

Review Article

Capnometry and anaesthesia

K. Bhavani-Shankar MD, H. Moseley FFARCS,
A.Y. Kumar MD, Y. Delph DA

In the last decade, capnography has developed from a research instrument into a monitoring device considered to be essential during anaesthesia to ensure patient safety. Hence, a comprehensive understanding of capnography has become mandatory for the anaesthetist in charge of patients in the operating room and in the intensive care unit. This review of capnography includes the methods available to determine carbon dioxide in expired air, and an analysis of the physiology of capnograms, which are followed by a description of the applications of capnography in clinical practice. The theoretical backgrounds of the effect of barometric pressure, water vapour, nitrous oxide and other factors introducing errors in the accuracy of CO₂ determination by the infra-red technique, currently the most popular method in use, are detailed. Physiological factors leading to changes in end-tidal carbon dioxide are discussed together with the clinical uses of this measurement to assess pulmonary blood flow indirectly, carbon dioxide production and adequacy of alveolar ventilation. The importance of understanding the shape of the capnogram as well as end-tidal carbon dioxide measurements is emphasized and its use in the early diagnosis of adverse events such as circuit disconnections, oesophageal intubation, defective breathing systems and hypoventilation is highlighted. Finally, the precautions required in the use and interpretation of capnography are presented with the caveat that although no instrument will replace the continuous presence of the attentive physician, end-tidal carbon dioxide monitoring can be effective in the early detection of anaesthesia-related intraoperative accidents.

La capnographie est maintenant un élément essentiel du monitoring des patients pendant l'anesthésie générale et tout anesthé-

Key words

CARBON DIOXIDE: end-tidal, measurement, monitoring;
MEASUREMENT TECHNIQUES: capnometry;
MONITORING: carbon dioxide.

From the Department of Anaesthesia, Queen Elizabeth Hospital, University of West Indies, Barbados, West Indies.

Address correspondence to: Dr. K. Bhavani-Shankar.

Accepted for publication 26th January, 1992.

siste doit comprendre les principes de fonctionnement de cette technique. La présente révision décrit les méthodes disponibles de mesure de gaz carbonique (CO₂) expiré, ainsi qu'une analyse de la physiologie associée aux différents capnogrammes. Une description des applications cliniques de la capnographie fait suite à ces énoncés théoriques. Les effets de la pression barométrique, de la vapeur d'eau, du protoxyde d'azote et de plusieurs autres facteurs affectant la mesure du CO₂ à l'aide d'infra-rouge sont décrits. La capnographie permet une mesure indirecte de la circulation pulmonaire, de la production de CO₂ et de la ventilation alvéolaire. Ces mesures sont influencées par de nombreux facteurs physiologiques qu'il importe de bien connaître afin de déterminer les limites de ce monitoring. Une bonne interprétation de la forme des courbes de capnographie est nécessaire afin de permettre la détection précoce d'incidents dangereux tels un défaut ou débranchement du circuit anesthésique, une intubation oesophagienne ou une hypoventilation. Le présent travail permet à l'anesthésiste de revoir toutes ces notions et rappelle que même si la capnographie ne remplace pas la vigilance du clinicien, elle peut permettre la détection rapide d'événements qui pourraient mener à des complications anesthésiques.

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Capnography is the graphic record of instantaneous carbon dioxide (CO₂) concentrations (capnogram) in the respired gases during a respiratory cycle. Capnometry is the measurement and display of CO₂ concentrations on a digital or analogue indicator. The measurement of CO₂ in the expired air directly indicates changes in the elimination of CO₂ from the lungs. Indirectly, it indicates changes in the production of CO₂ at the tissue level and in the delivery of CO₂ to the lungs by the circulatory system. Capnography constitutes an important non-invasive technique that can monitor CO₂ production, pulmonary perfusion and alveolar ventilation as well as respiratory patterns.^{1,2}

Although the first infra-red CO₂ measuring and recording apparatus was introduced in 1943 by Luft,³ capnography has gained widespread popularity only during the last decade. The early CO₂ monitors were extremely bulky, expensive to purchase and maintain, and unreliable. Their use was limited mostly to research. However, recent technological developments in solid state electronics have resulted in the availability of numerous varieties of small, reasonably priced CO₂ monitors. Studies on the evaluation of anaesthesia accidents and related injuries have demonstrated that adverse respiratory events such as hypoventilation, oesophageal intubation and circuit disconnection represented a major source of patient injury and financial liability in anaesthetic practice.⁴⁻⁸ Capnography has been shown to be effective in the early detection of these adverse events.⁹⁻¹³ Further, it has been concluded recently from a closed claims study that application of capnography and pulse oximetry together could have helped the anaesthetist prevent 93% of avoidable anaesthetic mishaps.⁷ Therefore it is logical to recommend the use of capnography to increase the safety of anaesthesia in an effort to detect anaesthesia-related accidents before irreversible damage is done to the patient.^{4,6-8,14} The improved clinical outcome could reduce the medico-legal and malpractice insurance burdens of anaesthetists. The guidelines to the practice of anaesthesia in Canada already state that CO₂ monitoring be performed on all patients undergoing general anaesthesia requiring endotracheal intubation.¹⁵

The purpose of this review is to present a concise description of the different methods of determination of CO₂ in expired air and the factors affecting its measurement, accompanied by an analysis of the physiology of the

capnogram and an overview of the clinical applications of CO₂ monitoring. The review concludes with a section devoted to the care and precautions that should be observed during the use of capnography.

Terminology

- FCO₂ - Fraction of CO₂ in the tidal gas.
- FACO₂ - Alveolar CO₂ fraction.
- FETCO₂ - End-tidal carbon dioxide fraction. Usually, the CO₂ concentration reaches a maximum at the end of exhalation. FETCO₂ is the maximum concentration recorded at the end of exhalation and indicates FCO₂ of alveoli (FACO₂) emptying last.
- PACO₂ - Alveolar partial pressure of CO₂.
- PaCO₂ - Partial pressure of CO₂ in arterial blood.
- PETCO₂ - Partial pressure (tension) of CO₂ measured at the end of exhalation.
- (a-ET)PCO₂ - Arterial to end-tidal PCO₂ gradient.

Principles of CO₂ measurement

There are four physical methods in use to measure CO₂ concentrations in the respiratory gases. In addition, the FEF end-tidal chemical detector, which changes colour on exposure to 4% CO₂, is also described.

(1) Mass spectrography

The mass spectrograph separates gases and vapours of differing molecular weights. The gas sample is aspirated into a high vacuum chamber (10⁻⁵ mmHg) where an electronic beam ionizes and fragments the components of the gas sample. The ions are accelerated by an electric field into a final chamber, which has a magnetic field, perpendicular to the path of the ionized gas stream. In the magnetic field the particles follow a path of which the radius of curvature is proportional to the charge:mass ratio. A detector plate analyses the various components of the gas and determines the concentration of each component. This system is very expensive and too bulky to use at the bedside. Mass spectrometers for clinical use are either "stand alone," designed to monitor a single patient continuously, or "shared," designed to monitor sequentially several patients in different locations (multiplexed). Up to 31 patients may be connected to a multiplexed system and the gas is simultaneously sampled from all locations by a large vacuum pump. A rotary valve (multiplexer) is used to direct the gas samples sequentially to the mass spectrometer. In a typical 16-station system, with an average breathing rate of 10 breaths · min⁻¹, each patient will be monitored about every 3.2 min. The user can interrupt the normal sequence of the multiplexer and call the mass spectrometer to his patient for a brief period of time.^{1,16}

(2) Raman spectrography

Raman spectrography uses the principle of "Raman Scattering" for CO₂ measurement. The gas sample is aspirated into an analyzing chamber, where the sample is illuminated by a high intensity monochromatic argon laser beam. The light is absorbed by molecules which then produce unstable vibrational or rotational energy states (Raman scattering). The Raman scattering signals (Raman light) are of low intensity and are measured at right angles to the laser beam. The spectrum of Raman scattering lines can be used to identify all types of molecules in the gas phase. Recently, "Raman scattering" has been incorporated into the newer monitors (RASCAL monitors) to identify and quantify instantly CO₂ and inhalational agents used in anaesthetic practice.¹⁷

(3) Infra-red (IR) spectrography

Infra-red spectrography is very compact and less expensive than other methods of measurement. It is the most popular means currently used to monitor CO₂. The wave length of IR rays is >1.0 μm while that of visible light lies between 0.4 and 0.8 μm. The IR rays are absorbed by polyatomic gases (non-elementary gases such as nitrous oxide (N₂O) and CO₂); water vapour also absorbs IR light. Carbon dioxide selectively absorbs specific wavelengths (4.3 μm) of IR light. Since the amount of light absorbed is proportional to the concentration of the absorbing molecules, the concentration can be determined by comparing the absorbance with that of a known standard. The CO₂ concentration measured by the monitor is usually expressed as partial pressure in mmHg, although some units display percentage CO₂ (FCO₂), by dividing CO₂ partial pressure by the atmospheric pressure.^{1,18}

(4) Photoacoustic spectrography (PAS)

Photoacoustic gas measurement (e.g., Bruel-Kjaer gas monitor) is based on the same principles as conventional IR-based gas analyzers: the ability of CO₂ and N₂O and anaesthetic agents to absorb IR light. However, they differ in measurement techniques. Infra-red spectrography uses the optical method, whereas PAS uses the acoustic technique which is based on the fact that if IR energy is applied to a gas the gas will expand and lead to an increase in pressure. If the applied energy is delivered in pulses the pressure will be intermittent, resulting in a pressure fluctuation. If the pulsation frequency lies within the audible range an acoustic signal is produced which can be detected by a microphone. The advantages claimed for PAS over IR spectrometry are high accuracy, increased reliability, reduced preventive maintenance, and less frequent need for calibration. Further, as the amount of IR light absorbed is measured directly without the use of a reference cell the zero point drift is nonexistent in PAS.

