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Sidestream Gas Monitoring with a Detachable Sample Cell – The LoFlo™ System

TECHNICAL CONSIDERATIONS

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ABSTRACT

The features and benefits of the LoFlo Sidestream system are highlighted and contrasted to conventional sidestream systems. The integration of the LoFlo system into existing mainstream monitors is also discussed.

INTRODUCTION

Non-dispersive infrared (NDIR) gas analyzers are widely used in medical applications and are defined as either (1) "diverting" or "sidestream"; and (2) "non-diverting" or "mainstream".[1] A mainstream gas analyzer includes a sample cell positioned in the breathing circuit through which a patient's inspiratory and expiratory gases flow. A sidestream type of gas analyzer samples gases from a sampling port in an adapter placed in a breathing circuit or from a nasal or oral cannula. The gas then passes through a sampling tube to the sample cell, where the gas components are measured. Typically, the sampling port is located on the patient side of an in-line filter. Condensation from a humidified sample gas, in combination with patient secretions, can block and contaminate the sampling tube, which may necessitate frequent replacement. To protect the sample cell from condensate, a portion of the sampling tube is made permeable to water vapor by using dehumidifying tubing such as NAFION® brand tubing, and/or a water trap is positioned at some point along the length of the sampling tube. The effectiveness of water trap and filter designs vary between manufacturers, but no water trap or filter is immune to eventual clogging and distortion of the capnographic waveform, particularly if preventive maintenance is inadequate. While more recent sidestream analyzer designs employ sampling ports that are located in the center of the adapter rather than at a wall and, therefore, are less likely to aspirate secretions, they are still susceptible to the problems outlined.

Additionally, sources of leaks both external and internal to the monitor, such as loose fittings, cracked or split sampling tubes, cracked filters, and partial disconnections, have been known to cause significant artifact in the capnogram output of conventional sidestream gas sampling systems. In fact, leaks and obstructions can occur at any of the numerous connection points and tubes within a sidestream sampling system. As it may be difficult or impossible to calibrate for such artifacts, leaks, and obstructions, the capnographic waveforms and end-tidal measurements that are generated by use of sidestream analyzers may provide values that are significantly different from the actual values.

These problems are further exacerbated by the fact that the sample cells of sidestream analyzers are typically reusable and nondisposable, and as such, made with windows that are formed from costly materials such as sapphire. Thus, condensation and contamination are likely to build up within such sample cells, reducing their reliability over time. While the reusable sample cells of some sidestream analyzers may be removed for cleaning, the cleaning process is often avoided due to the high costs associated with replacing such sample cells. As a result of not cleaning the sample cell, the accuracy of measurements diminishes over time due to the accumulation of contaminants in the sample cell. As the patient breathes, gases are continuously aspirated at sample flow rates ranging from 50 to 250 ml/min. To reduce the time delay associated with the transport of the gas sample through the sampling tube, conventional sidestream systems aspirate gas at sample rates of 180 ml/min or higher. However, it is desirable to remove as little gas as possible from the breathing circuit and at the same time faithfully reproduce the gas waveform. While effects such as mechanical mixing of the sample during transport in the sample line, and the resulting blurring of the waveform can be reduced by the selection of smaller bore tubing, the proper design of the flow path through the sample cell is critical to achieving optimal performance. Conventional designs of sample cells have sample cell chamber volumes that are too large and/or inlet and outlets that tend to distort the flow profile of the waveform.

Currently, the use of sidestream monitoring requires that careful attention be paid both to the physical setup, external and internal to the monitor; as a result, additional care must be taken in interpreting the capnographic waveform. Given these problems with conventional sidestream capnography, it is desirable to provide a sidestream gas analyzer that (a) is less prone to both internal and external leaks and obstructions,

(b) provides data that more accurately reflects the true capnographic waveform of a patient's respiration, (c) is more robust with respect to accumulation of condensate and patient secretions, and (d) facilitates an easy determination of problems and corrective actions at the point of care should any of the above-noted problems occur with the sampling tube and/or the sample cell.

THE LOFLO APPROACH

To address the problems noted above, the LoFlo Sidestream Gas Monitoring System includes a removable and disposable sample cell which effectively obviates the need for preventive maintenance of the sample cell.

