Laboratory Investigations

The most proximal and accurate site for sampling end-tidal CO_2 in infants

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The most proximal site to sample end-tidal CO_2 with reasonable accuracy in infants during pulmonary ventilation using a Mapleson D circuit remains controversial. The utilisation of high fresh gas flow near the site of gas sampling dilutes the expired gas and causes an underestimation of end-tidal CO_2. In this study a laboratory model was used to identify, qualitatively and quantitatively, the most proximal site in the Mapleson D circuit where the measurement of end-tidal CO_2 is not influenced by mixing with fresh gas. A fresh gas flow rate of between 2 and 15 $L \cdot min^{-1}$ with a respiratory rate of 20–30 $\cdot min^{-1}$ and a tidal volume of 30–100 $ml \cdot min^{-1}$ was evaluated. This experiment was divided into two parts. Firstly, an infant lung model was used to visualize the site of mixing between fresh gas and smoke-labelled exhaled gas. Secondly, fresh gas flow and expired gas flow were controlled and the end-tidal CO_2 concentration was measured along the length of the anaesthetic circuit to identify the site of mixing of fresh gas and expired gas during steady-state conditions. Three expired gas flows were studied at six fresh gas flows. In all our studies, the rate of fresh gas flow and expired gas flow influenced the site of mixing and degree of dilution but no mixing was observed distal to the point at which the endotracheal tube connector narrows to the diameter of the endotracheal tube ($P < 0.05$). This laboratory study allows us to suggest that the most proximal and acceptably accurate site to sample end-tidal Co_2 in infants during ventilation with the Mapleson D circuit is at the point of narrowing of the endotracheal tube connector with the endotracheal tube.

Chez l'enfant ventilé, la mesure du CO_2 télé-expiratoire avec un degré raisonnable de précision par le site le plus proximal du circuit Mapleson D demeure controversée. L'utilisation d'un grand débit de gaz frais près du site de l'échantillonnage dilue le gaz expiré et sous-estime le CO_2 télé-expiratoire. Pour l'étude, on utilise en laboratoire un montage permettant d'identifier qualitativement et quantitativement l'endroit le plus proximal du circuit Mapleson D où la mesure du CO_2 télé-expiratoire n'est pas influencée par la dilution avec les gaz frais. Un débit de gaz frais variant entre 2 et 15 $L \cdot min^{-1}$ associé à une fréquence ventilatoire de 20 à 30 $\cdot min^{-1}$ et à un volume courant de 30 à 100 $ml \cdot min^{-1}$ est évalué. L'expérience est divisée en deux parties. D'abord, le montage est utilisé pour visualiser le site du mélange entre gaz frais et le gaz expiré marqué avec de la fumée. Ensuite, le débit de gaz frais et le débit de gaz expiré sont contrôlés et la concentration télé-expiratoire de CO_2 est mesurée sur la longueur du circuit anesthésique pour identifier le site de mélange du gaz frais et du gaz expiré. Trois débits de gaz expiré sont étudiés avec six débits de gaz frais. Pendant toutes ces études, la vitesse du débit des gaz frais et du gaz expiré influence le site du mélange et le degré de dilution mais on n'observe pas de mélange à un site plus distal qu'au point où la canule endotrachéale se rétrécit au même diamètre que son raccord ($P < 0,05$). Cette étude en laboratoire permet de suggérer que le site le plus proximal et le plus précis pour évaluer le CO_2 télé-expiratoire chez l'enfant pendant la ventilation avec un circuit Mapleson D est le point où le raccord du tube endotrachéal se rétrécit pour sa jonction avec le tube endotrachéal.

Key words
ANAESTHESIA: paediatric;
CARBON DIOXIDE: end-tidal tension;
MEASUREMENT TECHNIQUES: capnometry.

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Intraoperative measurement of end-tidal CO_2 ($PETCO_2$) in infants during pulmonary ventilation with the Mapleson D circuit must be safe, convenient and accurate. There are four factors which influence the accuracy of expired gas sampling using a Mapleson D circuit in infants and children: (1) the sampling site; (2) the fresh gas flow rate; (3) the expired flow rate; and (4) the sampling flow rate of the capnometer. Because infants have low expiratory flow rates and a short respiratory cycle time, the fresh gas flow dilutes the expired gas to a larger extent than that observed in adults.[1] This causes an artificially low reading of the $PETCO_2$ concentration. Therefore, among those factors, the sampling site is particularly important.

