RESPIRONICS

OEM Capnography business

**Technical Considerations**

# Mainstream or Sidestream Capnography?

## Abstract

This paper provides an overview of mainstream and sidestream capnography, including their technical aspects, issues such as leaks, contamination, and artifacts, clinical implications, and benefits.


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## Introduction

Infrared measurement of carbon dioxide ($CO_2$) can be traced back to the 1860s (Figure 1).[1] The technology behind modern-day clinical monitoring of $CO_2$ (e.g., capnography) dates back to the 1940s.[2] In the 1950s, bulky and fragile infrared instruments were adapted for clinical use. Early mainstream devices were physically large, cumbersome, and considered impractical for clinical use because they obscured the patient's face. [2,3] As such, infrared sidestream (i.e., diverting) sampling systems were the predominant sampling modality in the 1950s through the 1970s. Representative infrared sidestream systems include rack mountable systems such as the Beckman LB-1 and LB-2 analyzers, considered the gold standard for $CO_2$ measurement in the 1970s.

Advancements in both mainstream and sidestream technology decreased the size of these devices to allow their inclusion in and interface to clinical multi-parameter monitors. However, it was not until the introduction of the HP 47210A in the early 1980s that mainstream devices began to be used widely 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. Sidestream technology continues to have fundamental limitations relating to the aspiration of a gas sample and the associated transport delay. This paper contrasts the two approaches to capnography.

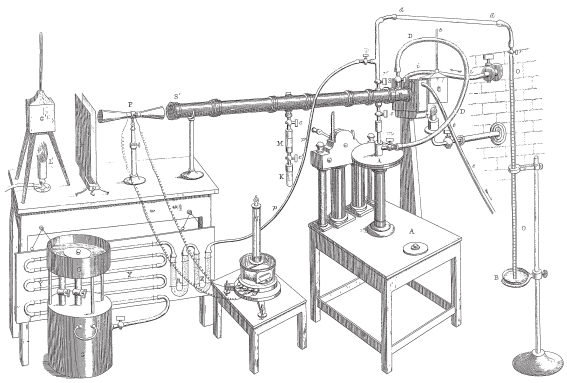


**Figure 1 –** *Tyndall's experimental apparatus used to measure $CO_2$ from the human breath with infrared radiation. Image from Tyndall J. Contributions to Molecular Physics in the Domain of Radiant Heat. 1872.*

## 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 $CO_2$ at the sample site versus measuring $CO_2$ in the monitor distant from the sample site.

The measurement of the partial pressure of a gas significantly distant from the sampling site affects various laws of physics including (1) water removal; (2) temperature and humidity conditions at the sampling site and sample cell; (3) mixing of the sample gas as it is drawn through the cell; (4) variable pressure drop across the tubing and possible misrepresentation of partial pressure values; and (5) dynamic distortions to the waveform. Only some of these effects can be compensated for, corrected by other measurements, or corrected by the assumption of nominal values.

With mainstream devices, the sensor consisting of the sample cell and infrared bench is placed at the airway. Sampling at the airway results in a "crisp" graphical representation of the time-varying $CO_2$ values (capnogram), reflecting in real time the partial pressure of $CO_2$ within the airway. On the other hand, sidestream devices aspirate a sample of gas from the breathing circuit through a 6- to 8-foot-long small bore (e.g., 1 mm inner diameter) tube at flow rates that may vary significantly (±20%). This sample is often passed through a filter or water trap and drying tubing prior to being analyzed in a sample cell. Using a remote location to measure $CO_2$ results in a delay time of up to several seconds (e.g., 3 seconds) and a rise time distortion greater than 200 ms (Figure 2). The typical delay of sidestream systems of 3 seconds relative to mainstream systems can be "significant because of the need to furnish as early a warning as possible" to the clinician.[8] Mainstream systems do not suffer from this time delay.

