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# Distribution of Waste Anesthetic Gases in the Operating Room Air

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**Epidemiologic and animal studies identify a strong relationship between chronic exposure to anesthetic gases and health hazards. Efforts to reduce exposure of personnel require an understanding of the distribution of anesthetic waste gases in the operating room air. Concentrations of nitrous oxide and halothane were measured at numerous stations throughout an operating room and a delivery room in the absence of personnel. Air conditioning flow rates and flow patterns were varied, as was the height of the anesthetic gas source. Air flow patterns were found to dominate the anesthetic gas distribution, while buoyancy effects were negligible. Venting waste gases at the floor does not significantly reduce exposure of personnel. Areas of high concentration were observed; their occurrences and locations varied strongly with air flow patterns. The exhaust grille is the best location for a single measurement of the average room concentration. Recirculating air-conditioning systems reduce energy costs; however, only the nonrecirculating portion of the air exchanges reduces waste gas concentrations.**

**(Key words: Anesthetics, gases, trace concentrations; Equipment, exhaust systems; Operating rooms, air conditioning.)**

EPIDEMIOLOGIC SURVEYS have shown that persons working in the operating room experience unusually high incidences of headaches, fatigue, and irritability,[1] as well as higher rates of spontaneous abortion,[1-4] congenital malformations in offspring,[3,4] cancer,[4] and hepatic disease.[4] In addition, exposure to trace concentrations of anesthetic gases is reported to impair cognitive and motor skills.[5,6] Although a cause–effect relationship has not been established, the above-mentioned epidemiologic data and supporting animal studies[7,8] indicate that inhalation anesthetics are the most likely offending agents.

Effective control measures designed to minimize the exposure of personnel to trace concentrations of waste anesthetic gases depend on an understanding of the distribution of such waste gases in the operating room air. The present studies were conducted in typical rooms in the absence of personnel and were designed to determine the gas distribution with reference to: 1) the role of the air-conditioning system, especially the flow rate and use of recirculation; 2) the location of air sampling sites when used to monitor exposure of personnel; 3) the effectiveness of venting waste gases to the floor.

In a previous study,[9] halothane concentrations were measured at nine points within a 3-foot radius of the anesthesia equipment, and at three distant points. The data were collected at regular times during a normal surgery schedule, independent of operating room activities. The study clearly identified the efficacy of scavenging in reducing the concentration of waste anesthetic gases. Other studies of the distribution of anesthetic gases have been directed toward the problem of explosion hazards in operating rooms. The data are limited and test conditions incompletely defined. The literature is discussed thoroughly by Whitcher *et al.*[10]

## Methods and Materials

The study was conducted in an obstetric delivery room and in an operating room. Each room contained the normal furniture plus measuring equipment. Patient care was not in progress.

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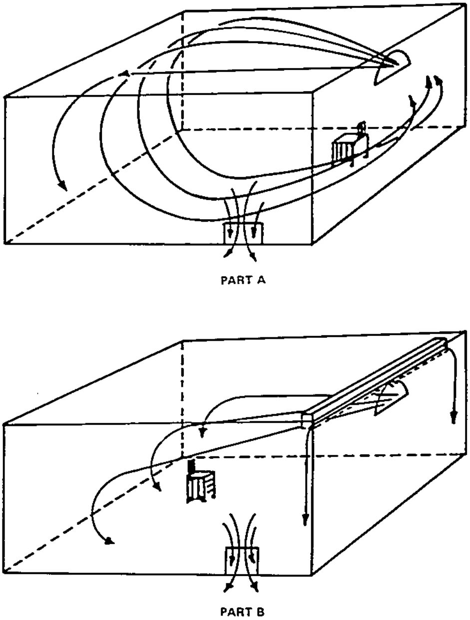

FIG. 1. Air distribution patterns: *A*, the delivery room; *B*, the operating room.

Anesthetic gases were introduced into the room by means of a standard gas machine, with the outlet tube located 92 cm or 2 cm above the floor. Gas sampling stations were spaced 106 cm apart to cover the floor area of the rooms and at three planes located approximately 2, 140, and 220 cm above the floor. In the delivery room, this resulted in a total of 36 sampling sites, and in the operating room, 48 sites. The gas samples were obtained at each station over a period sufficient for stabilization of the gas analyzer (~30 sec).

