

Continuous Intra-arterial Blood Gas Monitoring

B. VENKATESH

Intensive Care Unit, Royal Brisbane Hospital, Brisbane, QUEENSLAND

ABSTRACT

Objective: *To review the technology and the role of continuous intra-arterial blood gas monitoring in critical illness.*

Data sources: *Articles and published peer review abstracts on continuous intra-arterial blood gas monitoring.*

Summary of review: *The history of intermittent and continuous blood gas analysis and the development of technology of continuous blood gas monitoring are reviewed. A summary of the various clinical trials on the evaluation of continuous blood gas monitoring systems, and the various factors which might affect the performance characteristics in the clinical setting is also presented. The potential role and future applications of this technology in critical illness are described.*

Conclusions: *Over the last 10 years, a number of continuous intra-arterial blood gas monitoring systems have been developed. Only a few have reached commercial availability. While the performance characteristics of these systems are comparable, the levels of accuracy of these systems obtained in vitro are not consistently obtained in clinical trials. Arterial blood flow, wrist movement, wall effect and variability of blood gas analysers are some of the factors which determine the accuracy and reproducibility of these systems. Evidence to support the clinical usefulness of these monitors exists only in the form of case studies. Controlled studies demonstrating an improvement in outcome with the use of these monitors are lacking. (Critical Care and Resuscitation 1999; 1: 140-150)*

Key Words: Blood gases, electrodes, optodes, monitoring, bias, precision, blood flow, intensive care

Regular arterial blood gas analysis is essential for the management of critically ill patients. The results provide valuable information concerning the state of the patient's oxygenation, gas exchange, ventilation and acid-base homeostasis. Modern blood gas analysers incorporate a glass electrode for the measurement of pH¹, a Stow-Severinghaus electrode for the measurement of partial pressure of carbon dioxide (PCO₂)^{2,3} and a Clark electrode⁴ for the measurement of partial pressure of oxygen (PO₂). The scientific milestones culminating in the development of modern blood gas analysers are listed in Table 1.

Despite the rapidity of measurement, automation and the need for only small volumes of blood for analysis, the current techniques are intermittent and are not without problems (e.g. errors in sampling, storage and analysis of specimens. Table 2).⁵ Furthermore, the inter-

mittent nature of the measurement may provide only a snapshot of a continuously changing variable, potentially missing short-term trends. It is well known that arterial blood gases fluctuate even in stable patients in the intensive care unit (ICU)⁶ and often, a blood gas analysis is performed after a critical incident has occurred.

Recent advances in technology have shifted the thrust from intermittent analysis to continuous monitoring with the result that real time data are available continuously at the bedside. Pulse oximetry and capnography, routinely used in anaesthesia and intensive care, have greatly aided patient management and have increased patient safety, reducing the need for frequent blood gas analysis.⁷ However, these non invasive technologies do not replace arterial blood gas and pH analysis.

Correspondence to: Dr. B. Venkatesh, Intensive Care Unit, Royal Brisbane Hospital, Brisbane, Queensland 4029.
(e-mail: venkateshb@health.qld.gov.au)

Table 1. Major milestones in the development of blood gas analysis

1909	pH unit described by Sorensen
1922	Heyrovsky described PO ₂ measurement using mercury electrode
1933	McInnes <i>et al</i> , describe apparatus for pH measurement
1934	Kramer described continuous SaO ₂ measurement
1942	Ear oximeter first described by Millikan
1952	Dubois <i>et al</i> , described infra red technique for PCO ₂ measurement in expired air
1956	Clark electrode described Astrup developed a new technique for determining PCO ₂
1958	Severinghaus electrode described Prototype blood gas machine demonstrated by Severinghaus

Moreover, the inability of the pulse oximeter to differentiate between the various forms of dysaemoglobinaemias, the loss of its signal during low flow states, its propensity to motion artefacts and measurement errors when oxygen saturations are below 70%, reduces the specificity and sensitivity of pulse oximetry in the critically ill patient.⁸⁻¹⁰

Table 2. Problems associated with intermittent blood gas analysis*Pre analytical errors*

- Inadequate removal of dead space volume
- Presence of air bubbles in sample
- Incomplete mixing of specimen
- Delay in analysis
- Lack of storage in ice during transportation and while awaiting analysis
- Reduction in PO₂ induced by leukocyte O₂ consumption due to delayed analysis

Analytical

- Reproducibility and variability between analysers

Miscellaneous

- Lack of forewarning of a deleterious event
- Exposure of personnel to potentially infected blood
- Blood loss associated with repeated sampling

In view of the limitations associated with currently available monitors of blood gas status, the desire for continuous reliable blood gas monitoring is easily understood. The technical challenges confronting the development of a continuous intra-arterial blood gas

monitoring (CIABGM) system include 1) the need to miniaturise sensors for use with conventional intra-arterial cannulae without compromising the ease of simultaneous arterial blood sampling and fidelity of transduction of the arterial waveform, 2) the ability to produce accurate and reproducible data for a reasonable length of time to make it cost effective, and 3) the need to maintain the fluidity of blood.

