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Multipatient Anesthetic Mass Spectrometry:

Rapid Analysis of Data Stored in Long Catheters

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A centrally located mass spectrometer sequentially samples airway gases from ten anesthetized patients through 30 m long, 1.07 mm, ID, nylon catheters and three way solenoid valves. End-tidal and inspired concentrations of O_2, N_2, CO_2, N_2O, and halothane, enflurane, or isoflurane are displayed on a computer terminal screen in each OR with trend plots. While a gas sample from one room is being analyzed, all other catheters are slowly sampled in order to continuously store 20-s concentration profiles ready for analysis. The stored gas sample is analyzed at twice the rate it was sampled. The computer switches catheters after one breath has been validated from two comparable end-tidal P_{CO_2} values. Large flow changes produced by switching from one catheter to the next require regulation of the pump pressure in the mass spectrometer. This method reduces the time required to sample each room to 6.96 s (4–10 rooms). Catheter transit slows the response to a step increase of concentration by about 0.13 s (from 10 per cent–90 per cent) and prolongs the transit time through the catheter for a volatile anesthetic by about 0.04 s more than N_2. The monitoring facility is used in each room for an average of 5.5 h/day. Two years of experience suggest that it can facilitate detection of faulty technique and equipment, reduce cost of anesthetic agents by encouraging use of closed systems, increase patient safety, aid research and teaching, and diminish exposure of OR personnel to anesthetics. Inherent problems have resulted in an inoperative time of less than 2 per cent. (Key words: Equipment: computers; mass spectrometer. Measurement techniques: mass spectrometry. Monitoring: anesthetic gases; carbon dioxide; end-tidal gases; oxygen.)

RESPIRATORY GASES drawn through long sampling catheters from many patients may be analyzed sequentially by a single, centrally located mass spectrometer, typically in intensive care units.[1,2] Davies and Denison[3] investigated the performance of such sampling catheters, and concluded that they introduced no important errors. The time required to flush out a typical 30-m long sampling catheter and then analyze the gas sample for one full breath approximates 20 s. Mass spectrometers have been modified for use in anesthesia as well,[4,5] and with the installation of similar systems in large operating suites, it became apparent that the waiting time between analyses was too long to serve the needs of anesthesiologists. We report here the development and testing of a 10-room system which has been designed to reduce the sampling time required for each room to about 7 s. To accomplish this, a 20-s profile of airway concentrations, continuously stored in each sampling catheter, is rapidly analyzed until a single breath has been validated. This has permitted inspired and end-tidal concentrations to be displayed on computer terminals in each of 10 operating rooms about once per minute.

Until recently, mass spectrometers have been both too expensive and too unreliable for continuous operating room use. The cost (approximately $35,000) inhibits their use for single patient monitoring. However, the monitoring cost per patient can be reduced significantly by using one mass spectrometer for many patients. The total equipment and installation cost of a single mass spectrometer designed to serve an entire OR suite ($60,000) is competitive with multiple individual CO_2 and O_2 analyzers, and provides far more information. We felt that the system costs would be justified if 1) patient safety were enhanced; 2) closed-circuit anesthesia systems could be used routinely, decreasing cost of anesthetic gases; 3) resident education would be improved; and 4) clinical research of anesthetized patients would be facilitated.

Methods

A mass spectrometer (Chemtron, Med-Spec II®) measuring O_2, CO_2, N_2, N_2O, and volatile anesthetic agents was modified in several ways to improve its performance for OR use (see Appendix A). Figure 1 illustrates the pneumatic circuit modifications used to eliminate errors due to pressure surges at the mass spectrometer inlet caused by catheter switching. A computer (see Appendix B) was programmed to determine inspired and end-tidal concentrations of each gas, timed from the CO_2 waveform, to generate individual tabular and graphic displays for each OR terminal, to permanently store the data and to control a bank of thirteen solenoid valves. The 3-way solenoid

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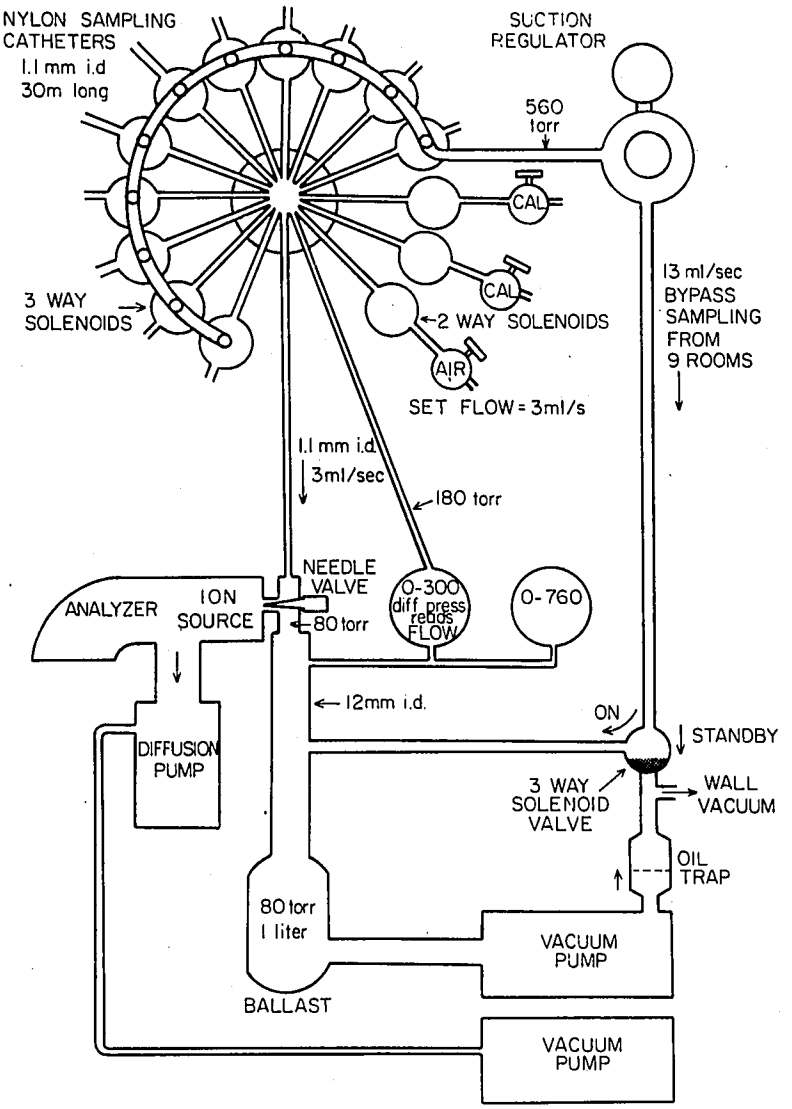