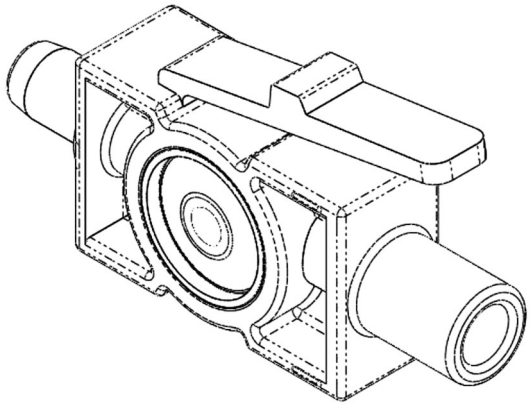

Figure 1 – LoFlo Sample Cell

The sample cell is inserted into a receptacle to which the measurement optics is mounted. The measurement optics (Fig. 5) consists of detector and source assemblies. The sample cell windows are configured and oriented so as to be properly aligned with the measurement optics when inserted into the sample cell receptacle. The detector assembly comprises a window of infrared radiation-transmitting material, a beam splitter, two filters, and data and reference detectors and fits into a circular opening in the sample cell receptacle. Rectangular depressions that surround the rounded opening in the sample cell receptacle mates with an edge of the rectangular housing of the detector assembly. The source assembly comprises an infrared emitter, a mounting, and a window of an infrared radiation-transmitting material. Two tabs on the source assembly allow a secure fit between the two pair of rectangular raised areas on the sample cell receptacle. Connectors on the source and detector assemblies provide the electrical interface to external electronics.

When a sample cell is inserted into the receptacle of a sidestream module, the sample pump turns on and infrared radiation emitted from a source assembly passes through a window of the sample cell, and through the interior of the sample cell, where a portion of the radiation is absorbed or attenuated by carbon dioxide. The unabsorbed infrared radiation then passes through another window into a detector assembly where the unabsorbed, or transmitted, infrared radiation is converted into signals. The signals are converted into digital form and converted into a partial pressure value.

The sample set consists of a sample cell, filter, sampling tubing, dehumidification tubing in some kits and an interface to the patient or the breathing circuit. The sample cell portion of the sample set is designed to permit easy connection with and disconnect from a receptacle that is either contained within the monitor or an external component of a monitor that directly or indirectly communicates with a monitor.

The sample cell is molded from an appropriate polymer, and has a passage defining the flow path for the gases being monitored. Typically, the optical path traverses the flow path with optical apertures in the wall of the sample cell and aligned along and on opposite sides of the flow passage allowing the beam of infrared radiation to enter the sample cell; traverse the gases in the flow passage; and, after being attenuated, exit from the sample cell to the filter and radiation detector. Transmissive windows in the optical apertures of the sample cell confine the gases to the sample cell flow passage and keep out foreign matter while minimizing the loss of infrared energy as the beam enters and exits from the sample cell. The distance traversed in the flow passage is known as the measurement path length and is the distance between the optical apertures of the sample cell. The greater this dimension, the larger the signal measured for the same partial pressure or concentration of the gas to be measured. Thus to achieve an acceptably quiet (noise-free) and fast response time signal, both the path length and volume of the sample cell must be carefully considered.

A latching arm of the sample cell mates with the sample cell receptacle to permit proper alignment of the measurement optics with the optical apertures in the sample cell and proper seating of the sample cell output port with the pneumatic input (Fig. 3). The sample cell receptacle's primary responsibility is to align the source assembly, detector assembly, and sample cell in a repeatable manner. When inserting the sample cell into the receptacle, the latching arm is successively depressed (Fig. 2) and the sample cell is pushed into the sample cell receptacle upon which a protrusion on the latching arm "snaps" into a slot located within the receptacle. To remove the sample cell from

the receptacle, the latching arm is depressed and pivots downward for release upon which the sample cell can then be removed from the receptacle. This device is simple to use and provides both familiar and intuitive operations for insertion and removal of the sample cell. The receptacle further contains a photo detector that can detect when a sample cell is present and serve as a signal to turn on the sampling pump.

