Mainstream Gas Analyzers

A Historical and Technological Perspective

Introduction

In an eloquent dissertation recently published in Anesthesia and Analgesia[1], Dr. Michael Jaffe recounts the historical record of the scientific and commercial development of mainstream CO_2 gas analyzers, or capnographs, for medical applications. Over time, the clinical community has come to depend on these devices to manage patients respiratory therapy in the intensive care environment, ensure safe intubation in the operating room, transport and emergency medical care, to mention just a few applications for this indispensible clinical tool. In his introduction to this article, Dr. Jeff Feldman, who practices at the Children's Hospital in Philadelphia, makes special note of the significance of this technology to patient safety, especially in the practice of anesthesia.[2]

It is not the purpose of this article to repeat Dr. Jaffe's research or findings but to add to them. This article represents the next chapter in the technical advancement of medical mainstream gas analyzers to include a significant level of miniaturization and integration, and the additional functionality of real-time anesthetic gas measurement and identification. This document will provide an overview and perspective of the design goals and technical challenges for a next-generation multi-gas mainstream sensor platform which the developers have set for themselves and ultimately achieved.

In order to provide the reader with a continuous perspective, it would help to summarize some of the key milestones and technical achievements in the development of the mainstream CO_2 sensor, as the baseline technological platform. In the same introduction to Jaffe's article, Dr. Feldman finds remarkable that *"Tyndall developed the ratio spectrophotometer in the nineteenth century with all the elements of modern capnometry: a source of infrared light, a chamber to contain the sample, and a detector to measure the light that passed through the specimen."* From Tyndall's time to the emergence of the first commercially successful capnograph more than 110 years of water passed under the proverbial bridge. However, until 2003 medical mainstream analyzers were limited to capnography, the detection and measurement of CO_2. In 2003 one Swedish company, PHASEIN, introduced the first (and only) fully integrated mainstream anesthesia multi-gas analyzer.

One, however, cannot forget the technical achievements in the field of infrared absorption by companies like Hewlett Packard, Siemens-Elema, Novametrix and Pryon, which led to the development of an industry committed to patient safety during anesthesia and critical care. The first practical and commercially successful CO_2 mainstream sensor was the HP 4710A Capnometer, a product whose designers had overcome a number of technical obstacles that had constrained the performance of capnometers of the day, including the performance of the IR source and detector, optical filter design and the electro-mechanics of the chopper wheel and motor design.[3] The 4710A's calculated and displayed the end tidal, instantaneous CO_2 values as well as the respiration rate, and had settable alarms for the $EtCO_2$ and respiration rate. More than 50000 units of this device has been sold.

Another noteworthy early mainstream capnometry product is the Siemens-Elema CO_2 Analyzer 930, marketed in Europe circa 1976, that in one arrangement was coupled with the Siemens Servo ventilator. The integration between the two devices provided clinical feedback and information relating to the effectiveness of the ventilation being administered. The CO_2 Analyzer 930 had achieved acceptably stable performance based on its filter chopper arrangement and a patented (analog) electronic drift compensation technique. [4,5]

More contemporary mainstream capnometers including those marketed by Novametrix were later followed by Novametrix-Respironics and Pryon who had developed a reliable, mass-producible solid-state IR source,[6] Nihon Khoden developed and marketed the TG-920 mainstream sensor that has been adapted for use with non-intubated patients, while the TG-950 is a more conventional mainstream device for use with intubated patients.

Every developer of infrared CO_2 sensors, past and present, has placed a great deal of design emphasis on stabilizing the infrared source for drift and output variations as well compensating them for the detector's sensitivity variations due to temperature and aging. Noteworthy is Nihon Khoden's implementation of their mainstream CO_2 sensor, which is achieved "without employing any mechanism for cyclically chopping the infrared light necessary for the PbSe radiation detector"[7] . Another mainstream sensor design not using a chopper wheel is the Novametrix-Respironics family of Capnostat mainstream sensors which were introduced in the mid-1990's; the most recent version of the device, the Capnostat 5, in 2005. These devices have been developed and designed to monitor a single gas – CO_2. A limitation of the chopper-less architecture is that the design cannot be extended to monitor multiple gases within a reasonable mechanical volume of a mainstream sensor.

