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Mainstream or Sidestream Capnography?

TECHNICAL CONSIDERATIONS

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ABSTRACT

Technical aspects of mainstream and sidestream capnography are described and contrasted. Issues such as leaks, contamination and artifacts are reviewed. The clinical implications of these different approaches are discussed and the benefits of mainstream capnography highlighted.

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INTRODUCTION

Infrared measurement of carbon dioxide monitoring (capnography) dates back to the 1940's [1,2]. In the 1950's these bulky and fragile instruments were adapted for medical use. Consistent with other gas measurement modalities such as mass spectrometry, these early devices were sidestream (i.e., diverting) sampling systems. Representative systems include rack mountable systems such as the Beckman LB-1 and LB-2 analyzers that were considered the gold standard for carbon dioxide measurement in the 1970's. Similarly, early mainstream devices [3] were physically large, cumbersome and impractical for clinical use. Advancements in both mainstream and sidestream technology decreased the size of these devices to allow their inclusion in clinical monitors. However, it was not until the introduction of the HP 47210A (Fig. 1) in the early 1980s that mainstream devices began to be used in the clinical environment [4,5].

While both mainstream and sidestream devices continued to improve in performance, the primary criticisms of mainstream technology have been largely overcome with the introduction of solid state sources, improved optics and miniaturization while sidestream technology still suffers from its fundamental limitations. This paper contrasts the two approaches to capnography.

Overview of Differences between Mainstream and Sidestream Capnography

A capnometer, by definition is either diverting (i.e., sidestream) or non-diverting (i.e., mainstream). A diverting capnometer transports a portion of a patient's respired gases from the sampling site, through a sampling tube, to the sensor whereas a non-diverting capnometer does not transport gas away from the sampling site [6,7]. In other words, one can view the difference between mainstream (non-diverting) capnography and sidestream (diverting) capnography as clinically measuring carbon dioxide at the sample site versus measuring carbon dioxide in the monitor distant from the sample site.

The measurement of the partial pressure of a gas significantly distant from the sampling site raises a number of "laws of physics" issues including (1) water removal, (2) different conditions at the sampling site and sample cell in terms of temperature and humidity, (3) mixing of the sample gas as it is drawn through the cell, (4) variable pressure drop across the tubing and the possible misrepresentation of the partial pressure values due to the above and other effects and (5) dynamic distortions to the waveform. While some of these effects can be compensated for or corrected by other measurements or by the assumption of nominal values, other effects cannot.

With mainstream devices, the sensor consisting of the sample cell and infrared bench is placed at the airway. This location results in a "crisp" graphical representation of the time varying CO_2 value (capnogram) that reflects in real-time the partial pressure of carbon dioxide within the airway. On the other hand, sidestream devices aspirate a sample of gas from the breathing circuit through a six to eight foot long small bore tube at a flow rate that may vary as much as ±20% (Table 2). This sample is then often passed through a water trap and drying tubing prior to being analyzed in a sample cell. Using a remote location results in a delay time of up to several seconds and a rise time

distortion of perhaps greater than 200 ms (Table 2). This delay in total response time can be significant due to the need to provide to the clinician an earliest warning as possible [8].

Comparisons of devices from different manufacturers are often complicated by the use of different terminology and definitions[1] for delay and rise time, resulting in confusion for the user. Tables 1 and 2 compare mainstream and sidestream in general terms and specific systems, respectively.

Mainstream Capnography Overview

Mainstream capnography can be viewed as illustrated in Figure 7(a). The sample cell, referred to as the cuvette, serves as the airway adapter and is located in line with the respiratory gas stream obviating the need for gas sampling and scavenging. It interfaces directly to the infrared (IR) bench. A source emits infrared radiation that includes the absorption band for carbon dioxide.

Carbon dioxide within the sample gas preferentially absorbs this radiation at some wavelengths and passes other wavelengths (Figure 9). Photodetectors, typically located on the other side of the airway adapter, measure the transmitted radiation as it passes through the IR transmitting windows of the cuvette. A multi-conductor, lightweight, flexible cable transmits the amplified detected signals to the monitor from which the partial pressure of carbon dioxide is calculated and displayed graphically in the form of a capnogram. The monitor contains only electronics associated with control and measurement functions of the infrared bench.

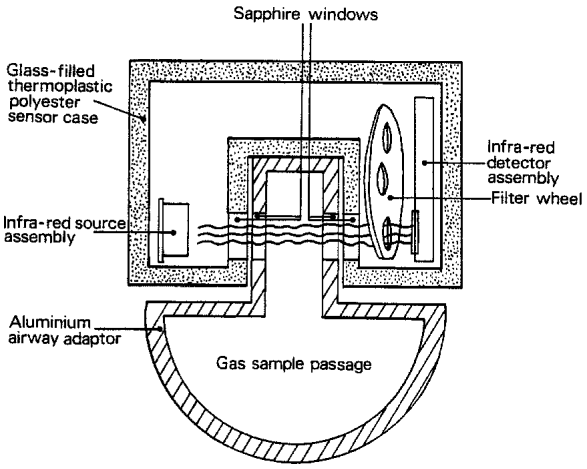

Figure 1. Cross-sectional view of a mechanical mainstream sensor (HP 47210A) (from Kinsella [4], © The Board of Management and Trustees of the British Journal of Anaesthesia. Reproduced by permission of Oxford University Press/British Journal of Anaesthesia.)