In an effort to avoid dilution when sampling exhaled gas, other investigators have measured the end-tidal CO_2 concentration in infants with a catheter placed at the distal tip of the endotracheal tube.[2] In children <12 kg body weight, this sampling site is superior to the usual site at the circuit elbow.[3] A previous study introduced the concept of sampling proximally within the endotracheal tube and demonstrated that $PETCO_2$ measured immediately distal to the endotracheal tube connector correlated with arterial PCO_2 when the fresh gas flow was interrupted.[4] A subsequent study using a constant fresh gas flow found no clinically important difference in sampling $PETCO_2$ at the distal end of the endotracheal tube and at 12 cm from the tip.[5] It was recommended that sampling $PETCO_2$ with a 23-G needle inserted through the wall of the endotracheal 12 cm from the endotracheal tube tip was appropriate.[5]

The acceptability of distal sampling of $PETCO_2$ in infants is questioned. There are several practical disadvantages associated with this technique which include the recurring obstruction of the sampling catheter by airway secretions, increased airway resistance due to partial obstruction of small endotracheal tubes, the necessity for additional equipment and the cost of the catheter. The most proximal site to sample $PETCO_2$ with acceptable accuracy has not been determined in infants and small children. Using a laboratory model we have investigated the effect of varying fresh gas flow rates and expired gas rates on $PETCO_2$ measurement using a Mapleson D circuit and sought to determine the most proximal and reasonably accurate site for sampling end-tidal CO_2 in intubated infants.

Methods

Experimental design

This study was designed to be performed in two parts. The purpose of the first part was to visualize the most proximal non-mixing site between fresh gas flow and smoke-labelled expired gas. The second part was to determine whether the perceived "best" proximal site demonstrated visually in the first part corresponded quantitatively to the most accurate site where end-tidal CO_2 is no longer diluted by the mixing effect from the fresh gas flow. The laboratory model consisted of a two-litre glass jar to which a 3.5-mm cuffed endotracheal tube was attached. To allow visualization of the smoke-labelled expired gas the endotracheal tube connector, elbow, and Ayre's t-piece were transparent. Fresh gas flow (FGF) – an air/oxygen mixture – was delivered by a calibrated flow meter to the Ayre's t-piece. The distal end of the Ayre's t-piece was connected to a ventilator by a standard non-compliant ventilator hose. To ensure homogenous gas mixture within the glass jar, a small, magnetically powered fan, was used. There was no gas leak in the system.

Experimental protocol

PART 1

A smoke-wire method was used to visualize the interface or the mixing area between fresh gas flow and expired gas flow. This technique has been used previously to study gas flows (laminar or turbulent) without disturbing normal flow characteristics.[6-8] The test lung was filled with dense smoke produced by the vaporisation of mineral oil. This vaporisation was achieved by using an electrically heated (310°C) stainless steel (nichrome) wire, approximately 0.1 mm in diameter which was placed within a seven foot long metal pipe.[7] Hydrocarbon oil was spread down to the wire by gravity from a reservoir which was mounted at the proximal end of the wire. To propagate the vaporised mixture to the distal end of the metal pipe, an electrically powered air compressor was used to generate flow impulses across the equipment. The abrupt cooling of the vaporised mixture into the test lung caused sudden condensation resulting in the formation of a dense, high visibility, white smoke, consisting of minute droplets (<1.0 μm).[9] The size of the oil droplet was determined by the size of the metal tubing connected between the reservoir and the wire. To ensure perfect mixing of the gas and the smoke, a magnetically powered fan was mounted inside the jar. When the test lung was completely filled with smoke, FGF was introduced into the circuit at the Ayre's t-piece and the model was mechanically ventilated. A Sechrist Infant Ventilator (Sechrist Industries, Inc., Anaheim, CA) or an Air-Shields Ventimeter (Air Shields, Hatboro, Pennsylvania) were used to ventilate the model. A high-speed shutter video camera (30 frames $\cdot$ sec^{-1}) was used to determine the site of mixing of fresh gas and smoke-labelled expired gas. A FGF of 2 to 15 L $\cdot$ min^{-1}, respiratory rates of 20 and 30 per

minutes, I:E ratio 1:2 and tidal volume of 30 to 100 ml were studied. Accurate tidal volumes were measured by a pneumotachometer. Pictures of the site of mixing between the fresh gas and expired gas were generated from individual frames of the videotape.