Technology and sensor design

Considerable effort has been devoted over the last thirty years to overcome some of these technical problems and the end result has been the development of single parameter¹¹⁻²² and multiparameter intravascular sensors.²³⁻²⁸ While several methods of analyte detection have been adapted, currently available continuous intra-arterial blood gas monitoring systems (CIABGMs) employ two general configurations; namely the fiberoptic system and the electrochemical system.

Fiberoptic systems

Fiberoptics transmit light to and from an indicator phase which possesses certain optical properties. These optical properties are altered in the presence of the analyte of interest to a known formula, the variables of which are usually determined during calibration. Fiberoptic systems fall into two general categories, fluorescent and absorbance. In fluorescent systems, the excitation wavelength of the incident light is absorbed by the dye, causing electrons to be briefly excited to a higher energy level. When the electrons return to a lower energy level, they emit energy in the form of light (i.e. fluorescence). This fluorescence is inhibited in the presence of oxygen and the so called oxygen 'quenching' can be mathematically described by the Stern - Volmer equation,²⁹ forming the basis of most fiberoptic oxygen sensors which have generally become known as 'optodes'.³⁰

In absorbance based systems, light is transmitted to an optical dye phase, the absorbance of specific wavelengths by the dye varies in an inverse relationship to the analyte of interest. The intensity of the returning light signal varies according to the analyte concentration and this relationship is described by Beer-Lambert's law.

An important feature of the fiberoptic sensor design is the principle of optical compensation. There is a potential for artefacts such as fiber bending or indicator degradation to compromise the integrity of the measurement. The use of a dual light signal with differing wavelengths, one at the peak absorbance level and one at the isobestic point allows the use of the ratio of the intensities at these wavelengths to determine analyte concentration. If both wavelengths are similarly

Table 3. Dye indicators in fiberoptic sensors

	pH	PO ₂
<i>Absorbance</i>		
	Phenol red	
	Bromothymol blue	
	Alizarin	
<i>Fluorescence</i>		
	4 methyl umbelliferone	
	Polyaromatics	
	pyrenetrisulfonic acid	Lanthanide
	Fluorescein derivatives	Fluorinated porphyrins

affected by artefacts and dissimilarly affected by the analyte, a compensation algorithm can be derived to eliminate artefact-induced perturbation. Other important aspects of sensor design include selection of non toxic dyes (Table 3), with appropriate absorption and emission wavelength characteristics, ease of attachment to an optical fiber, high intensity variation in the physiological range of measurement (i.e. sensitivity) and a rapid response time.

Electrochemical systems

Electrochemical systems measure voltage (potentiometric – a characteristic of the pH and the PCO₂ electrodes), or current (amperometric – a characteristic of the PO₂ electrode). Whilst potentiometric electrodes have found little application in

intravascular sensor technology, the Clark electrode has been successfully miniaturised in several commercial intravascular devices. The electrodes are poised at a fixed potential, immersed in an electrolyte solution and the current generated by the reduction of oxygen is linearly related to the partial pressure of oxygen in the solution.

Because the output current is dependent on the diffusion of oxygen to the sensor, there can be some sensitivity of the sensor to blood flow, although in most clinical situations this is negligible. The direct relationship between the amplitude of the current generated and the PO₂ makes the Clark electrode more sensitive at higher levels of PO₂. In contrast, the optodes bear an inverse relationship between the luminescence intensity and the PO₂ and are therefore potentially more sensitive at a lower PO₂.³¹ Electrochemical systems for intra-arterial measurement of pH and PCO₂ are not feasible as the sensing element is the glass electrode.

Temperature compensation

Temperature compensation of sensors is essential because all sensor chemistries involve steady states and rate constants which are temperature dependent. Furthermore, the activities of analytes in biological fluids are temperature dependent.

Conventionally, blood gas analysers measure temperature at 37°C and corrections must be made for comparisons with data at other temperatures.

Of the single parameter intravascular sensors, only the Continucath 1000 intravascular PO₂ sensor and the Neocath oxygen sensor for use in the umbilical artery of neonates, have reached commercial availability.

