, although the FGF reduced from a baseline value of 1.51 ± 0.89 l/min to 1.30 ± 0.82 l/min during Intervention-1 (P < 0.001), when the SAM messages to reduce flow were turned off (Intervention-2) FGF increased only marginally to 1.43 ± 1.00 l/min, with the change not statistically significant (P = 0.07).

In addition to static analysis, we conducted a trend analysis to evaluate the change in mean FGF over time during the four phases of the study. Figure 2 shows how the cumulative FGF varied within and across the four phases. In figure 2, the individual points represent the mean FGF for each case. The solid colored lines are the smoothed trends in the mean FGF values, whereas the colored band around the solid line represents the 95% CI for the mean FGF. The difference in the mean trends during the baseline and Intervention-1 phases shows that the FGF dropped abruptly upon initiating the real-time decision support messages at the start of Intervention-1. The mean FGF during Intervention-1 phase increased only slightly (slope = +0.068 l/min/month, P = 0.02) in spite of personnel changes as part of new resident rotations. However, when the messages to lower FGF were inactivated (Intervention-2), the mean FGF increased in a more rapid fashion (slope of +0.105 l/min/month; P = 0.03). Toward the end of Intervention-2, the FGF levels reached a value (2.10 ± 0.08 l/min, Loess Smoother) very similar to baseline FGF (2.10 ± 1.12 l/min). Mean FGM came down to a very similar level as with Intervention-1 when the messages were reactivated during Intervention-3.

For cases that last more than 3 h, the time trend of FGF for each of the inhalation agents for the first 2.5 h after procedure start is shown in figure 3. The FGF was averaged across cases for each time sample. Figure 3 shows the pattern of FGF adjustments in response to SAM messages. The first
PERIOPERATIVE MEDICINE

Table 3. Case and Agent Distribution among Cases during the Four Phases of the Study

<table>
<thead>
<tr>
<th>Phases</th>
<th>Monthly count of cases that used inhalation agents</th>
<th>% Sevoflurane cases</th>
<th>% Desflurane cases</th>
<th>% Isoflurane cases</th>
<th>Mean procedure duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Baseline (September 15, 2010–November 14, 2010) n = 1,714</td>
<td>857</td>
<td>70%</td>
<td>23%</td>
<td>7%</td>
<td>2.2 ± 2.1</td>
</tr>
<tr>
<td>†Intervention-1 (December 1, 2010–February 14, 2011) n = 2,232</td>
<td>893</td>
<td>76%</td>
<td>16%</td>
<td>7%</td>
<td>2.1 ± 1.7</td>
</tr>
<tr>
<td>‡Intervention-2 (February 15, 2011–April 14, 2011) n = 1,732</td>
<td>866</td>
<td>73%</td>
<td>19%</td>
<td>9%</td>
<td>2.3 ± 1.9</td>
</tr>
<tr>
<td>§Intervention-3 (April 15, 2011–June 14, 2011) n = 1,845</td>
<td>923</td>
<td>71%</td>
<td>18%</td>
<td>9%</td>
<td>2.3 ± 2.0</td>
</tr>
</tbody>
</table>

Procedure type
- General | 39% | 42% | 43% | 44%
- Orthopedic | 16% | 16% | 15% | 15%
- Gynecology | 10% | 7% | 7% | 6%
- Urology | 9% | 8% | 9% | 7%
- Head and neck | 7% | 7% | 6% | 6%
- Cardiothoracic | 6% | 5% | 7% | 7%
- Neurology | 6% | 5% | 4% | 4%
- Transplant | 3% | 2% | 2% | 3%
- Other | 6% | 8% | 6% | 6%

Differences between pairs of phases in the above variables were tested by the chi-square test and by two-sample t test with unequal variances.