PART 2

To determine the relationship between the mixing phase observed in Part 1 and its influence on the accuracy of $P_{ET}CO_2$ measurement, five percent CO_2 (PCO_2 38 mmHg) in oxygen was introduced continuously into the glass jar by a flowmeter calibrated for that gas at rates of 0.5, 1 and 2 $L \cdot min^{-1}$. Each flow rate represented the expired gas flow (EFG) studied. An air/oxygen mixture (FGF) was delivered to the Ayre's t-piece at rates of 0, 2, 3, 5, 10 and 15 $L \cdot min^{-1}$. A previously described in the first section, a fan was also used to ensure complete mixing of gases. The laboratory model was not mechanically ventilated. The distal end of the Ayre's t-piece was connected to an Air-Shields Ventimeter to reproduce a constant expiratory flow resistance. A pre-marked catheter with increments in centimeters was inserted into the anaesthetic circuit at the fresh gas flow inlet to facilitate measurement of $P_{ET}CO_2$. Sampling of the $P_{ET}CO_2$ along the anaesthetic circuit was obtained by withdrawing the catheter and measuring at 1 cm decrement from the distal end of the endotracheal tube to the proximal segment of the circuit (FGF inlet). The tip of the endotracheal tube was the most distal site of measurement (0 cm) and the fresh gas flow inlet the most proximal site (23 cm). The narrow portion of the endotracheal tube connector was at 12 cm. To ensure that the CO_2 concentration along the anaesthetic circuit was at steady-state before the beginning of the study period, the expired gas flow was delivered until a PCO_2 of 38 mmHg was recorded. Before each study period, the initial expired gas flow and the study sequence for the expired gas flow to be tested was determined using a random number table. The FGF was then started and expired gas samples were taken two minutes later. An infrared side-stream capnometer (Datex Instrumentarium Corp., Helsinki, Finland) with a sampling rate of 150 $ml \cdot min^{-1}$ was used to analyse the $P_{ET}CO_2$. The monitor was calibrated before each study period with dry gas of known composition (5% CO_2 and 36% N_2O). Five values were recorded at each site at ten-second intervals.

Statistical analysis

No statistical analysis was required for Part 1. All data obtained in Part 2 with parametric values are expressed as mean ± standard deviation. Repeated-measures or one-way analysis of variance was used for within or between groups analysis where appropriate. The Student-Newman-Keuls test was used for multiple comparisons. A $P < 0.05$ was accepted as statistically significant.

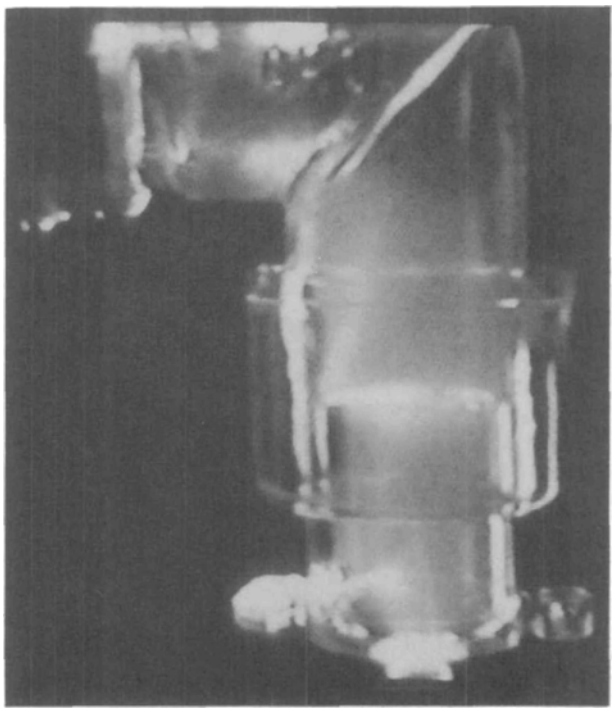

FIGURE 1 The interface between expired gas and the fresh gas flow is influenced by the fresh gas flow rate. At 2 $L \cdot min^{-1}$, the interface is at the elbow connector.

