Induction of inhalation anesthesia may require high fresh gas flow and vaporizer dial settings, especially when large animal circuit systems or induction chambers are used or during mask induction of anesthesia in large animals or humans. Under these circumstances, the output concentrations of vaporizers may be >20% lower than the dial settings and rapid decreases in output anesthetic concentrations and vaporizer temperatures have also been observed. The combination of a temperature-related decrease in anesthetic vapor pressure and the delayed response of the temperature compensation mechanism has been indicated as a possible cause.

These performance issues of vaporizers may be further challenged when they are cold. Data regarding the accuracy of various vaporizers at the highest vaporizer setting with high carrier gas flows are presented in their operation manuals, but those data are usually the result of immediate readings and do not reflect the ability of vaporizers to maintain their performance for 10 to 15 minutes, which would be necessary for induction of anesthesia. When data obtained during a few minutes of vaporization are reported in these manuals, the values were typically obtained at carrier gas flows <10 L/min or less than the maximum dial setting.

Induction of anesthesia with high concentrations of sevoflurane is often used in humans. It has been reported that the output concentration of a certain type of sevoflurane vaporizer decreased to <2% when fresh gas flow was 10 L/min and when a dial setting of 8% was used with vaporizers at low-fill states. This inaccuracy might have clinical relevance if it also occurs with other types of sevoflurane vaporizers.

The aims of the study reported here were to assess the accuracy of several isoflurane, halothane, and sevoflurane vaporizers during high oxygen flow and at maximum vaporizer dial settings at room temperature and to test sevoflurane vaporizers similarly during heating and at low-fill states.
Materials and Methods

Five isoflurane, b 5 halothane, b and 5 sevoflurane vaporizers were tested. Multiple vaporizers were mounted on anesthesia machines in tandem mode by use of various interlock systems. All of the vaporizers were tested by an external professional service within 6 months prior to the start of the study. During this test, oxygen was used as carrier gas and the output of these vaporizers was found to be within 20% (plus or minus) of the dial settings. These limits of acceptable accuracy were recommended by the International Organization for Standardization for anesthesia machines used for humans.11 All of the vaporizers and anesthesia machines used in the study were considered to be in good condition, and except for the halothane vaporizers, they were used regularly to provide anesthesia for small animal patients. The order in which the vaporizers were tested was determined by availability (ie, not used for clinical anesthesia at the time). Isoflurane, f halothane, g and sevoflurane were used as anesthetic agents. Calibrated flow meters on the anesthesia machines were used to measure oxygen flows. These flow meters were not recalibrated before each experiment because, in the authors’ opinion, small inaccuracies in oxygen flow would not influence the results of the study. The comparison of isoflurane and sevoflurane vaporizers would not be affected by possible small inaccuracies of the flow meters because these vaporizers were mounted on the same anesthesia machines and the same flow meters were used during their comparison. The same is true for the comparison of sevoflurane vaporizers at different conditions because the same sevoflurane vaporizers were used with the same flow meters during the entire study.

Gas samples were collected at the common gas outlet of the anesthesia machines via a T-piece adapter and polytetrafluoroethylene tubing provided with the refractometer that was used for the measurements. The free end of the T-piece adapter was connected to a long corrugated hose that led to an open scavenging interface of the hospital’s active scavenging system. The anesthetic machines were pressure tested before each experiment by use of a circle system. Careful attention was paid to ensure tight connection of the adapters and hoses and prevent contamination of the gas samples with room air. The samples were aspirated with a manual aspirator bulb into the refractometer, which was connected to the tubing provided with the refractometer. The refractometer was calibrated by the manufacturer before sale, and recalibration of the unit was not performed at the time of the study. The accuracy of this refractometer was claimed to be within 3% (plus or minus) of the readings.12 The excellent accuracy of refractometry is well documented, and it has been recommended to be used as the gold standard for testing vaporizers and anesthetic gas monitors.13,14

The ambient temperature was approximately 21°C to 23°C during the study, and it was controlled with air-conditioning. The ambient pressure was approximately 102 kPa in the city where the research was conducted at the time of the study. Three sets of experiments were conducted in this study.