The zero is reached when there is no gas present in the chamber. If no gas is present there can be no acoustic signal.¹⁹

Types of CO₂ monitors (capnometers)

There are two types of capnometers, depending on the location of the CO₂ sensors.

- (a) *Side-stream capnometer.* The sensor is located in the main unit itself and a tiny pump aspirates gas samples from the patient's airway through a capillary tubing (e.g., Datex Cardiocap II, Puritan Bennett CD-102, Ohmeda 5200, Spacelabs 540). The sampling tube is connected to a T-piece inserted at the endotracheal tube or anaesthesia mask connector, or can be inserted into the patient's nostril. The gas that is withdrawn from the patient often contains anaesthetic gases and so the exhaust gas from the capnometer should be routed to a gas scavenger or returned to the patient breathing system. The sampling flow rate may be high (>400 ml · min⁻¹) or low (<400 ml · min⁻¹). The optimal gas flow is considered to be 50–200 ml · min⁻¹ which ensures that the capnographs are reliable in both children and adults.^{1,18}
- (b) *Main-stream sensor capnometer.* A cuvette containing the CO₂ sensor is inserted between the endotracheal tube and the breathing circuit (e.g., Hewlett Packard 47210A, Nihon Kohden OIR-710A, Siemens 930). The IR rays traverse the respiratory gases to an IR detector within the cuvette obviating the need for gas sampling and scavenging. To prevent the condensation of water vapour which can cause falsely high CO₂ readings all main-stream sensors are heated above body temperature to about 39°C, but this cannot prevent occlusion of the optical windows of the "cuvette" by secretions or humidifier/ therapeutic aerosols. Facial burns may occur because of the proximity of the heated cuvette to the patient. Conventional main-stream analyzers have sensors which are bulky, heavy and connected by an electrical cord with the main analyzer all of which may produce traction on the endotracheal tube.^{1,18}

Accuracy of IR CO₂ monitoring

The accuracy of CO₂ measurements by the various methods described above can be affected by several factors. As IR spectrography is used more frequently in clinical practice, the factors are discussed with particular reference to IR spectrography.

(1) Atmospheric pressure

Changes in atmospheric pressure do not affect the CO₂ concentration (FCO₂) but rather what is interpreted as CO₂ by the detector.

A change in atmospheric pressure directly influences the reading of capnometers since CO₂ concentration is measured as partial pressure (direct effect). Further, an indirect effect is seen when a capnometer reports measurements in volume percent instead of partial pressure.²⁰

DIRECT EFFECT

This has two components.

- (a) An increase in pressure gives a proportionate increase in the number of radiation-absorbing CO₂ molecules which increases the CO₂ signal. A 1% increase in pressure causes a 1% relative increase in the CO₂ signal. This effect is eliminated by calibrating the capnometer with a known partial pressure of the CO₂ gas (mmHg = vol% × atmospheric pressure) from a commercially available calibrating gas. Given such a calibration, the capnometer will record CO₂ concentrations within its measurement cuvette as partial pressure regardless of changes in the atmospheric pressure.²⁰ However, if the capnometer is calibrated in volume percent, then the FCO₂ readings should be corrected for the changes in atmospheric pressure (a 1% increase in pressure produces a 1% relative increase in FCO₂ value).²¹
- (b) Changes in pressure also produce a second effect. An increase in pressure increases the intermolecular forces of CO₂ molecules, which increase the IR absorption. An increase in pressure by 1% causes a relative increase in the signal by 0.5 to 0.8% which can produce a small error.^{21,22} The maximal changes in the atmospheric pressure due to changes in the weather are of the order of 20 mmHg. This would result in a change in PCO₂ of less than 0.5 to 0.8 mmHg (measurement range of PCO₂, 30–40 mmHg) and, therefore, in routine clinical use corrections are unnecessary.²¹ However, in studies in which precision is needed corrections for variations in barometric pressure are useful.

Increases in the sampling flow rate of side-stream CO₂ sensors result in a reduction of pressure at the airway and lower apparent CO₂ measurements. However, if the unit is calibrated at the average prevailing atmospheric pressure and sampling flow does not change, the unit should be sufficiently accurate for clinical measurements. Further, application of PEEP (positive end expiratory pressure) increases the CO₂ reading. A PEEP of 20 cm H₂O increases the CO₂ reading by 1.5 mmHg.²⁰

Some units measure the pressure in their sensor and automatically adjust the CO₂ reading accordingly.^{18,20,22}

INDIRECT EFFECT

The indirect effect of atmospheric pressure results when an analyzer reports measurements in volume percent. In

conjunction with measurements of arterial blood gas tensions, it is preferable to record the readings as PCO₂ (mmHg) and not as volume percent. The atmospheric pressure at the time of measurement must be known to compute the PCO₂ value (mmHg = FCO₂ × atmospheric pressure).²⁰ However, if the atmospheric pressure at the time of measurement is different from the atmospheric pressure during the time of calibration, then the observed FCO₂ readings should be corrected for the two components of "direct effect" of atmospheric pressure changes before computing the PCO₂ value.^{21,22}

(2) Nitrous oxide

Nitrous oxide absorbs IR light (IR absorption spectra of N₂O = 4.5 μm whereas CO₂ = 4.3 μm) and the presence of N₂O therefore gives falsely high CO₂ readings. This effect can be eliminated by using a narrow band IR filter, which only allows the light most absorbed by CO₂ (about 4.3 μm) to pass. However, N₂O molecules also interact with CO₂ molecules producing a "collision broadening effect" which affects the sensitivity of the IR analyzer and causes an apparent increase in CO₂ reading. "Collision broadening" is a phenomenon where the spectral absorption peaks of a gas (CO₂) are broadened owing to the collision or proximity of molecules of another gas (N₂O).²⁰ The correction factors for the presence of various concentrations of N₂O have been studied and range from 0.94 at 70% N₂O (corrected PCO₂ = observed PCO₂ × 0.94) to 0.90 at 50% N₂O.²³ Most monitors provide some system of electronic compensation to reduce this effect. Alternatively, the simplest method of eliminating this error is to calibrate the instrument with a gas mixture which contains the same background gas concentration as that to be analyzed.^{18,22}

(3) Halogenated anaesthetic agents

The low concentrations of halogenated anaesthetic agents used during anaesthesia absorb IR energy at different wave lengths (around 3.3 μm) and their interference is not considered to be important.¹⁸

(4) Oxygen

Although oxygen (O₂) does not absorb IR light it may indirectly affect the absorption by CO₂ by collision with the CO₂ molecules and broadening the absorption peak. While it does not cause as large an effect as N₂O, oxygen causes a falsely low CO₂ reading. Some units automatically correct or have a user-actuated electronic offset for the concentration of O₂ encountered.¹⁸

(5) Water vapour

The presence of water vapour affects the CO₂ readings in two ways.

- (i) Effect of condensed water. Water vapour may condense on the window of the sensor cell, absorb IR light, and produce falsely high CO₂ readings. This interference can be prevented by heating the sensor above body temperature (main-stream sensor units) or by removing the excess water vapour, before it reaches the sensor (side-stream sensor units). Some side stream-sensor units use a special sampling tube made of Nafion®, a semipermeable polymer that selectively allows water vapour to pass from the interior of the tube to the exterior. Other side-stream units have liquid traps or moisture-absorbent filters that are usually interposed between the sampling tube and the analyzer that help to remove excessive water and secretions, thus the optical system is protected.^{18,20,22}
- (ii) Effect of water vapour. Main-stream IR analyzers measure the gas in the breathing circuit, which is generally saturated at body temperature. The exact water vapour pressure in the breathing circuit will depend on many factors including the use of heated humidifications, fresh gas flow, length of time in use and temperature.²⁰ In side-stream sensors the temperature of the sampling gases may decrease during the passage from the patient to the unit, resulting in a decrease in the partial pressure of water vapour. This causes an apparent increase in CO₂ concentration of about 1.5–2%.^{22,24} Further, if Nafion® tubing is used in the sample catheter, then it actually equilibrates the water vapour pressure inside the tubing to that of outside the tubing.²⁰ Therefore, PETCO₂ measurements should be corrected for the changes in water vapour, depending on the type of analyzer used, according to the manufacturer's instructions.^{22,24}

(6) Response time of analyzer

For accuracy, a capnograph needs a rapid response time. This response time has two components. The transit time and the rise time.²⁵

The transit time is the time required for the sample to move from the point of sampling to the detector cell. Prolonged transit time delays the appearance of the waveform at the detector, which causes a phase shift, but no distortion. However, a bolus of gas is subjected to dispersal caused by convection and diffusion during transit down the catheter. Such a dispersal converts a square wave front into a sigmoid shape, with loss of the highest and lowest gas concentration peaks. This results in an underestimation of PETCO₂, particularly in children. The extent of the error increases with increased length and width of the sampling tube, reduced sample flow rate (50 ml · min⁻¹) and higher breathing frequency of the patient (greater than 31 breaths · min⁻¹).^{26,27}