Results

Part 1

During exhalation, the smoke-labelled exhaled gas entirely displaced fresh gas from the endotracheal tube. Following the exhalation phase of the respiratory cycle and before the initiation of the next breath, a well defined interface between the fresh gas and smoke-labelled exhaled gas was observed (Figures 1 and 2). This interface advanced distally as the fresh gas flow increased but it was always proximal to the point where the endotracheal tube connector narrows to the diameter of the endotracheal tube. This was true at a fresh gas flow of up to 15 $L \cdot min^{-1}$. The site of mixing was qualitatively the same with both the Sechrist Infant Ventilator and the Air-Shields Ventimeter. Changes in tidal volume (30 to 100 ml) and respiratory rate (20 bpm) had no effect on the site of mixing as observed by the camera. The smoke-labelled exhaled gas was entirely cleared from the elbow and endotracheal tube with the delivery of the next breath.

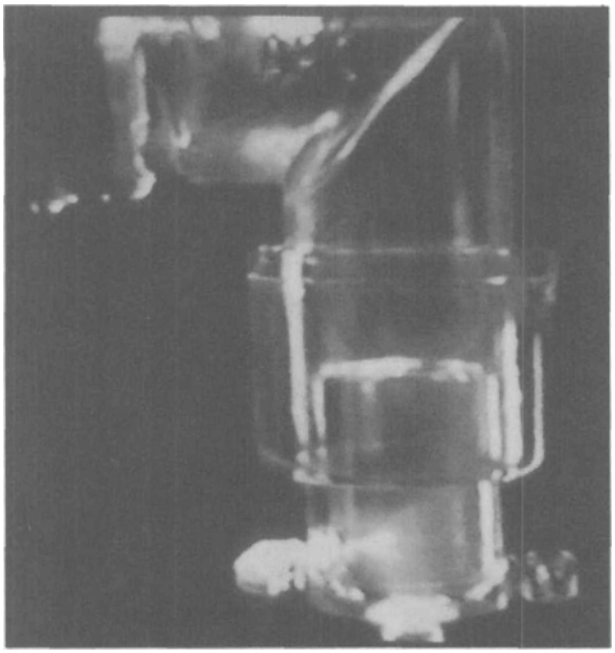

FIGURE 2 At 15 L · min^{-1}, the interface is advanced distally but proximal to the endotracheal connector.

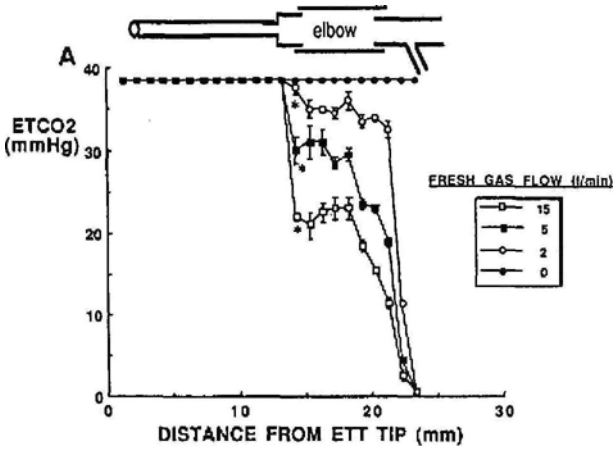

FIGURE 3 The site of mixing of fresh gas flow and expired gas is always proximal to the endotracheal tube connector. At an expired gas flow of 500 ml · min^{-1}, the influence of fresh gas flow rate on the site of mixing and the degree of dilution is significantly greater.