Comparisons of devices from different manufacturers are often complicated by the use of different terminology and definitions* for total system response time and rise time, resulting in user confusion. Table 1 compares mainstream and sidestream in general terms.

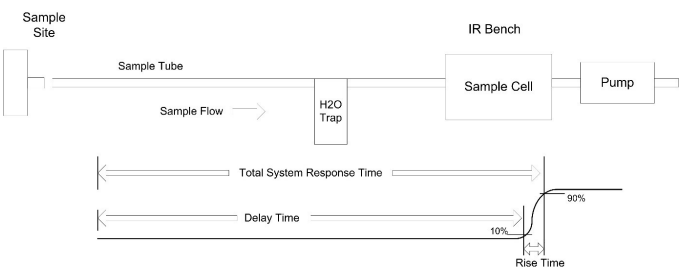



**Figure 2 –** *Physical components of a gas sampling system with total system response time, delay time, and rise time.*

** As defined by the International Standard ISO80601-2-55:2018. Medical electrical equipment -- Particular requirements for the basic safety and essential performance of respiratory gas monitors shall be used.*

## Mainstream Capnography Overview

Mainstream capnography can be viewed as illustrated in Figure 7(a). The sample cell, also referred to as the cuvette, serves as the airway adapter. It is located in-line with the respiratory gas stream, obviating the need for sidestream gas sampling and requisite scavenging if used with anesthetic agents. The airway adapter interfaces directly with the infrared (IR) bench.

A source emitting IR radiation and one or more photodetectors sensitive to these wavelengths are within the IR bench. $CO_2$ within the sample cell preferentially absorbs this radiation at some wavelengths and passes other wavelengths (Figure 3). Photodetectors, typically located on the opposite side of the airway adapter, measure the transmitted radiation as it passes through the IR transmitting windows of the cuvette. Prior to the introduction of integrated sensors needed to measure $CO_2$ (e.g., Capnostat 5 mainstream $CO_2$ sensor), devices would require the electronics associated with measurement and control functions of the infrared bench to be situated in the host system. These devices used multi-conductor cables to transmit the amplified detected signals to the monitor from which the partial pressure of $CO_2$ is calculated and displayed graphically in the form of a capnogram. With the introduction of integrated sensors, the measured capnogram and derived parameters (e.g., end-tidal $CO_2$, respiratory rate) can be transmitted to the monitor. This interface between the monitor and sensor has minimal impact on the monitor design and processing requirements.

The disadvantages of mainstream sensors presented by some authors, and by sidestream-only systems manufacturers, are primarily technological in nature and often relate to prior generations of that technology.[9-11] This includes possible damage during handling, increased mechanical dead space, issues of additional weight on airway, and use limited to intubated patients. In the past, mainstream IR benches have been considered vulnerable to costly damage if dropped onto a hard surface. While earlier IR benches were vulnerable primarily due to the use of moving parts such as chopper or filter wheels, newer mainstream IR benches often utilize all solid state designs (Figure 4) which can survive repeated 6-foot drops onto hard floors[12] and have been used in high impact areas such as the emergency room, ambulances, and transport since the early 1990s.

Claims of accidental extubation with mainstream $CO_2$ devices have not been confirmed in practice. A search of the FDA's Center for Devices and Radiological Health online MAUDE database found no reports resulting in unintended extubation while using mainstream sensors in breathing circuits.[13†]

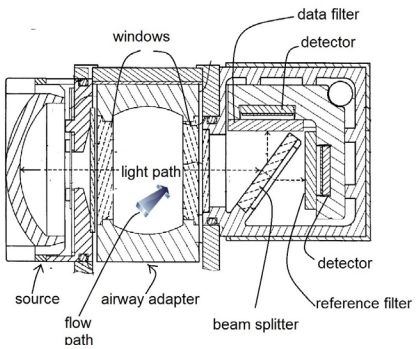



**Figure 3 –** *Cross-sectional view of the representative mainstream capnometer illustrating the path of the infrared light from the broadband source through the flowing gas in the airway adapter and into the detector, where the light is split into 2 components and the amount of light transmitted to a region where $CO_2$ is absorbed (i.e., data channel) and not absorbed (i.e., reference channel) is determined. Image adapted from US patent #US5793044.[14]*