The disadvantages of mainstream sensors presented by some authors and manufacturers of side-stream systems are primarily technological in nature and often relate to prior generations of that technology. These disadvantages are often listed in older reviews [9,10] of the technology while more recent reviews note otherwise [11]. This includes possible damage during handling, increased mechanical deadspace, issues of additional weight on airway, and use limited to only intubated patients. For example, the mainstream IR benches have been in the past termed "vulnerable to costly damage." While earlier IR benches were vulnerable primarily due to the use of moving parts such as chopper or filter wheels (Figure 1), newer mainstream IR benches often utilize all solid state designs (Figure 2) that have been shown to be robust enough to survive repeated 6 foot drops onto hard floors and have been in use in high impact areas such as the emergency room, ambulances and transport for over 10 years.

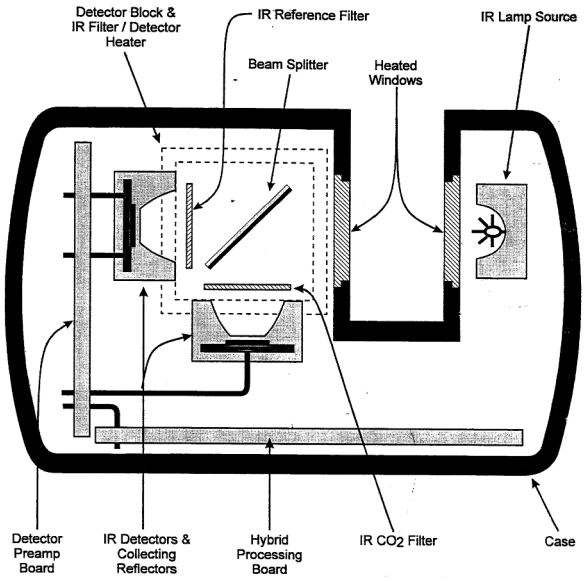

Figure 2. Cross-section of representative solid-state mainstream design (CAPNOSTAT®).

Additionally, claims of accidental extubation by mainstream devices have not been seen in practice. In fact, a recent search of the FDA's Center for Devices and Radiological Health online MAUDE[2] database found only one report relating to extubation and capnography which happened to be with a sidestream system [12].

[1] The definitions as defined by the international standard "ISO 9918–Capnometers for Use with Humans-Requirements" shall be used.

[2] October 2001 search represents reports of adverse events involving medical devices and consists of voluntary reports since June, 1993, user facility reports since 1991, distributor reports since 1993, and manufacturer reports since August, 1996.

Current generation mainstream devices, besides being relatively light, and low in deadspace have generally demonstrated better performance than sidestream system in terms of signal fidelity and end-tidal measurements particularly at higher respiratory rates in small children [13]. Careful airway adapter design and advances in technology have minimized the concerns for deadspace and weight for almost all patient populations and environments of use. Heated cuvette windows minimize effects from airway moisture. As with any airway adapter used for gas monitoring (either mainstream or sidestream), improper connection to other breathing circuit elements can cause artifacts in the capnogram. For example, a partial disconnection of a mainstream adapter may mimic a "curare-cleft" capnograph [14] but is easily recognizable.

For accurate end-tidal CO_2 monitoring, particularly with non-intubated patients receiving supplemental oxygen, sidestream sampling systems may not accurately reflect the capnogram because of the dilution effects of the supplemental flow of gases. Also, sidestream units do not adequately monitor both nasal and oral airflow. While mainstream devices may also be used on non-intubated patients, either as a sidestream sensor using an appropriate adapter or as a mainstream sensor with a facemask (Figure 3), the use of a low deadspace good sealing facemask combined with a mainstream airway adapter allows for superior CO_2 monitoring and volumetric capnography [15]. This is especially useful for field use (EMS) applications and during non-intubated conscious sedation.

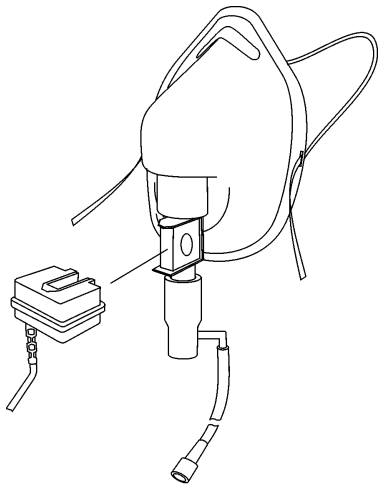

Figure 3. Face mask that allows mainstream capnography for use on non-intubated patients receiving supplemental oxygen (Respironics $CapnO_2$mask™)

Sidestream Capnography Overview

Sidestream gas analyzers utilize a long sampling plastic tube connected to an adapter in the breathing circuit (such as a T-piece at the endotracheal tube or mask connector) or a nasal catheter. The sample gas is continuously aspirated from the breathing circuit through the sampling tube and into the sample cell within the monitor (Figure 7(b)) at sample flow rates ranging from 50 to 250 ml/min (Table 2).

The location of the sampling port varies and may range anywhere from an elbow connected to an endotracheal tube to the wye connector. For example, it may be placed on the ventilator side of an in-line filter or HME. This results in a drier sampling tube with the inherent risk of significant distortion of the capnographic waveform and lower end-tidal values [16,17]. It may be also placed on the patient side of the filter resulting in possible accumulation of condensate and patient secretions in the sampling system. The sampling tube typically hangs free between the breathing circuit and monitor where it is vulnerable to being crushed, kinked and may be damaged during machine movement.