Part 2

The site of mixing of fresh gas and expired gas at all flow rates studied was always proximal to the point where the endotracheal tube connector narrows to the diameter of the endotracheal tube (Figure 3, 4, 5). This was true at a FGF of up to 30 times EGF. The influence of the FGF rate on the site of mixing and the degree of dilution

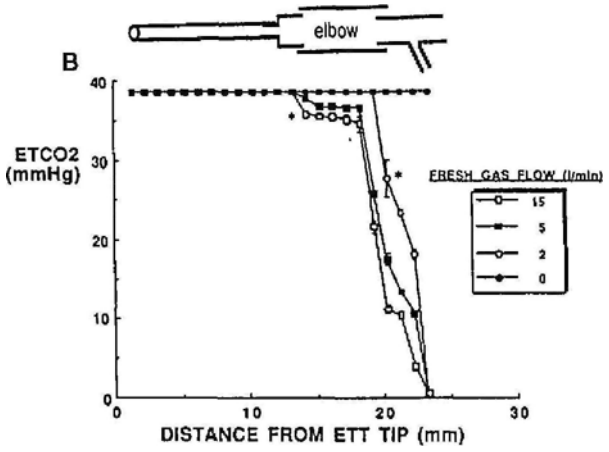

FIGURE 4 The site of mixing fresh gas flow and expired gas is always proximal to the endotracheal tube connector. At an expired gas flow of 1000 ml · min^{-1}, the influence of fresh gas flow rate on the site of mixing and the degree of dilution is smaller than observed at 500 ml · min^{-1}.

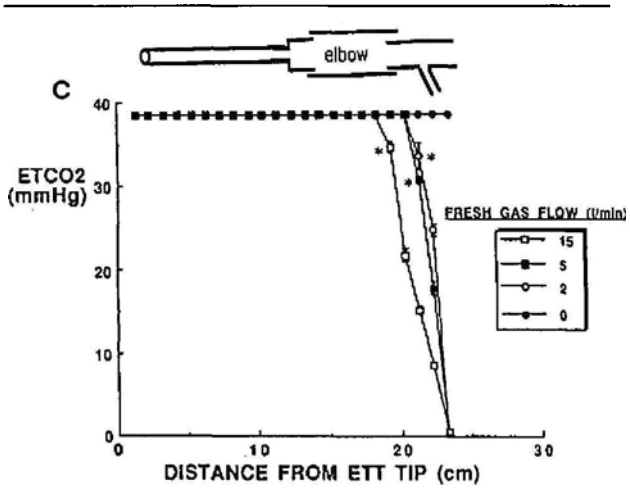

FIGURE 5 At an expired gas flow of 2000 ml · min^{-1}, the influence of fresh gas flow rate on the site of mixing and the degree of dilution is less important. It is also directly related to the amount of fresh gas used.

was greatest at lower EGF rates when compared with all distal sampling sites. At an EGF of 0.5 L · min^{-1} and all FGF rates studied, $P_{ET}CO_2$ became different at the sampling site 1 cm proximal to the point where the endotracheal tube connector narrows to the diameter of the endotracheal tube ($P < 0.05$) (Figure 3). Furthermore, at this sampling point, when the different FGF rates were compared, $P_{ET}CO_2$ was statistically different ($P < 0.05$). Similarly, at an EGF of 1 L · min^{-1} (Figure 4) and all FGF rates studied, the measured $P_{ET}CO_2$ was not different along the entire length of the endotracheal tube

until 1 cm proximal to the point where the endotracheal tube connector narrows to the diameter of the endotracheal tube ($P < 0.05$). However, at this sampling site, the effect of FGF rates on the $P_{ET}CO_2$ recorded was smaller than the difference observed at an expired flow rate of 0.5 $L \cdot min^{-1}$ ($P < 0.05$). It strongly suggests that the EGF is the determinant factor of the site of mixing. Figure 5 confirms that contention and shows that at an EGF of 2 $L \cdot min^{-1}$ and a FGF as high as 15 $L \cdot min^{-1}$, the $P_{ET}CO_2$ was different only at the sampling site 6 cm proximal to the narrowing point of the endotracheal tube connector ($P < 0.05$). Furthermore, at FGF rates of 5 and 2 $L \cdot min^{-1}$, differences did not occur until the sampling site was 8 cm proximal to the point of narrowing of the endotracheal tube connector. At this point, the effect observed at FGF of 5 $L \cdot min^{-1}$ and 2 $L \cdot min^{-1}$ were different ($P < 0.05$). Finally, in all cases, when the sampling reached within the Ayre's t-piece at the fresh gas inlet, the $P_{ET}CO_2$ quickly approached zero.