Current generation mainstream devices (Figure 4), besides being relatively light and low in deadspace, have generally demonstrated better performance than sidestream system in terms of signal fidelity, accuracy of end-tidal measurements (particularly at higher respiratory rates in small children),[14] and correlation with arterial $CO_2$ values.[15,16] 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 and/or treated 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[17] but is easily recognizable. For end-tidal $CO_2$ monitoring, particularly in 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. Additionally, sidestream units do not adequately monitor both nasal and oral airflow.

Mainstream devices may also be used on non-intubated patients as a mainstream sensor with a facemask. The use of a low dead space, well-sealing facemask combined with a mainstream airway adapter allows for $CO_2$ monitoring and volumetric capnography. This may be especially useful for field use (e.g., EMS) applications and during non-intubated conscious sedation.

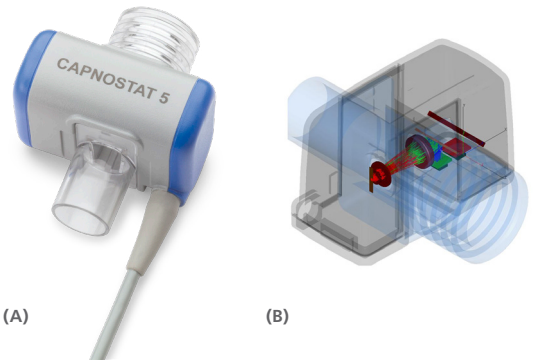



**Figure 4 –** *(a) CAPNOSTAT 5 sensor with airway adapter. (b) Transparent view Capnostat 5 sensor with an airway adapter illustrating single beam ratiometric optical configuration showing the IR source, beam splitter, mirror, and detectors (with a reference filter at 3.7 µm and data filter at 4.26 µm).*

*† July 2025 search of product class CCK Analyzer, Gas, Carbon-Dioxide, Gaseous-Phase and Product Problem: Mechanical Problem (as well as other searches) of reports of adverse events involving medical devices over the last 10 years.*

## Sidestream Capnography Overview

Sidestream gas analyzers (e.g., Respironics LoFlo Sidestream Module, Figure 5) utilize a long, thin plastic sampling tube connected to an adapter in the breathing circuit (such as a T-piece at the endotracheal tube or mask connector) or a nasal cannula sized for different patient populations (Figure 6a). The sample gas is continuously aspirated from the breathing circuit through the sampling tube and into the sample cell within the monitor (Figure 7b) at sample flow rates typically ranging from 50 to 250 mL/min.

The location of the sampling port varies and may range anywhere from an elbow connected to an endotracheal tube to the Y-piece connector. For example, it may be placed on the ventilator side of an in-line filter or Heat and Moisture Exchanger. This results in a drier sampling tube with the inherent risk of significant distortion of the capnographic waveform[18] and lower end-tidal values (mean difference 2.9 mm Hg) in mechanically ventilated patients).[19] It may also be placed on the patient side of the filter, increasing susceptibility to accumulation of condensate and patient secretions in the sampling system, which is dependent on the design of the sampling port in the airway adapter. The sampling tube typically hangs free between the breathing circuit and monitor where it could be crushed, kinked, tugged on, or damaged during movement of the anesthesia machine or ventilator.

