

Frequency Response of the Peripheral Sampling Sites of a Clinical Mass Spectrometer

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Mass spectrometers are used in ICUs and ORs to measure the concentration of medical and anesthetic gases gathered from multiple sites. This investigation was designed to determine the accuracy of a clinical system, which included 12 ICU bedside stations monitored by a medical mass spectrometer (Perkin-Elmer RMS III, Pomona, CA). Each site station was connected to the analyzing unit *via* two Teflon tubes, one permanently installed, 30-m long, and the second disposable, 2.4-m long. A gas mixture containing 95% O₂ and 5% CO₂, alternating with room air, was delivered to a solenoid valve and from there to the connecting tubes. Gas flow-rate, delay time, rise time, and peak and trough concentrations were determined for each gas at solenoid cycling frequencies of 25, 50, and 100/min. After the first set of measurements, the 30-m tubes were thoroughly cleaned and all measurements repeated. In addition, the authors also measured CO₂ delay and rise times when the gas was delivered to the mass spectrometer through an unused 30-m tube or a new 2.4-m tube.

Gas flow-rate increased from 143 ± 12 ml/min (mean ± SD) to 238 ± 9 ml/min after the tubes were cleaned. Delay time was identical for all gases at all solenoid cycling rates but decreased significantly ($P < 0.05$), from 11.5 ± 0.3 to 4.8 ± 0.7 s after the ceiling tubes were cleaned. As solenoid valve rate increased, the difference between measured and actual gas concentration increased. The lowest accuracy was 63.6 ± 2.1%, for CO₂ at 100 cycles/min. Even after the tubes were cleaned, peak measured values of CO₂ concentration were only 82.9 ± 4.7% of steady-state concentration at the highest solenoid valve cycling rate. When CO₂ passed through the tubes connecting active bedside stations to the mass spectrometer, rise time was 583 ± 14 ms. This value decreased to 453 ± 84 ms after the ceiling tubes were cleaned but remained significantly higher than when new 30-m (272 ± 3 ms) or 2.4-m (178 ± 2 ms) tubes were used.

The authors conclude that gas concentration measured by mass spectrometry can be quite inaccurate when gases are sampled from remote stations, especially at respiratory rates ≥ 50/min. This problem is largely related to the obstruction caused by the progressive accumulation of particulate materials in the long gas transport tubes. These errors cannot be detected by static self-calibration routines, but require dynamic testing. (Key words: Measurement techniques, mass spectrometry; accuracy; waveforms. Measurement techniques: capnography.)

FOR ALMOST 15 yr, medical mass spectrometers have been used to accurately measure the concentration of medical and anesthetic gases. Commercially available systems usually incorporate automatic calibration features to test their accuracy. The verification process, however, is usually restricted to the function of the mass spectrometer itself. Problems related to the collection and transport of gases from distant sampling sites are not identified by the automatic calibration functions.^{1,2} In clinical practice, however, mass spectrometers usually represent the central component of a network that collects respiratory gases from multiple intensive care (ICU) bedside locations or operating rooms.

Many factors can affect gas transport; the most significant are:

- 1) The rate at which gases are collected by the aspiration pump;
- 2) The downstream pressure of the pump;
- 3) The diameter of the tubes that transport gases, which can be affected by accumulation of fluids or particulate matter; and
- 4) The composition of the tubes, since some materials can absorb soluble gases.

We describe here a technique to determine dynamic response for different gases, respiratory rates, and lengths of transport tubes. The goal was to evaluate the influence of peripheral conditions on the accuracy with which a centralized mass spectrometry system measured gas concentrations.

Materials and Methods

The mass spectrometer tested (Perkin-Elmer RMS II, Pomona, CA) was located in an ICU and served 12 bedside stations. Each bedside station was connected to the analyzing unit through a 30-m Teflon tube installed in the ceiling of the ICU. A pump sequentially aspirated gases from each peripheral station and delivered them to the mass spectrometer. Flow rate was measured with a floating ball flowmeter (Brooks Instruments Division, Hatfield, PA). To simulate respiration, a solenoid valve alternatively delivered a gas mixture containing 5% CO₂ and 95% O₂, or room air, to the bedside port of the 30-m tube. An

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analog-to-digital converter connected to a minicomputer gathered and stored the gas concentrations values reported by the mass spectrometer.