The Technological Breakthroughs

PHASEIN AB, a Swedish company, founded by Robert Zyzanski and Anders Eckerbom, who have previously also founded Artema Medical AB, and who represent more than 50 years of experience in infrared gas analysis, dedicated to the development of respiratory gas analyzers, had set for itself a unique, and on the surface impossible challenge. The challenge was to design a mainstream multi-gas analyzer as the world's smallest anesthetic gas sensor for the measurement of oxygen, carbon dioxide, nitrous oxide and the potent inhaled anesthetic agents in the respiratory gases of patients. In addition, this analyzer would be functionally self sufficient requiring only operating power and providing all measured gas analysis values via a communication link back to the host monitor.

The technical challenges being faced in such a project include but are not limited to stable, repeatable, measurement of CO_2, N_2O, the potent inhaled anesthetic agents with identification, and oxygen. The unit is to be factory calibrated requiring no recalibration in the field, while being impervious to the effects of airway fluids and contaminants on measurement accuracy and repeatability. Like today's electronic watches, the sensor would be resistant to the effects of mechanical shock; be light-weight to minimize the potential for accidental extubation and kinking of airway tubing, especially in pediatric patients and infants. Another key design consideration affecting system integration and time to market is the simplification of the interface requirements to the host monitor. This design challenge is reminiscent of designing a complex precision movement and mechanism for a fine watch where nothing is left to chance in terms of craftsmanship and ultimate reliability. And, like a good watch, timing is everything.

Infrared Multi-gas Analyzer Design Overview

Respiratory gases can be potentially analyzed according to different measuring principles. The most common method of gas analysis, however, is through the medium of non-dispersive spectroscopy. This measuring principle is based on the fact that many gases absorb infrared energy at a wavelength specific to the gas being analyzed. Mainstream measuring gas analyzers based on non-dispersive spectroscopy measure light absorption at specific wavelengths directly in the patient's respiratory circuit. In an earlier design of one such gas analyzer, for example, a broadband infrared light beam is allowed to pass through the patient's respiratory circuit. The light beam is then divided by a beam splitter into two beams, which are registered by two separate detectors provided with optical band-pass filters having mutually different center wavelengths. One detector is used to calculate the intensity of the light beam at the absorption wavelength of the analysis substance, whereas the other detector is used to calculate a measurement of the reference intensity of the light beam at a wavelength different from the absorption wavelength of the analysis substance. This type of gas analyzer is well suited for the analysis of individual gases, such as carbon dioxide, for instance. However, intensity losses in the beam splitter and the size of the beam splitter make this type of analyzer unsuitable for mainstream multi-gas analysis.

In order to achieve multi-gas measurement capability in the new design, the measurement principle chosen by PHASEIN is that of a non-dispersive infrared analyzer based on the use of an infrared source, a sample chamber, in series with the patient's airway connection, through which the respiratory gas flows; a micro-optical rotor (MOR) with the appropriate optical filters, and a detector to acquire the optical energy specific to the gases being analyzed. But that's where the similarities to previously designed multi-gas analyzer implementations end.

Figure 1 shows a general schematic representation of the new mainstream multi-gas analyzer developed by PHASEIN.[8] The entire measurement head assembly is implemented in a space measuring less than 3.5cm x 3cm x 2.75cm, weighs only 20 grams of which the micro-optical rotor accounts for 0.75 grams, and consuming about one watt of power.

