FACTORS INFLUENCING CAPNOGRAPHY IN THE BAIN CIRCUIT

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ABSTRACT. The Bain circuit provides continuous fresh gas flow near the airway. The potential mixing of this fresh gas with expired gas may prevent reliable analysis of expired gas. We therefore investigated the interaction of sampling site, fresh gas flow rate, expiratory flow rate, and sampling flow rate on expiratory capnography. Sampling near the fresh gas outlet yielded inaccurate results under several of these conditions. The magnitude of the error was related to the fresh gas and expiratory flow rates. A reliable sampling region near the endotracheal tube was identified.

KEY WORDS. Anesthetic techniques: Bain circuit; Measurement techniques: Infrared capnography, Sampling site, Sampling flow rate; Monitoring: Carbon dioxide, Ventilation

During anesthesia, gases for capnography are often sampled through a special adapter or through a hole drilled in the elbow connector between the breathing circuit and the endotracheal tube [1]. Figure 1, a composite drawing of a modified Mapleson D (Bain) circuit, elbow connector, and endotracheal tube adapter, shows four possible sampling sites. All are easily accessible and, in our experience, well suited for use with valved breathing circuits that separate inspiratory and expiratory flows. The Bain circuit presents a different situation, however, because fresh gas flows continuously near these sampling sites. The fresh gas may mix with expired gas, particularly at low expiratory flow rates, which would prevent a reliable analysis of expired gas.

The primary aim of this study was to investigate the effects of fresh gas flow, sampling site, sampling flow rate, and expiratory flow rate on the accuracy of expiratory capnography when the Bain circuit is used. Four sampling sites—three in the elbow connector and one in the endotracheal tube adapter—were investigated to determine a site unlikely to be influenced by the other factors studied.

METHODS AND MATERIALS

The study was conducted using one lung of a modified bellows test lung (Vent Aid, Michigan Instruments Inc, Grand Rapids, MI). The modifications included incorporation of a small electric fan to ensure a homogeneous gas mixture in the test lung and construction of a port to admit a carbon dioxide–containing gas mixture. Otherwise, the device did not function as a lung; there was no tidal ventilation.

A 7.5 mm internal diameter, cuffed endotracheal tube was attached to the test lung. A new Bain breathing circuit (Respiratory Care Inc, Arlington Heights, IL)

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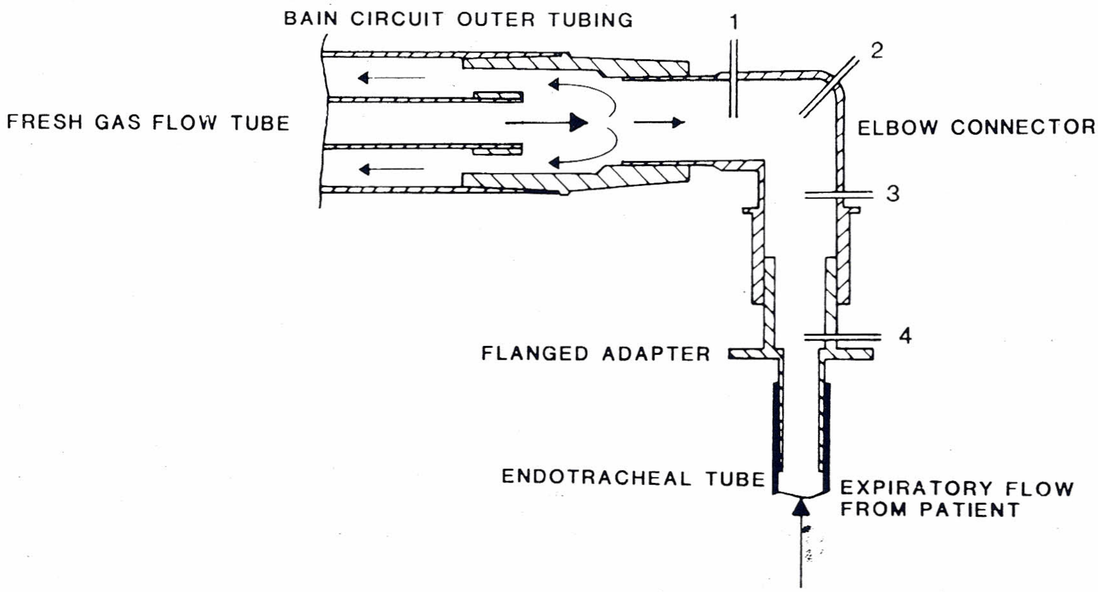