A symmetrically designed receptacle slot, combined with a protruding feature of a sample cell latching arm, allows accurate and repeatable alignment of the sample cell with the receptacle slot; this insures accurate alignment of the sample cell with the measurement optics which are affixed to the sample cell receptacle. Proper alignment of the measurement optics with the optical apertures is important so that sufficient infrared radiation passes through the gas within the sample cell to the detector assembly and that a constant path length between the source assembly and detector assembly would be maintained (Fig. 5). Also, proper seating of the sample cell output port with the sample cell receptacle pneumatic input is important so that a known negative pressure can be applied generating the desired flow rate of gas through the sample cell. When the sample cell is latched, the tapered end of the sample cell output port is securely seated against the sample cell seal of pneumatic input port, and provides a good seal. After exiting the sample cell through the output port, the gas enters the pneumatic system and into a pump of the sidestream module prior to exiting via the exhaust or scavenging port. To dampen vibrations from the operation of the pump, the pump is placed in an isolation boot. The port may vent the gas to the atmosphere, connect to a scavenging system or return the gas to the breathing circuit. The system is optimized for low flow using an integrated sample pump under active flow control.

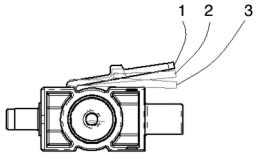

Figure 2 – Removable sample cell illustrating positions of latching arm.

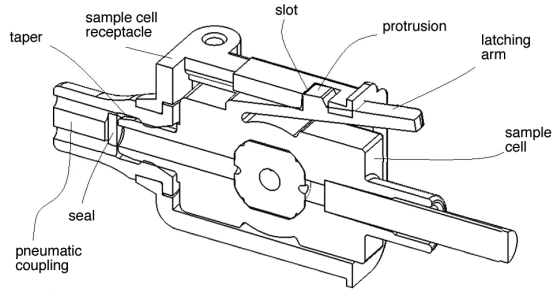

Figure 3 – Cross-sectional view of a sample cell secured to a sample cell receptacle by a latching mechanism.

The optical path of the sample cell does not simply transverse the flow path, but rather is parallel with the flow path for a substantial portion of the path length. To achieve this alternative flow path, the use of the "Z" configuration (Fig. 4) of the flow passage allows for optimal flushing of the sample cell by directing the flow of the gas sample intimately adjacent to the sample cell windows. This configuration effectively eliminates small volumes of "unswept" gas at the windows that tend to reduce response time and add a variable error component. The uniform flow passage from outside the sample cell, into the sample cell body and sample cell core is accomplished without unnecessary transitions and resultant turbulence.

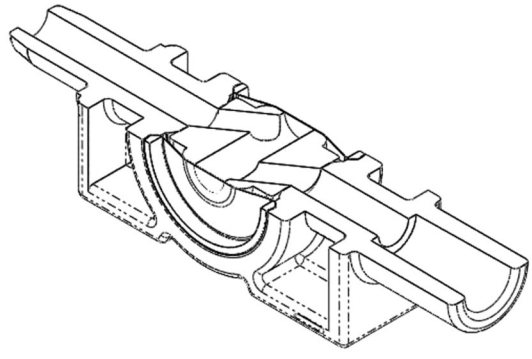

Figure 4 – Cross-sectional view of sample cell illustrating the flow path.

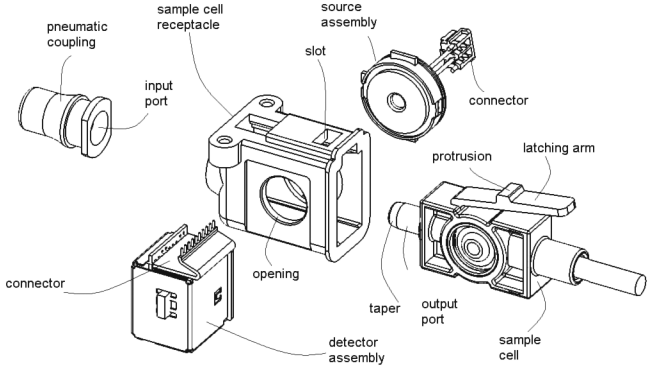

Figure 5 – Exploded view of the sample cell receptacle assembly from the detector assembly side.