FIG. 1. Solenoid valve assembly and pneumatic circuit designed to continuously aspirate all catheters and to reduce the pressure surges at the mass spectrometer needle valve caused by the switching of the catheters. (See Appendices A and C for more details.)

valve assembly (see figs. 1 and 2 and Appendix C) opens one catheter at a time into the mass spectrometer while continuously aspirating all other catheters at a low flow rate (1.4 ml/s) into a constant pressure vacuum line (560 torr, absolute), maintaining a 20-s concentration profile ready for rapid analysis by the mass spectrometer in every catheter. The computer terminals in each OR have a display screen and a keyboard used to enter the patient's name and hospital number, and request various displays.

Flexible polyethylene pipe conduits (¾ in, ID) were installed from the central location into each of the ten operating rooms. Electrical cables for the terminals and sampling catheters were inserted through these conduits. The catheters were attached to the airways of the patients as described in Appendix D. Nylon was chosen for the sampling catheters because it contains no plasticizers, is strong, inexpensive ($0.05/m) and wettable. The solubility of CO_2, N_2, and halothane in nylon is so slight that no detectable fall of concentration occurs even when a gas sample containing the gases is allowed to stand in the catheter for 10 min. Water condensation in the sample lines has not been a problem. Condensation does occur in the first segment, about 3 m in length, but beyond this, vapor pressure is reduced below the dew point as the gas stream is expanded. The wettable nylon walls allow water to move as a film rather than as droplets, increasing the surface area for evaporation.

The catheter length was set at 30 m, the distance to the farthest room to be sampled. An internal diameter of 1.07 mm was chosen to obtain a flow into the mass spectrometer of about 3 ml/s. The relationships of flow and transit time through the catheter to downstream pressure are illustrated in figure 3, and discussed in Appendix E.

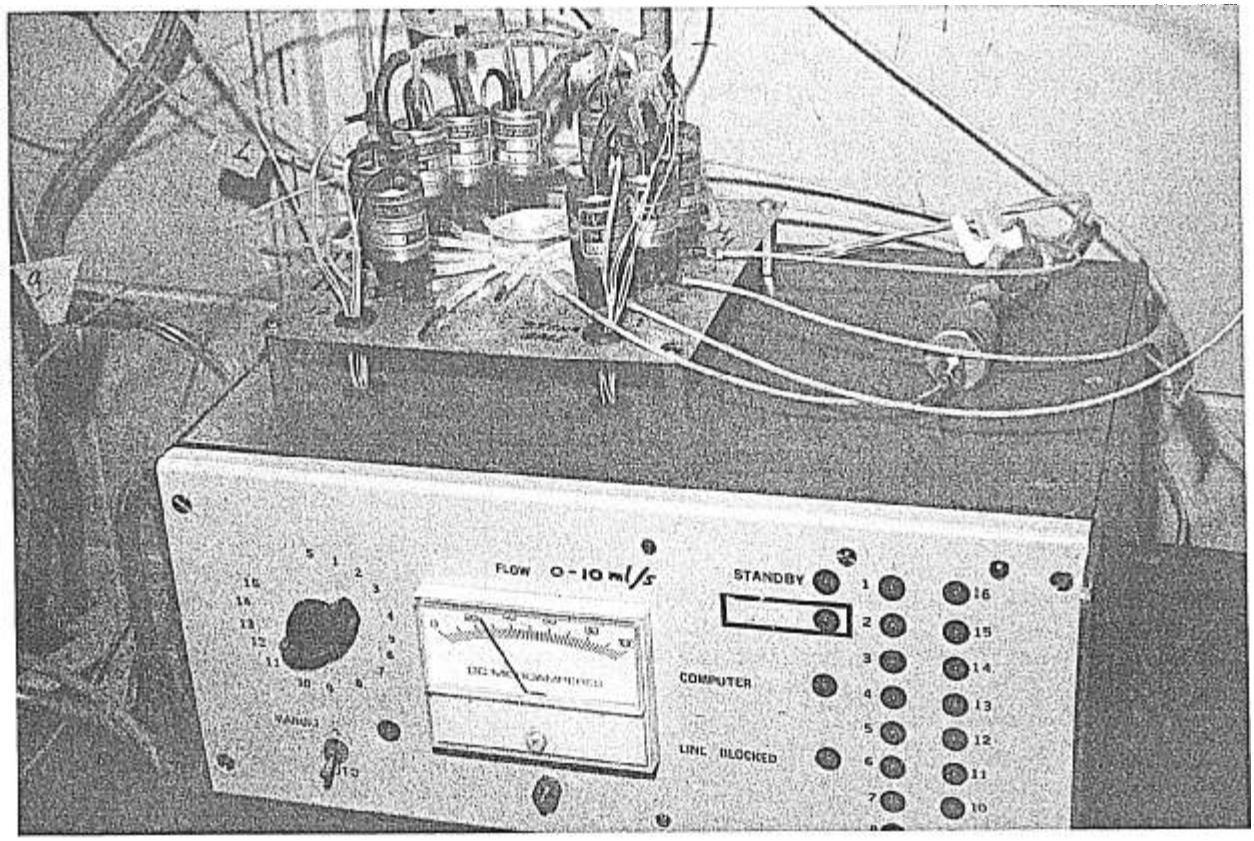

FIG. 2. The miniature 3-way solenoid catheter selection valves with sample flow meter, indicator lights, and manual room selection switch. (For size comparison, the valves are ¾ inch in diameter.)