Fig 1. Schematic of distal portion of the Bain circuit, plus connector and adapter. The position of the four sampling sites investigated is shown.

was connected to the endotracheal tube by one of three standard plastic elbow connectors. Each elbow had a single hole drilled into it at one of three possible locations (sites 1, 2, or 3, spaced at 2 cm intervals; see Fig 1). A blunt-tipped, 16 gauge, 1.2 mm internal diameter sampling needle was tightly glued into the hole in each connector so that the tip was in the center of the cross section of the connector. Another sampling hole was drilled and a probe similarly inserted into an endotracheal tube-to-elbow adapter just above the flange at site 4 (Fig 1).

The Bain circuit was attached to an Ohio Modulus I anesthesia machine (Ohio Medical Products, Madison, WI) with a Bain arm (Fig 2), the oxygen and air rotameters of which were verified against a calibrated flow meter. To mimic expiration during mechanical ventilation, the adjustable pressure-limiting (pop-off) valve of the Bain arm was closed. The ventilator hose was attached to an Ohio 7000 electronic ventilator, which did not cycle, used to produce the constant expiratory flow resistance normally imposed by the spill valve. The test lung was connected to the Bain circuit and purged with a mixture by volume of 10.8% carbon dioxide, 30% oxygen, and nitrogen. All gas analyses were performed with a Godart 17070 infrared capnograph (Scott Instruments, Inc, Miami, FL). The instrument was repeatedly calibrated with a calibration gas.

The influence of six different fresh gas flow rates (15.2, 13.2, 10.2, 7.2, 5.2, and 2.2 $L \cdot min^{-1}$), two sampling flow rates (200 and 500 $ml \cdot min^{-1}$), and three expiratory flow rates (1.0, 2.0, and 5.0 $L \cdot min^{-1}$) on the accuracy of capnographic analysis of gases obtained at each of the four sites was investigated. A 10.8 vol% CO_2 flow into the lung served to mimic the expiratory flow rate. The expiratory and sampling flows were routed through calibrated rotameters. All expiratory flows were steady and nonpulsatile.

To test each sampling site, we started with the highest fresh gas flow rate (15.2 $L \cdot min^{-1}$) at each combination of sampling and expiratory flow rates. At each rate of fresh gas flow, the CO_2 concentration, displayed on a calibrated strip chart recorder, was allowed to stabilize before recording. The fresh gas flow was then decreased to the next setting and the CO_2 reading was again allowed to stabilize. This procedure was repeated down to the lowest rate of fresh gas flow for all combinations of expiratory and sampling flow rates at each of the four sampling sites.

To establish standard deviations and significance of differences from the reference (lung) value of CO_2, each combination of fresh gas, expiratory, and sampling flow rates at each site was repeated five times in the same order. Statistical analysis was performed by analysis of variance (repeated measures on two factors) followed by unpaired *t* tests on the fresh gas flow and paired *t* tests on the sampling flow rate data. A $p \leq 0.05$ was considered significant.

RESULTS

The effect of fresh gas flow on the absolute error of measurement of CO_2 is shown in Figure 3. In this