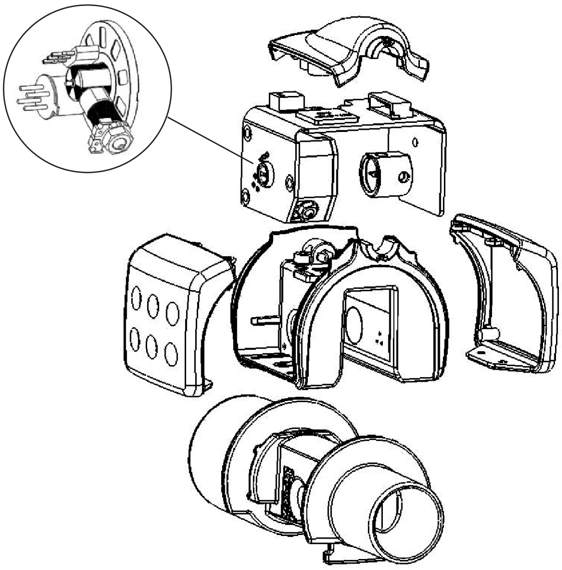


Figure 1

Some of the breakthrough technical achievements in this design include a custom designed, fast response, temperature compensated, infrared source; a custom designed, digitally controlled, micro-optical rotor into which the band-pass optical and reference filters are embedded; and finally an infrared detector/receiver. The sensor head measures infrared light absorption at nine different wavelengths in order to precisely determine gas concentrations in any mixture. The entire measurement head operation is digitally controlled by a high-performance, low power, DSP and microcontroller. The sensor head is factory calibrated and all calibration values are permanently stored in the microcontroller's memory.

The World's Smallest Infrared Multi-gas Spectrometer

The Challenge

Fitting a fully-featured, high performance, anesthesia multi-gas analyzer into a volume smaller than 29 cubic centimeters presented a number of significant technical challenges. Foremost of these challenges was to reduce the size of infrared spectrometer, the heart of the system.

In gas analysis, the light from an IR-emitter passes through the gas mixture of a measuring chamber and is filtered by a narrow-band optical band-pass filter. The gases absorb infrared light at gas-specific wavelengths and during the passage through the gas mixture, the gases in the mixture absorb some of the infrared energy. The partially absorbed light is detected by an IR-detector and the intensity of the detected light is determined. By measuring the intensity of the light that not was absorbed by the gas or the gases, a quantification of the concentration of a gas or gases in the gas mixture can be obtained. Extending this fundamental principle to the challenge of analyzing unknown mixtures of patient gases such as carbon dioxide, nitrous oxide, and one or more of the volatile inhaled anesthetic agents (Halothane, Enflurane, Isoflurane, Sevoflurane and Desflurane) and to identify which gases and/or agents that are present in the mixture, several, and as many as nine optical filters may be required. In the marketplace there are a number of commercial embodiments representing the fundamentals of infrared spectrometry. Some are based on the use of a traditional rotating filter wheel (Artema, Criticare), or an oscillating diffraction grating (Andros/Luma Sense Technologies), or a stationary filter and detector array (Datex/GE Healthcare). In all these embodiments a number of fundamental limitations and constraints, such as technology limitations, size, weight and power consumption, prevent their use as mainstream sensors.

Conceptually, a spectrometer incorporating a rotating filter wheel offers the potential to be reduced in size and weight if the motor could be omitted and if filter elements could be made smaller and be spaced closer together. However, in order to maximize signal output at the detector when a particular filter is coincident with the emitter, sample cell, and detector; and to prevent cross-talk between the channels, it may be necessary to maintain the respective spacing between the filter openings of the filter wheel sufficiently large in order to be able to determine a reference intensity. If the respective spacing is made smaller, for example, in order to obtain a smaller filter wheel or to enable the analysis of more than three gases, it might give rise to cross-talk between the filters (i.e. the detector signal does not decrease to its reference level during the periods between two consecutive filters). This may, for example, lead to a degraded signal to noise ratio, which, in turn, deteriorates the accuracy and reliability of the measurement. The problem is further compounded when a large number of filters are needed to resolve and identify five or six gases. As the spaces between the filters are made progressively smaller, the cross-talk between the filters increases.[9]

The dependence on inter-filter spacing to maximize detector signal and minimize cross-talk is a limiting factor to reduce size of the infrared spectrometer, and makes the technology unsuitable for use in mainstream analyzers.