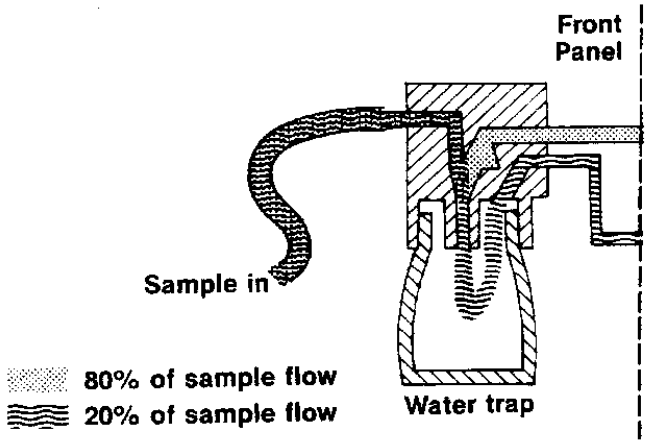

Figure 4. Illustrative Water trap of a capnometer. Sample gas is separated into two parts. The lighter portion (approx. 80%), which contains no particulate water, is drawn into the measuring chamber. Because the heavier portion (approx. 20%) takes longer to make the 180-degree turn, the particulate matter falls out (owing to inertia) into the water trap jar. (Adapted from Mogue LR et al. J Clin Monit. 1988; 4(2): 115-21. © Lippincott Williams & Wilkins, with permission)

The sampled gas that is withdrawn from the patient may contain anesthetic gases and as such should be routed back to a gas scavenging system or returned to the patient breathing system to avoid "pollution" of the operating room environment [18], costs associated with greater usage of anesthetic gases [19], and possible exposure risks in underventilated areas [20,21].

Condensation from humidified sample gas in combination with patient secretions can block and contaminate the sampling line requiring frequent replacement. To protect the sample cell from condensate, the distal end of the sampling tube is often connected to a water trap and water vapor permeable tubing such as Nafion® tubing. Water trap and filter design effectiveness vary between manufacturers but no water trap or filter is immune to eventual clogging and distortion of the capnogram particularly if preventive maintenance is inadequate. In one monitor, transposed sampling tube connections to water trap resulted in mixing of inspired and expired gases and a dramatic damping of the capnographic waveform [22]. To make matters worse, the distortion by some water traps may only be apparent under specific conditions, appear in either the inspiratory or expiratory phase and change as a function of respiratory rate [23] (Figure 5).

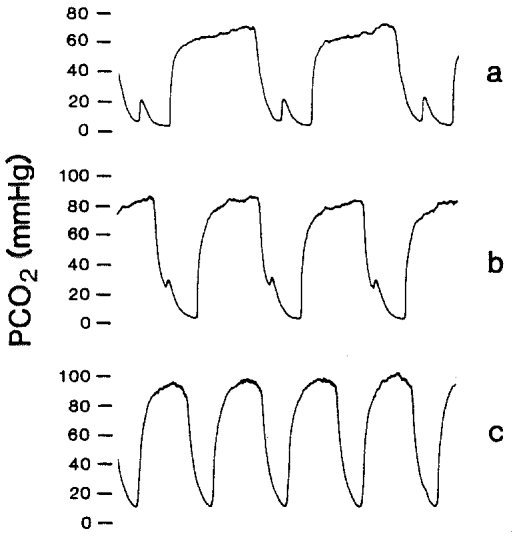

Figure 5. Distortion as a function of respiratory rate. Capnograms recorded experimentally with the endotracheal tube partially obstructed (A) 6 breaths/min, the CO_2 artifact appears during the inspiratory phase, (B) 8 breaths/min the artifact appears in the expiratory phase (C) 12/min, the artifact is disguised by the expiratory phase. (Adapted from Van Genderingen HR, et al. Capnogram artifact during high airway pressures caused by a water trap. Anesthesia & Analgesia. 1987; 66(2): 185-7. © Lippincott Williams & Wilkins, with permission)

Additionally, sources of leaks external to the monitor such as loose fittings [25], cracked or slit sampling tubes [26,27], cracked sample filters [28] and cracked airway adapters [29] along with sources of leaks internal to the monitor such as partial disconnection [30] (Figure 6) have been reported as causes of significant artifact in the capnogram. Leaks as well as obstructions can occur at any of the numerous connection points and tubes within the sidestream sampling system. The resulting distorted waveforms and the end-tidal values can be significantly different from actual, may not be detectable by normal calibration procedures [30] and pose a potential hazard to the patient. However, sidestream systems with an external removable sample cell are less susceptible to errors of this type. While more recent designs of airway adapters for sidestream systems reduce the likelihood of aspirating secretions by the use of sampling ports that are located in the center of the adapter rather than at the wall, they are still susceptible to the problems outlined above.

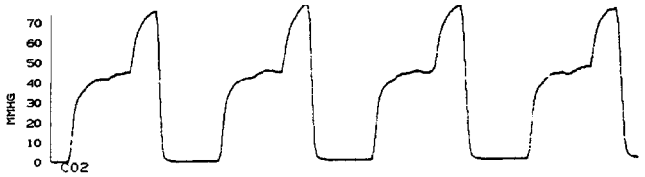

Figure 6 – Patient capnogram resulting from an internal gas analyzer leak, consisting of a long plateau phase followed by a brief peak. Plateau PCO_2 values correlated well with $PaCO_2$, whereas peak PCO_2 values were over 30 mmHg higher than $PaCO_2$. (From Healzer JM et al. Internal gas analyzer leak resulting in an abnormal capnogram and incorrect calibration. Anesthesia & Analgesia. 1995;81(1):202-3 © Lippincott Williams & Wilkins, with permission)

Even with no leaks or obstructions in the sampling system, significant distortion of the capnogram may still occur. At the sample tubing-airway interface, expired gas may be diluted with entrained ambient air whenever the gas flow rate falls below the "constant" sample flow rate [31]. The design of the sampling tube and its positioning within the breathing circuit or nares (if a nasal catheter is used) can affect the quantity of surrounding air that is entrained along with the expired gas. Within the sample tube itself dispersion may occur due to the effects of velocity profile and diffusion. [31] Additionally, the sample flow rate may vary significantly as a function of a number of factors including the sample tube length [32], airway pressure, and the presence of an exhaust line occlusion [33].