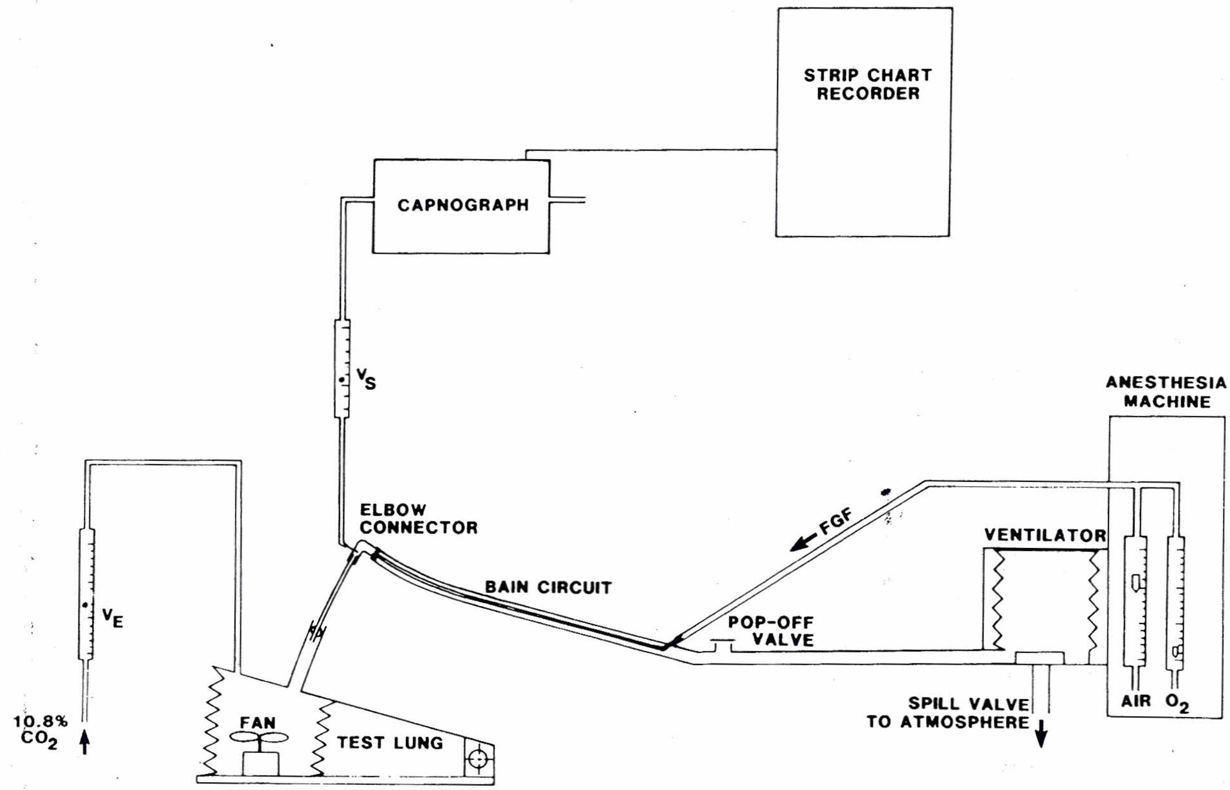

Fig 2. Experimental setup for determining absolute error of measurement of CO_2 at steady state. V_E = *expiratory flow;* V_S = *sampling flow;* FGF = *fresh gas flow.*

study, the maximum achievable vol% error was 10.8. The maximum observed vol% error was 8.9, noted at site 1. Significant errors were also noted at site 2, but only at high fresh gas flow rates (13.2 and 15.2 L · min^{-1}). The effect was most dramatic at site 1, which is closest to the fresh gas outlet. The magnitude of the error was always greater at site 1 than at site 2. No error was noted at sites 3 or 4 at any of the six fresh gas flow rates examined.

Comparison of the two sampling flow rates yielded no consistent pattern of significant differences in absolute error of CO_2 measurement, as shown in Figures 3 and 4.

Figure 4 illustrates that higher expiratory flow rates were associated with smaller absolute errors at sampling site 1. The effect of fresh gas flow at this site is almost completely abolished at an expiratory flow of 5 L · min^{-1}. At site 2, no absolute error in capnography occurred with either the 2 or 5 L · min^{-1} expiratory flow.

In respect to the influence of sampling site on the absolute error, no error in steady-state capnography was observed at sites 3 and 4 under any of the conditions examined. At site 2 errors were found only at the lowest examined expiratory flow rate (1.0 L · min^{-1}). At site 1 errors occurred under most of the study conditions.