The rise time (T₉₀) is the time taken by the output from

the capnometer to change from 10% of the final value to 90% of the final value in response to a step change in PCO₂. Alternatively, rise time may be specified as T₇₀ which is the time taken to change from 10% to 70% of the final value.²⁸ The rise time is dependent upon the size of the sample chamber and the gas flow.²⁵ Slower flow rates increase the time required to flush the infra-red sample cell, which can increase the rise time. The rise times of capnographs for clinical use range from 50–600 ms. Carbon dioxide waveform is a function of rise time of the capnometer. Prolonged rise time can reduce the slope of phase II resulting in an underestimation of anatomical dead space.^{24,27} The rise time of commercially available CO₂ analyzers is fast enough to measure PETCO₂ in adults, with 5% accuracy (less than 30 breaths · min⁻¹). However, when the ventilatory rate is high, as in children, faster analyzers with rise time (T₇₀) of 80 ms are necessary to measure PETCO₂ values with 5% accuracy (at 100 breaths · min⁻¹ and I:E ratios less than 2:1).²⁸

The response time of the CO₂ monitors has been considerably reduced in newer units by (i) the use of more powerful amplifiers, (ii) minimising the volume of the sampling chamber and tubes and (iii) the use of relatively high sampling flow rates (150 ml · min⁻¹). In order to achieve predictable PETCO₂ values and CO₂ waveforms it is recommended that the response time of the analyzer be less than the respiratory cycle time of the patient.²⁹

(7) Alinearity of CO₂ analysis

The CO₂ concentration of the gas used to calibrate the analyzer should be as near as possible to the range of concentrations to be measured in order to ensure the greatest accuracy in the measurement.²⁴

FEF end-tidal CO₂ detector

A pH-sensitive chemical indicator is enclosed in a plastic housing and is connected to the gas stream between the endotracheal tube and the anaesthesia circuit. The pH-sensitive indicator changes colour when exposed to CO₂. The colour varies between expiration and inspiration, as CO₂ level increases or decreases. The colour changes from purple (when exposed to room air) to yellow (when exposed to 4% CO₂). The response time of the device is sufficiently fast to detect changes of CO₂ breath-by-breath.¹¹

Physiological considerations

The concentration of CO₂ in the alveoli is a ratio of CO₂ output into the lungs (V̇CO₂) and alveolar ventilation. The following equation describes the principal determinants of the PACO₂.

$$\text{PACO}_2 = \text{BP} \times [\text{mean FICO}_2 + (\text{VCO}_2 / \text{alveolar ventilation})]$$

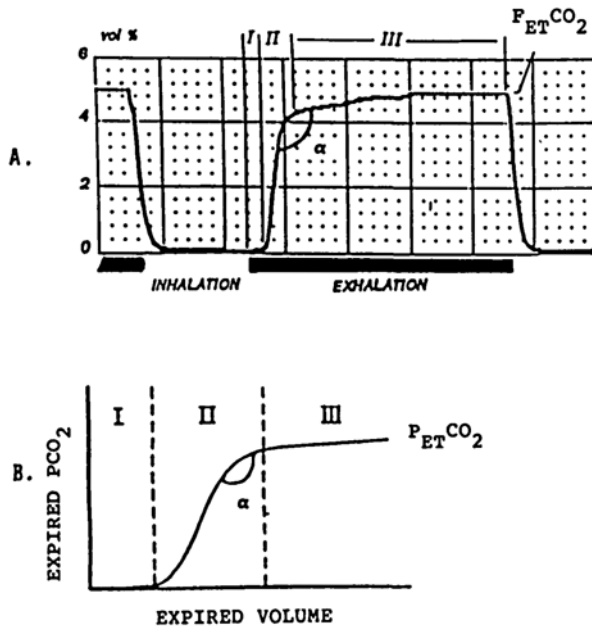


FIGURE 1 (A) Capnogram – FCO₂ trace against time. (B) Capnogram – PCO₂ trace against expired volume (SBT-CO₂). The capnograms can be divided into three phases. Phase I, II, and III.

where BP = barometric pressure in a dry phase and FiCO₂ = inspired CO₂ fraction.

End-tidal CO₂ tension is dependent on PACO₂ and, therefore, is influenced by changes in barometric pressure, FiCO₂, determinants of $\dot{V}CO_2$ (CO₂ production in tissues and CO₂ transport to the lungs), and determinants of alveolar ventilation (minute ventilation and physiological dead space).³⁰

Analysis of a capnogram

The recording of a capnogram may be at two speeds. A high speed capnogram (about 7 mm · sec⁻¹) gives detailed information about each individual breath whereas the overall CO₂ changes (trend) can be followed at a slow speed (about 0.7 mm · sec⁻¹). In the high speed capnogram, changes in FCO₂ or PCO₂ are plotted against time (Figure 1A). Although this method is convenient for clinical use, more accurate information can be obtained from the single breath test for CO₂ (SBT-CO₂), where the FCO₂ or PCO₂ changes are recorded against the volume of the expired gas rather than time (Figure 1B).^{31,32} The SBT-CO₂ gives a better reflection of \dot{V}/\dot{Q} status of the lung.

SBT-CO₂

A typical SBT-CO₂ trace is shown in Figure 1B. The trace can be divided into three phases.

Phase I Represents the CO₂-free gas from the airways (anatomical and apparatus dead space).

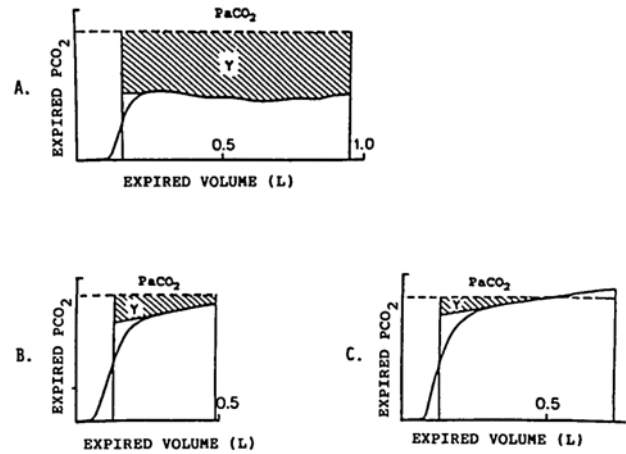


FIGURE 2 (A) SBT-CO₂ trace recorded during anaesthesia/IPPV. The horizontal phase III suggests synchronous alveolar emptying. (B) SBT-CO₂ trace recorded during anaesthesia/IPPV, small tidal volume: (a-ET)PCO₂ = 2.25 mmHg. (C) SBT-CO₂ trace recorded during anaesthesia/IPPV in same patient as in tracing (B), large tidal volume: (a-ET)PCO₂ = -1.5 mmHg (modified with permission from author reference 31).

Phase II Consists of a rapid S-shaped upswing on the tracing (due to mixing of dead space gas with alveolar gas).

Phase III The alveolar plateau represents CO₂-rich gas from the alveoli; it almost always has a positive slope indicating a rising PCO₂.

FACTORS RESPONSIBLE FOR SLOPE OF PHASE III

West and his colleagues pointed out that PCO₂ sampled at the lips increases for two different reasons:³³

- (i) *Cyclical variation in alveolar CO₂*. CO₂ is being continuously excreted into the alveolar gas during respiration. This results in a cyclical variation in alveolar PCO₂, values being greater during expiration than inspiration.
- (ii) *The late emptying of alveoli with lower ventilation/perfusion (\dot{V}/\dot{Q}) ratios and, therefore, relatively higher PCO₂*. If all the alveoli had the same PCO₂, then irrespective of the emptying patterns, phase III would be nearly horizontal. However, this *ideal* situation does not occur, even in normal lungs which have a wide range of \dot{V}/\dot{Q} ratios. Some alveoli have a higher \dot{V}/\dot{Q} ratio (over ventilated) than ideal alveoli and hence they have a relatively lower PCO₂. Others have a lower \dot{V}/\dot{Q} ratio than ideal alveoli (under ventilated) resulting in a relatively higher PCO₂. The delayed emptying of these alveoli with low \dot{V}/\dot{Q} (high PCO₂) contributes to the rising slope of phase III. The mechanisms producing this effect are as follows^{31,32}
 - (A) *Within the terminal respiratory unit*. Ventila-

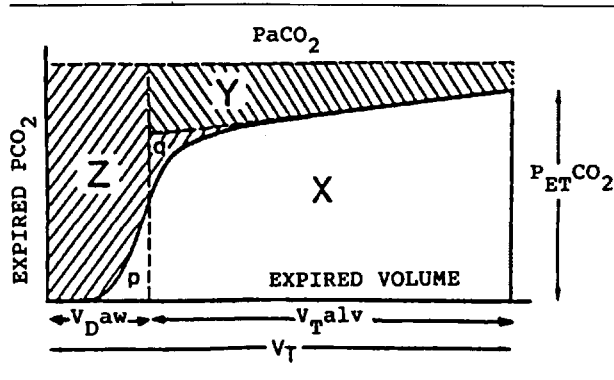


FIGURE 3 Physiological dead space and its subdivisions (modified with permission from author reference 31).

tion:perfusion (\dot{V}/\dot{Q}) mismatch within the unit may be due either to incomplete gas mixing (*alveolar mixing defect*) or to the fact that the maximum ventilation and maximum perfusion to that unit are out of sequence in respect to time (*temporal mismatching* – perfusion is highest during the latter part of expiration when ventilation is lowest). The scatter of \dot{V}/\dot{Q} ratios produced as a result is axially distributed with those alveoli having low \dot{V}/\dot{Q} ratio (higher PCO_2) being distributed distally and emptying later.

(B) *Between respiratory units.* There may be a regional variation in ventilation per unit perfusion producing a spectrum of \dot{V}/\dot{Q} ratios (*spatial mismatching*). Under these circumstances, the slope of phase III is determined by the nature of emptying of the alveolar units: synchronous or asynchronous. If the units empty synchronously, the gas from well-perfused and under-perfused alveoli is expired simultaneously, resulting in a horizontal phase III or else a phase III with minimal slope (Figure 2A). However, if the units empty asynchronously, units with longer time constants, hence higher PCO_2 , would empty later (*sequential emptying*) resulting in a rising slope of Phase III (Figure 2B).