The use of sidestream monitoring requires that careful attention be paid both to the physical setup external and internal to the monitor, as well as careful interpretation of the capnographic waveform.

TECHNICAL ISSUES

Infrared Spectroscopy

Infrared absorption methods of gas measurement can be sensitive and selective as well as provide a continuous, accurate, precise, and rapid response that is not saturated nor damaged by high concentrations of the "target" gases. One target gas is carbon dioxide which has a very strong absorption band at 4.26 mm. Various approaches for infrared absorption measurement of CO_2 have been implemented (Table 2). The source of infrared radiation may be broadband or narrow band. It may be pulsed or constant (with a mechanical chopper). For narrow band emission, some sidestream monitors use an electric discharge source consisting of a hermetically sealed glass tube containing a gas. The gas is excited by the application of a high voltage, radio frequency electromagnetic field. This results in the emission of a narrow IR spectrum.

The detection of the infrared radiation typically uses a detector sensitive in the IR band such as lead selenide detector. Benches with broadband sources also utilize reliable and stable narrow band filters in front of the detectors to measure in band signal for CO_2 and separately out of band signal as a reference channel. Thus one can select only a portion of the CO_2 band effectively eliminating any interference from water vapor or even closer bands of N_2O. The absorption of the IR radiation by CO_2 is non-linear, affected by the presence of other gases and proportional to gas concentration, path length and absorption coefficient of the particular gas. The non-linearities, path length and specifics of the bench design are compensated for by an empirical lookup table that translates the measured signals to a value in CO_2 which is then corrected by most manufacturers for the effects of gases such as oxygen and nitrous oxide.