The instrumentation included infrared analyzers with reading accuracies to within 10 per cent. The time constant of the nitrous oxide ($N_2O$) analyzer (calibrated from 5 to 850 ppm) was 1.4 sec, and that of the halothane analyzer (calibrated from 0.3 to 20 ppm) was 22 sec. Because of the slow response time of the halothane infrared analyzer, halogen leak detectors,§ with time constants of approximately 1 sec, were used to monitor rapid changes in halothane concentrations. The leak detectors require frequent zeroing and recalibration and are not intended for long-term, continuous measurements. All data were continuously recorded on a multichannel chart recorder.

The air flow into the room was measured by laminar flowmeters (Balcone) with accuracies to within ±20 per cent. A hot-wire anemometer was also used to take flow measurements. A hot-wire anemometer measures velocity at a point. Thus, by taking a series of velocity measurements across the outlet of the laminar flow cone, volumetric flow can be calculated. Although the average of these read-

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§ These are ionizing detectors and are often used in the refrigeration industry.

ings was consistent with the Balcone reading, the large variations in flow velocity made numerical integration of point values inaccurate. The gas machine flowmeters were compared with an accurately calibrated flowmeter and were found to be within a reading accuracy of ±5 per cent. Any comparison of expected and measured concentrations, therefore, involves analyzer errors, air-conditioning flow rate errors, and anesthetic gas flow errors, resulting in an overall accuracy to within approximately ± 25 per cent.

In the delivery room (fig. 1A), a high-velocity ceiling and wall jet produced considerable entrainment and a major eddy. Nitrous oxide and halothane concentrations were measured at the normal air-conditioning flow rate of 1,000 ft³/min (21.3 room changes/hr) and at a reduced flow rate of 450 ft³/min (10.4 room changes/hr). In addition, the anesthetic gas mixture was released at two levels, 92 and 2 cm above the floor. In the operating room (fig. 1*B*), an x-ray positioning beam obstructed normal flow and produced a jet down the center of the room 50 to 80 cm below the ceiling, with no observable major eddy. Nitrous oxide and halothane concentrations were measured at the normal air-conditioning flow rate of 1,200 ft³/min (19.5 room changes/hr). The conditions of these four tests are listed in table 1.

An earlier set of experiments also measured concentrations of $N_2O$ and halothane with air-conditioning flows of 240 ft³/min (5.1 room changes/hr) in the delivery room and 625 ft³/min (10.2 room changes/hr) in the operating room. At each flow rate, gas was released 92 cm above the floor and at floor level. In these experiments, results of some of the $N_2O$ analyses were quantitatively uncertain, but the halothane results and qualitative data were valid.

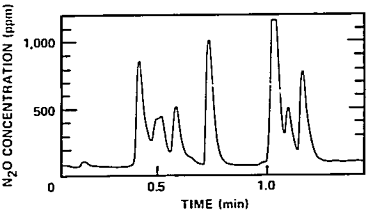

FIG. 2. Continuous chart recording of $N_2O$ concentration showing hot spot.

## Results

The gas analyzers were set to measure the gas concentrations at the air-conditioning exhaust grille and the gas "leak" was established. Tests were not conducted until the concentrations reached equilibrium. This occurred in approximately three room air exchanges, which is consistent with analysis assuming perfect mixing of the gases.

Inspection of a chart recording (fig. 2) identifies a certain sampling site as a "hot spot" area, where the concentration of $N_2O$ varies rapidly and reaches 10 to 15 times the room average (data from the delivery room, at an air-conditioning flow rate of 5.5 room changes/hr). The variations in $N_2O$ concentration were associated with proportionate variations of halothane concentration. Because such

TABLE 1. Test Conditions

| | Room | Air-conditioning Flow | | Height of Anesthetic Gas Source (cm) | Anesthetic Gas Flow (l/min) | | Ratio of Flow Rates $N_2O$/Halothane | Expected Average Concentrations* (ppm) | |
|---|---|---|---|---|---|---|---|---|---|
| | | ft³/min | Room Changes/hr | | $N_2O$ | Halothane | | $N_2O$ | Halothane |
| Test 1 | Delivery | 1,000 | 21.3 | 92 | 3.0 | 0.050 | 60 | 106 | 1.77 |
| Test 2 | Delivery | 1,000 | 21.3 | 2 | 3.0 | 0.050 | 60 | 106 | 1.77 |
| Test 3 | Delivery | 450 | 10.4 | 92 | 3.0 | 0.050 | 60 | 238 | 3.93 |
| Test 4 | Operating | 1,200 | 19.5 | 92 | 3.0 | 0.050 | 60 | 88 | 1.47 |