*Totally 1,900 cases. Cases less than 10 min long (16) and with no inhalation agents (170) were excluded. †Totally 2,509 cases. Cases less than 10 min long (27) and with no inhalation agents (250) were excluded. ‡Totally 1,958 cases. Cases less than 10 min long (23) and with no inhalation agents (203) were excluded. §Totally 2,071 cases. Cases less than 10 min long (26) and with no inhalation agents (200) were excluded.

SAM message to reduce FGF appeared within a time window of 10–22 min (10-min delay built into the rules plus 12 min sampling period for FGF messages) after procedure start. It is during the period from procedure start to approximately 20 min after that the most reduction in FGF was observed. For desflurane and isoflurane, the FGF rates were kept constant after they were reduced from induction levels. However, for sevoflurane, the anesthesia provider increased the flow to 2 l/min when the anesthetic agent consumption reached 2 MAC-h under low flow condition. This action by the anesthesia provider is in response to the SAM message that notifies the provider when 2 MAC-h of sevoflurane have been delivered with FGF level below 2 l/min.

The audit of actual agent consumption performed by the pharmacy department is shown in table 5. Monthly consumption was reduced by 38 bottles for sevoflurane, 25 bottles for desflurane, and 8 for isoflurane when SAM decision support messages were activated. This translated to $104,916 of annual savings at our institution. As is evident from table 4, when decision support to reduce FGF was inactivated during Intervention-2, the agent consumption increased. When the decision support was reactivated in Intervention-3, the agent consumption levels returned to approximately the same levels as in Intervention-1.

Discussion
Reducing wastage of inhalation anesthetic agents by minimizing FGF is a safe and established strategy to contain cost. Unlike previous attempts that focused on providing retrospective feedback in the form of e-mail reminders and reports,13,14 we used a real-time decision support system, SAM, to alert the anesthesia provider that the FGF may be excessive. This approach has several advantages. Most notably, real-time notification elicits real-time response from the care provider, thus allowing adjustments to FGF in real time. Additionally, an automated system such as SAM obviates the need for manual and resource-intensive interventions such as retrospective report generation and announcements.

Real-time decision support through AIMS add-on software had been developed by others previously.19–23 These attempts also focused on solving issues related to billing and quality of care.22,23 SAM is a similar software tool that was developed with University of Washington resources to interface with the AIMS system used in our hospital. SAM is a low-cost and low-maintenance software that shares hardware with an AIMS system. It runs in the background, with minimal interaction with AIMS, detecting and notifying issues concerning quality of care, billing, and compliance.
### Table 4. Cumulative and Agent Specific Mean FGF for Each Phase of the Study; and the FGF Comparison between Baseline and Intervention Periods

<table>
<thead>
<tr>
<th></th>
<th>All Cases</th>
<th>Sevoflurane Cases</th>
<th>Desflurane Cases</th>
<th>Isoflurane Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>2.10 ± 1.12</td>
<td>2.27 ± 1.05</td>
<td>1.51 ± 0.89</td>
<td>2.36 ± 1.61</td>
</tr>
<tr>
<td>(September 15–November 14)</td>
<td>(n = 1,714)</td>
<td>(n = 1,194)</td>
<td>(n = 401)</td>
<td>(n = 119)</td>
</tr>
<tr>
<td><strong>Intervention-1</strong></td>
<td>1.60 ± 1.01</td>
<td>1.65 ± 0.99</td>
<td>1.30 ± 0.82</td>
<td>1.77 ± 1.42</td>
</tr>
<tr>
<td>(December 1–February 14)</td>
<td>(n = 2,232)</td>
<td>(n = 1,700)</td>
<td>(n = 362)</td>
<td>(n = 170)</td>
</tr>
<tr>
<td><strong>Intervention-2</strong></td>
<td>1.87 ± 1.15</td>
<td>1.95 ± 1.07</td>
<td>1.43 ± 1.00</td>
<td>2.19 ± 1.72</td>
</tr>
<tr>
<td>(February 15–April 14)</td>
<td>(n = 1,732)</td>
<td>(n = 1,257)</td>
<td>(n = 323)</td>
<td>(n = 152)</td>
</tr>
<tr>
<td><strong>Intervention-3</strong></td>
<td>1.59 ± 1.02</td>
<td>1.66 ± 1.05</td>
<td>1.31 ± 0.71</td>
<td>1.62 ± 1.16</td>
</tr>
<tr>
<td>(April 15–June 14)</td>
<td>(n = 1,845)</td>
<td>(n = 1,339)</td>
<td>(n = 343)</td>
<td>(n = 163)</td>
</tr>
</tbody>
</table>