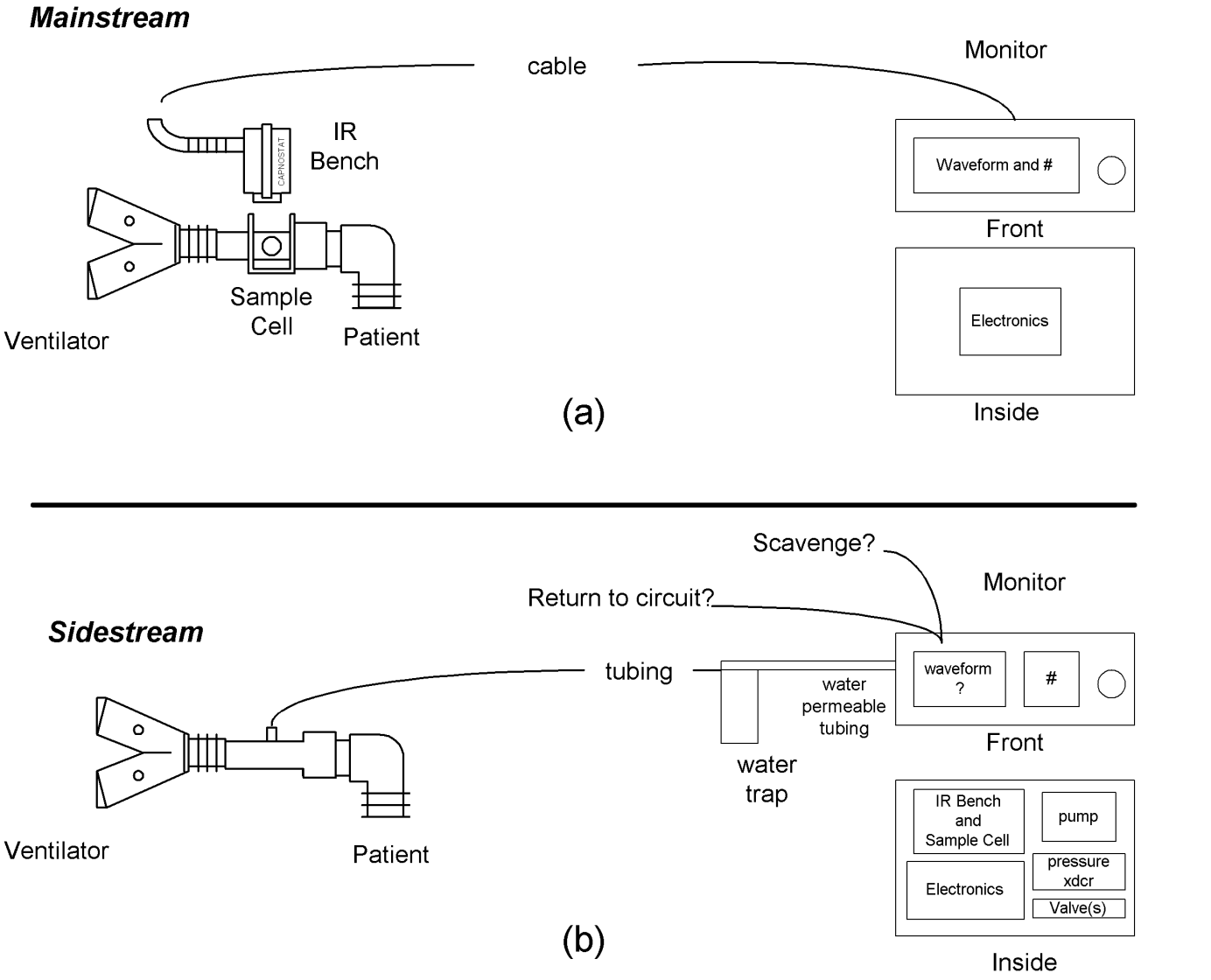

Figure 7. Mainstream vs. Sidestream Sampling Methods for Breathing Circuits

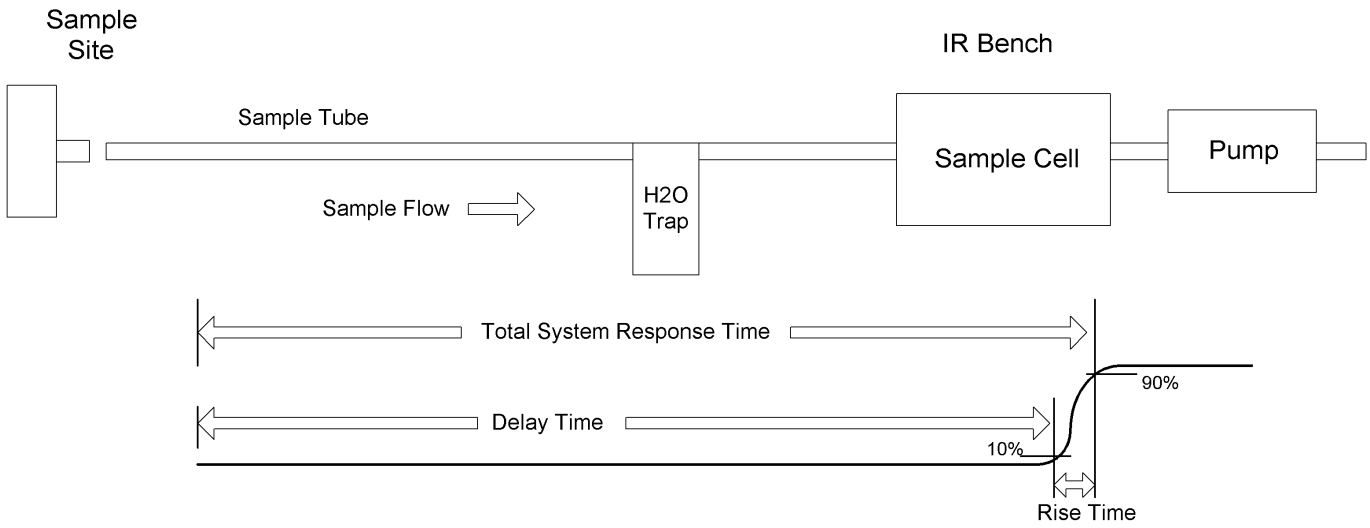

Figure 8 – Physical Components of a gas sampling system with total system response time, delay time and rise time illustrated. Mainstream systems do not suffer from the depicted delay time.

Interference Effects

The measured absorption of CO_2 can be altered by cross-interference and collision broadening due to the presence of gases such as nitrogen, nitrous oxide and oxygen. Cross-interference, the overlapping of absorption bands of other gases, can occur from nitrous oxide due to the presence of strong absorption bands that slightly overlap both edges of the carbon dioxide band (Figure 9). The impact of this effect can vary significantly between devices [34]. However, the use of narrow band sources or narrow band filters in front of the detector with sufficiently small half power bandwidths can effectively eliminate the effect of cross-interference.

On the other hand, collision broadening tends to be less device-specific [34] and is a complex function of the total pressure and the presence of other gases. Carbon dioxide displayed as a partial pressure constituent in a gas mixture and changes in atmospheric pressure and circuit pressure will alter this relationship. Pressure influences the width of the IR absorption band. As pressure decreases (either due to changes in total pressure or the partial pressure of CO_2), less intermolecular collisions occur and the bandwidth narrows. Similarly, as the pressure increases, more collisions occur and the bandwidth increases. [36] In effect, the absorption band is spread out and the use of narrow band sources or filters fail to correct for this effect. This effect is typically compensated for in the system's software using nominal values.

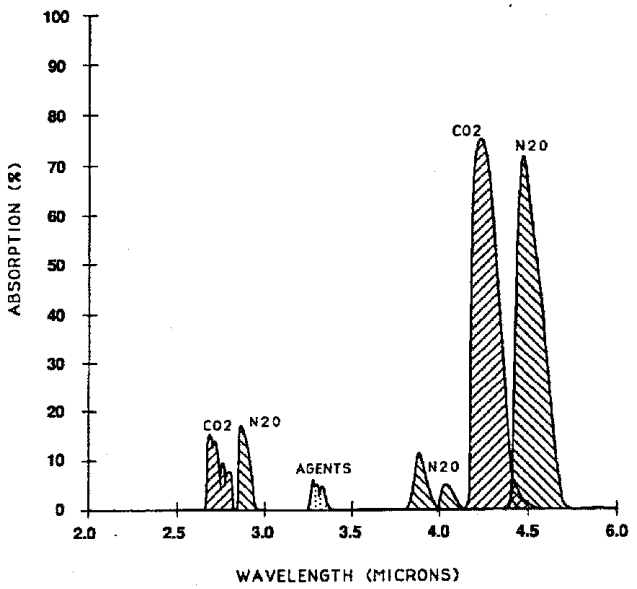

Figure 9. The infrared absorption spectrum for the gases carbon dioxide (CO_2) and nitrous oxide (N_2O) and the volatile anesthetic agents. (From Raemer DB. Accuracy of end-tidal carbon dioxide tension analyzers. J Clin Monit. 1991; 7(2): 195-208. © Lippincott Williams & Wilkins, with permission)

Water Vapor

Mainstream infrared analyzers, when located near the patient connection, measure gas near Body Temperature and Pressure, Saturated conditions (BTPS). Water vapor effects can cause cross-interference (absorption band overlap) and collision broadening but the band at 4.26 microns is relatively free from

any water vapor absorption effects and shows minimal collision broadening effects. Partial pressure dilution effects, on the other hand, are of concern. This has been effectively minimized in mainstream systems by heating the airway adapter and its windows above body temperature or by using coatings. How close the exact water vapor pressure is to BTPS conditions depends on factors including the presence and type of humidification, fresh gas flow, length of time in use and ambient temperature [35]. Normally, exhaled gas is fully saturated at or slightly less than 37°C. This results in a water vapor pressure of 47 mmHg.