The slope of the phase III is dependent, therefore, on the emptying patterns of various alveoli with different \dot{V}/\dot{Q} ratios as well as continuous CO_2 excretion into the alveoli. The relative contributions of all the above mechanisms cannot be separated and all occur simultaneously. The angle between phases II and III, which has been referred to as the alpha (α) angle, increases as the slope of phase III increases. The alpha angle (primarily linked to variations in time constants within the lung) is thus an indirect indication of \dot{V}/\dot{Q} status of the lung (Figure 1).¹

Other factors, such as changes in cardiac output, CO_2 production, airway resistance and functional residual capacity (FRC) may further affect the \dot{V}/\dot{Q} status of the various units in the lung, and thus influence the height or the slope of phase III.

The CO_2 trace against time also can be considered as three phases as above (Figure 1A). After phase III is complete, the descending limb makes an almost right angle turn and rapidly descends to the base line. It represents the inspiratory phase during which the fresh gas (CO_2 free) is inhaled when the CO_2 concentration falls to zero. The CO_2 trace against time is convenient and adequate for clinical use and this is the method most commonly used by capnographs. However, the slope of the phase III in an SBT- CO_2 trace gives a better reflection of \dot{V}/\dot{Q} status of the lung. The gradient of the phase III slope may be less obvious in the CO_2 trace against time.^{31,32} Further, the physiological dead space can be determined only from an SBT- CO_2 trace.

Dead space and SBT- CO_2

The SBT- CO_2 trace can be used to determine physiological dead space and its components. A horizontal line (dotted line in the Figure 3) representing $PaCO_2$ (arterial blood sampled during the $PETCO_2$ recordings) is drawn on the SBT- CO_2 trace. The area under the curve, X, is the volume of CO_2 in the breath and represents effective ventilation. The remaining area below the horizontal dotted line represents wasted ventilation (physiological dead space). A vertical line is constructed through phase II so that the two areas p and q are equal. Area Z represents anatomical dead space and area Y represents alveolar dead space. Therefore, physiological dead space is represented by area Z plus area Y.^{31,32}

(a-ET) PCO_2 as an index of alveolar dead space

Under normal circumstances, the $PETCO_2$ (PCO_2 from alveoli which empty last) is lower than $PaCO_2$ (average of all alveoli) by 2–5 mmHg.^{34–37} This is due to the alveolar dead space which is the result of temporal, spatial and alveolar mixing defects in the normal lung. Changes in alveolar dead space correlate well with changes in (a-ET) PCO_2 only when phase III is flat or has a minimal slope. In this case, the area Y representing alveolar dead space is almost rectangular and $PaCO_2 > PETCO_2$ (Figure 2A). However, if phase III has a steeper slope the terminal part of phase III may intercept the line representing $PaCO_2$, resulting in either zero or negative (a-ET) PCO_2 gradients even in the presence of an alveolar dead space (represented by the triangular shaded area, Y, in Figure 2C).^{31,32} Therefore, the (a-ET) PCO_2 is dependent both on alveolar dead space as well as factors that influence the slope of phase III. This implies that an increase in the alveolar dead space need not always be associated with an increase in the (a-ET) PCO_2 . The (a-ET) PCO_2 may remain the same if there is an associated increase in the slope of the phase III. For example, it has been observed during cardiac surgery that alveolar dead space was increased at

the end of cardiopulmonary bypass but as the slope of phase III was also increased there was no change in $(a-ET)PCO_2$.^{38,39}

Negative $(a-ET)PCO_2$ gradients

Negative $(a-ET)PCO_2$ values were observed more than 30 yr ago by Nunn *et al.*, during anaesthesia although no explanation was offered.³⁴ Fletcher *et al.* observed negative or zero $(a-ET)PCO_2$ values in 12% of normal subjects during anaesthesia and IPPV with large tidal volumes and low frequencies.³⁵ Negative values were also observed during anaesthesia in 50% of pregnant subjects,³⁶ in 8.1% of patients after post-cardiac bypass (PCB)⁴⁰ and in 50% of infants.⁴¹

Large tidal volume and low frequency ventilation result in (i) better ventilation of dependent well-perfused alveoli which improves \dot{V}/\dot{Q} matching (small area Y in 2C). (ii) Gas emptying from slow alveoli to reach the mouth, whereas it would have remained in the airways with small frequent breaths. Under these circumstances the low \dot{V}/\dot{Q} areas (alveoli with higher PCO_2) make a more substantial contribution to the gas exchange. The net effect of these factors is to enable the terminal part of phase III to exceed mean $PaCO_2$, resulting in negative $(a-ET)PCO_2$ (Figure 2C).³⁵

The increased cardiac output and increased CO_2 production, reduced FRC and low compliance associated with pregnancy may result in greater cyclical variations in alveolar PCO_2 during a respiratory cycle and also in more alveoli with long time constants. During expiration, $PaCO_2$ increases towards $PvCO_2$ (partial pressure of mixed venous CO_2) more rapidly in pregnant subjects because a larger amount of CO_2 is evolved into a lung which becomes smaller as expiration continues. Further, pregnant subjects resemble obese in some features namely reduced FRC and low total compliance and hence may exhibit a biphasic slope reminiscent of phase IV of the nitrogen closing volume test. The PCO_2 of most alveolar gas is less than $PaCO_2$ but, in the terminal part of the expirate, PCO_2 rises rapidly and may exceed $PaCO_2$. The combined effect of these two mechanisms increases the slope of phase III (Figure 4B) and the likelihood of sampling a $PETCO_2$ greater than $PaCO_2$.^{36,39,42-44}

The presence of a wide range of \dot{V}/\dot{Q} mismatching and reduced FRC may result in negative $(a-ET)PCO_2$ values in patients after cardiopulmonary bypass.^{39,40} Increased CO_2 production and reduced FRC may be responsible for the negative $(a-ET)PCO_2$ values observed in infants.⁴¹

Cardiac output and $(a-ET)PCO_2$

Reduction in cardiac output and pulmonary blood flow result in a decrease in $PETCO_2$ and an increase in $(a-ET)PCO_2$. Increases in cardiac output and pulmonary

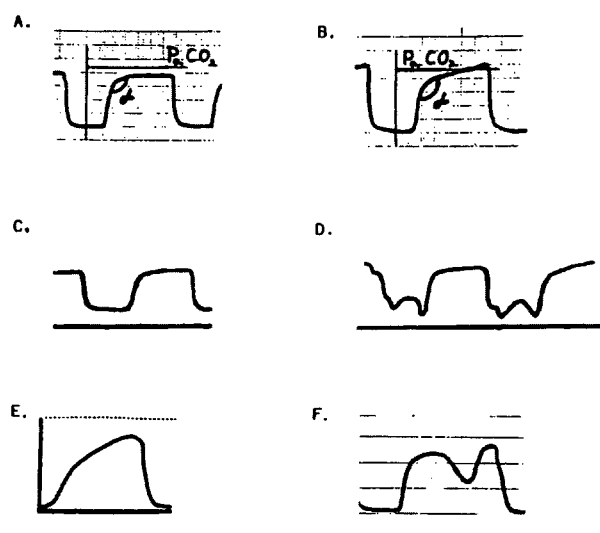


FIGURE 4 (A) Normal capnogram, $PaCO_2 > PETCO_2$. (B) Capnogram during Caesarean section anaesthesia. Phase III has a steeper slope than that in figure 4A. $PETCO_2 > PaCO_2$. (C) Rebreathing caused by exhausted soda lime. The base line is elevated above zero. (D) Capnogram during the use of Bain anaesthetic circuit. Inspiratory base line and phase I are elevated above zero due to rebreathing. Note the rebreathing wave during inspiration. (E) Obstructive pulmonary disease: prolongation of phase II and a steeper phase III slope. (F) Waning neuromuscular blockage "curare cleft" - a dip in phase III indicating spontaneous respiratory effort. Mode of ventilation (A to F): IPPV. (Capnogram 4E reproduced with permission from Datex instrumentation, Helsinki, Finland.)

blood flow result in better perfusion of the alveoli and a rise in $PETCO_2$.^{2,37} Consequently alveolar dead space is reduced as is $(a-ET)CO_2$. The decrease in $(a-ET)PCO_2$ is due to an increase in the alveolar CO_2 with a relatively unchanged arterial CO_2 concentration, suggesting better excretion of CO_2 into the lungs. The improved CO_2 excretion is due to better perfusion of upper parts of the lung.³⁷ Askrog found an inverse linear correlation between pulmonary artery pressure and $(a-ET)PCO_2$.³⁷ Thus, under conditions of constant lung ventilation, $PETCO_2$ monitoring can be used as a monitor of pulmonary blood flow.^{2,45}

Clinical applications

Various factors result in either increased or decreased/absent $PETCO_2$ (Table). It is more advantageous to have a continuous recording of the capnogram than simply a digital display of $PETCO_2$ since an analysis of the capnogram gives more information and better insight into the clinical situation. This permits early diagnosis and therefore the early institution of corrective action when abnormalities develop. There is only one normal capnogram and all variations must be recognized and corrected where possible (Figures 4 and 5). Abnormalities should be found by analyzing the various phases of capnogram for