The Micro-Optical Rotor

The technological development by PHASEIN facilitates the use of a miniature micro-optical rotor integrating a six pole magnet and a number of circularly arranged infrared optical filters. The rotor is driven by a software controlled stator coil and offers significant advantages compared to conventional solutions involving a filter wheel driven by a motor. With this arrangement, the spacing between the optical filters has been reduced to the point where nine filters (seven filters for the quantification and identification of the gases in the mixture, and two reference filters) can be implemented in a 14 mm diameter rotor weighing 0.75 grams. By comparison, one of the smallest conventional filter wheels used in a commercial multi-gas analyzer has a diameter of 26 mm and weighs 14.5 grams. The development of the micro-optical rotor is made possible by eliminating the signal processing dependence on maintaining a minimum spacing between consecutive filters to reduce the effects of cross-talk between the filters. Figure 2 illustrates the size relationship between the micro-optical rotor, center, to that of a traditional filter wheel, on the right, used in a commercially-available gas analyzer.

Figure 2

A patented signal processing algorithm which incorporates detection of the signal peaks corresponding to the coincidence of a filter element with the IR emitter and detector is utilized to determine the intensity of the measured signal. However, due to the small dimensions of the micro-optical rotor, particularly the filter components, the detector signal will not decrease to its reference level during the "dark" periods, (i.e. during periods between two consecutive filters of the filter wheel when the incident light impinges on the filter wheel part between the consecutive filters). The algorithm is based on the idea of using the measured signal during the light periods, (i.e. during the periods when the emitted light impinges on the optical filters) to estimate an intensity of the peaks in the signal, (i.e. when the signal corresponds to a filter). And the peaks of the measurement signal are utilized for determining the reference intensity. An additional benefit of this signal measurement method is that it allows the respective spacing between consecutive filter apertures or openings to be made smaller and hence the filter apertures can be made larger further improving signal to noise ratio which, in turn, provide for an improved accuracy and reliability of the signal measurements. A synchronization method is utilized to accurately correlate the position of each of the unique filters with the instantaneous signal being analyzed.[10]

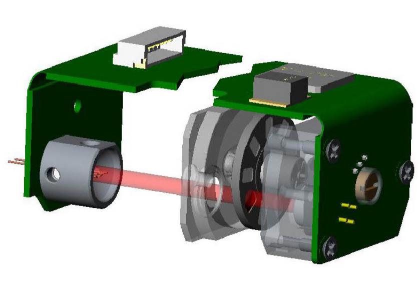


Figure 3

Figure 3 illustrates the internal structure of the PHASEIN multi-gas analyzer, which serves as a platform for a number of the company's products.

Key System Components

Other key elements of the PHASEIN infrared spectrometer include the IR emitter and detector; the optical band-pass filters, the RISC digital signal processor (DSP), and the patient airway adapter. Design requirements for this spectrometer were to provide the end-user with rugged, maintenance-free, stable operation over a wide temperature range. The spectrometer was further designed to be efficiently manufactured and calibrated, without requiring further periodic calibration in the field.

Infrared Emitter

The IR emitter incorporates a special alloy filament containing aluminum. A proprietary manufacturing process results in a very stable and high emissivity layer of AlO_2 on the surface of the filament. The thickness of the filament wire is more than 10 times that of traditional tungsten filaments yielding a very rugged component that essentially has an unlimited lifetime.