In side-stream systems the temperature of the sampled gases decreases toward room temperature during its transit from the patient connection to the monitor. [37] This results in condensate forming on the walls of the tubing and a resulting decrease in the partial pressure of water vapor from the BTPS value of 47 mm Hg to much lower values. With the inclusion of water permeable tubing, such as Nafion® brand tubing, the water vapor pressure in the tubing will tend to equilibrate with the water vapor pressure in the room.[3] This decrease in water vapor pressure can cause an apparent increase in CO_2 concentration [38]. Sidestream devices compensate with software for water vapor removed and as a result may introduce errors since assumed conditions may be very different from actual, and physical conditions may change over time. Mainstream capnometers will correctly read the partial pressure of CO_2 at the conditions in the breathing circuit typically at or near BTPS and do not require software compensation for water vapor.

Contamination Issues

Condensed water or water-like mixtures have other very serious effects such as obstruction of the sampling line or airway adapter. If droplets appear within the cuvette optical path, severe scattering and absorption can occur. However, true single beam ratiometric optical systems (i.e., the CAPNOSTAT) can successfully compensate for the contamination if scattering/absorption effects are not spectrum dependent. Dust particles and optically opaque particles do not appreciably affect system precision.

Contaminants may partially obstruct the sampling tubes of side-stream capnometers and increase resistance to flow in these tubes thus affecting the response time and accuracy of the CO_2 measurement. In more severe cases, the sampling tube may be occluded. Some monitors compensate by either increasing the sampling flow or attempting to purge the sample tubes when an increased pressure drop is sensed across a flow restriction. In spite of the presence of water traps and water permeable tubing, liquids may be aspirated into the monitor's internal components. This can result in degradation of the monitor's performance as seen by distorted waveforms and deterioration over-time of these internal components. This degradation of performance would require monitor checks to be performed. This may not be possible in an "expeditious" manner due to the responsibilities of the anesthesiologist during a surgical procedure or the critical care physician in the intensive care unit and may lead to the discounting or disregarding of the capnograhic values.

Clinical Implications

Mainstream and sidestream capnography has been reviewed and contrasted. The limitations of the technologies and design choices and their performance in the different clinical environments and patient populations that they may be used on must be considered. Their value as a "front-line" monitor is well established [39]. A detailed study of adverse events found that capnography was critical for the detection of general anesthesia incidents. The study also reported failures of capnography to detect problems when it should have and it was noted that about a third of these failures were due to problems with sidestream gas sampling and a third due to the improper setting of alarms. Also, the importance of capnography during clinical events such as cardiac or respiratory arrest cannot be underestimated. In fact "of all monitors currently in use during cardiac arrest, capnography furnishes the best real-time, continuous information regarding the effectiveness of resuscitative efforts." [8,40] Therefore, it is of critical importance that the capnography technology used be robust, artifact free and accurately reflect what is being monitored.

Use in Neonatal Patients – Generally, sidestream capnographs may not be accurate in neonatal and pediatric patients because they aspirate a significant portion of the patient's total ventilation [41]. For example, a neonate with a ventilation of 250 ml/min (tidal volume of 5 and rate of 50 b/min) and a sidestream sampling rate of 50 ml/min is losing 20% of his ventilation to the sidestream sampling system. With a ventilation of 50 ml/min (1 ml and 50 b/min) the consequences can be

[3] *Note that the driving force here is the water vapor pressure gradient, not the total pressure. Thus, the only issue is whether it is wetter inside or outside. (From Perma Pure® website).*

quite severe. Older sidestream designs used sample rates as high as 250 ml/min but newer designs have reduced the flow rate, the diameter of the sampling tube and sample cell. This tradeoff decreases the ventilation levels that can be monitored while at the same time potentially increasing the possibility of occlusion.

Use of Water Traps – The use of water traps, particularly in intensive care, can easily lead in some designs to partial failure or blockage of the trap causing dramatic changes in waveforms and end-tidal values. This is particularly significant in systems that do not show the capnogram.

End-tidal CO_2 – The specifics of each manufacturer's algorithm for end-tidal measurements such as averaging windows, breath-to-breath averaging and its definition of end-tidal values must be considered when interpreting data. This is particularly important if no waveform is displayed. Unfortunately, whether the reported end-tidal value is the partial pressure of CO_2 at the end of expiration or the largest value during the "expiratory" period defined by the capnogram (which can be elongated by rebreathing) or something entirely different depends upon the manufacturer, and often is not disclosed.

Extubation – Historically, the primary concerns of mainstream based systems are related to size and weight. However, the reduction in both size and weight have alleviated these concerns to the point that with proper attention to the breathing circuit, the risks of extubation are minimal. In fact there are no reports of an extubation attributable to the use of a mainstream sensor [12]. Endotracheal tube position is commonly verified by observing expired CO_2 during a series of manual short breaths. It has been noted that the long transport delays often associated with side-stream sampling may result in an excessive delay in observing the presence of expired CO_2 and possible false diagnosis of esophageal intubation [42].