TABLE Various factors that influence PETCO₂

PETCO ₂	Factors			
	CO ₂ output	Pulmonary perfusion	Alveolar ventilation	Technical errors or machine faults
PETCO ₂ increased	Fever Thyrotoxicosis Malignant hyperthermia Sodium bicarbonate Tourniquet release Venous CO ₂ embolism	Increased cardiac output Increased blood pressure	Hypoventilation Bronchial intubation Partial airway obstruction Rebreathing	Exhausted CO ₂ absorber Inadequate fresh gas flows Leaks in breathing system Faulty ventilator Faulty valves
PETCO ₂ decreased or absent	Hypothermia	Reduced cardiac output Hypotension Hypovolaemia Pulmonary embolism Cardiac arrest	Hyperventilation Apnoea Total airway obstruction Partial airway obstruction Accidental tracheal extubation	Circuit disconnection Sampling tube leak Malfunction of ventilator

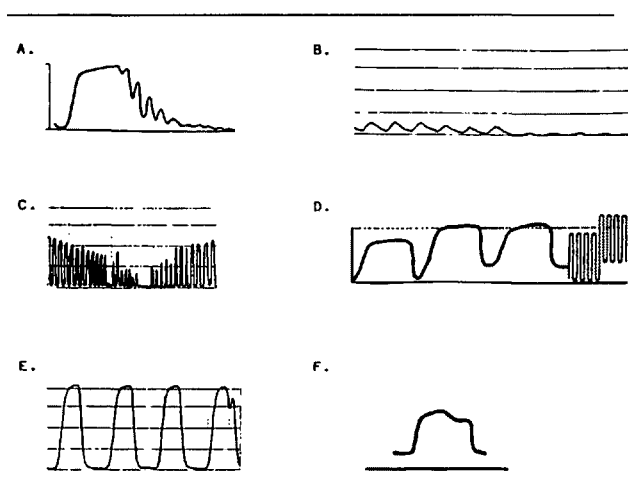


FIGURE 5 (A) Cardiogenic oscillations. Ripple effect, superimposed on the plateau and the descending limb, resulting from small gas movements produced by pulsations of the aorta and heart. (B) Oesophageal intubation. CO₂ is rapidly flushed out on ventilation of the stomach and PETCO₂ decreases. (C) Cardiac arrest: PETCO₂ decreases rapidly following the collapse of pulmonary perfusion. The capnogram following the resuscitation. (D) Sudden upward shift in base and top line: contamination of CO₂ monitor with secretions and mucus. (E) Paediatric capnogram during the use of Jackson-Rees circuit (spontaneous respiration). (F) Dilution of PETCO₂ by fresh gas flow during the use of PEEP or CPAP in IMV BIRD ventilator producing constant flow. Mode of ventilation: IPPV except in E (spontaneous). (Capnograms A to D reproduced with permission from Datex instrumentation, Helsinki, Finland.)

individual breaths as well as observing trends over a period of time. Five characteristics should be inspected, viz., height, frequency, rhythm, base line and shape. Abnormalities in each phase of the capnogram are associated with either patient- or equipment-related problems.

An elevated inspiratory base line and phase I indicates CO₂ rebreathing, which is abnormal with circle breathing

systems, and suggests either an exhausted CO₂ absorbent in circle system (Figure 4C) or incompetent valves.⁴⁶⁻⁵⁰ It is normally anticipated with the Bain anaesthetic system during controlled ventilation (Figure 4D).⁴⁹⁻⁵¹

Prolongation or slanting of the expiratory upstroke (phase II) occurs when there is obstruction to expiratory gas flow (e.g., asthma, bronchospasm, obstructive pulmonary disease, and kinked endotracheal tube)^{8,22,48-50,52} or in the presence of leaks in the breathing system.⁵¹ A side-stream capnograph may allow gas mixing within the sampling tube (dispersion) if sampling rate is slow (50 ml · min⁻¹) or if the tubing is too long or has too wide a bore, or both. Such dispersion of gases can also result in prolongation of the expiratory upstroke.^{27,29}

The slope of the expiratory plateau (phase III) can be increased during pregnancy as a normal physiological variation (Figure 4B).⁴² Besides, it can also result from factors that produce obstruction to expiratory gas flow which may also result in a prolonged phase II (Figure 4E).^{22,48-54} A dip in the plateau (curare cleft – Figure 4F) indicates a spontaneous respiratory effort during mechanical ventilation.^{9,51}

The descending limb can be prolonged or slanted, when the inspiratory valve of a closed circuit system is incompetent⁴⁸ or because of the use of side-stream sensor capnographs, with a prolonged response time.²⁷ The capnograph with a prolonged response time also results in the prolongation of phase II and is observed commonly in children.^{27,29} At slow respiratory rates it is common to see a ripple effect, referred to as cardiogenic oscillations, superimposed on the expiratory plateau and the descending limb of the capnogram. This arises from small gas movements created largely by the pulsations of the aorta and heart (Figure 5A).^{1,50,51}

Increases in metabolism raise the height of the plateau whereas decreases in metabolism, cardiac output and

effective circulating blood volume reduce the height.^{2,49} A sudden elevation in both the base line and the PETCO₂ usually indicates contamination of the sample cell with water, mucus or dirt, whereas a gradual rise suggests rebreathing.⁵⁵

(1) PETCO₂ as an estimate of PaCO₂

Measurements of PETCO₂ constitute a useful non-invasive tool to monitor PaCO₂ and hence the ventilatory status of patients during anaesthesia or in the intensive care unit. In normal individuals, the (a-ET)PCO₂ may vary from 2–5 mmHg.^{34–37} It can vary from patient to patient and is dependent on several factors. It increases with age, pulmonary disorders (emphysema), pulmonary embolism, decreasing cardiac output, hypovolaemia and anaesthesia itself.^{2,37,53,54} It decreases with large tidal volumes and low frequency ventilation.³⁵ In pregnant subjects, as well as in infants and smaller children, the (a-ET)PCO₂ is lower than in non-pregnant adults and PETCO₂ reflects PaCO₂.^{36,41,42}

Changes in PETCO₂ can often be regarded as indicative of changes in PaCO₂. The PETCO₂ is even more useful if its relationship to PaCO₂ can be established initially by blood gas analysis. Thereafter, changes in PaCO₂ may be assumed to occur in parallel with those in PETCO₂ thus avoiding repeated arterial puncture. However, the variations in (a-ET)PCO₂ during major surgery may be of the same magnitude as the inter-individual variations and caution must be used in the precise prediction of PaCO₂ from PETCO₂ measurements. Several factors such as changes in body position, temperature and pulmonary blood flow, as well as mechanical ventilation and cardiopulmonary bypass, can result in changes in the ventilation perfusion status of the lungs. This in turn alters the alveolar dead space fraction and the slope of phase III, and this affects (a-ET)PCO₂. Further, there is no consistent correlation between (a-ET)PCO₂ and the various factors mentioned.⁴⁰

(2) Adequacy of spontaneous respiration

Capnography can be used to monitor the adequacy of spontaneous ventilation, not only during general anaesthesia and recovery but also in the awake unintubated patient either in the intensive care unit or during regional anaesthesia. In addition, CO₂ monitoring can serve as an apnoea monitor. The samples can be drawn from the nasal cavity using nasal adaptors or cannulae.^{56–59} Gases can also be sampled from the nasal cavity during the administration of oxygen using a simple modification of the standard nasal cannulae. End-tidal CO₂ tension, thus measured, is a good predictor of PaCO₂ even when oxygen is being administered simultaneously.^{57,59} This may be of particular benefit in monitoring the ventilatory status of patients with chronic respiratory failure where excessive oxygen therapy

can produce CO₂ narcosis. However, the major limiting factor is the admixture of end-tidal gas with air or insufflated oxygen resulting in a falsely low PETCO₂ particularly in mouth breathing patients, or in those who may require more than 4 l · min⁻¹ of nasal oxygen, or in patients who are hypoventilating.^{57,59}

(3) Adjustments of fresh gas flow rates (FGF) in rebreathing systems

The FGF required with various rebreathing systems during anaesthesia can be adjusted precisely by continuous monitoring of PETCO₂ and this prevents hypercarbia.

(4) Integrity of anaesthetic apparatus

Anaesthetic mishaps due to airway problems, leaks and disconnections in the anaesthesia system often develop and may become apparent only when a crisis occurs. Circuit leaks which decrease the minute volume may not be indicated by airway pressure monitoring but may be detected by CO₂ monitoring because the PETCO₂ gradually increases. Airway pressure monitors used to detect breathing system leaks occasionally fail to detect some disconnections. Under these circumstances a CO₂ monitor would detect disconnection instantaneously in paralysed patients.¹⁸ Carbon dioxide monitoring gives an early warning of CO₂ retention by the patient due to a faulty Bain anaesthetic system, an exhausted CO₂ absorbent in a semi-closed anaesthetic system, leaks in the anaesthetic system, disconnections within the anaesthetic machine or malfunction of valves in circle anaesthetic systems.^{9,14,18,46–49,60}

Further, a total occlusion or accidental extubation of the endotracheal tube results in an abrupt decrease in PETCO₂, whereas a partially kinked or obstructed tube can result in either increased or decreased PETCO₂, or in no change in PETCO₂ depending on the severity of the obstruction.^{2,9,13} Capnography is considered more valuable than capnometry in detecting partially kinked endotracheal tubes, as distortions in CO₂ waveforms (prolonged phase II, steeper phase III, irregular height of the CO₂ waveforms) occur earlier than changes in PETCO₂.^{13,48,52} However, it should be noted that endotracheal tube obstruction must be severe (at least 50% occlusion) to produce changes in PETCO₂ or in the CO₂ waveforms.^{13,48}