DISCUSSION

The results indicate that, of the three variables studied in conjunction with sampling site, all except sampling flow rate may influence the accuracy of capnography at certain sites with the Bain circuit. Samples obtained from a site near the fresh gas outlet (site 1) are unreliable even at low rates of fresh gas flow (see Fig 3). Although it may be intuitively obvious that mixing would occur at site 1, it is clinically relevant and useful to know that there is a site in the elbow connector (site 3) and beyond (site 4) where no error was noted under any of the conditions examined. Any site further away from the fresh gas outlet than site 3 should therefore be equally acceptable for capnography, whether via a sampling needle inserted into the endotracheal tube or a probe in the endotracheal tube flanged adapter (site 4), as we used.

That the magnitude of the fresh gas flow rate influences the results at sites 1 and 2 serves as a reminder that acceptable end-tidal CO_2 values do not necessarily

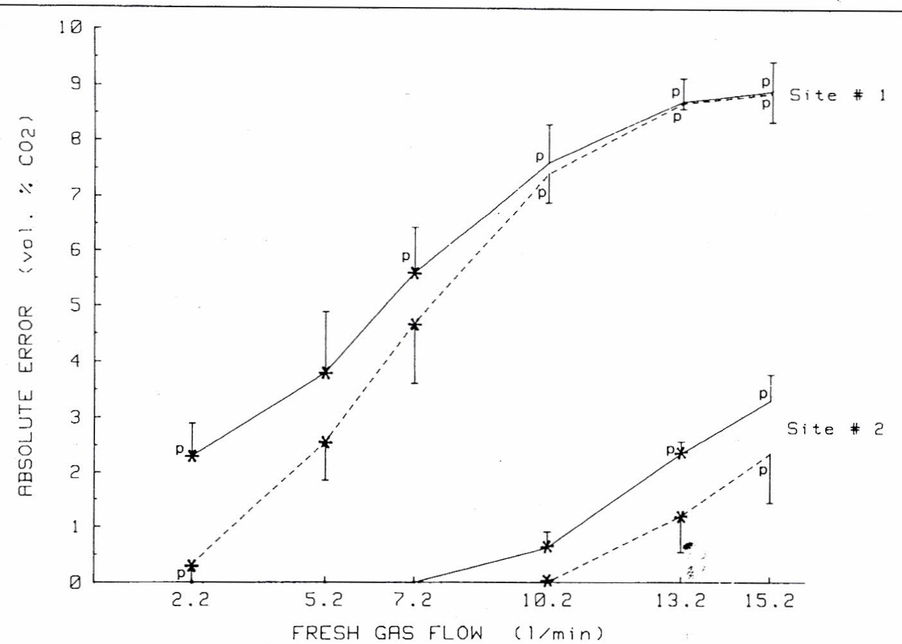

Fig 3. Influence of fresh gas flow and sampling flow at sampling sites 1 and 2 on absolute error of measurement of CO_2 with an expiratory flow rate of 1.0 L · min^{-1}. No error was observed at sites 3 and 4 under any of the conditions investigated. Maximal possible vol% error was 10.8. Dotted lines represent a sampling flow rate of 0.2 L · min^{-1}; solid lines represent a rate of 0.5 L · min^{-1}. An asterisk indicates a significant difference ($p \leq 0.05$) between the two sampling flows at the same fresh gas flow rate; p *indicates an absolute error for fresh gas flow significantly different ($p \leq 0.05$) from the absolute error at a fresh gas flow of 5.2 L · min^{-1}.*

reflect adequate alveolar ventilation, especially if obtained from a sampling probe placed at site 1. At high fresh gas flow rates with the Bain circuit one can thus easily be misled into overestimating actual alveolar ventilation. Again, this problem appears to be statistically significant only at site 1.

We were unable to demonstrate a statistically significant effect of sampling flow rate on capnography. When the expiratory flow was 5 L · min^{-1}, no mixing was noted at common clinical settings for fresh gas flow at any of the sites. As the expiratory flow rate was reduced, however, mixing became evident. The clinician must bear this in mind when capnography is used to estimate arterial carbon dioxide tension ($PaCO_2$) and gas is sampled near the fresh gas outlet of the Bain circuit.