When the solenoid valve opens a catheter to the mass spectrometer, the first few seconds of stored gas sample is suddenly decompressed from a pressure of 560 torr to 180 torr (absolute). The expansion of gas washes out the solenoid manifold and tubing to the mass spectrometer in about 0.2 s. The stored sample is then analyzed in the next 7 s. This period will usually contain at least two end-tidal P_{CO_2} peaks for respiratory rates above 6 breaths/min. When acceptable end-tidal and inspired values are identified, the computer displays all gas concentrations on the terminal in that OR and switches the solenoids to the next active room. Figure 4 shows an example of rapid analysis of stored data.

The computer breath detection algorithm is described in Appendix F. The computer switches the mass spectrometer to the succeeding room when one of the following criteria is met: 1) two valid expirations have been recorded; 2) no CO_2 over 7 torr has been detected in 5 s; or 3) 15 s have elapsed. At the beginning of an anesthetic procedure, service is requested by entering the patient's name and hospital number. Until a breath has been detected (that is, a P_{CO_2} over 7 torr), that room is scanned for 5 s in each cycle, while the measured data are displayed but not stored. If after an hour CO_2 has never been detected, service will cease for that room. Once the first breath has been recorded, all data are stored as well as displayed. At the end, service is terminated, either on command or when no CO_2 has been detected for 15 min.

A table of inspired and end-tidal concentrations with respiratory rate, time of day, and age of sample in seconds is displayed on each OR terminal. Also displayed are the numbers of the active rooms, showing which is being sampled currently. Trend plots with a table of all the most recent gas concentrations are available upon request by each anesthetist (see fig. 5). The user may select by a single keystroke a standard "default" trend plot of end-tidal P_{CO_2} and volatile gas scaled automatically to display the entire case. End-tidal O_2 is displayed if no volatile gas is used. Other gases, time bases, and concentration ranges may also be requested. In addition, a calibration mode may be selected, presenting a table of the mean and range of concentration of all gases during a 5-s sample, to test the calibration of the mass spectrometer, flow meters, and vaporizers.

We attempted to make the system safe and easy to

understand and use in several ways. 1) The display always indicates which key strokes may be used next, or what information is required to start or proceed. 2) The common displays are selected by single keystrokes, the concentration ranges and time base being selected by the computer. 3) Time of day is kept by the computer clock and displayed continuously. 4) The OR terminals are isolated from the program such that it is impossible to disrupt the system by incorrect keystrokes. 5) To make the sampling system simple and always ready to use, the catheter is permanently attached to the elbow connector between the mask or endotracheal tube and the breathing circuit. 6) The terminal emits a "beep" when a new analysis is displayed.

Results

The monitoring system has been used continuously in ten ORs for the past 20 months. During the 10-month period ending October 1980, the system has been used to monitor patients 1134 ± 166 hours/month, an average for each room of 5.5 h/day. Failures have progressively decreased such that the system has been inoperable on the average less than 6 hours per month during the last 8 months. No protests have arisen relating to permanent storage of the potentially incriminating data. To date, 14 research investigations involving over 525 patients have used information provided by the system. The use of closed-system anesthesia has increased from approximately 2 per cent to 12 per cent. The availability of

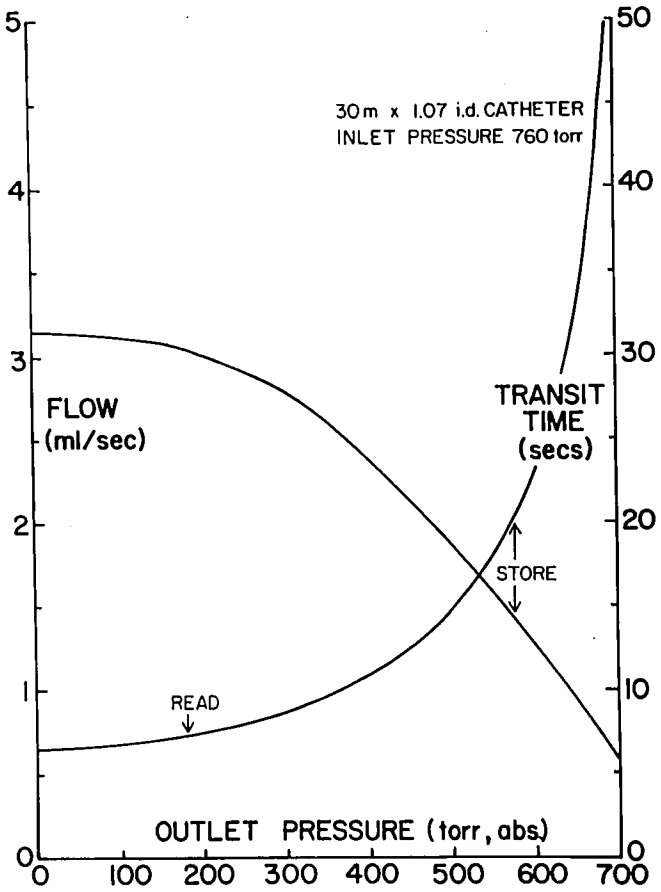

FIG. 3. The effects of pressure on flow and transit time in a 30-m catheter. The "read" and "store" arrows indicate the outlet catheter pressures during the analysis and storage modes, respectively. The inlet pressure is 760 torr.