Optical Filters

Traditional narrow band optical filters show a shift in their center wavelength as a function of temperature. For a gas analyzer this means that sensitivity changes with temperature. The traditional solution to this problem is to stabilize the spectrometer at an elevated temperature, which means a slower start up time and higher power consumption. The optical filters used in the PHASEIN spectrometer are manufactured using a special thin film deposition process that balances out the layer thickness variations created by changes in temperature. Therefore the center wavelength drift with temperature of these filters are virtually eliminated.

Infrared Detector

The PHASEIN infrared spectrometer utilizes a pyroelectric detector having a sensitive area of just 0.8 x 1.6 mm. The detector is responsive to the entire spectral range from 4 to 10 µm, necessary for reliable agent measurements and identification. Pyroelectric detectors have low noise characteristics at room temperature and are insensitive to temperature variations. By comparison, traditional PbSe sensors used in many mainstream CO_2 analyzers cannot be used above 5 µm, and are therefore not suitable for agent measurements. Their sensitivity is also very temperature dependent. Thermopile detectors used in some multi-gas analyzers cover the full spectral range but are slow in response. Designs using such sensors therefore normally require a number of detectors (one for each optical filter) mounted in a thermally stable array, e.g. a large block of aluminum.

System Processor

A 41-MIPS RISC DSP powers the spectrometer. Each second this processor performs the following tasks:

- Extract nine optical filter signals from a 10.000 samples/sec data stream.
- Digitally filter the nine signals to remove high and low frequency noise.
- Iteratively solve a 5 by 5 non-linear matrix equation at a rate of 240 Hz for agent measurements and identification.
- Iteratively solve a 2 by 2 non-linear matrix equation at a rate of 80 Hz for CO_2 and N_2O measurements.
- Regulate and supervise the emitter and MOR, measure two temperatures and ambient pressure.
- Apply pressure and temperature corrections, calculate waveforms and extract respiratory parameters.
- Communicate with the host device and supervise sensor operation.

Patient airway adapter

An important part of a mainstream gas analyzer is the replaceable airway adapter. Each airway adapter used becomes an integral part of the analyzer's optical pathway and must therefore achieve perfect alignment between the emitter and the micro-optical rotor. In addition, condensation of moisture from the patient exhaled breath creates droplets on the inner walls of the airway adapter if the surface is hydrophobic. Such droplets scatter the infrared beam thus adversely affecting the gas measurements. If the surface is hydrophilic however, condensation creates a film of water that does not scatter the IR beam. PHASEIN has therefore developed a highly effective proprietary hydrophilisation process involving the use of plasma etching that permanently modifies the surface structure of the airway adapters. Unlike competing products, the PHASEIN airway adapter does not utilize any heaters to avoid fogging of the adapter windows, consuming less power and not requiring a warming-up period.[11] Figure 4 is a photograph of the plasmatization process, and Figure 5 is an illustration of the water droplets forming on the inside of the airway adapter. The plasmatization process converts the droplets into an optically-harmless water film.