### Scavenging

The sampled gas withdrawn from the patient during surgery may contain anesthetic gases and thus should be routed to a gas scavenging system to avoid "pollution" of the operating room environment[20] and exposure risks to staff in underventilated areas.[21,22]

### Condensation/Contamination

Condensation from humidified sample gas in combination with patient secretions can block and contaminate different components of the sampling system, necessitating their replacement. To protect the sample cell and optical bench from condensate, the distal end of the sampling tube often includes an integrated filter which may also be connected to a water trap and water vapor permeable drying tubing (e.g., Nafion®). Water trap and filter design effectiveness vary between manufacturers, but no water trap or filter is completely immune to eventual clogging and distortion of the capnogram, particularly if preventive maintenance is inadequate. Recent designs of airway adapters for sidestream systems have reduced the likelihood of aspirating secretions with sampling ports located away from the wall of the adapter (e.g., LoFlo) (Figure 6b).[24]

### Leaks and obstructions

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] have been reported as causes of significant artifact in the sidestream 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 deviate significantly from actual ones, which may not be detectable by normal calibration procedures.[30] However, sidestream systems with removable sample cells (e.g., LoFlo) are less susceptible to these errors.

Significant distortion of the capnogram may occur even in the absence of leaks or obstructions in the sampling system. For example, as the respiratory rate increases, the shape of the waveform changes with the eventual loss of an apparent expiratory plateau. (Figure 8). 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 sampling tube design and positioning within the breathing circuit or nares (if a nasal cannula is used) can affect the quantity of surrounding air that is entrained along with the expired gas. Within the sample tube, 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 various factors including the sample tube length,[32] airway pressure, and the presence of an exhaust line occlusion.[33]

Sidestream monitoring requires close attention to the physical setup external and internal to the monitor, as well as careful interpretation of the capnographic waveform. Designs such as the LoFlo module offer a simpler pneumatic design with a removable sample cell, which can help to alleviate many of these issues.



**Figure 5 –** *Respironics LoFlo Sidestream Module with external sample cell.*

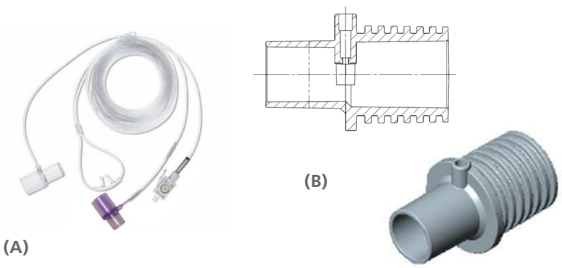



**Figure 6 –** *LoFlo sidestream accessories: (a) Airway adapters (adult-clear and neonatal-purple) and representative nasal cannula with sampling tube and sample cell; (b) View and cross-sectional view of sidestream airway adapter illustrating offset of sampling port.[23]*

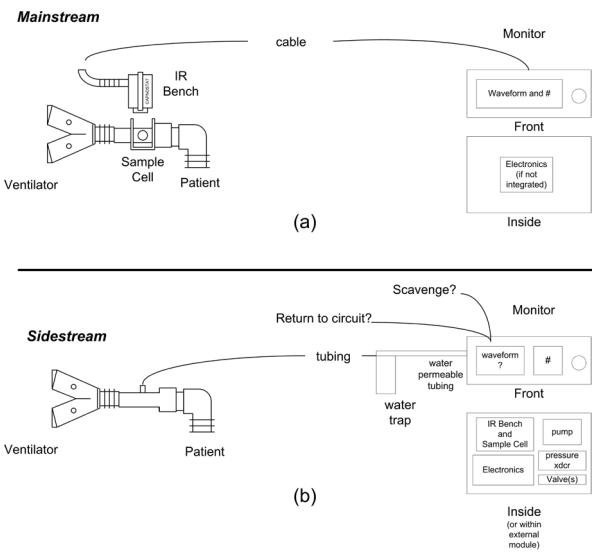



**Figure 7 –** *This diagram shows the difference in breathing circuits between mainstream and sidestream sampling methods.*

## Infrared Spectroscopy

Infrared absorption-based sensors are widely used for the measurement of $CO_2$ and anesthetic agents. These sensors can be sensitive and selective as well as provide a continuous, accurate, and rapid response.‡ $CO_2$, which has a strong absorption band at 4.26 µm, has been measured using technically different infrared absorption techniques by different manufacturers. The source of infrared radiation may be broadband or narrow band. It may be pulsed or continuous (with a mechanical chopper). For narrow band emission, some sidestream monitors use an electric discharge source with a hermetically sealed glass tube containing a gas excited by the application of a high voltage, radio frequency electromagnetic field.