Experiment 1—Five isoflurane, 5 halothane, and 5 sevoflurane vaporizers were tested at an oxygen flow of 10 L/min and maximum dial settings (5%, 5%, and 8%, respectively) at room temperature (21°C to 23°C). Each vaporizer was filled to the maximum level indicator with the appropriate anesthetic agent at least 2 hours before the experiment. The temperature of the vaporizer wall was measured with a thermistor, which was attached to the side of the vaporizer (approx 2 cm from the bottom). The thermometer system was accurate to within 0.115°C (plus or minus), according to the manufacturer, but the thermistor was not recalibrated at the time of study. After obtaining baseline vaporizer wall temperature measurements (0 minutes), anesthetic agent concentration and vaporizer wall temperature were measured at 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15 minutes after starting the test. Heat loss resulting from vaporization was calculated for each vaporizer by use of the measured concentration values and published physicochemical parameters (eg, latent heat of vaporization) of the anesthetic agents.13,15

Experiment 2—Five sevoflurane vaporizers were tested at an oxygen flow of 10 L/min and a dial setting of 8%. The vaporizers were filled with sevoflurane to the maximal level indicator and were wrapped with a circulating hot water blanket, which was used in this hospital for warming anesthetized patients. The temperature of the heating pump was set to 42°C. An interval of at least 2 hours was allowed for the vaporizers to equilibrate with the temperature of the heating blanket before testing.

Anesthetic agent concentrations were measured once every minute for 15 minutes (beginning at 1 minute after starting the test). Vaporizer wall temperature was not measured in this experiment. Direct measurement of the temperature of the anesthetic liquid would have been a suitable method, but it was not possible to obtain that measurement with this type of vaporizer.

Experiment 3—Five sevoflurane vaporizers were tested at an oxygen flow of 10 L/min and a dial setting of 8% at room temperature. A volume of liquid anesthetic agent was drained from or poured into these vaporizers to ensure that the surface level of the agent was slightly higher than the minimum level indicator. The amounts of liquid anesthetic agent in the vaporizers were not standardized because the aim was to test accuracy at a range of low-fill states. An interval of at least 2 hours was allowed for stabilization before testing. Anesthetic agent concentrations were measured once every minute for 15 minutes (beginning at 1 minute after starting the test). Data were collected but not analyzed when the surface level of the agent decreased below the minimum indicator.

Data analysis—Data are reported as mean ± SD. Accuracy was defined as the mean of the absolute values of the differences between measured concentrations and the dial setting expressed as a percentage of the dial setting. Accuracy was considered to be satisfactory when it was within 20% (plus or minus) of the dial settings.15 Precision was defined as the mean of SDs of the concentration measurements. A 2-factorial ANOVA
Results

Experiment 1—In each type of vaporizer, the isoflurane, halothane, and sevoflurane concentrations significantly (P < 0.001) decreased during the 15-minute test period (Figure 1). The concentrations at the 0.5- and 15-minute time points were 5.3 ± 0.2% and 4.5 ± 0.2% for isoflurane, 5.3 ± 0.3% and 4.4 ± 0.4% for halothane, and 7.8 ± 0.2% and 5.6 ± 0.2% for sevoflurane, respectively. The isoflurane and halothane concentrations were similar, and significant differences between those sets of values were not detected via a 2-way ANOVA. However, the 2-way ANOVA revealed a significant (P < 0.001) interaction between the sevoflurane data and data for each of the other 2 anesthetic agents, indicating a difference in the shapes of the concentration-versus-time curves. During the initial 5 minutes of vaporization, sevoflurane concentrations decreased to a greater extent, compared with the decreases in concentrations of the other 2 agents. Despite the continuous decrease in concentrations, isoflurane and halothane concentrations remained within the recommended 20% (plus or minus) deviation from the dial setting. Sevoflurane concentrations were within 20% (plus or minus) of the dial setting during the initial 4 minutes only and then decreased further. Sevoflurane vaporizers were accurate to within 23% (plus or minus) of the dial setting. The precision (ie, SD) of isoflurane and sevoflurane vaporizers was similar, but the precision of halothane vaporizers was lower, as indicated by the greater variability of halothane concentrations (P < 0.001).