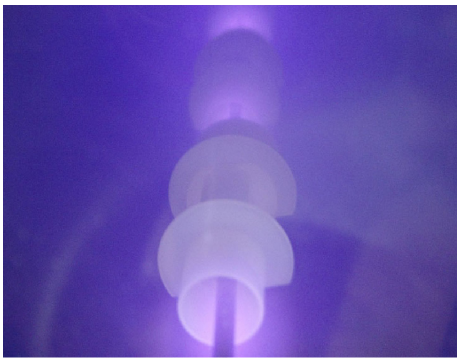


Figure 4

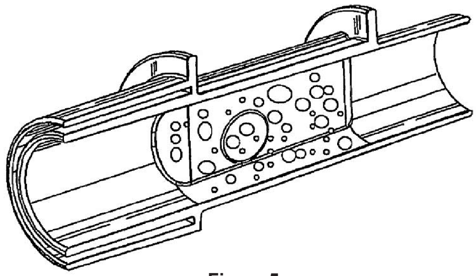


Figure 5

Oxygen Measurement

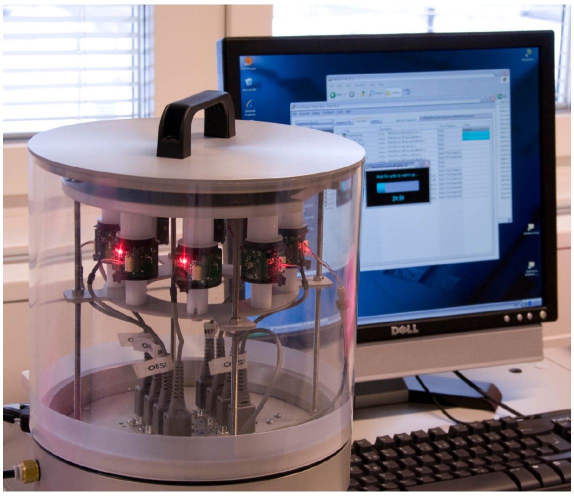
In addition to infrared measurements of CO_2, N_2O and the five volatile inhaled anesthetic agents, the analyzer design also incorporated the ability to measure inspired oxygen from within the airway adapter, on a breath-by-breath basis, utilizing a high-performance "fuel cell"-type O_2 sensor.

Manufacturing and Calibration Process

The manufacturing and calibration of each sensor is performed in a fully automated process where robots and specially designed test and calibration equipment are used, as shown in Figure 6. Each sensor is characterized in terms of linearity, span, zero, temperature and pressure sensitivity. An individual calibration matrix is automatically generated and stored in the calibration memory of each sensor. The pressure and temperature calibration chamber is shown in Figure 7. The sensor design and the full characterization factory calibration process ensure that the sensor will work in any clinical environment without the need for periodic user calibrations.

Sensor assembly

Figure 6



Pressure and temperature calibration
Figure 7

Factory gas calibration and testing is performed in a fully automatic station, shown in Figure 8. Depending on model, each sensor is subjected to up to 20 different gas mixtures under various environmental conditions.

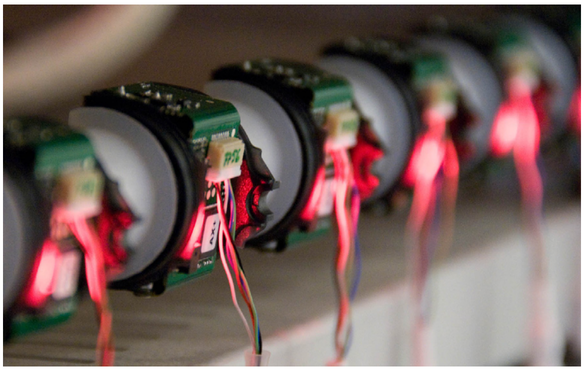


Figure 8

Durability

Many gas sensors are used in portable applications and must therefore withstand very harsh environments. To ensure compatibility with these environments, PHASEIN subjects all its products to a comprehensive testing program. For instance, EMMA analyzers are drop-tested multiple times from three meter height onto a concrete floor. Interface cable performance is also crucial for sensor durability. The picture below, Figure 9, shows a stress test where a gas sensor interface cable is bent for a total of 50,000 times while under load.