The detection of the infrared radiation typically uses a detector sensitive in the IR band, such as a 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 minimizing 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 internal processing 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 ($N_2O$). Some manufacturers (e.g. Respironics Novametrix) provide compensation for helium (e.g., Heliox). These gases and other gases to be used for interference testing are specified in the standard for respiratory gas monitors.[6]

The measured absorption of $CO_2$ can be altered by cross-interference and collision broadening due to the presence of gases such as nitrogen, $N_2O$, and oxygen. Strong absorption bands of these other gases slightly overlap both edges of the $CO_2$ band (Figure 9b). 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 low half power bandwidths can effectively reduce the effect of cross-interference.

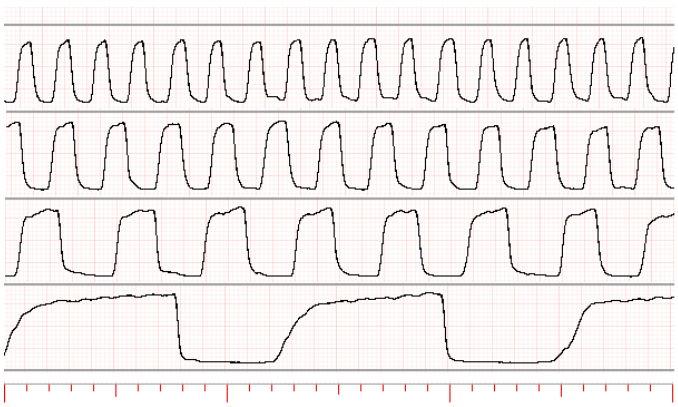


**Figure 8 –** *Distortion as a function of respiratory rate (in a sidestream system). Change in capnogram (in same subject) with increasing respiratory rate (35, 25, 15, 5 breaths/min shown from top to bottom) in a sidestream system (with each tick mark at 1 second intervals on the x axis).*

Collision broadening tends to be less device-specific[34] and is a complex function of the total pressure and the presence of other gases. $CO_2$ 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 $CO_2$), fewer 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 are unable to completely correct for this effect. This effect is often compensated for in the system's software using nominal values.