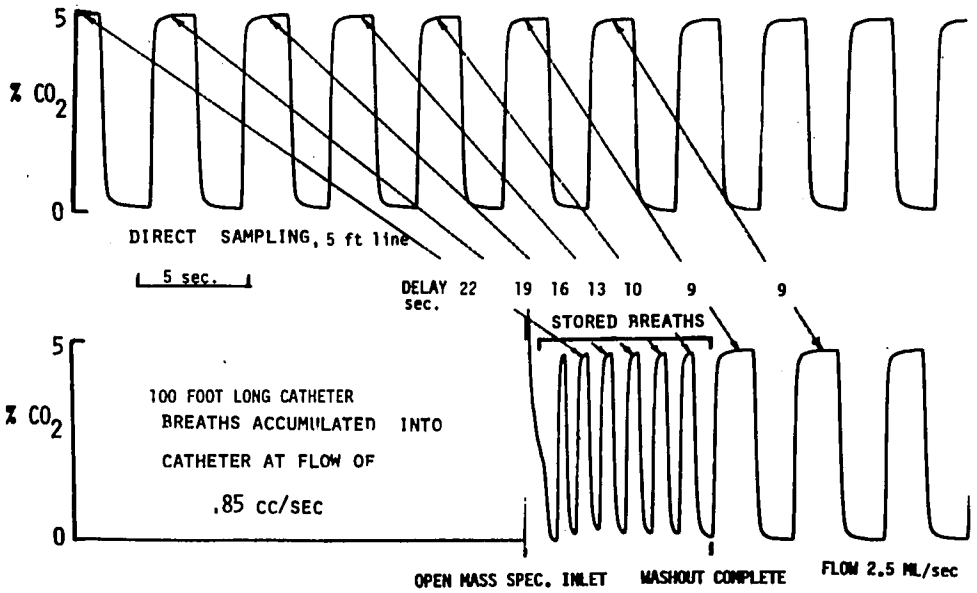

FIG. 4. A recording of the output of two mass spectrometers simultaneously sampling a simulated respiratory CO_2 waveform, to show the operation of the long catheter as an information storage and delay line. The upper trace was recorded through a 2-m catheter. The lower trace shows the signal when the second mass spectrometer begins to sample at a high flow rate (2.5 ml/s) from a 30-m catheter which had been storing data at a low flow rate (0.85 ml/s). The arrows connect corresponding breaths with the delays ranging from 22 s to the 9-s transit time for this catheter. Note that the first two stored breaths are analyzed in 1.1 s, approximately 3.5 times faster than they actually occurred.

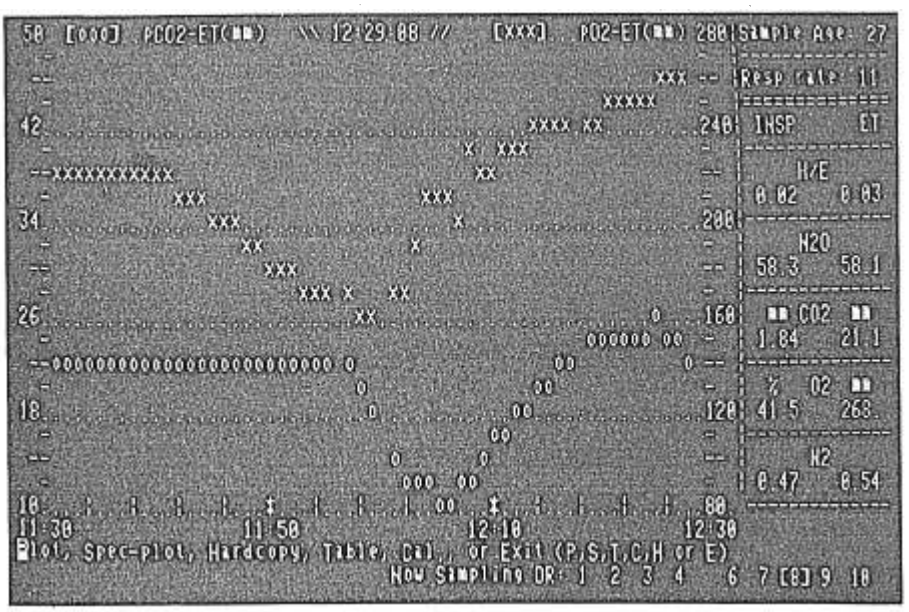

FIG. 5. Typical display of a trend plot of end-tidal CO_2 (o) and O_2 (x) on an OR computer terminal showing the effect of an air embolus during a craniotomy in the sitting position. The CO_2 scale is on the left axis and the O_2 on the right. The horizontal axis is a time scale from 11:30 A.M. to 12:30 P.M. "Sample age" is the time in seconds since the values in the table were last updated. The next to the last line indicates key stroke options (P, S, T, C, H or E) to display the standard or default *P*lot, or a *S*pecial plot, a *T*able without plot, a *C*alibration mode, or to obtain a *H*ardcopy, or *E*xit from monitoring. The bottom line indicates that all rooms but OR 5 are active and the mass spectrometer is presently analyzing the gas sample from OR 8.

end-tidal P_{CO_2} values has changed clinical practice considerably. It has reduced the need for arterial blood gas analysis in establishing the level of artificial ventilation, as well as in determining the adequacy of spontaneous ventilation. A single blood-gas analysis is often used to establish the magnitude of the $P(A\text{-}a)_{CO_2}$ difference.[6]

The time required to sample a single room is 6.96 ± 0.48 s (mean ± SD, n = 84,900) when four or more rooms are in use. The frequency of sampling each patient is 5/min with a single active room, 2/min with 2–4 rooms, decreasing to once a minute (64 ± 6.8 s interval) with ten active rooms.