* These concentrations were calculated using equation 1 and the measured air-conditioning flow rate and anesthetic gas leak rate.

hot spots depend strongly on many variables (the air-conditioning flow pattern, positions of the anesthetic gas source and furniture, movement of personnel, etc.) their locations and magnitudes are not predictable. In the delivery room they were located near the wall containing the air-conditioning inlet in the far right corner of the room (fig. 1A) at heights of 140 and 220 cm in Tests 1 and 3 and at a height of 2 cm in Test 2. In the operating room during Test 4, hot spots were located throughout the far half of the room between the gas machine and the wall carrying the air-conditioning inlet (fig. 1*B*) but only at a height of 140 cm. In an earlier series of tests (results not shown), they shifted to the near half of the room near the floor (fig. 1*B*) when the air-conditioning flow was reduced. Observation of these hot spots, well away from the anesthetic gas machine, indicates their possible importance in the exposure of operating room personnel.

The test conditions for the four experiments are shown in table 1. The average concentrations at the three measurement heights are presented in table 2, and overall averages, values measured at the exhaust grille, and maximum readings are listed in table 3.

## Discussion

The distribution of anesthetic gases throughout the room is a function of air-current mixing, diffusion, and buoyancy. Molecular diffusion is far too slow to contribute to the observed distributions. Because $N_2O$ and halothane vapors are heavier than air (specific gravities 1.5 and 6.8, respectively), if bouyancy effects were present, they could be detected either by the distributions of both gases or by their relative distributions. For perfectly mixed gases, separation due to differences in molecular weight does not exist at a detectable level unless very large acceleration gradients (many thousands of g's) are present.[11,12] However, if a discrete bolus of gas is introduced into air, buoyancy forces initially do raise or lower the gas (a volume of warm air is a direct analogy). Eventually diffusion will result in the uniform distribution of all gases, but this process is too slow to have affected the present studies. When the gases from the gas machine are perfectly

TABLE 2. Observed Average Concentrations of Anesthetic Gases in Operating and Delivery Rooms (with SD and Concentration Ratios at Three Heights)

| | Height 220 cm | | | Height 140 cm | | | Height 2 cm | | |
|---|---|---|---|---|---|---|---|---|---|
| | $N_2O$ (ppm) | Halothane (ppm) | $N_2O$/ Halothane | $N_2O$ (ppm) | Halothane (ppm) | $N_2O$/ Halothane | $N_2O$ (ppm) | Halothane (ppm) | $N_2O$/ Halothane |
| Test 1 | 113 ± 49<br>(100 ± 21)* | 1.80 ± 0.72<br>(1.60 ± 0.32) | 63 ± 3 | 119 ± 22<br>(115 ± 19) | 1.88 ± 0.41<br>(1.80 ± 0.32) | 64 ± 2 | 116 ± 25 | 1.76 ± 0.35 | 66 ± 2 |
| Test 2 | 100 ± 13<br>(97 ± 6) | 1.76 ± 0.27<br>(1.69 ± 0.07) | 57 ± 4 | 106 ± 18<br>(103 ± 14) | 1.94 ± 0.35<br>(1.87 ± 0.28) | 58 ± 2 | 110 ± 14 | 2.00 ± 0.25 | 55 ± 1 |
| Test 3 | 104 ± 46<br>(92 ± 20) | 1.54 ± 0.40<br>(1.46 ± 0.30) | 62 ± 4 | 114 ± 66<br>(89 ± 15) | 2.11 ± 0.99<br>(1.72 ± 0.25) | 53 ± 4 | 130 ± 24 | 2.06 ± 0.41 | 64 ± 4 |
| Test 4 | 71 ± 11 | 1.08 ± 0.14 | 65 ± 4 | 143 ± 107<br>(74 ± 18) | 2.53 ± 1.81<br>(1.37 ± 0.32) | 56 ± 3 | 97 ± 20 | 1.66 ± 0.34 | 59 ± 3 |

* Data in parentheses do not include hot spots.