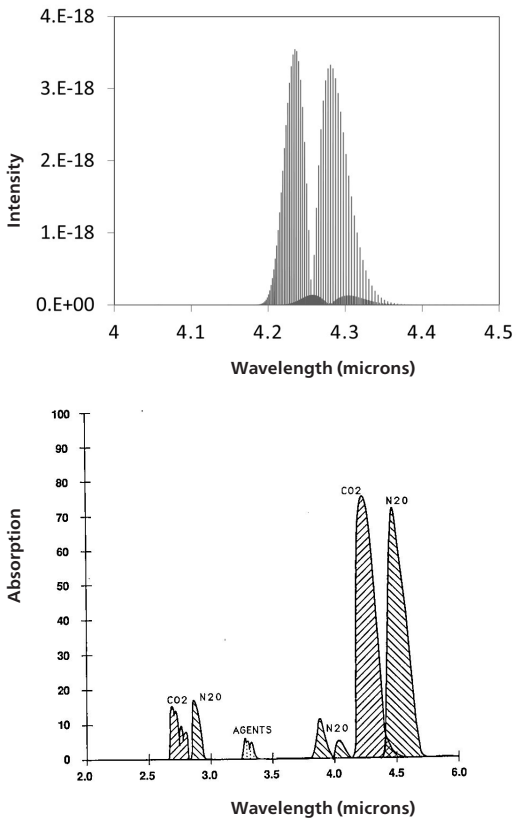



**Figure 9 –***(a) Line spectra for $CO_2$ at 4.24 microns. The number of $CO_2$ molecules in the volume interrogated by the infrared light beam determines how much energy is absorbed; this dependence on frequency can be seen by a plot of the line intensities for $CO_2$ at 296 K (values for 12C16O2 from the HITRAN database at HITRAN.org). (b) The infrared absorption spectrum for the gases $CO_2$ and $N_2O$ and the volatile anesthetic agents. Adapted from Raemer DB. J Clin Monit. 1991.*[35]

‡ *Internal data on file.*

**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 adapter | Remote from breathing circuit/patient, either in monitor or external module |
| **Size of airway adapter/Dead space** | Small/Low (<1 mL in neonates) | Small/Low (<1 mL in neonates) |
| **Weight of airway connection** | Airway adapter light; additional weight associated with sensor | Airway adapter light; additional weight associated with tubing |
| **Location of airway connection** | Between endotracheal type and Y-piece (typical) | Between endotracheal type and Y-piece (typical), may be distal to in-circuit filter or HME |
| **Use on non-intubated patients** | Yes, with facemask or mouthpiece; cannot be interfaced with nasal cannulas | Yes, with nasal cannula or oxygen prongs |
| **Connecting tube or cable** | Thin, light weight flexible cable; no sampling tube | Several foot long sampling tube (LoFlo sampling tube 101 inches) |
| **Required components to "sample" gas** | Airway adapter and sensor | Airway adapter/nasal cannula, sampling tube, filters/water trap, optional water permeable tubing and remote bench |
| **Cost of replacing airway connector** | Single patient use airway adapter; inexpensive (life typ e.g., patient's stay of vent) | Airway adapter with tubing and filter; much more expensive than mainstream airway adapter; on very wet patient, may require regular changes; contamination of analyzer and pneumatic system may be costly to replace unless using a robust design with a removable sample cell |
| **Sensing unit (components)** | Optics and associated electronics | Optics and associated electronics, - added cost with brushless pump, manifold and pressure sensor |
| **Can be used in collaboration with simultaneous oxygen administration** | Yes, with ventilators and facemasks - captures oral/ nasal expired gases | Yes, with nasal cannula - probable dilution of sample with supplemental $O_2$ |
| **Easy to use when patient in unusual positions such as in the prone position** | Yes | Yes |
| **Sample volume drawn** | None | 50-250 mL/min - with anesthesia, requires scavenging of waste gases |
| **Warmup** | | |
| **Warm-up time** | Varies | Varies |
| **User tasks during warmup** | Zero and calibration may be required for some devices | Zero and calibration may be required for some devices |
| **Zeroing and Calibration** | | |
| **Zeroing** | Manual - user uses either zero cell or zeroes on room air | May be automatic - requires internal valving or external gas tanks |
| **Zeroing during use** | Manual (as above) | As above - note loss of signal |
| **Calibration (span)** | Routinely not required | Routinely not required |
| **Response and Signal Fidelity** | | |
| **Delay between sampling and waveform display** | None | Less than 3 seconds (for 50 mL/min) (function of sampling flow rate) |
| **Sensor 10-90% rise time** | Typically < 60-70 ms | Typically > 200 ms (note function of accessory in use) |
| **Waveform display** | Crisp; no apparent blurring of capnogram due to transport and dispersion of gases | Smooth appearance due to filtering by sample line artifact and slower response time |
| **Accuracy of waveform shape** | Excellent | Variable - depends upon sampling rate, mixing, pneumatic pathway design proximal to sample cell and sample cell design |
| **Compensation** | | |
| **Compensation for $N_2O$ concentration** | Manual or automatic | Manual or automatic |
| **Compensation for $O_2$ concentrations** | Manual or automatic | Manual or automatic |
| **Barometric pressure compensation** | Yes | Yes |
| **Airway pressure compensation** | Not required - in circuit partial pressure of $CO_2$ measured | Pressure fluctuations due to pump and circuit variations may be compensated with measurement of pressure |