When an abrupt change of gas concentration is sampled through these long catheters, some deterioration of the signal occurs (see table 1). A pulse of end-tidal gas lasting 0.6 s will reach only about 95 per cent of the true value before reversing direction again. Thus respiratory rates above 40/min will appear to show falling end-tidal and rising inspired P_{CO_2}. (To some extent the anesthetic gas concentrations will be similarly erroneous. However, the error is smaller since inspired anesthetic concentration is usually closer to the end-tidal value than is P_{CO_2}.)

TABLE 1. Transit and Rise Times of a Step Change of Concentration Sampled Through a Long Catheter*

Gas	Rise Time (seconds)			Transit Time (seconds)		
	1 m	30 m	Increase by Catheter	1 m	30 m	Increase from N_2 Due to Catheter
N_2	0.08	0.20	0.12	0.23	6.44	—
CO_2	0.16	0.25	0.09	0.26	6.47	0.00
Halothane	0.145	0.28	0.135	0.27	6.52	0.04

Note: In addition to the above, the radial manifold and 1-m inlet catheter add 0.037 s to the 10–90 per cent rise times, and 0.115 to all transit times.

* Transit time is measured to 50 per cent of the final response, and rise time is the time from 10 per cent to 90 per cent of the response to a step change. Conditions: 30 m × 1.07 mm, ID; 760 to 80 torr pressure drop; 3 ml/s flow; transient from 68 per cent N_2O, 6 per cent CO_2, 25 per cent O_2, 0.7 per cent halothane to air.

The long sampling catheters have caused minimal problems. They have occasionally been kinked or cut accidentally. The defect may be spliced with a larger, tight-fitted nylon segment. Soda lime dust has caused four solenoid valves to stick. (They were cleaned by flushing water through them. We have avoided use of filters in each line because the extra dead space would impair the transient response.) Two catheters had been irreversibly plugged with blood and had to be replaced, and four required back flushing with a syringe and water, and drying with compressed gas.

Discussion

The first two years of experience have been marked by a continuous process of modification of both the equipment and the computer program in response to problems and to suggestions from the users. The information provided by monitoring anesthetic and respiratory gases has not been readily available in the typical OR suite but has proved valuable to us. It is the consensus of the faculty that the system substantially aids the education of residents and medical students.

There have been no untoward events caused by system malfunctions, but a variety of "incidents" have been observed, documented, and treated because the

monitoring was available. Unintentional administration of anesthetics has been recognized. It was found that volatile anesthetics are often extracted from "kettle" vaporizers when the vaporizer enabling valve is in the "on" position and positive pressure ventilation is used. Errors in flow meters and vaporizers have been detected. The plots of gas concentration have been useful to alert the anesthesiologist of unintentional concentration changes. Inboard leakage of air under a poorly fitting mask becomes evident when inspired N_2 concentration rises.

Apparatus failures detected with the monitoring system have included: intermittently stuck (open) "dome" valves in a circle absorber causing sudden large rises in inspired and end-tidal P_{CO_2}; exhausted soda lime despite the lack of color change; unintentional leak of volatile agents into the systems; inboard leak of N_2 through malfunctioning "pop-off" valves and ventilators using negative (suspended bellows) pressure; errors in polarographic O_2 sensors which may become sensitive to N_2O with battery failure;[7] and errors in blood gas electrodes have been detected when readings were incompatible with end-tidal gases.

Clinical problems made evident by the monitoring system have related to diagnosis of hypo- and hyperventilation, inappropriate dose of volatile agents, mismanagement of manual artificial ventilation, and identifications of circulatory effects of anesthetics. Air embolism has been identified in neurosurgery by sudden falls of end-tidal P_{CO_2} (fig. 5). Diagnoses have often been facilitated by the graphic displays of the gas concentrations.

We believe that monitoring of anesthetic and respiratory gases has added substantially to clinical research, education of residents and medical students, and the clinical care of our patients.

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References

1. Turney SF, Blumenfield W, Wolf S, et al: Respiratory monitoring. Ann Thorac Surg 16:184–192, 1973
2. Riker JB, Haberman B: Expired gas monitored by mass spectrometry in a respiratory intensive care unit. Crit Care Med 4:223–229, 1976
3. Davies NJH, Denison DM: The uses of long sampling probes in respiratory mass spectrometry. Resp Physiol 37:335–346, 1979
4. Davis WOM, Spence AA: A modification of the MGA 200 mass spectrometer to enable measurement of anesthetic gas mixtures. Br J Anaesth 51:987, 1979
5. Graham J, Kay B, Greer W, et al: Mass spectrometers in anaesthesia. Br J Anaesth 52:1055, 1980
6. Nunn JF, Hill DW: Respiratory dead space and arterial to end-tidal CO_2 tension difference in anesthetized man. J Appl Physiol 15:383–389, 1960
7. Piernan S, Roizen MF, Severinghaus JW: O_2 analyzer dangerous: senses N_2O as battery fails. ANESTHESIOLOGY 50:146–149, 1979
8. Taylor G: Dispersion of soluble matter in solvent flowing slowly through a tube. Proc R Soc A 219:186–203, 1953

APPENDIXES

Appendix A. Mass Spectrometer Modifications

A Med-Spec II® 8-channel mass spectrometer was obtained with collectors for the respiratory and anesthetic gases and helium and acetylene, the latter two for use in measuring lung volume and pulmonary blood flow. It was modified in several ways for multipatient monitoring.

Anesthetic Identification. The three volatile agents we use (halothane, enflurane, and isoflurane) are partially fragmented in the mass spectrometer ion source. Each has a major ion fragment at mass 67 which is used for analysis. Another fragment appears at mass 51. The ratio of 67/51 is used for identification since it is a characteristic of each agent. It is 7.5 for halothane, 1.45 for enflurane, and 0.44 for isoflurane. Each also has a different calibration factor at mass 67. Enflurane and isoflurane provide signals 2.67 and 0.92 times, respectively, those of halothane at the same concentration. An electronic circuit senses the 67/51 ratio, determining which agent is present, indicates this to the computer, and adjusts the gain at mass 67 appropriately.