(5) Accidental oesophageal intubation

When used with the standard technique of listening to breath sounds, CO₂ monitoring is probably the best way to detect oesophageal intubation. Although CO₂ may be present in the stomach it is rapidly flushed out during ventilation of the stomach and the PETCO₂ reading would decrease, resulting in a flat capnogram (figure 5B).^{10,12} Recently, PETCO₂ detectors, which change colour on

exposure to 4% CO₂, have been used successfully to confirm tracheal intubation. These detectors can be used where CO₂ monitors are not available.¹¹ It should be noted that in the presence of carbonated beverages in the stomach a PETCO₂ as high as 38 mmHg can be observed with oesophageal ventilation and it may take at least six breaths for PETCO₂ to decrease to zero. However, the CO₂ waveforms produced as a result are abnormal in shape and, therefore, could be detected earlier by capnography than capnometry.⁶¹

(6) *Blind nasal intubation*

Continuous recordings of CO₂ at the proximal end of the nasal tracheal tube facilitate guiding of the tube towards the larynx during blind nasal intubation in the spontaneously breathing patient. As the tube is moved away from the larynx, the end-tidal recordings decrease.⁶² Carbon dioxide recordings can be replaced by audio signals that are proportional to CO₂ concentration (audio capnometry). This has the advantage that one does not have the distraction of looking at the capnometer during the procedure.⁶³

(7) *Proper positioning of double lumen-tubes*

In addition to the standard methods available PETCO₂ monitoring of each lung may be a valuable adjunct not only for assuring proper tube placement, but also for detecting dislodgement of double-lumen tubes during the course of anaesthesia. Correct placement of double-lumen tubes can be checked by analyzing individual CO₂ waveforms from each lung during clamping and unclamping procedures. Further, periodical monitoring of CO₂ waveforms from individual lungs may be useful to monitor ventilation of each lung particularly when the patient is prepared, draped, or when the chest is not available for auscultation, or the quality of breath sounds is not clear enough.⁶⁴ To monitor CO₂ waveforms from each lung the author's practice is to incorporate a three-way stopcock into the sampling tube. The stopcock can be used to direct the flow from either lung individually or from both lungs simultaneously into the CO₂ monitor, thus obviating the need for two CO₂ monitors.⁶⁵

(8) *Hypermetabolic states*

Dangerous hypermetabolic conditions such as malignant hyperthermia, thyrotoxic crisis, and severe sepsis, can be detected by CO₂ monitoring. Increased metabolic rates cause greater CO₂ production, which can cause PETCO₂ to increase. An increasing PETCO₂ may, therefore, be an early warning sign of an impending hypermetabolic crisis.⁶⁶

(9) *Detection of pulmonary embolism*

A rapid decrease of PETCO₂ in the absence of changes in

blood pressure, central venous pressure and heart rate indicates an air embolism without systemic haemodynamic consequences. A reduction in cardiac output also results in a decrease of PETCO₂ measurement. Therefore, in the event of a rapid decrease in PETCO₂ associated with a reduction in cardiac output, a rise in the pulmonary arterial pressure confirms the occurrence of pulmonary embolism.⁶⁷

(10) *Venous CO₂ embolism*

End-tidal CO₂ monitoring is essential during laparoscopy, as it may help in the early detection of venous CO₂ embolism (accidental insufflation of CO₂ into the veins). In addition, CO₂ is also absorbed from abdominal cavity. A transient but rapid rise in PETCO₂, has been suggested as a useful early sign of venous CO₂ embolism.⁶⁸

(11) *Cardiopulmonary resuscitation*

End-tidal CO₂ monitoring during closed chest compression is one of the most exciting recent developments in CPR. It holds the promise of making available information about the effectiveness of resuscitative efforts, that, heretofore, have been unavailable. It is non-invasive, easy to apply to the intubated patient and the theory of its use during CPR is relatively simple. During closed chest compression the blood flow to the lungs is low so that relatively few alveoli are perfused. Since tidal volumes delivered with a resuscitation bag tend to be large, many alveoli are ventilated that are not perfused and consequently, the PETCO₂ is low. If the blood flow to the lungs improves, more alveoli are perfused and PETCO₂ will increase (Figure 5C). Under these circumstances the CO₂ presentation to the lungs is the major limiting determinant of PETCO₂ and it has been found that PETCO₂ correlates well with measured cardiac output during resuscitation.⁶⁹ Therefore PETCO₂ can be used to judge the effectiveness of resuscitative attempts and thus lead to changes in technique that could improve the outcome. Further, the PETCO₂ may have a prognostic significance. It has been observed that non-survivors had lower PETCO₂ than survivors and no patient with PETCO₂ <10 mmHg could be successfully resuscitated.⁷⁰

(12) *High frequency jet ventilation (HFJV)*

Assessment of the adequacy of HFJV is usually done by a series of arterial blood gas measurements. Monitoring PETCO₂ can be used successfully to determine PaCO₂ levels during HFJV. This is done by delivering a single breath of large tidal volume and measuring PETCO₂ during brief interruption of HFJV. If PaCO₂ can be measured simultaneously by arterial puncture, then (a-ET)PCO₂ can be determined and subsequent monitoring of HFJV can be done by measuring PETCO₂ in periodically given single large breaths.⁷¹

(13) (a-ET)PCO₂ and PEEP

Positive end expiratory pressure (PEEP) can be applied to improve oxygenation, when hypoxaemia is caused by acute alveolar oedema, or in early adult respiratory distress syndrome (ARDS). Certain levels of PEEP (the inflection pressure on pressure volume compliance curve) must be reached in any particular patient before improvement in oxygenation is achieved. When oxygenation is at its best (optimum PEEP) the (a-ET)PCO₂ is least. As the level of PEEP is increased beyond this the (a-ET)PCO₂ increases again and oxygenation worsens. Therefore it has been suggested that (a-ET)PCO₂ can be used as a sensitive indicator in order to titrate PEEP in patients with early ARDS or with alveolar oedema.⁷²

Care and precautions

(1) Testing the capnometer

Before any interpretations are made of PETCO₂ readings or CO₂ waveforms one should ascertain that the capnometer is functioning correctly. A leak due to a split in the sampling tube may result in low PETCO₂ measurements, or contamination of the unit with secretions or mucus may cause a distorted CO₂ waveform (Figure 5D). A quick, but less accurate, method is to record a normal CO₂ tracing (e.g., one's own). The typical CO₂ wave form (Figure 4A) with PETCO₂ readings between 38–42 mmHg, confirms the proper functioning of the capnometer.^{51,73}

However, for accurate measurements capnometers should be calibrated first, zeroing the monitor to room air, and then administering a gas of known CO₂ concentration. As the changes in barometric pressure affect the PETCO₂ measurements, calibration procedures should be performed using the same type of sampling tube as will be used when the analyzer is connected to the patient sampling. Omission of the standard narrow 2 m long sampling tube (at the time of calibration) will result in the absence of a large pressure drop across the ends of the tube, and a measuring error thus becomes inevitable during subsequent clinical use.⁵¹

(2) Infants and children

In infants and small children, great caution has to be exercised when monitoring PETCO₂. A sampling flow rate of 150 ml · min⁻¹ yields consistently accurate estimates of PaCO₂ and an acceptable capnogram in neonates, infants and children and, therefore, is considered appropriate.⁷⁴ Occasionally, the alveolar plateau that should be present for accurate PETCO₂ measurements may not be present in infants, due to the small tidal volumes and rapid respiratory rates. Despite this lack of an end-tidal plateau (Figure 5E), the PETCO₂ measurements approximate the PaCO₂.⁷⁴

Sampling can be performed from the proximal (between

the endotracheal tube and breathing circuit) or distal part of the endotracheal tube. The distal measurements are higher and estimate PaCO₂ more accurately than proximal measurements.^{41,75} The difference between the two sites is due to several factors, such as patient weight, type of ventilator, breathing circuit, fresh gas flow, and gas sampling characteristics of capnometer.⁷⁵ Difficulties associated with distal site sampling include an increased risk of disconnection at the site of insertion of catheter or needle into the tracheal tube and blockage of the catheter by secretions. Proximal site sampling is easy and carries minimal risk of blockage or contamination by secretions and is, therefore, preferred by most clinicians.⁷⁵

(3) Capnometers which use inspired gases as zero reference

Capnometers with side stream-sensors use ambient air (CO₂-free) as the zero reference for CO₂. However, a few main-stream capnometers (e.g., Siemens 930) use the inspiratory CO₂ concentration (FiCO₂) as the zero reference. This can result in errors in the estimation of PETCO₂ in the presence of rebreathing where FiCO₂ is not zero.

(4) Sampling of gases from closed circuits

When side-stream capnometers are used in closed circuit anaesthesia with very low flows, approximately 150 ml of gases per minute would be lost from the system, unless the sampling gases are returned.

(5) Condensation of water, secretions, therapeutic aerosols and water aerosols from humidifier

Water droplets, patient secretions and coalescence of water aerosols from humidifiers in breathing circuits may result in an accumulation of water and secretions in breathing hoses. The contaminant enters the sampling tubes and increases flow resistance in the tubing thus affecting accuracy of the CO₂ measurement. The sampling tubes may also be occluded. Some units either increase the sampling flow or reverse the flow (purge) when a drop in pressure from a flow restriction is sensed. This will help to clear the secretions from the tube. If the occlusion is not cleared the sampling tube must be replaced. Occasionally, liquids can enter the main unit of the analyzer despite the presence of water traps where they can cause corrosion and form residues. This can degrade the performance of the CO₂ monitor by interfering with the sampling flow or fouling the sensor, in which case the chamber will require cleaning. It should be noted that positioning the sampling tube upwards away from the patient decreases the frequency with which liquids are drawn into the tubes.¹⁸

(6) Technical problems in CO₂ sampling

Falsely low PETCO₂ values frequently arise due to errors in sampling of the end-tidal gas.