**Table 1 (continued)** – Comparison of Mainstream and Sidestream Carbon Dioxide Analyzers

| Features | Mainstream | Sidestream |
|---|---|---|
| **Moisture and Contamination** | | |
| **Changes in water vapor pressure that can affect accuracy** | Not affected | Affected due to condensation and unknown drying of sample at sample site |
| **Moisture handing** | Sensor at airway adapter uses a heater or coating to minimize condensation; water droplets may condense on window but usually clear rapidly | Water traps/filter may clog; use of Nafion tubing (adds cost) but can reduce impact of high humidity levels in circuit |
| **Potential of cross-contamination between patients** | None - disposable or reusable airway adapters available | Varies - disposable airway adapters/ sampling tubings; potential exists if gas returned to patient breathing circuit without adequate precautions |
| **Gas scavenging** | N/A - closed system | Gas outlet of sensor can be scavenged; potential "pollution" risk with anesthetic agents |

## Water Vapor

Mainstream infrared analyzers, when located near the patient connection, measure the respired gases at conditions that are likely near Body Temperature and Pressure, Saturated conditions (BTPS). Water vapor effects can cause cross-interference 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 with respect to sidestream systems.

With sidestream sampling, the temperature of the sampled gases tends to decrease towards ambient temperature (e.g., room) 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 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.‡ This decrease in water vapor pressure causes an increase in $CO_2$ concentration.[39]

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 ones, 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 of the Sample Cell or Tubing

Condensed water or water-like mixtures may obstruct the sampling line or airway adapter or interfere with the flow of gas within the sampling line. If droplets appear within the sample cell's optical path, scattering and absorption can occur. However, true single beam ratiometric optical systems (i.e., CAPNOSTAT) can successfully compensate for contamination if scattering or 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 sidestream capnometers and increase resistance to flow in these tubes thus degrading the response time and accuracy of the $CO_2$ measurement.

Some monitors compensate by increasing the sampling negative pressure (or suction) when an increased pressure drop is sensed across a flow restriction. Despite the presence of filters, water traps, and water permeable tubing, liquids could be aspirated into the monitor's internal components. This can degrade the monitor's performance if the contamination affects the optical performance of the sample cell. The degradation may be seen as a sudden change in the displayed waveform or a deterioration over time and requires monitor checks. This may not be possible in a timely manner due to the responsibilities of the anesthesiologist during a surgical procedure or the critical care physician in the intensive care unit (ICU), potentially leading to the discounting or disregarding of the displayed capnograhic values. The use of a system with a removable sample cell can help mitigate these issues.

**Sidestream $CO_2$ Module**




**Mainstream Sensor**



## Clinical Implications

The limitations of mainstream and sidestream capnography technologies, design choices, and their performance in different clinical environments and patient populations must be considered, with mainstream preferred for patients connected to therapeutic devices such as ventilators and sidestream preferred with the use of nasal cannulas. Capnography has been considered a front-line monitor for decades.[40] An analysis of adverse events found that capnography was critical for the detection of general anesthesia incidents. Authors reported failures of capnography to detect problems when it should have. One third of these failures were due to problems with sidestream gas sampling and one third were due to improper alarm setting. Additionally, the importance of capnography during clinical events such as cardiac or respiratory arrest cannot be underestimated. In fact, it has been noted that of the monitors in use during cardiac arrest, capnography provides the best real-time, continuous information regarding the effectiveness of the resuscitative efforts.[8,41] Therefore, it is critical that the capnography technology used be robust, free of artifact, and an accurate reflection of what is being monitored.