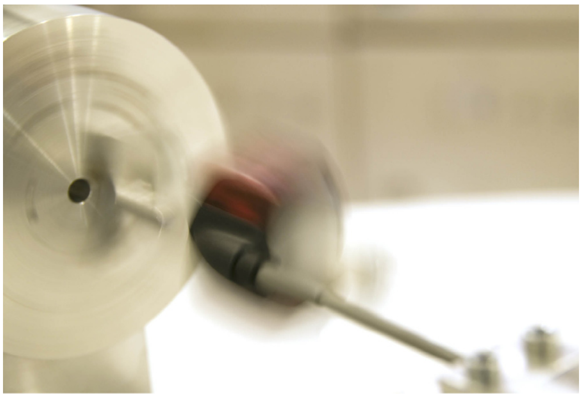


Figure 9

Plug-In and Measure…™

The Plug-In and measure concept is derived from the fact that with exception of its external packaging, the multi-gas analyzer developed by PHASEIN is functionally complete. In other words, it does not require that an external interface board be embedded inside the host monitor. The analyzer's integrated microprocessor calculates, formats, and serially transmits through RS-232 or USB, gas concentration values, waveform data and status information ready to be displayed on the host monitor display, thereby significantly simplifying the product integration tasks, and shortening the system integrator's product timeline to market.

IRMA

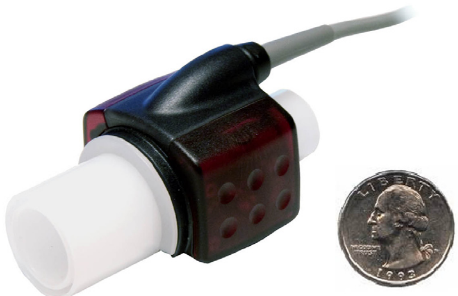


Figure 10

The first family of products introduced by the Company in 2003, based on the infrared analyzer platform described above, is the IRMA (InfraRed Mainstream Analyzer). This family of mainstream analyzers includes a capnography sensor (IRMA CO_2) and a multi-gas (CO_2, N_2O, and five potent inhaled anesthetic agents) sensor (IRMA AX). Agent ID was added to the multi-gas sensor in 2007 (IRMA AX+). Although it has been noted above that that mainstream CO_2 have been historically available from a variety of other suppliers, the IRMA AX/AX+ are the first fully integrated mainstream analyzers designed specifically for monitoring anesthetized patients in the OR. From a clinical point of view, in the OR, the mainstream analyzer provides a high level of performance in terms of measurement accuracy and response time even in the presence of high airway humidity and fluids without the requirement to empty water collection traps. An additional benefit of the mainstream technology is superior performance with pediatric and neonatal patients because the sensor does not divert any patient gas from the airway. Figure 10 shows an IRMA AX+ sensor with its patient airway adapter in place.

In a comparison study between a monitor fitted with the IRMA multi-gas sensor and a state-of-the-art sidestream multi-gas monitor, the Datex-Ohmeda S/5 with airway module M-CAiOV, it was determined that rise time was 2 to 4 times shorter for the mainstream monitor. At a high breath rate (60 BPM), the sidestream system displayed damped O_2 and CO_2 traces with amplitude of less than 65% of the mainstream system. The authors believe that for pediatric monitoring and demanding applications such as metabolic monitoring and measurements of functional residual capacity combining gas concentration with flow/volume measurements the performance of side-stream monitors (SSGM) is suboptimal. The authors further believe that this is a disadvantage for tailoring pediatric ventilatory performance. For more demanding applications - even in adults - such as metabolic monitoring and measurements of functional residual capacity where gas concentration analysis is combined with ventilation volume measurements, the technical limitations of sidestream analyzers hamper precision. Thus, rapid response main-stream multi-gas measurement would improve pediatric monitoring.[13]

EMMA

Figure 11

The EMMA is a standalone, ultra-compact CO_2 monitor, derived from the IRMA CO_2 platform. It was developed to satisfy the needs of the emergency medical care and patient transport, as well as to address a number of pre-hospital applications. One of its most common uses is for proof of-intubation and short-term CO_2 monitoring during emergency patient transport. The EMMA is a hand-held, battery-powered self-contained mainstream device, and uses a disposable airway adapter. It detects and displays $EtCO_2$ values and respiratory rate on a breath-by-breath basis, and includes visual and audible alerts for both $EtCO_2$ and respiratory rate. The device operates for up to eight hours on two standard AAA batteries, weighs only about 60 grams including batteries, and requires no field calibration. It takes less than a second to display accurate measurements on its built-in LED display.[14] Figure 11 shows the EMMA emergency capnometer displaying endtidal CO_2 and respiratory rate.