Admixture of end-tidal gas with air can result from leaks in the sampling system, poor anaesthetic face mask fit and during sampling of end-tidal gas from the nasal cavity in mouth breathing patients.

Admixture of end-tidal gas with fresh gas flow (FGF) can occur during the use of T-piece breathing systems on the Ayre principle (e.g., Jackson Rees, Bain anaesthetic system) or during the use of certain lung ventilators, which produce a constant flow (Figure 5F). The problem of admixture of the end-tidal gas by the FGF from the breathing circuits can be minimized by interposing a right angle adaptor between the breathing system and the endotracheal tube, and interposing the sampling tube on the patient's side of the angle piece.⁷⁶

(7) Tachypnoea

Caution has to be exercised while monitoring PETCO₂ during low tidal volume frequent breathing. Errors can result for two reasons.

- (a) With frequent low tidal volume breathing, exhalation may not be complete and alveolar gases may not have fully migrated to the patient's airway. Therefore the end-tidal gas is not a good representative of the alveolar gas.⁵⁵
- (b) Analyzers may underestimate PETCO₂ when breathing frequency is greater than 30 breaths · min⁻¹, particularly if the response time of the analyzer is greater than the respiratory cycle time of the patient.^{26,28,29}

Under these circumstances of low tidal volume and frequent breathing during anaesthesia the accuracy of PETCO₂ can be improved by an assisted single large tidal volume. This is rewarded with adequate alveolar gas and measured PETCO₂ (squeeze PETCO₂) is a more representative sample of alveolar gas than the passive PETCO₂. Therefore "squeeze PETCO₂" could be used as the basis for assessing PaCO₂ and, thus, alveolar ventilation.⁵⁵

(8) Hypoventilation

In patients breathing spontaneously, hypoventilation may result in diminished expiratory gas flow rates. When the expiratory flow rate of the patient decreases below the rate of sampling into the capnometer, CO₂ free gases are aspirated into the capnometer. This can result in erroneously low values for PETCO₂ particularly if sampling flow rate is high. The use of lower sampling flow rates (150 ml · min⁻¹ or less) may produce more accurate determinations of PETCO₂.⁵⁹

Conclusion

Capnography can instantaneously identify potentially life-threatening conditions such as oesophageal intubation, circuit disconnection, defective anaesthetic systems, hypoventilation and airway obstruction. It can indirectly

monitor cardiac output and CO₂ production. Therefore, capnography has assumed an important place in the anaesthetists' armamentarium to increase patient safety not only in the operating room but also in the recovery room and intensive care unit. It may be noted that the introduction of "new standards" (in technology and in guidelines to professional practice) has coincided with a period of improvement in the outcome of anaesthesia and subsequent reduction in incidence of major intraoperative accidents and resultant legal action.^{6,77-79} Since the "standards" include several items in addition to capnography one cannot assume any absolute cause-and-effect relationship with capnography alone.⁷⁹ Neither, on the other hand, should one ignore its potential value for lack of positive proof. Studies on cost effectiveness and cost benefit in the future will probably prove the efficacy of capnography in reducing anaesthesia-related morbidity, mortality and legal claims. In the meantime, further research should be directed to improving the reliability of the capnometers as well as minimizing the problems associated with CO₂ sampling, while at the same time making capnometers more economical. While anaesthetists have appreciated the value of capnography in the last decade, physicians in other specialities will appreciate its value in the future, as research has already begun to show the value of capnography outside the domain of anaesthesia.^{80,81}

Acknowledgements

We gratefully acknowledge the help of Dr. Simon Parsons, FFARCS, Consultant Paediatric Cardiac Anaesthetist, Guys Hospital, London, in the preparation of the revised manuscript. The authors are also indebted to Professor A. P. Adams, FFARCS, PhD, Chairman, Department of Anaesthetics, Guys Hospital, London, England, for reviewing this manuscript.

References

- 1 Kalenda Z. Mastering Infrared Capnography. The Netherlands: Kerckebosch-Zeist, 1989.
- 2 Leigh MD, Jones JC, Motley HL. The expired carbon dioxide as a continuous guide of the pulmonary and circulatory systems during anaesthesia and surgery. *J Thorac Cardiovasc Surg* 1961; 41: 597-610.
- 3 Luft KF. Über eine neue methode der registrierenden gasanalyse mit hiffe der absorption ultraroter strahlen ohne spektrale zerlegung. *Zeitschrift Fur Technische Physik* 1943; 24: 97-104
- 4 Caplan RA, Posner KL, Ward RJ, Cheney FW. Adverse respiratory events in anaesthesia: a closed claims analysis. *Anesthesiology* 1990; 72: 828-33.
- 5 Cooper JB, Newbower RS, Kitz RJ. An analysis of major errors and equipment failures in anaesthesia management:

- considerations for prevention and detection. *Anesthesiology* 1984; 60: 34–42.
- 6 *Eichhorn JH*. Prevention of intraoperative anesthesia accidents and related severe injury through safety monitoring. *Anesthesiology* 1989; 70: 572–7.
 - 7 *Tinker JH, Dull DL, Caplan RA, Ward RJ, Cheney FW*. Monitoring devices in prevention of anesthetic mishaps: a closed claims analysis. *Anesthesiology* 1989; 71: 541–6.
 - 8 *Weingarten M*. Anesthetic and ventilator mishaps: prevention and detection. *Crit Care Med* 1986; 14: 1084–6.
 - 9 *Coté CJ, Liu LMP, Szyfelbein SK, et al*. Intraoperative events diagnosed by expired carbon dioxide monitoring in children. *Can Anaesth Soc J* 1986; 33: 315–20.
 - 10 *Birmingham PK, Cheney FW, Ward RJ*. Esophageal intubation: a review of detection techniques. *Anesth Analg* 1986; 65: 886–91.
 - 11 *O'Flaherty D, Adams AP*. The end-tidal carbon dioxide detector. Assessment of new method to distinguish oesophageal from tracheal intubation. *Anaesthesia* 1990; 45: 653–5.
 - 12 *Linko K, Paloheimo M, Tammisto T*. Capnography for detection of accidental oesophageal intubation. *Acta Anaesthesiol Scand* 1983; 27: 199–202.
 - 13 *Murray IP, Modell JH*. Early detection of endotracheal tube accidents by monitoring carbon dioxide concentration in respiratory gas. *Anesthesiology* 1983; 59: 344–6.
 - 14 *Lillie PE, Roberts JG*. Carbon dioxide monitoring. *Anaesth Intensive Care* 1988; 16: 41–4.
 - 15 Guidelines to the practice of anaesthesia as recommended by the Canadian Anaesthetist's Society. Toronto, 1989.
 - 16 *Raemer DB, Philip JH*. Monitoring anesthetic and respiratory gases. In: Blitt CD (Ed.). *Monitoring in Anesthesia and Critical Care Medicine*. 2nd edition. New York: Churchill Livingstone, 1990: 373–86.
 - 17 *Tremper KK, Barker SJ*. Fundamental principles of monitoring instrumentation. In: Miller RD (Ed.). *Anesthesia Vol I*. 3rd ed. New York: Churchill Livingstone, 1990: 957–99.
 - 18 Carbon dioxide monitors. *Health Devices* 1986; 15: 255–85.
 - 19 *Møllgaard K*. Acoustic gas measurement. *Biomedical Instrumentation and Technology* 1989; 23: 495–7.
 - 20 *Raemer DB, Calalang I*. Accuracy of end-tidal carbon dioxide tension analyzers. *J Clin Monit* 1991; 7: 195–208.
 - 21 *Olsson SG, Fletcher R, Jonson B, Nordström L, Prakash O*. Clinical studies of a gas exchange during ventilatory support – a method of using the Siemens-Eléma CO₂ analyzer. *Br J Anaesth* 1980; 52: 491–9.
 - 22 *Paloheimo M, Valli M, Ahjopalo H*. A guide to CO₂ monitoring. Finland: Dateg Instrumentarium, 1988.
 - 23 *Kennell EM, Andrews RW, Wollman H*. Correction factors for nitrous oxide in the infrared analysis of carbon dioxide. *Anesthesiology* 1973; 39: 441–3.
 - 24 *Fletcher R, Werner O, Nordström L, Jonson B*. Sources of error and their correction in the measurement of carbon dioxide elimination using the Siemens-Eléma CO₂ analyzer. *Br J Anaesth* 1983; 55: 177–85.
 - 25 *Parbrook GD, Davis PD, Parbrook EO*. Gas chromatography and mass spectrometry. In: *Basic Physics and Measurement in Anaesthesia*. 3rd ed. London: Butterworth-Heinemann, 1990: 257–64.
 - 26 *From RP, Scamman FL*. Ventilatory frequency influences accuracy of end-tidal CO₂ measurements: analysis of seven capnometers. *Anesth Analg* 1988; 67: 884–6.
 - 27 *Pasucci RC, Schena JA, Thompson JE*. Comparison of a sidestream and mainstream capnometer in infants. *Crit Care Med* 1989; 17: 560–2.
 - 28 *Brunner JX, Westenskow DR*. How the rise time of carbon dioxide analysers influences the accuracy of carbon dioxide measurements. *Br J Anaesth* 1988; 61: 628–38.
 - 29 *Schena J, Thompson J, Crone RK*. Mechanical influences on the capnogram. *Crit Care Med* 1984; 12: 672–4.
 - 30 *Nunn JF*. *Applied Respiratory Physiology*. 3rd edition. London: Butterworths, 1987: 221–3.
 - 31 *Fletcher R*. The single breath test for carbon dioxide. Thesis, Lund, 1980.
 - 32 *Fletcher R, Jonson B, Cumming G, Brew J*. The concept of deadspace with special reference to the single breath test for carbon dioxide. *Br J Anaesth* 1981; 53: 77–88.
 - 33 *West JB, Fowler KT, Hugh-Jones P, O'Donnell TV*. The measurement of the inequality of ventilation and of perfusion in the lung by the analysis of single expirate. *Clin Sci* 1957; 16: 549–65.
 - 34 *Nunn JF, Hill DW*. Respiratory dead space and arterial to end-tidal CO₂ tension difference in anesthetized man. *J Appl Physiol* 1960; 15: 383–9.
 - 35 *Fletcher R, Jonson B*. Dead-space and the single breath test for carbon dioxide during anaesthesia and artificial ventilation. *Br J Anaesth* 1984; 56: 109–19.
 - 36 *Shankar KB, Moseley H, Kumar Y, Vemula V*. Arterial to end-tidal carbon dioxide tension difference during Caesarean section anaesthesia. *Anaesthesia* 1986; 41: 698–702.
 - 37 *Askrog V*. Changes in (a–A)CO₂ difference and pulmonary artery pressure in anesthetized man. *J Appl Physiol* 1966; 21: 1299–305.
 - 38 *Fletcher R, Malmkvist G, Niklasson L, Jonson B*. On line-measurement of gas-exchange during cardiac surgery. *Acta Anaesthesiol Scand* 1986; 30: 295–9.
 - 39 *Shankar KB, Moseley H, Kumar Y*. Negative arterial to end-tidal gradients. *Can J Anaesth* 1991; 38: 260–1.
 - 40 *Russell GB, Graybeal JM, Strout JC*. Stability of arterial to end-tidal carbon dioxide gradients during postoperative cardiorespiratory support. *Can J Anaesth* 1990; 37: 560–6.
 - 41 *Rich GF, Sconzo JM*. Continuous end-tidal CO₂ sampling within the proximal endotracheal tube estimates arterial CO₂ tension in infants. *Can J Anaesth* 1991; 38: 201–3.