We were interested in examining the factors that might limit the accuracy of capnography during the latter portion of expiration. Our investigation therefore did not use phasic ventilation, and we did not examine the effect of initially accelerating and eventually decelerating changes in gas concentrations. Ultimately, however, expiratory flow rate does approach zero, and end-tidal gas, which is most representative of $PaCO_2$, is exhaled.

Steady-state conditions were used to eliminate inaccuracies imposed by the response time of the capnograph (0 to 90% response to a step change in 150 ms). Eliminating this factor as an influence allowed a more controlled examination of the variables studied. The sampling flow rates used are typical of capnographs in common use. The expiratory flows were chosen to represent transient conditions encountered near the end of any complete expiration.

Our results (see Fig 4) imply that sampling at expiratory flow rates lower than those we studied, i.e., those occurring even closer to end expiration, would result in absolute error curves to the left of those shown. In the worst case, if the expiratory flow rate decreased below the sampling flow rate, the curves would approach maximum error (10.8 vol% CO_2 absolute in our study).

The absolute error does, of course, depend on the concentration of CO_2 used, and the errors shown in Figures 3 and 4 would have been smaller had we used a lower concentration of CO_2.

As our study was steady state by design, it is difficult to assess whether these results exaggerate the clinical situation, that is, represent the worst case, or whether other factors, such as instrument response time, sam-

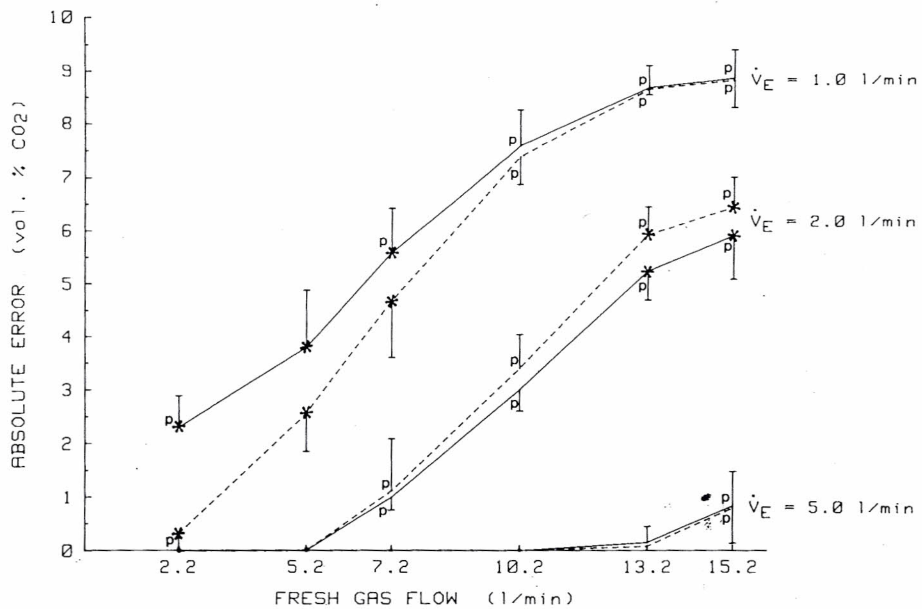

Fig 4. Influence of fresh gas flow and three expiratory flow rates ($\dot{V}_E$) on absolute error in analysis of gas sampled from site 1 at two sampling rates. Dotted lines represent a sampling flow rate of 0.2 L · min^{-1}; solid lines represent a rate of 0.5 L · min^{-1}. An asterisk indicates a significant difference (p $\leq$ 0.05) between the two sampling flows at the same fresh gas flow rate; p *indicates an absolute error for fresh gas flow significantly different (*p *$\leq$ 0.05) from the absolute error at a fresh gas flow of 5.2 L · min^{-1}.*

pling tube caliber, or sampling tube length, have an influence. To minimize error we recommend using a distal sampling site in the elbow connector (site 3), in the endotracheal tube adapter (site 4), or beyond. These sites appear sufficiently remote from the jet effect of the fresh gas outlet of the Bain circuit.

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