Discussion

This infant lung model showed that the most proximal site for end-tidal gas measurement where the measurement of $P_{ET}CO_2$ is uninfluenced by mixing with fresh gas during mechanical ventilation with a modified Mapleson D circuit is at the point of narrowing of the endotracheal tube connector with the endotracheal tube. Visualization of the site of mixing by means of smoke-labelled exhaled gas technique provided direct evidence that an interface between the fresh gas flow and expired gas existed. The flow study showed quantitative evidence that at a fresh gas flow of up to 30 times the expired gas flow, gas mixing did not occur beyond the point of narrowing of the endotracheal tube connector.

Gravenstein *et al.* showed similar results studying the effect of mixing between the fresh gas flow and the expired gas during ventilation with a Bain anaesthetic circuit.[10] They too studied the effect of comparable FGF and EGF on the most appropriate site to record $P_{ET}CO_2$ and concluded that the most accurate site to measure $P_{ET}CO_2$ was at the elbow connector. One determinant of the effect of FGF on the dilution of the exhaled CO_2 is the expiratory flow rate. The lowest EGF studied by these investigators was 1.0 $L \cdot min^{-1}$ whereas the present study reports similar observations with an expired gas flow of 0.5 $L \cdot min^{-1}$. Our evaluation of an expired gas flow as low as 0.5 $L \cdot min^{-1}$ was prompted because this level occurs in infants and small children. This speculation is confirmed by Epstein *et al.* who reported, that in infants and small children with a weight of 2.2 to 3.7 kg, mean expired flow of less than 1000 $ml \cdot min^{-1}$ is often observed.[11] Furthermore, they showed, using pneumotachographic recordings, that, at the end of the expiration phase, the presence of even lower flows may be recorded due to airway collapse.[11] Consequently, the recording of end-tidal gas in this group of patients canbe easily affected by expired gas dilution due to the large FGF.

Although we did not study the effect of the sampling flow rate in this model, it has been shown that this variable did not influence the accuracy of the capnographic recording.[10] It is suggested that the sampling flow rate be less than the expired flow for at least 90% of the expiratory time. However, because small infants have a short respiratory time cycle which causes phase IV of the expiratory flow to be shorter or often nonexistant (no plateau),[12] the time response and the sampling flow rate could affect the accuracy of the end-expiratory gas measurement. A sampling flow rate of 500 $ml \cdot min^{-1}$ is necessary to abolish the normal end-expiratory plateau and cause a decrease in the CO_2 concentration.[11] It is demonstrated that a high sampling rate tends to entrain undesired fresh gas flow and cause an underestimation of the CO_2 recording. The present study used a sampling flow rate of 150 $ml \cdot min^{-1}$ which should not have caused any inaccuracy in the CO_2 measurement. Finally, side-stream capnometer may add to the inaccuracy in $P_{ET}CO_2$ measurement especially when the total delay time necessary for the sample to reach the capnometer exceeds the respiratory cycle time. This condition is often observed in small infants with small tidal volumes and short respiratory cycle times due to their high respiratory rates.[13-14]

We had postulated that the Sechrist Infant Ventilator, which actively vents gas during exhalation by a Venturi jet, may produce different results from the conventional Air-Shields Ventimeter ventilator. Badgwell *et al.* reported that, in small infants of <12 kg body weight undergoing pulmonary ventilation with an Air-Shields Ventimeter and an Ayre's t-piece breathing circuit, distal sampling of end-tidal CO_2 improved accuracy probably by reducing the effect of dilution caused by the fresh gas flow.[3] Hiller *et al.* using a Sechrist Infant Ventilator with an Ayre's t-piece, reported in 37 healthy infants and children that proximal end-tidal CO_2 measurement accurately approximates $PaCO_2$ while using a side-stream capnometer and that distal sampling was no longer necessary even in infants of <12 kg.[15] They concluded that, compared with an Air-Shields Ventimeter, the Sechrist Infant Ventilator diverts the excess in fresh gas through a valve during expiration and limits the air entrapment effect. In the present investigation, visualization failed to show a qualitative difference in the site of mixing between the two ventilators.