The temperature of the vaporizer walls significantly (P < 0.001) decreased during the 15-minute test period (Figure 2). The mean decrease in vaporizer temperature was 3.6 ± 0.5°C, 4.3 ± 0.9°C, and 1.8 ± 0.2°C for isoflurane, halothane, and sevoflurane vaporizers, respectively, during this period. There was no significant difference between the temperatures of the isoflurane and halothane vaporizers; compared with either of those vaporizers, the temperature of the sevoflurane vaporizers decreased significantly (P < 0.001) more slowly and to a lesser extent. Water condensation, indicating colder temperature, was frequently observed on the lower part of the walls of the isoflurane and halothane vaporizers at the site of the temperature probe and near the liquid agent container. However, water condensation was never evident on the sevoflurane vaporizers, and by means of manual palpation, the temperature of the vaporizers was estimated to be similar at all locations along their surfaces. The heat loss of the vaporizers was calculated to be 9,426, 8,480, and 12,847 J (2,253, 2,027, and 3,071 calories) for the isoflurane, halothane, and sevo-
flurane vaporizers, respectively, and these values were significantly ($P < 0.001$) different from each other.

**Experiment 2**—Heating significantly increased the output concentrations of sevoflurane vaporizers and improved their accuracy to within 11.7% (plus or minus) of the dial setting (Figure 3). The output concentrations of the heated sevoflurane vaporizers were $9.1 \pm 0.4\%$ at 1 minute and $6.6 \pm 0.2\%$ after 15 minutes. There was a significant ($P < 0.001$) interaction between the sevoflurane concentrations of the heated versus nonheated vaporizers (determined by use of the 2-factorial ANOVA), indicating a difference in shapes of the concentration-versus-time curves probably because of a greater decrease in concentration during the initial 3 minutes of the test period in the heated vaporizer group. The precision of the heated sevoflurane vaporizers was significantly ($P < 0.001$) less than that of the nonheated vaporizers.

**Experiment 3**—When the sevoflurane vaporizers were tested at low-fill states, the liquid anesthetic agent decreased to the minimum level indicator at 3, 5, 7, 8, and 9 minutes, respectively, after initiation of flow in the 5 different machines. Data collected after these time points were discarded, leading to an unequal amount of data at each time point in this group (Figure 4). To compare these data with data obtained from the vaporizers at full-fill states, we used the first 9 minutes of the sevoflurane data collected during experiment 1. The median sevoflurane concentrations were 6.3% (range, 5.7% to 7.5%) for the vaporizers at full-fill states and 6.5% (range, 5.4% to 7.9%) for the vaporizers at low-fill states.

**Discussion**

In the present study, the output of all 3 vaporizer types decreased during the 15-minute test period at high oxygen flows and maximum vaporizer dial settings. Despite the decreasing concentrations, isoflurane and halothane vaporizers maintained accuracy within 20% (plus or minus) of the dial setting (Figure 3). This finding contrasts with those of the studies of Steffey et al., in which another type of isoflurane vaporizer or halothane-specific vaporizers filled with isoflurane were tested under similar conditions and the output was often $< 20\%$ of the dial setting. More specifically, an isoflurane vaporizer type, which is still used in veterinary anesthesia, was tested with an oxygen flow of 12 L/min and a dial setting of 5%, and the output concentrations were $3.75\%, 3.2\%,$ and $3\%$ at 0.5, 5, and 15 minutes, respectively, after initiation of flow. Direct comparison of those results with the data obtained in the present study is difficult because slightly higher flows were used in the previous study; however, isoflurane outputs in the present study were so much higher (5.3%, 4.8%, and 4.5%, respectively, at the same time points) that it seems to justify the conclusion that the...
isoflurane vaporizers we tested may perform better at high flow conditions and maximum dial settings. Another fact that supports this conclusion is that findings of that same study indicated that isoflurane output concentration was approximately 1% at 0.5 minutes after initiating an oxygen flow of 9 L/min with a dial setting of 5%. This value is >1% lower than the initial concentration in our experiment (at 0.5 minutes), despite the fact that we used slightly higher flow rates. In our previous study, the same vaporizer type as that used in the present study provided higher isoflurane outputs than the outputs reported by Steffey et al with dial settings of 3%, 4%, and 5% and oxygen flows of >6 L/min. One explanation for the higher isoflurane output concentration of the vaporizer tested in the present study is that this vaporizer type is calibrated with air in the factory, and when it is used with oxygen as carrier gas, it generally produces output concentrations that are higher than the dial settings. On the basis of the indirect evidence reported here, the isoflurane vaporizer we tested in the present study may be a better choice than the one tested by Steffey et al when rapid vaporization of a large amount of isoflurane is required. A direct comparison under similar conditions would confirm or refute such a prediction.