Stabilization. To prevent calibration variations during warm-up, we found it useful to alter the standby mode in order to keep the filament continuously heated with a low, constant emission current (about 2 μamp). The ion source was temperature regulated (about 55° C) using an external heater and an internal thermistor. The ion collectors were replaced with gold-plated Faraday cups to avoid changes in sensitivity due to surface films (oxides, nitrides). The output signals were buffered with operational amplifiers. The N_2O signal was found to be more stable at mass 44 than at 30 (NO^+), due to variable overlap from the strong N_2 and O_2 peaks at 28 and 32. Utilizing the carbon ion fragment (C^+), CO_2 is detected at mass 12. To obtain the N_2O signal, the CO_2^+ component is electronically subtracted from the total signal at mass 44. The mass spectrometer requires a calibration check twice daily, and a few hours per month maintenance by in-house personnel.

Pressure Regulation. Details of the special pneumatic system are shown in figure 1. When the solenoid valves switch to a new room, the pressure in the new catheter is 560 torr, whereas the pressure in the radial manifold is 180 torr. The resulting sudden decompression of the new sample is helpful since it rapidly washes out the inlet system. However, as supplied, the mass spectrometer had no pressure regulation and the transient rise in pressure overwhelmed the summing circuitry, which is used to force the total of all gas concentrations to 100 per cent. Furthermore, even small rises of pressure can increase the apparent ratio of heavy to light molecular weight gases. Therefore, we modified the mass spectrometer to regulate the pressure at the needle-valve in-

let to the analyzer chamber in the following ways: The tubing between the needle valve and the pump was replaced by 12 mm, ID, albumin pipe to reduce resistance. A reservoir volume of 1 liter was inserted in this line to damp out pump pressure "noise". The standby sampling flow from the rooms not being analyzed (about 13 ml/s) was directed into this buffer reservoir, thereby keeping the total sample pump flow constant during switching. This flow floods the sample pump, raising the pressure to about 80 torr, thereby reducing by 10-fold the transient changes produced by switching one of these catheters. In addition, the pneumatic arrangement shown in figure 1 partially cancels the pressure transient in the buffer reservoir because the previous room catheter refills from the bypass line at the moment of switching, just as the new catheter dumps a high pressure load into the radial manifold. With this regulation, the peak pressure rise at the needle valve at the time of switching is 14 per cent, decaying 63 per cent back to base line in 0.6 s. This was determined in the non-summing or emission mode by recording the rise in N_2 and O_2 signals when switching between two catheters sampling air. When using the summing circuitry, the maximum error is 2.5 per cent, which is corrected to zero error after .05 s. The system thus provides valid data within 0.2 s after switching catheters, delayed only by the washout of the solenoid manifold.

Appendix B. Computer

A DEC (Digital Equipment Corporation) PDP11/10® in the OR is linked by a coaxial cable to a PDP11/34 in the laboratory. The 11/10 is to be replaced by an 11/34 to permit additional features such as measurement of lung volumes and pulmonary blood flow by rebreathing methods, handling of analog inputs from the OR, etc. The program is written in Fortran IV using DEC's multiuser system RSX 11M. Data are stored on large or floppy disks. Appropriate stand-alone computers capable of handling the entire program would include DEC's LSI 11/23.

Appendix C. Solenoid Valve Control Unit

Each long sampling catheter is connected to a miniature 3-way, 24-v solenoid valve (General Valve series 3, orifice diam. 0.050 in) as illustrated in figures 1 and 2. In order to minimize dead space, the valves were circularly mounted around a small radial manifold machined from Lucite.® Nylon catheter segments wedged into the Lucite® are connected to the valves using Silastic® tubing. The manifold collects gas from one open valve and delivers it directly to the mass spectrometer needle valve through a 1.1-mm (ID) catheter, bypassing the standard mass spectrometer inlet solenoids and tubing. The normally open port of each 3-way valve connects the nine other sampling lines to suction regulated to 560 torr. The computer addresses the solenoids sequentially, skipping inactive rooms. A pressure transducer measures sample flow by determining the differential pressure across the inlet tubing resistance (~ 30 torr·s·ml^{-1}) between the radial multiplexing manifold and the buffer reservoir in the mass spectrometer. If this flow falls below 1 ml/s, a "blocked catheter" signal is transmitted to the room in question, and sampling passes to the next room. Signal lights are used to indicate the room being sampled, the absence of computer function, and provide warnings for incorrect use of manual calibration switches. A manual room selection switch is used for servicing.

Appendix D. Patient Connector

A BD Luer Lock female tubing adaptor (#3210) is mounted on an aluminum mask-ET elbow (Dupaco 32002®). Its conical tip projects into the center of the air stream. The small hole at the end of the adaptor acts as a sampling catheter stop and also helps prevent entry of particulate matter into the catheter. A Tuohy-Borst BD 3098 male catheter compression fitting attaches the catheter to the 3210.

Appendix E. Long Catheter Function and Theory

The flow Q (molecules/s) in a catheter of length L (cm) and radius a (cm) is a function of inlet and outlet pressures, Pi and Po, (dynes·cm^{-2}), temperature T (°K), Boltzman's constant k (1.38×10^{-16} erg/°K per molecule), and viscosity of the gas, n (poise). Density d is the density at the inlet (molecules/ml). V is bulk velocity at the inset (cm/s); A is cross sectional area (cm^2); t is transit time (s). When Po < 0.1 Pi:

$$Q = \frac{a^4(Pi)^2}{16LnkT} = dVA \qquad (1)$$

$$t = \frac{32L^2n}{3a^2(Pi)} \qquad (2)$$

When Po > 0.1 Pi, flow is reduced by the fraction $(1 - y^2)$ and transit time is increased by the fraction $(1 - y^3)/(1 - y^2)^2$, where y is the ratio Po/Pi.