It is difficult to compare sampling sites for intraoperative $P_{ET}CO_2$ measurement in infants and small chil-

dren due to a number of variables that may influence the results. Previous investigations have shown conflicting results.[5,16] Rich, using a rabbit model, found no clinical difference in $P_{ET}CO_2$ along the entire length of the endotracheal tube in a Mapleson D system.[5] Scheiber *et al.*, however, using a pig model, found distinct differences in $P_{ET}CO_2$ along the length of the endotracheal tube in a circle system.[16] Patient characteristics (i.e., cardiac or pulmonary disease, temperature, etc.), the type of ventilator and its settings, the anaesthetic circuit, the presence of a leak in the circuit, the sampling site, the fresh and expiratory gas flow rates and the characteristics of the capnometer have all been demonstrated to influence the measured $P_{ET}CO_2$.[14,17-19] We chose to use a laboratory model to enable us to control, as much as possible, the variables which are known to influence the intraoperative measurement of $P_{ET}CO_2$ in infants.

There are several methodological considerations that merit comment. In this context, for the test lung to be a valid model, it must have an expired tidal volume identical to that delivered and a duration of exhalation similar to the mechanically ventilated infant lung. There was no leak in the system and therefore the exact tidal volume delivered to the test lung was "exhaled" during the expiratory cycle. In an identical manner to the mechanically ventilated infant lung, the duration of exhalation of the test lung was shorter than the expiratory cycle time. It is during this time that the fresh gas flow displaces exhaled CO_2 from the circuit prior to the initiation of the next breath.

The flow study examined the influence of FGF and EGF on the site of mixing during exhalation. We chose EGF rates according to pneumotachographic recordings of 2.5 kg infants during mechanical ventilation.[11] Fresh gas flow rates were based on those commonly used intraoperatively. By not ventilating the system, we focused on the dynamics of mixing during exhalation. The site of mixing and the degree of dilution observed in this study were greater than that in the ventilated infant because the time for mixing to occur was prolonged (two minutes). These results exaggerate the clinical situation. However, even with a prolonged time for mixing and dilution to take place, no mixing occurred distal to the point of narrowing of the endotracheal tube connector. As expected, at lower EGF rates, the influence of FGF rate on the site of mixing and degree of dilution was increased.

The visualization study examined both the inspiratory and expiratory cycles of ventilation. It demonstrated that following active exhalation the fresh gas displaces the exhaled gas from the elbow toward the endotracheal tube connector largely by a volume effect. However, it is also important to note that at the higher fresh gas flow volume it did not affect the exhaled gas beyond the point of narrowing of the endotracheal tube connector before the next breath. This study demonstrated graphically that varying FGF rate affects the measurement of $P_{ET}CO_2$ if the sampling catheter is located between the FGF inlet and the elbow connector. It was interesting and unexpected that during the expiratory cycle a definite interface developed between fresh gas flow and the expired gas, delineating the two gases rather than mixing them. However, it remains possible that subtle mixing not discernible to the eye or the camera shutter may have occurred within the smoke/fresh gas interface. If so, it would be clinically unimportant.

The design of our experiment may be criticised insofar as a smoke-labelling technique was used to visualise the expired gas. The vaporisation of mineral oil as a means of opacifying the expired gas raises concern that the flow characteristics, whether turbulent or laminar, may have been changed as a result of altering the density and the viscosity of the gas mixture. This technique produces a time-line of smoke which has been extensively studied and approved for a wide variety of flow velocities studies either in a turbulent or laminar flow pattern.[6] The diameter of the suspended droplets in the vaporised mixture was 0.15 to 1.0 μm.[9] The effect of the total viscosity of this air-oil mixture is negligible (about 0.1%).[7] Production of smoke with these characteristics has enabled investigators to visualise flow without disturbing the flow field especially if the gas flow velocity is in an adequate range which is generally estimated to be less than 20 $cm \cdot sec^{-1}$.[8] However, if smoke caused an alteration in the flow characteristics of the exhaled gas, the effect would have been to increase the average density of the expired gas and therefore increase the Reynold's number. Such an increase would favour a maintenance of the normal turbulent flow which one would expect to find in these circumstances. A change in density of this magnitude is unlikely to alter flow characteristics greatly.