Table 4. Data on the physical characteristics of the intravascular sensors

Sensor	Type	Measures	Temperature compensation	Size	90% in vitro response times (Sec)			Calibration
					pH	PCO ₂	PO ₂	
PB 3300	Optode	pH, PCO ₂ and PO ₂	Yes	0.55 mm	30	84	48	In vitro 15 min
CDI 3M	Optode	pH, PCO ₂ and PO ₂	Yes	0.6 mm	N/A	N/A	N/A	In vitro 15 min
Optex	Optode	pH, PCO ₂ and PO ₂	Yes	N/A	N/A	N/A	N/A	In Vitro
Paratrend 7	Hybrid Electrode-Optode	pH, PCO ₂ and PO ₂	Yes	0.5 mm	78	143	70	In Vitro 30 min

Development of continuous blood gas monitoring systems

Problems with cannula occlusion, thrombus formation and excessive drift have been reported by Pfeifer *et al*, and Rithalia *et al*, with the Continucath system.^{21,32}

Multiparameter Sensors

A number of systems have been developed based on the above theoretical principles. Broadly, these can be grouped into two: pure optode based systems and hybrid electrode-optode systems. Three devices, based entirely on optode technology, are the CDI 1000 (Cardiovascular devices, Irvine, California),^{23,24,33} Optex Biomedical (Texas) 26 and the PB3300 (Puritan Bennet).^{28,34,35} The Paratrend 7 (P7), a product of Diametrics Medical, UK, is a hybrid electrode-optode system incorporating a fiberoptic pH and PCO₂ sensor with an amperometric oxygen sensor and a thermocouple to facilitate temperature compensation.^{27,36-41} The PB 3300 and the Paratrend 7 systems have been widely evaluated and are commercially available. A cross section of the Paratrend 7 sensor tip is illustrated in Figure 1.

The comparative physical and performance characteristics of the various blood gas monitoring systems are presented in Tables 4 and 5. Although there are a number of desirable features with CIABGM (Table 6), none of the currently available systems achieve all of the requirements of these systems.

Evaluation of continuous blood gas monitoring systems

CIABGMs are usually evaluated in the following manner: 1) *in vitro*, where the sensors are evaluated by bubbling a calibration gas containing a known concentration of O₂ and CO₂ through blood in a bubble tonometer⁴² and comparing the data from the sensors with the expected values, 2) *in vivo*, in animal models and in human clinical trials where the data from the sensors are compared with data from a blood gas analyser. The latter are taken as the reference standards.

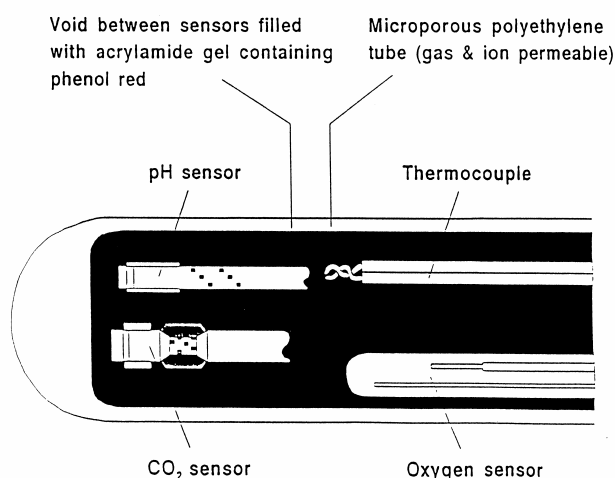


Fig. 1 A cross section of the Paratrend 7 sensor tip

Table 5. Clinical performance of the currently available intravascular and extracorporeal sensors

Investigator	Sensor	Patient number	Clinical setting	pH Bias ± Precision	PCO ₂ Bias ± Precision	PO ₂ Bias ± Precision
Barker ²³	Optode	14	Operating room (OR)	- 0.03 ± 0.04	- 0.5 ± 0.62	- 1.2 ± 3.1
Smith ²⁵	Optode	5	Operating room	- 0.01 ± 0.02	0.42 ± 0.33	- 0.79 ± 1.6
Zimmerman ²⁶	Optode	5	ICU	- 0.02 ± 0.037	0.23 ± 0.81	- 0.79 ± 1.76
Larson ³⁴	Optode	29	OR/ICU	0.01 ± 0.04	0.16 ± 0.44	0.04 ± 1.2
Venkatesh ²⁷	Electrode-optode	14	ICU (Radial)	0.02 ± 0.06	0.22 ± 0.6	0.4 ± 3.4
Venkatesh ³⁶	Electrode-optode	10	ICU (Femoral)	0.006 ± 0.07	0.22 ± 1.65	0.8 ± 2.7
Venkatesh ³⁷	Electrode-optode	20	Cardiopulmonary bypass	0.01 ± 0.06	0.53 ± 0.33	0.5 ± 6
Shapiro ⁶²	Extracorporeal optode	117	ICU	- 0.004 ± 0.03	-0.09 ± 0.28	- 0.28 ± 1.2

pH expressed in pH units. PCO₂ and PO₂ expressed in kPa.