One important application for the EMMA is its use in emergency vehicles and aircraft. It allows emergency medical technicians to check the expired carbon dioxide levels of patients who have been intubated. Intubation is the insertion of an endotracheal tube into the trachea of a critically ill patient who requires mechanical ventilation – smoke inhalation victims, for example. The procedure requires a great deal of skill and is currently only performed by paramedics in the pre-hospital environment. The EMMA is used to ensure that the tubing has been placed in the trachea, not the esophagus, and also verify whether it becomes dislodged due to patient movement. Although there are clinical methods for confirming the correct placement of the endotraceal tube, the monitoring of CO_2 is the only “sure fire” method to prevent catastrophic, inadvertent esophageal intubation.[15] Furthermore, the EMMA is used to by clinicians establish the correct level of ventilation during a patient’s emergency transport. The clinical importance of monitoring capnography in pre-hospital settings cannot be overemphasized. Examples of such applications include capnography in cardiopulmonary resuscitation (CPR); the use of Capnography in trauma resuscitation; the use of capnography in pediatric emergencies, and the use of capnography as a prognostic indicator of outcome in cardiac arrest.[16]

Summary

Infrared spectroscopy for medical applications has evolved for more than forty years through ground breaking work at Hewlett Packard, Siemens-Elema, Novametrix and Pryon. Until the introduction of the IRMA technology, enabled by the development of the micro-optical rotor technology, mainstream monitoring has been limited to CO_2 analysis only, and multi-gas analyzers were solely based on sidestream technology.

PHASEIN's infrared spectrometer, which serves as the platform for the IRMA family of products, now extends monitoring to all the gases which may be utilized during anesthesia in the OR (CO2, N_2O, O_2, five potent inhaled anesthetic agents measurement and identification) into the mainstream realm.

The improved clinical performance in terms of waveform response time, without the latency normally expected from conventional sidestream monitors who divert sample flows as large as 200 ml/min, makes the IRMA mainstream sensors especially suitable for pediatric and neonatal applications. In addition, the IRMA mainstream family of sensors have overcomes the limitations of conventional multi-gas monitoring technologies; namely susceptibility to liquids and secretions being drawn into their sample lines and potentially occluding or damaging the gas bench. The hydrophilic treatment of the airway adapter's optical windows prevents the formation of water droplets which would interfere with the optical transmission through the adapter.

The IRMA family of mainstream sensors is fully integrated and, other than an RS-232 (or USB) connector; do not require any internal hardware support in the host patient monitor. Based on the company's Plug-In and Measure concept, the principal system integration task is simplified to adding the necessary software in the host patient monitor to acquire and display the measured gas parameters. Based on this concept, any of the IRMA sensors can be interchangeably used with a suitable host monitor, depending on the clinical application.

This technology supports the growing trend for implementing portable devices that can be moved with the patient from location to location, or brought to the patient location, or used as a cost effective solution in cost sensitive markets such outpatient surgery and office-based surgery environments. As markets for such capabilities expand, product such as the IRMA family of fully integrated mainstream analyzers are expected to meet the demand of medical equipment manufacturers for technologies that consume low power and are sufficiently compact and lightweight to support mobility. Product characteristics such as ruggedness, small size and portability represent the next generation of patient monitoring, especially as an increasing number of medical procedures are performed in outpatient centers, physician offices and nontraditional care settings.[17]

In capnography applications where an extraordinary level of portability, low power consumption, and high performance is required, the self-contained display and user interface, of the EMMA device are applicable to uses in natural disasters, war zones, for care in rural or remote areas, and to provide medical care at home and during in-hospital or emergency patient transport.

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