- 42 Shankar KB, Moseley H, Kumar Y, Vemula V, Krishnan A. The arterial to end-tidal carbon dioxide tension difference during anaesthesia for tubal ligations. *Anaesthesia* 1987; 42: 482–6.
- 43 Jones NL, Robertson DG, Kane JW. Differences between end-tidal and arterial PCO₂ in exercise. *J Appl Physiol* 1979; 47: 954–60.
- 44 Fletcher R. Arterial to end-tidal CO₂ tension differences. *Anaesthesia* 1987; 42: 210–1.
- 45 Weil MH, Bisera J, Trevino RP, Rackow EC. Cardiac output and end-tidal carbon dioxide. *Crit Care Med* 1985; 13: 907–9.
- 46 Pyles ST, Berman LS, Modell JH. Expiratory valve dysfunction in a semiclosed circle anesthesia circuits – verification by analysis of carbon dioxide waveform. *Anesth Analg* 1984; 63: 536–7.
- 47 Berman LS, Pyles ST. Capnographic detection of anaesthesia circle valve malfunctions. *Can J Anaesth* 1988; 35: 473–5.
- 48 Van Genderingen HR, Gravenstein N, Van der Aa JJ, Gravenstein JS. Computer-assisted capnogram analysis. *J Clin Monit* 1987; 3: 194–200.
- 49 Weingarten M. Respiratory monitoring of carbon dioxide and oxygen: a ten-year perspective. *J Clin Monit* 1990; 6: 217–25.
- 50 Good ML. Capnography: a comprehensive review. American Society of Anesthesiologists Refresher Course Lectures: San Francisco, 1991: 431.
- 51 Adams AP. Capnography and pulse oximetry. In: Atkins RS, Adams AP (Eds.). *Recent Advances in Anaesthesia and Analgesia*. London: Churchill Livingstone, 1989: 155–75.
- 52 Smalhout B, Kalenda Z. *An Atlas of Capnography*. 2nd ed. Utrecht: Kerckebosch-Zeist, 1981.
- 53 Hoffbrand BI. The expiratory capnogram: a measure of ventilation-perfusion inequalities. *Thorax* 1966; 21: 518–23.
- 54 Tulou PP, Walsh PM. Measurement of alveolar carbon dioxide tension at maximal expiration as an estimate of arterial carbon dioxide tension in patients with airway obstruction. *Am Rev Respir Dis* 1970; 102: 921–6.
- 55 Swedlow DB, Irving SM. Monitoring and patient safety. In: Blitt CD (Ed.). *Monitoring in Anesthesia and Critical Care Medicine*. 2nd ed., New York: Churchill Livingstone, 1990: 33–64.
- 56 Lenz G, Heipertz W, Epple E. Capnometry for continuous postoperative monitoring of nonintubated, spontaneously breathing patients. *J Clin Monit* 1991; 7: 245–8.
- 57 Roy J, McNulty SE, Torjman MC. An improved nasal prong apparatus for end-tidal carbon dioxide monitoring in awake, sedated patients. *J Clin Monit* 1991; 7: 249–52.
- 58 Brampton WJ, Watson RJ. Arterial to end-tidal carbon dioxide tension difference during laparoscopy. *Anaesthesia* 1990; 45: 210–4.
- 59 Bowe EA, Boyson PG, Broome JA, Klein Jr EF. Accurate determination of end-tidal carbon dioxide during administration of oxygen by nasal cannulae. *J Clin Monit* 1989; 5: 105–10.
- 60 Martin DG. Leak detection with a capnograph. *Anaesthesia* 1987; 42: 1025.
- 61 Sum Ping ST, Mehta MP, Symreng T. Reliability of capnography in identifying esophageal intubation with carbonated beverage or antacid in the stomach. *Anesth Analg* 1991; 73: 333–7.
- 62 Linko K, Paloheimo M. Capnography facilitates blind nasotracheal intubation. *Acta Anaesthesiol Belg* 1983; 34: 117–22.
- 63 Omoigui S, Glass P, Martel DLJ, *et al.* Blind nasal intubation with audio-capnometry. *Anesth Analg* 1991; 72: 392–3.
- 64 Shafieha MJ, Sit J, Kartha R, *et al.* End-tidal CO₂ analyzers in proper positioning of the double-lumen tubes. *Anesthesiology* 1986; 64: 844–5.
- 65 Shankar KB, Moseley H, Kumar AY. Dual end-tidal CO₂ monitoring and double-lumen tubes. *Can J Anaesth* 1992; 39: 100–1.
- 66 Baudendistel L, Goudsouzian N, Coté C, Strafford M. End-tidal CO₂ monitoring: its use in the diagnosis and management of malignant hyperpyrexia. *Anaesthesia* 1984; 39: 1000–3.
- 67 Smelt WLH, De Lange JJ, Booij LHDJ. Capnography and air embolism. *Can Anaesth Soc J* 1986; 33: 113–5.
- 68 Shulman D, Aronson HB. Capnography in the early diagnosis of carbon dioxide embolism during laparoscopy. *Can Anaesth Soc J* 1984; 31: 455–9.
- 69 Falk JL, Rackow EC, Weil MH. End-tidal carbon dioxide concentration during cardiopulmonary resuscitation. *N Engl J Med* 1988; 318: 607–11.
- 70 Sanders AB, Kern KB, Otto CW, Milander MM, Ewy GA. End-tidal carbon dioxide monitoring during cardiopulmonary resuscitation. A prognostic indicator for survival. *JAMA* 1989; 262: 1347–51.
- 71 Mason CJ. Single breath end-tidal PCO₂ measurements during high frequency jet ventilation in critical care patients. *Anaesthesia* 1986; 41: 1251–4.
- 72 Blanch L, Fernandez R, Benito S, Mancebo J, Net A. Effects of PEEP on the arterial minus end-tidal carbon dioxide gradient. *Chest* 1987; 92: 451–4.
- 73 Mogue LR, Rantala B. Capnometers. *J Clin Monit* 1988; 4: 115–21.
- 74 McEvedy BAB, McLeod ME, Kirpalani H, Volgyesi GA, Lerman J. End-tidal carbon dioxide measurements in critically ill neonates: a comparison of sidestream and mainstream capnometers. *Can J Anaesth* 1990; 37: 322–6.

- 75 Hillier SC, Badgwell JM, Mcleod ME, Creighton RE, Lerman J. Accuracy of end-tidal PCO₂ measurements using a sidestream capnometer in infants and children ventilated with the Sechrist infant ventilator. *Can J Anaesth* 1990; 37: 318–21.
- 76 Gravenstein N, Lamptang S, Beneken JEW. Factors influencing capnography in the Bain circuit. *J Clin Monit* 1985; 1: 6–10.
- 77 Eichhorn JH. Did monitoring standards influence outcome? *Anesthesiology* 1989; 71: 808–10.
- 78 Brown FN, McIntyre RW. Is the tide turning? *Can J Anaesth* 1990; 37: 4–6.
- 79 Duncan PG, Cohen MM. Pulse oximetry and capnography in anaesthetic practice: an epidemiological appraisal. *Can J Anaesth* 1991; 38: 619–25.
- 80 Chopin C, Fesard P, Mangalaboyi J, et al. Use of capnography in diagnosis of pulmonary embolism during acute respiratory failure of chronic obstructive pulmonary disease. *Crit Care Med* 1990; 18: 353–7.
- 81 Chambers JB, Kiff PJ, Gardner WN, Jackson G, Bass C. Value of measuring end-tidal partial pressure of carbon dioxide as an adjunct to treadmill exercise testing. *BMJ* 1988; 296: 1281–5.