The results of this laboratory investigation indicate that the most proximal site to sample $P_{ET}CO_2$ accurately in infants during ventilation with the Mapleson D circuit is at the point of narrowing of the endotracheal tube connector with the endotracheal tube even at a fresh gas flow rate as high as 15 $L \cdot min^{-1}$. These observations suggest that it may not be necessary to measure $P_{ET}CO_2$ through a catheter at the distal end of the endotracheal tube in anaesthetised infants and children.

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References

1 *Kaplan RF, Paulus DA.* Error in sampling of exhaled gases (Letter). Anesth Analg 1983; 62: 955–6.

2 *Steward DJ, Creighton RE.* The uptake and excretion of nitrous oxide in the newborn. Can Anaesth Soc J 1978; 25: 215–7.

3 *Badgwell JM, McLeod ME, Lerman J, Creighton RE.* End-tidal P_{CO_2} measurements sampled at the distal and proximal ends of the endotracheal tube in infants and children. Anesth Analg 1987; 66: 959–64.

4 *Bissonnette B, Lerman J.* Single breath end-tidal PCO_2 estimates of arterial CO_2 in infants and children. Can J Anaesth 1989; 36: 110–2.

5 *Rich GF, Sullivan MP, Adams JM.* Is distal sampling of end-tidal CO_2 necessary in small subjects? Anesthesiology 1990; 73: 265–8.

6 *Corke T, Drubka R, Nagib H.* A new technique for introducing controlled sheets of smoke streaklines in wind tunnels. International Congress on Instrumentation in Aerospace Simulation Facilities. Shrivenham, England: IEEE 1977; 74–80.

7 *Torii K.* Flow visualization by smoke-wire technique. *In*: Asanuma T (Ed.). Flow Visualization. Proceedings of the International Symposium on Flow Visualization. New York: Hemisphere Publishing Corporation, 1977; 251–8.

8 *Kasagi N, Hirata M, Yokobori S.* Visual studies of large eddy structures in turbulent shear flows by means of smoke-wire method. *In*: Asanuma T (Ed.). Flow Visualization. Proceedings of the International Symposium on Flow Visualization. New York: Hemisphere Publishing Corporation, 1977: 245–51.

9 *Merzkirch W.* Flow Visualization, 2nd ed. New York: Academic Press, Inc., 1987; 24–30.

10 *Gravenstein N, Lampotang S, Beneken JEW.* Factors influencing capnography in the Bain circuit. J Clin Monit 1985; 1: 6–10.

11 *Epstein RA, Reznik AM, Epstein MAF.* Determinants of distortions in CO_2 catheter sampling systems: a mathematical model. Respir Physiol 1980; 41: 127–36.

12 *Taussig LM, Harris TR, Lebowitz MD.* Lung function in infants and young children. Functional residual capacity, tidal volume, and respiratory rate. Am Rev Respir Dis 1977; 116: 233–9.

13 *Fletcher R, Jonson B.* Deadspace and the single breath test for carbon dioxide during anaesthesia and artificial ventilation. Effects of tidal volume and frequency of respiration. Br J Anaesth 1984; 56: 109–19.

14 *Schena J, Thompson J, Crone RK.* Mechanical influences on the capnogram. Crit Care Med 1984; 12: 672–4.

15 *Hillier SC, Badgwell JM, McLeod ME, Creighton RE, Lerman J.* Accuracy of end-tidal PCO_2 measurements using a sidestream capnometer in infants and children ventilated with the Sechrist infant ventilator. Can J Anaesth 1990; 37: 318–21.

16 *Schieber RA, Namnoum A, Sugden A, Saville AL, Orr RA.* Accuracy of expiratory carbon dioxide measurements using the coaxial and circle breathing circuits in small subjects. J Clin Monit 1985; 1: 149–55.

17 *Lindahl S, Offord KP, Johannesson GP, Meyer DM, Hatch DJ.* Carbon dioxide elimination in anaesthetized children. Can J Anaesth 1989; 36: 113–9.

18 *Dumpit FM, Brady JP.* A simple technique for measuring alveolar CO_2 in infants. J Appl Physiol 1978; 45: 648–50.

19 *From RP, Scamman FL.* Ventilatory frequency influences accuracy of end-tidal CO_2 measurements. Analysis of seven capnometers. 1988; 67: 884–6.