Unlike the accuracy of isoflurane and halothane vaporizers, the accuracy of sevoflurane vaporizers was not within the recommended 20% (plus or minus) deviation from the dial setting. The main reasons for this difference were likely related to the higher dial setting of sevoflurane (8%, compared with 5% for the isoflurane and halothane vaporizers) and the lower vapor pressure of this anesthetic agent (160, 238, and 243 mm Hg for sevoflurane, isoflurane, and halothane, respectively, at 20°C). The combination of these factors results in a much greater oxygen flow through the vaporizing chamber of the sevoflurane vaporizers (4.2 L/min, according to our calculation) than the flows through the isoflurane or halothane vaporizers (1.7 L/min) under the conditions of this study. Therefore, another explanation for the inaccuracy of the specific sevoflurane vaporizers tested in the present study may be the possibility that such high oxygen flow (4.2 L/min) may not become fully saturated with anesthetic agent in the vaporizing chamber. Interestingly, despite the fact that the sevoflurane vaporizers vaporized the most liquid anesthetic agent and their heat loss was calculated to be the largest of all vaporizer types in the present study, the decrease in their wall temperature was less than the decrease in temperature detected in the isoflurane or halothane vaporizers. Differences in vaporizer construction may explain this discrepancy.

Because the sevoflurane vaporizers did not perform according to the specifications of the International Organization for Standardization under the conditions of the present study, these vaporizers were heated with circulating hot water blankets in an attempt to increase their output. This application of heat improved vaporizer accuracy, and sevoflurane concentrations were within the recommended 20% (plus or minus) deviation from the dial setting. The shape of the sevoflurane concentration-versus-time curve for the heated vaporizers remained similar to the one that was recorded from vaporizers held at room temperature, but the rate of decrease in anesthetic agent was greater in the presence of heat. This finding is similar to results of a previous study, in which vaporizers were tested at different temperatures (15°C, 22°C, and 30°C) and the rate of decrease in isoflurane output concentrations was greater at higher temperatures. This contrasts with the results of another study in which halothane output remained stable when a vaporizer (similar to the halothane vaporizers used in the present study) was heated electrically and an oxygen flow of 10 L/min and dial setting of 4% were used for 30 minutes. These differences can possibly be explained by the fact that in the present study and in the study of Steffey et al, the vaporizers were constantly heated (by use of hot water blankets or warm water bath, respectively), and in the study of Gootjes and Moens, the electrical heating unit was switched on or off automatically when a sensor detected a change in vaporizer temperature.

Sevoflurane vaporizers tested in the present study maintained accuracy even at low-fill states. Therefore, induction of anesthesia with high flows and dial settings is possible with undiminished accuracy at low-fill states, and refilling the vaporizer with liquid anesthetic agent can be carried out soon after induction when the patient is more stable. This contrasts with the findings of Seropian et al. The present study confirmed that the type of sevoflurane vaporizer tested can be used with an oxygen flow of 10 L/min and a dial setting of 8% even at low-fill states.

Overall, the isoflurane and halothane vaporizers tested in the present study complied with the recommendations of the International Organization for Standardization, but the sevoflurane vaporizers did not. Fill state did not affect the accuracy of this type of sevoflurane vaporizer. Interestingly, the sevoflurane vaporizers were more accurate when they were heated. Heating of a sevoflurane vaporizer may be useful in certain situations, but it should always be accompanied by measurements of inspired anesthetic concentrations because heating of vaporizers is not a standard method and it may harm the anesthetized patient, resulting in legal proceedings.

References

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