SIDESTREAM SAMPLING SETS

Two of the available sidestream sample sets, all of which include a sample cell and sampling tube, are shown in Figures 6 and 7. These sample sets may include various additional components, such as filters, dehumidification tubing, oxygen delivery tubing, and a Luer fitting. The sample sets may be interfaced to the patient's airway by a nasal cannula, airway adapter or a low deadspace airway adapter.

Sets for intubated patients

- Adult/Pediatric Humidified – (sample cell, filter, NAFION® dehumidifying tubing, airway adapter)
- Adult/Pediatric Non-humidified – (sample cell, filter, airway adapter)
- Pediatric/Infant Humidified – (sample cell, filter, NAFION® dehumidifying tubing, low deadspace airway adapter)
- Pediatric/Infant Non-humidified – (sample cell, filter, low deadspace airway adapter)
- General Purpose Humidified – (sample cell, filter, NAFION® dehumidifying tubing, Luer fitting)
- General Purpose Non-humidified – (sample cell, filter, Luer fitting)

Sets for non-intubated patients

- Adult/Pediatric/Infant Without O_2 Delivery – (sample cell, filter, nasal cannula)
- Adult/Pediatric Without O_2 Delivery – (sample cell, filter, oral/nasal cannula)
- Adult/Pediatric With O_2 Delivery – (sample cell, filter, nasal cannula, O_2 port)
- Adult/Pediatric With O_2 Delivery – (sample cell, filter, oral/nasal cannula, O_2 port)

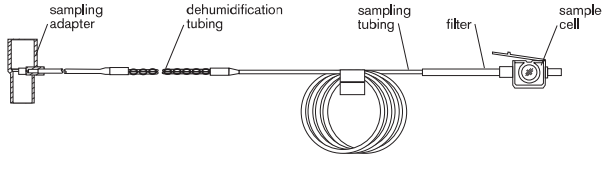

Figure 6 – Pediatric/adult sampling set for use with a humidified breathing circuit, which includes a sample cell, filter, dehumidification tubing, and an airway adapter.

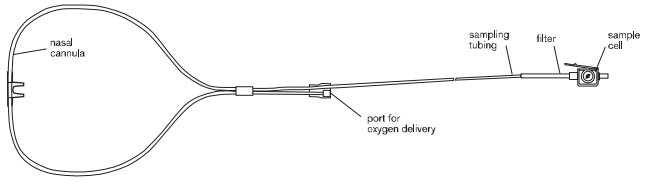

Figure 7 – Sampling set for non-intubated patients with oxygen delivery, including a sample cell, a filter, a nasal cannula, and an optional port for oxygen delivery.

SYSTEM INTEGRATION WITH EXISTING MAINSTREAM–ONLY MONITORS

LoFlo technology may be incorporated into a monitoring system as an external sidestream module or a sidestream module to be included within a multi-parameter system. To permit this novel technology to be made available to the existing installed base of multi-parameter monitors, technology has been developed (patent pending) that enables external sidestream gas sensor modules to be interfaced with existing systems designed only to interface to the Capnostat® mainstream CO_2 sensors. To accomplish this the sidestream module must emulate the mainstream sensor's physical, signal/control and power interfaces. The emulation of the signal/control interface of a mainstream gas sensor system also requires a means to translate adverse conditions in the sidestream gas sensor system into conditions the monitor will recognize as interfering or error conditions so that these conditions can be detected and the operator alerted. These conditions include the presence of liquids including condensed water and other containments in the airway. In the case of the sidestream sensor, these conditions are the presence of such liquids or contaminants in the sample tube running between the airway and the sidestream gas measurement system. However, in the case of the sidestream gas sensor there exists an additional condition that may interfere with the sensor's operation. This is a leak or disconnection of the sampling tubing. The pump control circuitry uses a pressure sensor to measure pressure drop near the measurement chamber of the sidestream gas sensor, and a flow sensor to measure the flow through the sampling tube. Using these sensors, the control circuitry detects the interfering conditions. Detection of an occlusion caused by the presence of contaminants in the sampling tube is accomplished via the flow sensor. Detection of a leak or disconnect of the sample tubing is accomplished via the measurement chamber pressure sensor. The detection of either of these conditions is then used to simulate the effect of contamination that occurs in the mainstream gas sensor.