During each experiment, the solenoid valve was operated at rates of 25, 50 and 100 cycles/min, with a duty cycle of 1:1.[†]

From each bedside, at each solenoid valve cycling rate, and for each of the three gases considered, the following data were obtained.

Gas flow rate. This variable measured, in milliliters per minute, the rate at which gases were aspirated by the suction pump.

Delay time. This variable measured the time interval, in seconds, from the opening of the solenoid valve to the detection of a 50% change in gas concentration by the mass spectrometer.

Peak and trough concentration. These variables indicated the highest and lowest gas concentration detected during each solenoid valve cycle. To facilitate comparison between gases with different absolute concentrations, values were expressed as a percentage of the steady-state concentration present in the calibrated gas mixture.

Rise time. This variable represented the time required, in milliseconds, to detect a 5–95% gas concentration change during a solenoid valve cycle.

The same variables were also measured, for CO₂ alone, in the following experimental conditions:

- 1) Using a new 30-m tube not installed in the ceiling;
- 2) Directly connecting the solenoid valve to the mass spectrometer through a 2.4-m tube.

After obtaining an initial set of data, the long tubes connecting each bedside station to the mass spectrometer were thoroughly cleaned with a 1% detergent solution, (7X Cleaning Solution, Flow Laboratories New York, NY) mixed with 0.5% sodium hypochloride. This was followed by a rinsing solution of equal parts of alcohol and distilled water. The tubes were then dried with compressed air delivered at 20–30 psi. Afterward, measurements through the ceiling tubes were repeated as above.

Each value of delay time and rise time represents the arithmetic mean of ten solenoid cycles. Individual data points never varied by more than $\pm 2\%$ from the mean.

For each gas, values obtained at different solenoid cycling rates from each of the 12 bedside stations studied were analyzed by one-way analysis of variance. When statistical significance among groups was present, differences between groups were compared by Sheffe's test for multiple comparisons.

For each gas and respiratory rate, values obtained before and after cleaning the long tubes were compared

using Student's *t* test for paired data. Data obtained from all bed-sides were combined together since they belonged to populations with equal variance.

For CO₂ concentration only, a one-tailed Student's *t* test for unpaired data was used to compare delay time and rise time obtained from bedside stations, both before and after cleaning the tubes, with data obtained using a new 30-m tube, and with data obtained using a 2.4-m tube directly connected to the mass spectrometer.

For all statistical tests, a *P* < 0.05 was accepted as significant. All statistical tests were performed using a commercial package (RS1 V3.0; BBN, Billerica, MA).

Results

After cleaning the 30-m ceiling tubes, gas flow rates significantly increased from 143 ± 12 ml/min (mean \pm SD) to 238 ± 9 ml/min. The accuracy of measurement of gas concentration, expressed as a percentage of the steady-state values (fig. 1), also significantly increased after cleaning. The difference was noticeable for all gases at solenoid cycling rates of 50 and 100/min, and for CO₂ also at a rate of 25/min (table 1). Delay time and rise time significantly decreased after cleaning the ceiling tubes (table 2). When a new 30-m tube was used, gas flow rate was 240 ± 1 ml/min. Rise time was significantly shorter than with clean or uncleaned patient tubes at solenoid cycling rate of 25 and 50/min (table 2). When a 2.4-m tube was directly connected to the mass spectrometer gas flow was 240 ± 1 ml/min. Rise time again decreased as compared with the 30-m tubes, regardless of whether they were clean, unclean, or new (table 2).

Discussion

This study showed that inaccurate values can be reported by a clinical mass spectrometer even when self-calibration tests perform flawlessly. The problem lies in the long transport tubes that carry gases from bedside locations to the analyzing unit. Over time, airborne matter such as airway secretions can deposit in the tubes, reducing the lumen without actually obstructing it. As a consequence, gas flow to the analyzing unit decreases, but this event is not evident unless gas flow rates are measured or a complete block occurs.