TABLE 3. Observed Concentrations of Anesthetic Gases (with SD and Concentration Ratios)

| | Average Concentration $N_2O$ (ppm) | Average Concentration Halothane (ppm) | Average $N_2O$/Halothane | Average Concentrations at Exhaust (ppm) | | | Maximum Concentrations at Height 140 cm (ppm) | |
|---|---|---|---|---|---|---|---|---|
| | | | | $N_2O$ | Halothane | $N_2O$/Halothane | $N_2O$ | Halothane |
| Test 1 | 116 ± 33<br>(110 ± 22)* | 1.81 ± 0.51<br>(1.72 ± 0.34) | 64 ± 3 | 134 ± 9 | 2.27 ± 0.11 | 60 ± 3 | 400 | 4.0 |
| Test 2 | 105 ± 15<br>(103 ± 12) | 1.89 ± 0.31<br>(1.85 ± 0.25) | 56 ± 3 | 123 ± 4 | 2.22 ± 0.05 | 55 ± 1 | 250 | 2.9 |
| Test 3 | 116 ± 49<br>(104 ± 27) | 1.90 ± 0.70<br>(1.75 ± 0.41) | 59 ± 6 | 159 | 2.96 | 54 | ∞† | 7.2 |
| Test 4 | 103 ± 69<br>(81 ± 20) | 1.76 ± 1.2<br>(1.37 ± 0.37) | 60 ± 5 | 90 ± 4 | 1.47 ± 0.06 | 61 ± 5 | ∞† | ∞† |

* Data in parentheses do not include hot spots.
† Concentrations beyond instrument ranges.

mixed, they will act as a single gas of uniform molecular weight. However, when the gases are stratified, differential buoyancy forces exist. The data in table 2 reveal no significantly higher concentration of waste gas going down from 220 to 2 cm. Tests 3 and 4 did not have significant floor-to-ceiling eddies; thus, ceiling levels were somewhat reduced by the mixing patterns, not buoyancy, because levels were generally higher at 140 cm than at 2 cm. For example, in the operating room, where the air currents were predominant at midlevel (140 cm), concentrations of $N_2O$ and halothane were higher at 140 cm than at either 2 or 220 cm. The ratio of $N_2O$ to halothane did not decrease with decreased sampling height and, therefore, $N_2O$–halothane separation did not occur. Nitrous oxide and halothane were found throughout the room in the same ratio in which they were introduced. This result was probably due to thorough mixing in the gas machine. Air currents are clearly identified as the primary factor in the distribution of anesthetic gases in an operating room.

One method considered for reducing the exposure of personnel is to exhaust the anesthetic gases at floor level. Comparison of Tests 1 and 2, in table 2, shows no reduction in concentrations at the 140-cm level. The earlier series of tests collected five sets of comparative halothane concentrations with anesthetic gas sources at 92 cm and at floor level. The data were inconsistent but, on the average, concentrations decreased by 13 and 25 per cent at 220 and 140 cm and increased by 7 per cent at 2 cm. This early series covered a wide range of air flow patterns and velocities. The results indicated that venting anesthetic gases at the floor produces slight, if any, reduction in the exposure of personnel.

In the absence of "hot spots," the distribution of anesthetic gases is generally uniform. This can be observed in tables 2 and 3, particularly in the latter, where the maximum standard deviation is 27 per cent of the mean. The average concentration without hot spots is normally within 10 per cent of those predicted for anesthetic gas and air-conditioning flow rates; however, the data from Test 3 are only within 50 per cent of the predicted concentration. This phenomenon was observed repeatedly. As the flow rate decreases, mixing decreases and a high-concentration zone exists between the anesthetic gas source and the air-conditioning exhaust grille. This phenomenon was observed by random sampling but is not well reflected in the sampling site data. With a surgical procedure in progress, however, the presence of flow obstructions and the movements of personnel would increase mixing, and a more uniform and higher concentration would result. In addition, a decrease in mixing was associated with increased maximum concentrations at the 140-cm level (table 3).