The effects of catheter length and diameter on flow and transit time, calculated from the above equations when downstream pressure is near zero (80 torr), are shown in figure 6. The measured effect of downstream pressure on transit time and flow in our 30-m catheter is illustrated in figure 3. Figure 7 illustrates the storage characteristics of a 30-m long catheter as we use it. The first one-half second of data is discarded during washout of the inset. This accounts for approximately 2–3 s of stored, real-time data. During the next 7.5 s, the remaining 17–18 s of stored data are analyzed. The first compression of the data (fig. 8) falls from about 5:1 initially, to about 2:1 after 2 s, remaining relatively constant for the next 5.5 s, and then falls to 1:1 after 8 s. This stored information generally is sufficient to permit detection and analysis of two end-tidal P_{CO_2} peaks and progression to the next room. If switching does not occur before 8 s, the mass spectrometer samples the non-stored data, for which transit time is 6.5 s (fig. 3). To minimize the time required to sample every room, the optimum choice for the amount of time compression depends on the mean respiratory rate of the entire OR suite. An incorrect amount of time compression can result in a 50–100 per cent increase in sampling time. In general, the higher the mean respiratory rate, the less time compression is required. For example, in a pediatric hospital no time compression may be desired.

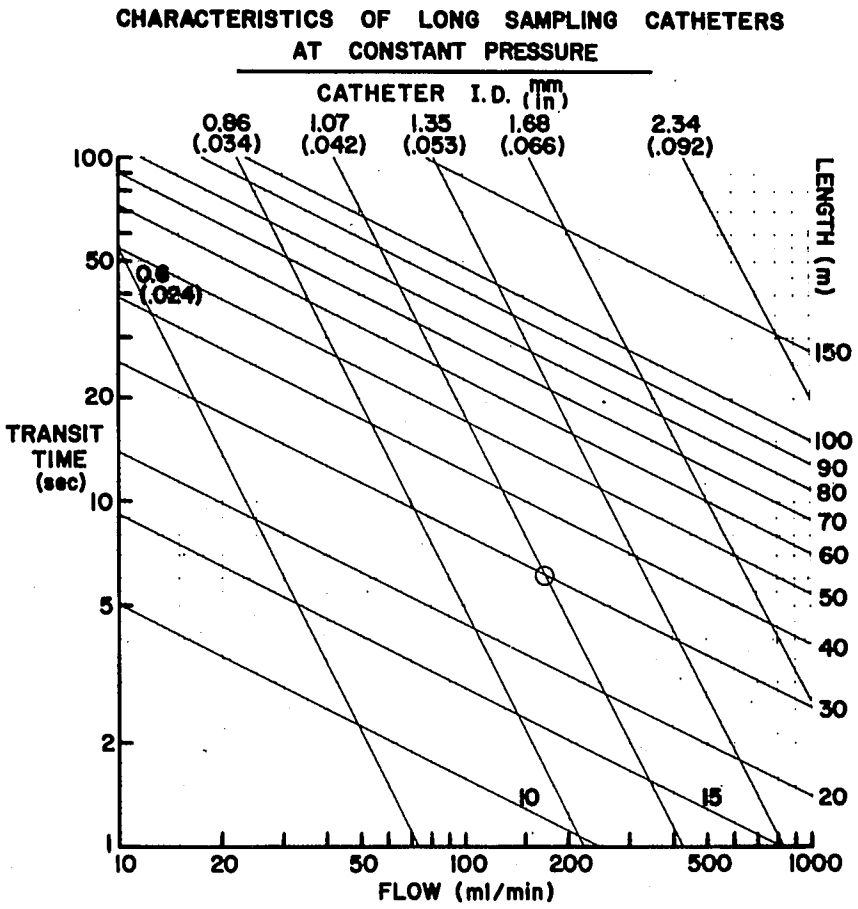

FIG. 6. The effects of catheter diameter and length of flow and transit time, as computed from equation 1, Appendix E. Pi = 1,013,300 (760 torr), Po = 106,663 (80 torr), n = 0.000181 (air), T = 293. Read at the intersection of appropriate length and diameter isopleths. (Our catheter is indicated by the circle.)

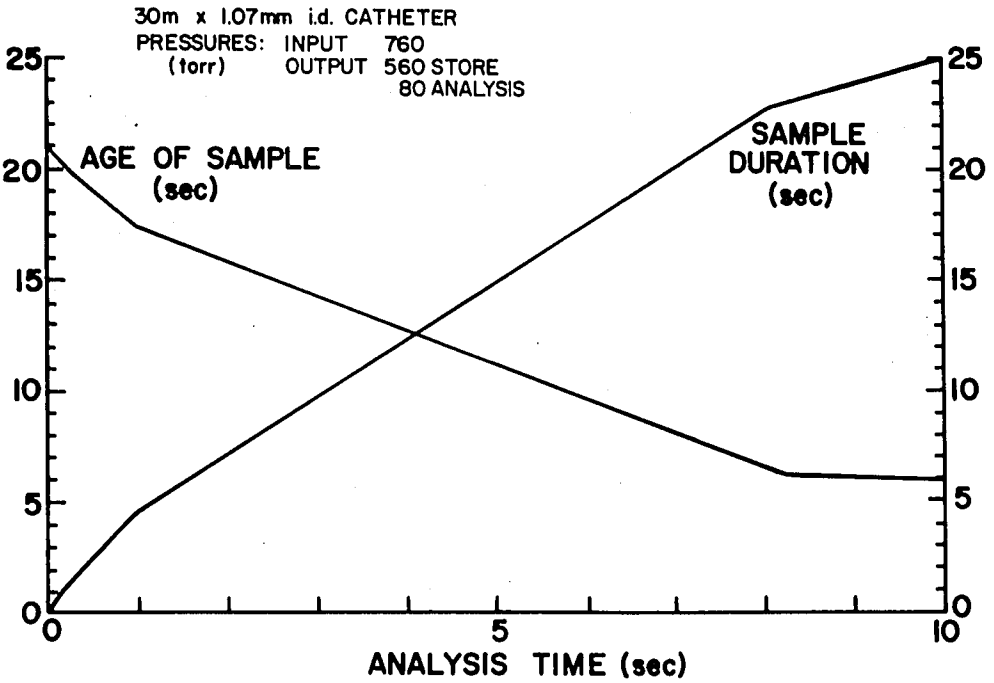

FIG. 7. The observed age and duration of sample exiting from a 30-m catheter as a function of analysis time. "Sample duration" indicates how many seconds of input sample have been analyzed at any time, *e.g.*, after 5 s of analysis, 15 s of input data have been analyzed. Downstream pressure during storage (before time 0) is 560 torr and during analysis is 180 torr at the solenoid manifold.