### Use in Neonatal Patients

Generally, sidestream capnographs may not be accurate in neonatal and pediatric patients because they may aspirate a significant portion of the patient's total ventilation.[42] For example, a neonate with a ventilation of 250 mL/min (tidal volume of 5 and rate of 50 breaths per minute) and a sidestream sampling rate of 50 mL/min loses 20% of their ventilation to the sidestream sampling system.
With a ventilation of 50 mL/min (1 mL and 50 breaths per minute), the consequences can be severe. Older sidestream designs used sample rates as high as 250 mL/min but newer designs have reduced the flow rate and diameter of the sampling tube and sample cell. This tradeoff decreases the ventilation levels that can be monitored while 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 especially significant in systems that do not show the capnogram.

### End-tidal $CO_2$ and Respiratory Rate

The specifics of each manufacturer's algorithm for end-tidal gas and respiratory rate measurements such as averaging windows, breath-to-breath averaging and its definition of end-tidal values, and even the method it uses to determine a breath must be considered when interpreting data.[43] 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 systems have been related to size and weight. However, the reduction in both size and weight have alleviated these concerns—with proper attention to the breathing circuit, risks of extubation are minimal. There are no known reports of extubation attributable to the use of a mainstream sensor. Endotracheal tube position is commonly verified by observing expired $CO_2$ during a series of manual short breaths.
The long transport delays often associated with sidestream sampling may result in an excessive delay in observing the presence of expired $CO_2$ and possible misdiagnosis of esophageal intubation.[44]

### Burns

Since the windows of the mainstream sample cell are heated slightly above body temperature, concerns of burn have been raised. However, the temperature during normal operation of a heated mainstream sensor will not reach a temperature high enough to cause skin redness. Proper attention to fail-safe design that limits the amount of power delivered have 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.

### Artifacts

Artifacts in sidestream $CO_2$ waveforms can take on many forms. For example, increasing dampening of the response (Figure 10) occurs at higher breathing frequencies. 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.[14] For example, a falsely low value for end-tidal $CO_2$ may lead the clinician to believe that alveolar ventilation is sufficient when, in fact, it is not. It is also noted that the inability of the capnogram to return to zero baseline on inspiration, a common artifact of sidestream recordings, indicate $CO_2$ rebreathing and result in unnecessary changes in fresh gas flow of the patient circuit.[14]

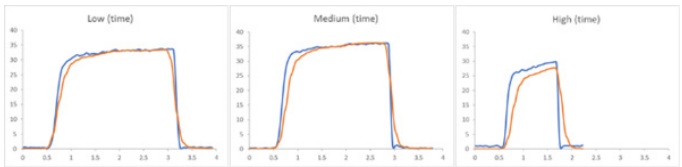



**Figure 10 –** *Time domain capnograms obtained simultaneously using mainstream (blue) and sidestream (orange) techniques at low (9 br/min) , medium (12 br/min), and high (20 br/min) breathing frequencies. Blunting of the transition zones between phases 2 and 3 is apparent when using sidestream capnography, with these distortions and differences in end-tidal values becoming more pronounced at the highest breathing rate. Adapted from Tolnai J et al. Sci Rep. 2024.*[45]

## Conclusions

The shape and trends of the $CO_2$ waveforms contain valuable physiologic information that is not available from other sources.[46,47] Considered by some as a vital sign,[48,49] omitting the $CO_2$ waveform is akin to omitting the ECG and arterial waveforms in the critical care setting. 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.

As such, the waveform must reflect what's occurring at the airway. For the intubated or ventilated patient, mainstream capnography is the preferred modality since it reliably reflects what is occurring at the airway, allows for the estimation of key parameters such as $CO_2$ elimination and deadspace when married with a flow sensor, and has proven itself as robust in difficult clinical environments such as the ICU. For the non-intubated patient, the sidestream modality is preferred since it allows for easy monitoring of spontaneously breathing and ambulatory patients when used with a nasal cannula.

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