To reduce energy costs, many new hospitals are considering recirculating air-conditioning

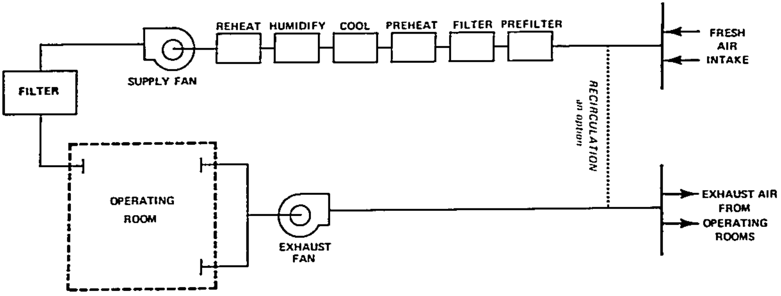

FIG. 3. Air-conditioning systems.

systems. A typical air-conditioning system is shown in figure 3, with the recirculation path indicated as optional. A typical recirculating system consists of five fresh air changes per hour and 20 filtered recirculated changes per hour. Although the high-efficiency particulate air (HEPA) filters remove bacteria, they do not remove anesthetic gases, and these gases are returned into the room. At air-conditioning flow rates of the order of 20 room changes/hr, the anesthetic gas distribution was found to be uniform and consistent with measured flow rates, as stated above. Assuming uniform distribution and equating anesthetic gas inflow, the concentration (C) in parts per million is

$$C = \frac{60 \times I \times 10^6}{n(1 - r)V} \qquad (1)$$

where

I = rate at which anesthetic gases are introduced (not including recirculated) in l/min
n = number of room air changes per hour
r = fraction of air changes recirculated
V = volume of room in liters

Using this equation, the concentrations of anesthetic waste gases can be predicted for various air-conditioning systems. For example, a typical recirculating system consists of 25 air changes/hr, of which 20 changes are with recirculated air and five changes with fresh air. A typical non-recirculating system has 15 fresh air changes/hr. With this 3:1 ratio in fresh air changes/hr, the concentrations with the non-recirculating system are only 33 per cent of those with the recirculating system, assuming the same waste gas leak rate.

An initial investigation has compared energy consumptions of various heating and air-conditioning systems: non-recirculating, recirculating and non-recirculating with heat recovery. The heat-recovery systems have a heat exchanger between entrance and exit ducts to preheat or precool entering air. The three common types of heat exchangers utilize heat pipes,[¶] thermal wheels,[**] and air–water–air units.[††] The first two require the ducts to run side by side at the heat exchanger, while the latter does not. The thermal wheel allows for minor cross-contamination of the air streams, while the others do not. Manufacturers' data on the sizes and performances of available air–water–air units

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[¶] Evaporation and condensation of a refrigerant within a sealed pipe increase the heat flow rate. The two air flow streams are sealed from each other, but they must run side by side at the exchanger.

[**] A large corrugated wheel rotates sections from the outgoing air stream to the incoming air stream. The treated surface of the wheel absorbs moisture as well as heat and transfers both to the opposite air stream. A small percentage (.04 per cent) of the flow streams mix.

[††] The system is essentially two water-filled radiators, one in each stream, with a pump to carry the heated or cooled water from one air duct to the other. The pump can exchange water between widely separated ducts.

were not available. The calculations were based on inlet (55 F, 80 relative humidity [RH]) and exhaust (70 F, 40 per cent RH) conditions for the 65,000-cubic foot per minute (cfm) system operating at Stanford Hospital, and assume 24 hr/day operation. Temperature and humidity data were used for Chicago, Houston, Los Angeles and San Francisco.[13] Energy consumption results are shown in table 4. The actual economics of the systems are difficult to quantify and are constantly varying. However, any new installation should compare the possibility of personnel exposure-related health hazards with the initial installation and energy costs of air-conditioning systems, the effectiveness of scavenging, and the potential introduction of pollutants in the future.

A review of air flow patterns and anesthetic gas distributions indicates that high flow rates and a major eddy pattern (Tests 1 and 2, table 1 and fig. 1A) produce the best mixing and have reduced hot spot effects compared with low flow rates (Test 3, table 1), or a central jet with no major eddy (Test 4, table 1 and fig. 1*B*). It should be remembered that the positions and magnitudes of hot spots are a function of other variables as well, and that the effects of such areas on exposure of personnel have not been determined.

An extensive study of anesthetic gas concentrations is facilitated when a single sampling site adequately represents the average exposure level. These studies indicate that values measured at the exhaust grille are highly representative at high air-conditioning flow rates (approximately 15 changes/hr); however, at low air-conditioning flow rates (less than 10 changes/hr), the concentration across the grille varies and multiple measurements must be obtained. As a precaution, no single sampling site can be considered representative until $N_2O$ measurements prove thorough mixing.