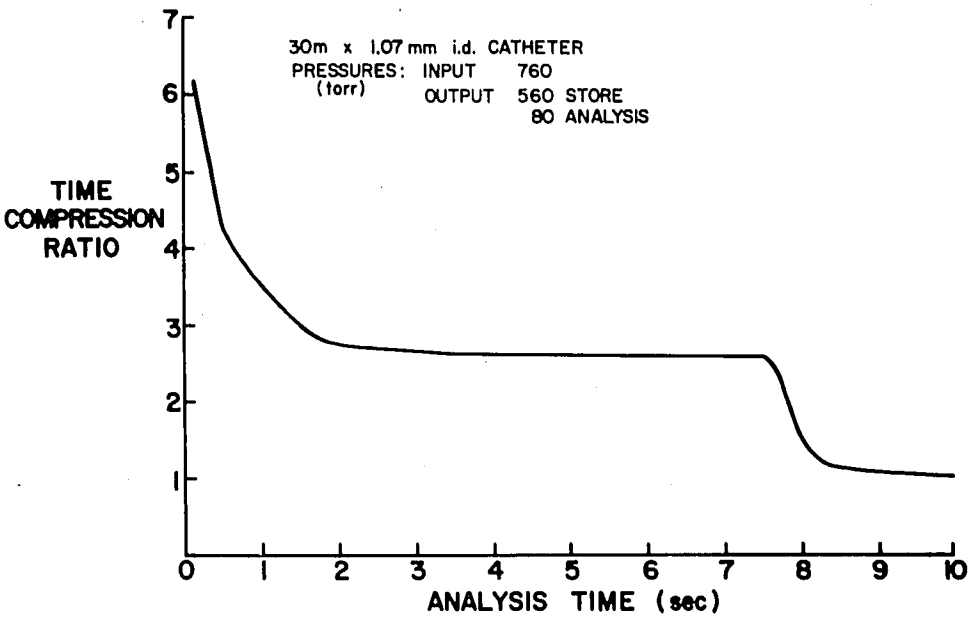

FIG. 8. The time compression ratio is Vo/Vi, where V is gas flow rate, ml/s, and the subscripts i and o refer to inflow of a sample, and its later outflow from the catheter. Vo decreases during the first 3 s, while Vi increases (not shown), but this new sample does not exit until after 8 s. After 8.5 s, a new, non-stored sample appears after a transit delay through the catheter of 6.5 s.

In order to optimize the catheter sampling system, a number of different catheter sizes were tested. We also tested the use of a small inlet orifice followed by a large diameter catheter, making the assumption that the decompressed gas should flush through the catheter more rapidly. We found that the 1.07 mm (ID) catheter provided slighly less delay and slightly less smearing of the front at a given flow rate than did a larger catheter with a flow limiting inlet orifice. However, we have not tested whether, for longer distances, better response characteristics could be obtained by combining small and large sampling catheters.

The effect of the long catheter on the fidelity of the signal is shown in table 1 for the 30-m catheter, 1.07 mm (ID), flowing at 3 ml/s. The mass spectrometer has slightly slower responses to CO_2 and halothane than to N_2, due to the higher gain amplifiers. After passing through the catheter, the step response for halothane is 45 ms slower than the CO_2 response, whereas the instrumental response (seen with a short catheter), is 15 ms faster for halothane than for CO_2. The slower rise times for heavier gases are probably due to the effect of density on Taylor (lateral) diffusion[8] at the moving front. The longer transit time for halothane is due to its slight adsorption on catheter walls, a chromatographic effect.

Step changes in concentration sampled at 1.4 ml/s in the storage delay mode show the same 10–90 per cent rise time when read by the mass spectrometer at 3 ml/s, but this rise time, *e.g.*, 0.28 s for halothane, represents 2 times as long, or 0.56 s at the inlet because of the data compression (fig. 8). The frequency response is thus about halved for stored sample. For this reason, the program waits for new, non-stored sample if respiratory frequency is above 20/min.

Appendix F. Computer Breath Detection Algorithm

The time of inspired and end-tidal maxima are determined from the CO_2 waveform. A valid expired breath is recognized when a CO_2 peak follows a trough by more than 0.75 s and then falls by at least 7 torr, its concentration being within 3 torr of the preceding peak. The computer chooses the peak with higher P_{CO_2} and displays the concentration of each gas as end-tidal concentration at that time. The inspired concentrations are taken as those at the time when CO_2 was at its lowest value. If CO_2 fails to rise over 7 torr during the first 5 s, the computer switches to the next room. If CO_2 varies by less than 7 torr during 15 s of sampling, a no breaths message is transmitted together with all gas values at the times of the highest and lowest P_{CO_2}. If the time from trough to peak is less than 0.75 s, the computer continues to sample for a maximum of 15 s. Each gas signal is sampled every 8.3 ms and averaged every 33 ms to reduce 60 Hz noise. Respiratory frequency is computed from the time between end-tidal P_{CO_2} peaks, corrected for the known time compression in the long catheters.