As a matter of policy, we clean the long tubes in the ICU ceiling every 12 months using the technique described in the Method section.³ This investigation was performed immediately before and after a scheduled cleaning. Values reported by the mass spectrometer prior to cleaning were inaccurate even at rates of 25 cycles/min, a not uncommon respiratory frequency for critically ill patients. The discrepancy between actual and measured gas concentrations increased rapidly with higher frequencies and reported values became virtually meaningless at 100 cycles/min (table 1).

[†] Readers interested in more extensive technical details, including a diagram of the apparatus used, may contact the first author.

Carbon Dioxide Measured Concentration as Percentage of Actual Concentration

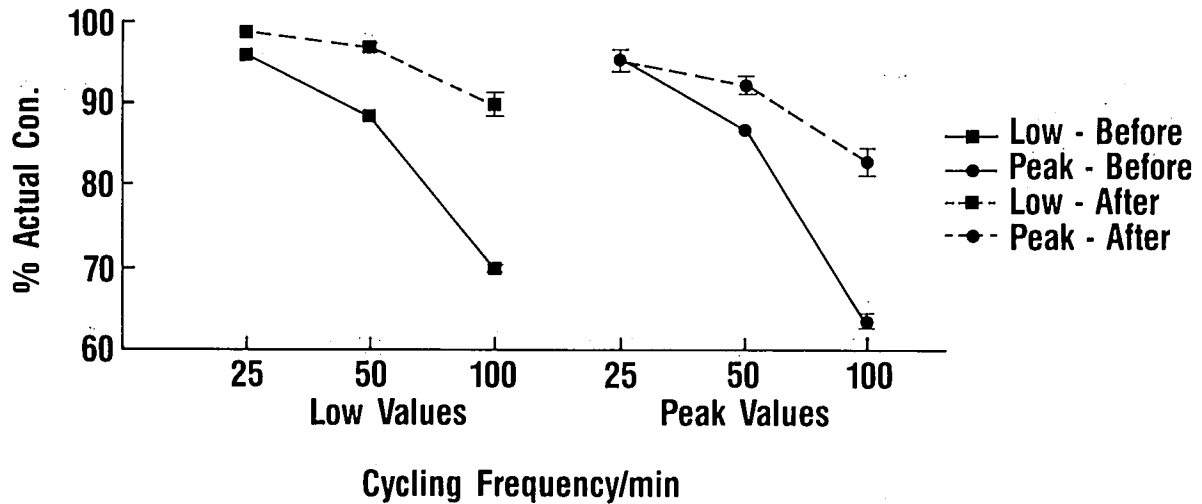


FIG. 1. Trough and peak measured CO₂ concentration, expressed as percentage of steady-state delivered CO₂ concentration.

After a thorough cleaning of the ceiling tubes, delay and rise times decreased significantly while measured peak and trough gas concentration closely approximated actual steady-state values at solenoid valve cycling rates of 25 and 50/min, but not at 100/min. At that rate, in fact, there was a paradoxical shortening of observed rise time, presumably related to significant damping of trough and peak values. These findings suggest that commercially available mass spectrometers cannot accurately measure changes in gas concentration at respiratory rates within the range that can be observed in ICUs.

The waveforms displayed by the mass spectrometer do not immediately reveal the presence of artifactual data; indeed, they could represent either real pathologic conditions or instrument failure. For instance, a low end-expiratory CO₂ could be caused by pulmonary embolism, whereas a high end-inspiratory CO₂ could reflect re-breathing of exhaled gases due to a faulty respirator circuit.

In this study, the degradation of the signal was most evident for CO₂; though the loss of accuracy at peak and trough CO₂ concentrations was comparable to that of O₂