Baseline vs. Intervention-1, mean (95% CI)

- Δ = −0.50, (−0.56, −0.43)
- Δ = −0.62, (−0.70, −0.54)
- Δ = −0.20, (−0.33, −0.08)
- Δ = −0.59, (−0.95, −0.22)

P < 0.001

Intervention-1 vs. Intervention-2, mean (95% CI)

- Δ = 0.27, (0.20, 0.34)
- Δ = 0.30, (0.22, 0.37)
- Δ = 0.13, (−0.01, 0.27)
- Δ = 0.42, (0.07, 0.77)

P < 0.001

Intervention-2 vs. Intervention-3, mean (95% CI)

- Δ = −0.28, (−0.35, −0.21)
- Δ = −0.29, (−0.37, −0.21)
- Δ = 0.12, (−0.25, 0.01)
- Δ = −0.57, (−0.89, −0.24)

P < 0.001

Intervention-1 vs. Intervention-3, mean (95% CI)

- Δ = −0.01, (−0.08, 0.05)
- Δ = 0.01, (−0.07, 0.08)
- Δ = 0.01, (−0.11, 0.12)
- Δ = −0.15, (−0.43, 0.13)

P = 0.7

Two-sample t-test with unequal variances was used to compare mean FGF between pairs of phases. The difference in mean FGF between each pair and the 95% CI for the difference were calculated. This comparison was done for all cases and separately for each type of the inhalation agent.

FGF = fresh gas flow.

**Fig. 2.** Trend in mean FGF from September 15, 2010 to June 14, 2011: A smoothed version of FGF trend is shown in which Loess smoother was used individually for each period. The smoothing parameter α was equal to 1.2 except for the intermediate period between baseline and the Intervention-1 period when α was set to 2. The gray circles represent the mean FGF for each case. The times when resident personnel changes occurred during Intervention-2 and Intervention-3 are shown with the help of red arrows. FGF = fresh gas flow.
For this study, SAM was enhanced to provide decision support toward reduction of inhalation agent wastage. To the best of our knowledge, this is the first attempt at reducing agent wastage, using an AIMS-based real-time decision support. However, an anesthesia machine specific tool, the Low Flow Wizard (LFW; Dräger, Lübeck, Germany), exists for real-time optimization of FGF, but the effectiveness of this system has not been rigorously documented.

In this study, for safety reasons, we chose to adhere with the current Food and Drug Administration recommendations (only for the United States) for FGF levels when using various inhalation agents. Though no specific lower limit for FGF is recommended for desflurane and isoflurane, we used a target of 1 l/min as a compromise between the need to change anesthetic levels rapidly and minimizing agent wastage. However, for sevoflurane, Food and Drug Administration recommends that low flow anesthesia (1 l/min) be maintained only for 2 MAC-h of agent consumption, to minimize exposure to compound-A. However, interestingly, more recent studies have indicated that compound-A toxicity has not been detected in humans.

The goal of our study was to change institutional behavior and patterns in managing FGF in an attempt to reduce wastage of inhalation agents. For this reason, we did not analyze provider-level behaviors toward adjusting FGF. However, the time trends of FGF changes during Intervention-2 and Intervention-3 (fig. 2) provide some indication of the effect that real-time decision had on the...
computed as the average value of the mean FGF between
higher-than-expected result. First, the average FGF was
1.6 l/min. Several factors could have contributed to this
FGF that was achieved with real-time decision support was
120–160 min after the start of procedure.