Burns – Since the windows of the mainstream sample cell are heated to slightly above body temperature, burn issues have been raised by some authors. The temperature during normal operation of a heated mainstream sensor will not reach a temperature high enough to cause even redness of the skin. Proper attention to fail-safe design that limits the amount of power delivered have all but eliminated this concern.

Nonintubated subjects – Issues relating to nonintubated subjects have also been raised. The dual use of some mainstream devices and their interfacing to facemasks allow their use in an even broader array of patients and clinical conditions than sidestream systems.

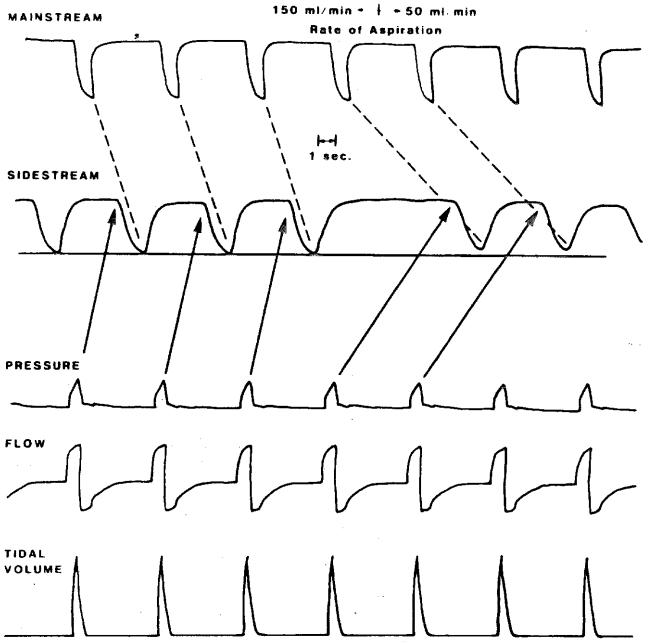

Figure 10. Relationship between capnogram (both mainstream and sidestream) and other "pneumatic" parameters of pressure and flow. Note the time delay and dampening effects from reducing the sample flow rate in the sidestream system (from [43])

Artifacts – Artifacts in sidestream CO_2 waveforms can take on many forms. For example, excessive dampening of the response (Figure 10) can occur. In some circumstances the artifact may resemble physiologic changes which may be characteristic of diseases such as some forms of restrictive or obstructive lung disease. [13] For example, a falsely low value for end-tidal CO_2 may lead the clinician to believe that alveolar ventilation is adequate when, in fact, it is not. [13] It is also noted that "the inability of the capnogram to return to zero baseline on inspiration, a common artifact of sidestream recordings, may suggest rebreathing of CO_2 and prompt unnecessary changes in fresh gas flow or modifications to the patient circuit." [13]

Volumetric Capnography and Beyond

Coupling mainstream capnography with mainstream flow and pressure measurement provides the capability of measuring anatomic and physiologic deadspace ratios, CO_2 elimination, pulmonary capillary blood flow and a whole range of physiologic indices that allow insight into many cardiopulmonary disorders including adult (acute) respiratory distress syndrome, chronic obstructive pulmonary disease, asthma, and pulmonary embolism.

Conclusions

The shape and trends of the CO_2 waveforms contain valuable information that is not available from any other source. Omitting the CO_2 waveform is like omitting the ECG and arterial waveforms or worse. Subtle changes in waveforms can reflect actual or impending problems with endotracheal tubes, ventilators, circuit valve, soda lime absorbers, airway mechanics, respiratory drive, cardiovascular systems, level of neuromuscular blockade, and other important conditions. It is important that the waveform faithfully reflect what's occurring at the airway. [44]

Mainstream capnography reliably reflects what is occurring at the airway and has proven itself as a robust and widely applicable monitoring method for the present and future.

Table 1. Comparison of Mainstream and Sidestream Carbon Dioxide Analyzers

Features	*Mainstream*	*Sidestream*
Airway Connections		
Location of infrared analysis unit ("bench"/sensor)	At the airway connector	In the monitor
Size of airway connector	Small	Small
Weight of airway connection	Airway adapter light; additional weight associated with sensor	Airway adapter light; additional weight associated with tubing
Location of airway connector	End of endotracheal tube (typically)	End of endotracheal tube (may replace "angle" connector)
Use on extubated patients	Yes with a facemask or mouthpiece. Some monitors use a special airway adapter and contain a pump to convert to sidestream mode	Yes with nasal adapter or oxygen prongs
Connecting tube or cable	Thin, medium weight flexible cable No sample tube	Small bore sample tube
Required components to "sample" gas	Airway adapter and sensor	Airway adapter, sample tube, filters, water trap (optional), water permeable tubing
Airway connector disposable or reusable	Sensor reusable; airway adapters are reusable or disposable	Airway adapters are reusable or disposable
Durability of airway connector	Durable	Varies
Cost of replacing airway connector	Sensor expensive to replace; Airway adapter inexpensive	Airway adapter inexpensive but on very wet patients may require hourly change, contamination of analyzer and pneumatic system may be costly to replace unless using system with removable sample cell
Can be used in collaboration with simultaneous oxygen administration	Yes with facemask. Accurately captures both oral and nasal gases. Mouthpiece or where available Sidestream mode with nasal cannula	Yes with nasal prong. Probable dilution of sample with supplemental O_2 present
Easy to use when patient is in unusual positions such as in prone position	Yes	Yes
Sample volume drawn	None	Less than 250 ml/min (sampled gas may be returned to circuit)
Deadspace added to airway connector	Low (< 1 ml in neonates)	Low