TABLE 1. Accuracy of Gas Concentration Measurements

	CO ₂		O ₂		N ₂	
	Trough	Peak	Trough	Peak	Trough	Peak
Solenoid Rate						
25/min						
Before	95.9 ± 0.5*	95.9 ± 0.6	99.1 ± 0.2	98.7 ± 0.2	99.6 ± 0.2	98.1 ± 0.3
After	98.6 ± 0.8	94.7 ± 3.8	99.6 ± 0.2	99.2 ± 0.3	99.5 ± 0.2	99.0 ± 0.62
50/min						
Before	88.3 ± 0.7*	87.2 ± 0.7*	95.1 ± 0.7*	95.5 ± 0.5*	94.9 ± 0.6*	93.3 ± 0.6*
After	96.8 ± 1.1	92.2 ± 3.5	99.2 ± 3.5	98.6 ± 0.3	99.7 ± 0.2	98.4 ± 0.7
100/min						
Before	70.0 ± 0.9*	63.6 ± 2.1*	74.1 ± 1.3*	77.8 ± 1.0*	72.6 ± 1.0*	70.5 ± 0.9*
After	89.7 ± 4.17	82.9 ± 4.7	95.2 ± 2.6	95.2 ± 1.9	95.1 ± 2.4	93.5 ± 3.1

Values indicate the measured gas concentration as a percentage of actual steady-state gas concentration. Gases were sampled through 30-m tubes connected to bedside stations.

All values mean ± SD. Before: Values obtained before cleaning

30-m tubes. After: Values obtained after cleaning 30-m tubes. Trough: Lowest values measured during a 10 cycle/period. Peak: Highest value measured during a 10 cycle/period.

* Accuracy increased significantly after cleaning long tube ($P < 0.05$).

TABLE 2. Delay Time (s) and 5-95% Rise Time (ms)

	CO ₂	O ₂	N ₂
	Delay Time		
Before	11.5 ± 0.3†	11.5 ± 0.3†	11.5 ± 0.3†
After	4.9 ± 0.7	4.8 ± 0.7	4.8 ± 0.7
	Rise Time		
Solenoid Rate			
25/min Before	583 ± 19*	504 ± 12*	510 ± 15*
After	453 ± 84	256 ± 37	253 ± 32
New 30-m tube	272 ± 3‡§		
Direct connection	178 ± 2‡§¶		
50/min Before	433 ± 37*	406 ± 5*	410 ± 15*
After	326 ± 31	245 ± 35	248 ± 35
New 30-m tube	248 ± 1‡§		
Direct connection	174 ± 3‡§¶		
100/min Before	219 ± 20	214 ± 5	217 ± 5
After	218 ± 18	194 ± 10	196 ± 10
New 30-m tube	200 ± 2		
Direct connection	180 ± 2		

All values are mean ± SD. Before: Values obtained before cleaning the 30-m tubes. After: Values obtained after cleaning the 30-m tubes.

* Rise time decreased significantly after cleaning the ceiling tubes ($P < 0.05$).

† Delay time decreased significantly after cleaning the ceiling tube

($P < 0.05$). Delay time and Rise time of different gases at different solenoid cycling rates, before and after cleaning the ceiling tubes.

‡ Rise time significantly shorter than that of uncleaned tubes.

§ Rise time significantly shorter than that of clean tubes.

¶ Rise time significantly shorter than that of new 30-m tubes.

and N₂, the prolongation of rise time was more pronounced. This phenomenon presumably is dependent on the greater density of CO₂, a function of its greater molecular weight.⁴ Particulate matter deposited in the tubes may also affect CO₂ measurement through chromatographic absorption. Finally, the tubes supplied by the manufacturer of the mass spectrometer are made of Teflon and, therefore, CO₂ may dissolve in their walls. The combined result is a slower transport of CO₂, as compared with N₂ and O₂ and, therefore, a slower rate of change in measured CO₂ concentrations. The reduced flow rates that occur through narrowed tubes accentuate this difference, further distorting CO₂ waveforms by prolonging rise time and shortening alveolar plateau. However, this capnographic image is also similar to that observed in patients with severe obstructive lung disease or other conditions that cause dishomogenous alveolar emptying; thus, erroneous clinical impressions and decisions are possible.

Even under ideal circumstances, using a new 30-m tube that was not bent to place it into the ceiling, CO₂ rise time was 50% longer than when gases were sampled through a shorter tube. Since this distortion is intrinsically

related to the transport of gases through long Teflon tubes, it appears difficult to eliminate.

This investigation demonstrates that clinicians should not unquestioningly rely on information provided by centralized mass spectrometers, even if self-calibration routines have been successful. Dynamic testing from each peripheral station should also be performed under conditions comparable to those encountered in clinical practice.

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