Because 2 MA c-h consumption is
2 MAc-h of low flow agent consumption, produced an FGF
sevoflurane, a second message to return flow to 2 l/min after
the same for the remainder of the procedure. However, for
both desflurane and isoflurane, the FGF values were kept
within a time window of 10–22 min after procedure start.

Anesthesia personnel’s behavior when adjusting FGF When
the real-time reminder to reduce FGF was turned off during
Intervention-2, the behavior to reduce flow ingrained
through SAM messages during Intervention-1 slowly began
to wane. When providers (residents mainly) were rotated,
it seemed to have accelerated the group behavior toward
baseline practice, when SAM was not used. Reactivating
the SAM messages to reduce FGF in Intervention-3 seemed
to have brought the desired behavior back almost
instantaneously in spite of personnel change.

The average time trend showing FGF adjustments
between procedure start and end (Figure 3) highlights how
closely real-time decision support can guide anesthesia pro-
viders to adhere to a desired behavior. As can be observed
in figure 3, the first notification to reduce FGF is generated
within a time window of 10–22 min after procedure start.
This is based on the delay of 10 min built into the decision
logic to initiate FGF messages and the sampling time of
SAM (12 min). Anesthesia providers reduced the FGF set-
ting to the target level (1 l/min with a tolerance of 0.2 l/
min) for all agents within the 10–22 min time window. For
both desflurane and isoflurane, the FGF values were kept
the same for the remainder of the procedure. However, for
sevoflurane, a second message to return flow to 2 l/min after
2 MAC-h of low flow agent consumption, produced an FGF
adjustment to 2 l/min. Because 2 MAC-h consumption is
dependent on the agent concentration and FGF, the actual
reminder to increase FGF to 2 l/min was generated not after
exactly 2 h of reducing the flow, but rather over a period of
120–160 min after the start of procedure.

Though the target value of FGF was 1 l/min, the average
FGF that was achieved with real-time decision support was
1.6 l/min. Several factors could have contributed to this
higher-than-expected result. First, the average FGF was
computed as the average value of the mean FGF between

### Table 5. Consumption of Inhalation Agents during the Four Phases of the Study Obtained through Auditing Pharmacy Supply Stock

<table>
<thead>
<tr>
<th>Number of Bottles</th>
<th>Sevoflurane (250 ml Bottles)</th>
<th>Desflurane (240 ml Bottles)</th>
<th>Isoflurane (100 ml Bottles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (bottles/month)</td>
<td>134</td>
<td>74</td>
<td>66</td>
</tr>
<tr>
<td>Intervention-1 (bottles/month)</td>
<td>96</td>
<td>49</td>
<td>58</td>
</tr>
<tr>
<td>Intervention-2 (bottles/month)</td>
<td>113</td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>Intervention-3 (bottles/month)</td>
<td>95</td>
<td>45</td>
<td>43</td>
</tr>
<tr>
<td>Baseline vs. Intervention-1 (savings in bottles/month)</td>
<td>38</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>Cost per bottle ($)</td>
<td>133</td>
<td>145</td>
<td>8</td>
</tr>
<tr>
<td>Cost savings/month ($)</td>
<td>5054</td>
<td>3625</td>
<td>64</td>
</tr>
<tr>
<td>Total annual cost saving ($)</td>
<td>$104,916</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Audit of the inhalation agents’ stock was performed by the Department of Pharmacy. At the start of a new intervention, the current stock of agent bottles in all the ORs and satellite pharmacy were audited. To calculate the agent consumption during an intervention, the agent stock at the end of the intervention was subtracted from the sum of the agents purchased and the OR/Pharmacy stock at the start of the intervention. The baseline consumption was obtained from the Department of Pharmacy that keeps agent purchase information and average consumption of inhalation agents.

OR = operating room.