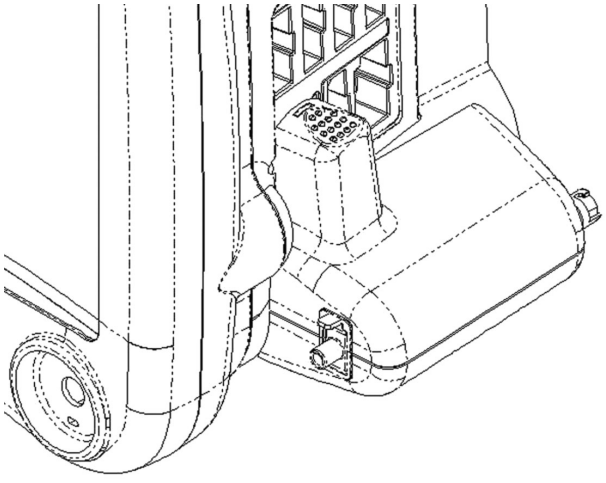

Figure 8 – Perspective view of a sidestream sampling module with LoFlo™ technology interfaced to a mainstream connection on a multi-parameter system.

CONCLUSIONS

The LoFlo approach of sidestream gas measurement does not suffer from the disadvantages associated with conventional sidestream measurement techniques. This is achieved by providing a method that includes low sample cell volume, sufficient path length and a flow profile undisturbed by its flow through the sample cell. A detachable sample cell in conjunction with sample line occlusion detection and alert allows for quick and easy determination of secretion and water accumulation within the sampling tubing and the measurement system. Corrective actions can then be rapidly undertaken at the point of care.

REFERENCES

[1] International Organization for Standardization. ISO 9918. Capnometers for Use with Humans – Requirements, 1993.

Table 1 – Specifications of Selected Sidestream IR Capnometers

	Sidestream			
	Respironics Novametrix	**Datex-Ohmeda**	**Oridion**	**SIMS BCI**
Model	LoFlo™	Capnomac Ultima™	VitalCap™	CapnoCheck® Plus
Source	Pulsed Source Solid State	–	Pulsed Source Electric Discharge	Pulsed Source with Narrow Band Filter
Sampling Flow ml/min	50	200	50	120
Data Sample Rate (Hz)	100	–	40	–
Interference Comp. **N_2O** **O_2**	Per host monitor	Yes Yes	Included in CO_2 accuracy specs –	Yes with nominal value –
Calibration method	None required	Every 6 months	Self Cal, Check 1x yr	Manual 2 point
Response Time (ms) **Delay Time (ms)** **Rise Time (ms) (t 10-90) ***	< 3 Seconds < 2800 < 200 (All patient types)	– – < 360	2450 typ; 2900 max Approx 2000 190 neo 250 adult	– – 375 (0 to 90%)
Accuracy CO_2	0 - 40 mmHg ± 2 mmHg 41-70 mmHg ± 5% of actual 71- 100 mmHg ± 8% of actual	0-76 mmHg 0.2 vol% 1.5 mmHg 76-114 mmHg not specified	0 - 40 mmHg ± 2 mmHg 41-70 mmHg ± 5% of actual 71- 100 mmHg ± 8% of actual	0-38 mmHg: ± 2 mmHg 39-76 mmHg: ± 5% of readings 77-99 mmHg: ± 8% of readings
Time to reach "full" accuracy specifications (min) after powerup	3	–	20	–
Frequency Response	All specifications ± 12% of actual from 80 to 150 Breath/min Note: No Mode Switching Required.	–	All specifications ± 12% of actual from 81 to 150 Breath/min >60 bpm, use the neonatal mode. Assumes: $ETCO_2$ is higher than 18.8 mmHg in neonatal mode	–
Purging Mode	None required	Pulls water and mucous to trap	Monitor clears circuit if blocked	–
Liquid Trap/Filter	In-line filter water vapor permeable tubing available	Gas-permeable and liquid-impermeable filter	Water vapor-permeable tubing, and hydrophobic filters	Water trap/filter

Notes:

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. (per ISO 9919)

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