It is of interest to relate the results of these studies to the distribution of waste gases when a surgical procedure is in progress. In the course of a routine monitoring program during clinical anesthesia at Stanford Hospital there are occasional cases in which there is a failure in the scavenging connections. The leak rates are therefore equivalent to those used in the present study. The observed concentrations and distributions of the anesthetic gases away from the leak source were consistent with those found when no operation was in progress. Therefore, the conclusions drawn from the model studies relate well to the clinical situation.

In conclusion,

(a) Nitrous oxide and halothane are not separated by buoyancy effects and are present

TABLE 4. Energy Consumption in Heating and Cooling Operating Room Air

| | Energy Consumption, BTU's/Year* | | | |
|---|---|---|---|---|
| | Non-recirculating | Recirculating† | Heat Pipes | Thermal Wheels |
| Chicago | | | | |
| Heating | $11.8 \times 10^9$ | $0.03 \times 10^9$ | $5.8 \times 10^9$ | $0.59 \times 10^9$ |
| Cooling | $6.7 \times 10^9$ | $4.6 \times 10^9$ | $6.0 \times 10^9$ | $5.2 \times 10^9$ |
| Houston | | | | |
| Heating | $2.4 \times 10^9$ | 0.0‡ | $1.2 \times 10^9$ | 0.0 |
| Cooling | $23.6 \times 10^9$ | $12.0 \times 10^9$ | $21.0 \times 10^9$ | $15.7 \times 10^9$ |
| Los Angeles | | | | |
| Heating | $0.97 \times 10^9$ | 0.0 | $0.38 \times 10^9$ | 0.0 |
| Cooling | $7.4 \times 10^9$ | $6.9 \times 10^9$ | $7.3 \times 10^9$ | $7.1 \times 10^9$ |
| San Francisco | | | | |
| Heating | $2.6 \times 10^9$ | 0.0 | $1.0 \times 10^9$ | 0.0 |
| Cooling | $2.37 \times 10^9$ | $2.32 \times 10^9$ | $2.354 \times 10^9$ | $2.347 \times 10^9$ |

* Based on air supplied at 55 F, 80 per cent RH; exhausted at 70 F, 50 per cent RH with the room heating load assumed constant. Based on 24 hr/day usage, 65,000 cfm.

† Assuming an optimum system that mixes supply and exhaust air in the appropriate ratio to minimize heating and cooling. The maximum recirculation was 80 per cent.

‡ The assumed constant heat load from the room was sufficient to heat incoming air.

throughout the room in a concentration similar to the expected level.

(b) Venting waste gases at the floor reduces the concentrations to which personnel are exposed only slightly, if at all.

(c) Hot spots (areas of highly concentrated anesthetics) exist, related to air-conditioning flow rates and to other variables. Hot spots could surround the head of any person in the operating room with high concentrations of anesthetic gases, and may be critical in the exposure of personnel.

(d) Reducing the air-conditioning flow rate increases the average concentration of the anesthetic gases and the concentrations present in hot spots.

(e) Monitoring the average concentration of anesthetic gases in the operating rooms studied was accomplished at the air-conditioning exhaust grille. The validity of this procedure for any given operating room should be established by demonstrating similar concentrations in areas occupied by personnel.

(f) Air-conditioning systems that create major floor-to-ceiling eddies have been observed to produce extensive mixing, thus reducing areas of high concentration. Effective systems include entrainment-type inlets at flows of approximately 15–20 room changes/hr.

(g) Heat-recovery systems should be considered for use in new installations.

(h) Recirculating air exchanges do not reduce the average concentrations of anesthetic gases. Consequently, if a recirculating system providing five fresh air exchanges per hour is compared with a non-recirculating system providing 15 fresh air exchanges per hour, the recirculating system would tolerate only a third the leak rate of anesthetic gases if the objective were to expose personnel to equivalent concentrations of waste gases with the two systems. In other words, with a recirculating system the anesthesia equipment, including scavenging devices, and the techniques of the anesthetist must be three times as effective in preventing anesthetic waste gas from leaking into the room.

Equipment for gas analysis was lent by Wilkes Scientific, General Electric, and Inficon.

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