For some cases FGF could not be reduced for a medical reason such as the use of nitric oxide. The AIMS note to document this aspect was implemented on December 1, 2010 at the start of Intervention-1. During the remainder of the study (December 1, 2010–June 14, 2011, i.e., 6.5 months) only 76 cases of 5,840 general anesthesia cases (1.3%) had documented that FGF could not be lowered for a medical/technical reason. Of the 76 instances, 58% of the time, it was because nitric oxide was used, 4% because of leaks, and 38% because of other reasons, which we could not identify. Though we could identify such cases in the AIMS database after we instituted the FGF decision rules, it proved difficult to identify similar cases during the baseline period because the necessary AIMS note was not available before December 1, 2010. For this reason and because these cases constitute a small fraction (1.3%), we did not exclude these cases from the analysis.

Subsequent to the completion of the study, we kept the SAM rules to lower FGF activated, and these rules are still being used in daily practice at our institution. Interestingly, the mean ± SD FGF for the postintervention period from July 2011 to December 31, 2011 (6 months) was 1.37 ± 0.76 l/min, lower than value of 1.60 ± 1.01 l/min observed during Intervention-1 when the SAM messages were initially activated. This observation possibly indicates the positive long-term benefit of decision support toward ingraining desired provider behavior.

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The decision support used in this study was meant to meet our goal to have a fairly simple, yet unobtrusive, method to remind anesthesia providers to lower FGF and hence to reduce wastage of anesthetic agents. However, future enhancements can further improve the system. Specifically, by the comparison of inspired and expired anesthetic agent concentration the onset of maintenance can be better identified, resulting in a better trigger for SAM notifications. In addition, rather than a fixed target for FGF, more optimal, case by case targets could be adopted to improve SAM decision support.

Actual cost savings due to a reduction of FGF at a particular institution will depend on the baseline inhalation agent usage and FGF settings. In our institution, a large academic medical center, the average FGF was 2.1 l/min. Observational studies\textsuperscript{5,9} have reported a similar value at other academic medical centers. However, other institutions have also reported higher FGF rates in the range of 3–4 l/min.\textsuperscript{1,2,10,12}

The higher the preintervention FGF, the more savings the institution can expect through real-time decision support. In our institution, sevoflurane and then desflurane were the main inhalation agents of choice, with much less expensive isoflurane used less than 10% of the time. It could be argued that additional economic savings could be achieved if we had encouraged usage of isoflurane in place of sevoflurane or desflurane. Though we plan to do this as a future step, as the first attempt at applying decision support to optimize inhalation agent cost savings, we chose an approach, that is, reduction of excess FGF, with little impact on clinical practice.

The audit of anesthetic agent consumption had some limitations. There could have been residual amounts of anesthetic agents in the vaporizers, which we did not measure and account for in the waste calculation. Because the number of ORs and hence anesthesia machines remained the same during the period of the study we assumed that the residual agent in the vaporizers was approximately a constant factor at the start and end of each intervention. Additionally, for the baseline period before initiating the study, we did not perform an audit, but rather used the average inhalation agent consumption information obtained from the Department of Pharmacy.

It is important to note that our method to reduce FGF through real-time notification will only work if the anesthesiologists are equipped to measure and export FGF. Additionally, the AIMS system should be capable of recording FGF information. Most new anesthesia machines are capable of measuring and exporting FGF data to an AIMS. In a recent article that discussed strategies of managing FGF, Feldman\textsuperscript{16} highlights emerging technologies related to anesthesia delivery system, which makes it possible to use low FGFs in closed-circuit anesthesia. However, such technologies are expensive and require specialized anesthesia machines. In comparison, our method of using real-time decision support to optimize FGF is simpler and far less expensive.

In summary, our study was able to demonstrate the usage of a real-time decision support tool to change and maintain the behavior of anesthesia providers toward adopting low FGF when using inhalation agents. In terms of usage, this effort translated to a 28% reduction in sevoflurane, 33% reduction in desflurane, and a 12% reduction in isoflurane.

References