Table 1 continued. Comparison of Mainstream and Sidestream Carbon Dioxide Analyzers

Features	*Mainstream*	*Sidestream*
Warm-up		
Warm-up time	Varies	Varies
User tasks during warm-up	Zero and calibration may be required by some devices	Zero and calibration may be required by some devices
Zeroing and Calibration		
Zeroing	Manual–user can mount sensor on zero cell or adapter and wait for stabilization (< 20 sec)	Automatic–requires internal valving and sometimes external gas tanks
Accuracy of zeroing	Accurate–may use separate ref cell or airway adapter	Accurate–uses sample tubing and adapter that will be used during monitoring
Zeroing during use	Manual only, user must mount sensor on zero cell or adapter and wait for stabilization (< 20 sec)	Automatic at preset intervals or manual
Calibration (span)	Routinely not required.	Routinely not required
Calibration to reference gas cylinder	Not frequently required. User attaches sensor to reference cell	Calibration is normally required once every 1–6 months
Response and Signal Fidelity		
Delay between sampling and waveform display	None	Less than 3 seconds
Sensor 10-90% rise time	Typically < 70 millisecs	Typically > 200 millisecs
Waveform display	Crisp. No deformity of capnogram due to non-dispersion of gases	Smooth appearance because it is filtered by the sample line artifact and slower response time
Accuracy of waveform shape	Excellent No affect due to variable pressure drop	Variable–depends upon factors including sample rate, mixing, and sample cell design
Numeric display	Breath to breath or averaged end-tidal and breathing frequency.	Breath to breath or averaged end-tidal and breathing frequency.
Moisture and Contaminations		
Changes in water vapor pressure	Not affected	Affected due to condensation and drying of sample

Table 1 continued. Comparison of Mainstream and Sidestream Carbon Dioxide Analyzers

Features	*Mainstream*	*Sidestream*
Moisture and Contaminations, contined		
Moisture handling	Sensor at airway adapter contains a heater or other means to prevent condensation, water droplets may condense on window but usually clear rapidly	Water trap–modern water traps can be extremely efficient but may clog (some use Nafion® tubing which equilibrates with ambient humidity)
Potential of cross-contamination between patients	None–Disposable or reusable airway adapter can be sterilized and then reused at no risk of contamination.	Varies–airway adapter and sample tubes can be disposed at low cost or sterilized and reused at no risk of contamination provided no purging or return of gas to patient breathing circuit
Zeroing and Calibration		
Gas scavenging	Not required	Gas outlet on monitor can be scavenged or permanently installed to return sampled gas to a connector at expiratory valve on circle system; potential "pollution" risk with anesthetic agents
Use in true closed circuit anesthesia	Yes	Yes, provided sampled gas returned to circuit
Compensation		
Compensation for nitrous oxide concentration	Manual or automatic	Manual or automatic
Compensation for oxygen concentrations	Manual or automatic	Manual or automatic
Barometric pressure compensation	Yes.	Yes.
Airway pressure compensation	Not required.	Pressure fluctuations due to sampling system (i.e, pump variations) may be compensated with measurement of pressure
Numeric display	Breath to breath or averaged end-tidal and breathing frequency	Breath to breath or averaged end-tidal and breathing frequency
Neonatal Use		
Suitable for Neonatal use	Yes. Low deadspace neonatal airway adapters available	Varies
Monitor		
Size and weight of monitor	Medium to small. Bedside and handheld	Medium. Bedside and handheld
Battery-operated monitor available	Yes	Yes

Table 2. Specifications of Selected Mainstrean and Sidestream IR Capnometers

	Mainstream		***Sidestream***		
	Agilent	**Respironics**	**Datex-Ohmeda**	**Oridion**	**SIMS BCI**
Model	M1016A	CO_2SMO Plus!®	Capnomac Ultima™	VitalCap™	CapnoCheck® Plus
Source	Steady state source with chopper wheel	Pulsed source solid state	–	Pulsed source electric discharge	Pulsed source with narrow band filter at source
Sampling Flow ml/min ±%	n/a**	n/a**	200 ± 20 ±10%	50 ±7.5 ±15%	120±20 ±17%
Sample Rate (Hz)	–	87	–	40	–
Interference Comp.					
N_2O	Yes****	Yes ***	Yes	Included in CO_2 accuracy specs	Yes with nominal value
O_2	Yes****	Yes***	Yes	–	–
Calibration method	Reference Cells	Zero Cell or use adapter (< 20 sec)	Every 6 months	Self Cal, Check 1x yr	Manual 2 point
Response time (ms)	< 125	< 60	–	2450 typ; 2900 max	–
Delay time (ms)	Negligible	Negligible	–	Approx 2000 190 neo	–
Rise time (ms) (10%–90%) *	< 125	< 60	< 360	250 adult	375 0 to 90%
Purging mode	n/a	n/a	Pulls water and mucous to trap	Monitor clears if circuit blocked	–
Liquid trap/filter	n/a	n/a	Gas-permeable and liquid impermeable filter	Water vapor-permeable tubing, water trap and hydro-phobic filters	Water trap/filter

(Data excerpted from Product Comparison Table–Outpatient Care Technology August/September 2001, product literature and manuals from the individual manufacturers or its OEMs and other publications)

Notes:

n/a = not applicable

Dash shown if data was not available to author.

* Unless otherwise noted rise time is the time required to achieve a rise from 10% to 90% of the final CO_2 value in the capnometer when a step function change in CO_2 concentration or partial pressure occurs at the sample site. (ISO 9919)

** Mainstream devices listed can operate in sidestream mode using mainstream sensor with sidestream adapter/module.

*** User selectable values

**** Nominal value assumed unless actual values available.

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