The degree of agreement between the sensor and the blood gas analyser (BGA) can be quantified in terms of bias and precision⁴³. Bias is a consistent difference in the measured value of a known variable, while precision is the reproducibility of the measurements of the variable. Data can also be presented graphically as a Bland-Altman plot (Figure 2).

Table 6. Desirable features of a CIABGM

- 1) Easy to use and maintain and provide data for at least 72 hours
- 2) Able to pass through standard 20G cannulae without interfering with the arterial waveform or sampling
- 3) Bias and precision levels of 5% in vitro and 10% in vivo for PCO₂ and PO₂ during stable cardiovascular function
- 4) Trend blood gases reliably under conditions of varied blood flow
- 5) Cost effective

There has been a tendency to use the Pearson Correlation coefficient to describe agreement between the CIABGM and the BGA. This is inappropriate as the Pearson Correlation coefficient measures the strength of a relationship between two variables and not the agreement between them. Therefore variables which have a systematic difference may show a perfect correlation, but may have large bias and imprecision.

Despite encouraging results in vitro and in animal testing, the same degree of bias and precision has not been achieved consistently with intravascular sensors in clinical trials. Some of the factors which could explain the discrepancy are discussed below.

Factors producing a dissociation between a BGA and a CIABGM measurement

Accuracy of the blood gas analyser: Although the blood gas analyser is used as the reference standard for evaluation of intra-arterial blood gas monitors in clinical trials, numerous pitfalls exist with intermittent blood gas analysis which can induce errors (Table 2).⁴⁴⁻⁴⁸ Substantial measurement differences exist between individual blood gas analysers from the same or different manufacturers on the same blood sample due to differences in calibration techniques, sample chamber design, sample introduction technique, sample size, warming and the electronics.⁴⁹⁻⁵¹ BGAs are recalibrated at frequent, predetermined intervals in contrast to that of a CIABGM. Whilst quality control limits exist for bench top BGAs,⁵² no such regulatory

measures have been developed for CIABGMs.

Arterial blood flow: Theoretical considerations and experimental data support the notion that blood flow down the artery in which the sensor is placed may impact on sensor performance. Blood sampling for blood gas measurement is achieved by aspirating a sample of blood from the arterial line; initially to clear the 'dead space' followed immediately by another sample for the blood gas analysis. Removal of the dead space volume has the effect of drawing a specimen of blood from the central arterial tree. An intra-arterial sensor placed in a peripheral artery measures gases in the peripheral arterial blood which theoretically should be the same as those of a central arterial sample if there is good peripheral blood flow. In the presence of peripheral circulatory failure, the sensor is in a relatively stagnant pool of blood and the measurements obtained from the sensor may not agree with those from a conventional arterial sample. Significant reduction or cessation of blood flow can create a gradient in blood gas values between the blood being pumped by the heart and the blood being sensed peripherally so that sensors may not reflect central blood gas concentrations accurately and may respond to changes in cardiopulmonary function with a significant time delay. Experimental data also exists to support this hypothesis.^{21,36,53} In one of the preliminary trials with a CIABGM, the author observed large biphasic changes in temperatures (Figure 3) as measured by the thermocouple of the intravascular sensor, during sampling of the blood for arterial blood gases and subsequent flushing with a heparinised saline. This suggested that the sensor was not in contact with a continuous flow of blood and that contact with warm core blood during sampling caused the temperature to increase. Likewise the drop in temperature, due to the heparin flush following the sampling, would not be of such magnitude if there was good peripheral flow. Measurements at these time points were often associated with large offsets in PO₂ measurements (as PO₂ is the most flow dependent variable). Evidence for the flow hypothesis also exists in a recently published study, where there was a trend towards better sensor performance in patients with improved arterial flow.⁵⁴

Wall effect: Mahutte *et al*, observed sudden unexplained decreases in sensor PO₂ readings, which were overcome by alteration of wrist position or retraction of the sensor into the cannula.²⁴ The decreases in PaO₂ termed the "wall effect" were thought to be due to contact between the sensor and the arterial wall and hence reading some average of blood PO₂ (~12-13kPa) and tissue PO₂ values (~ 5.5kPa).

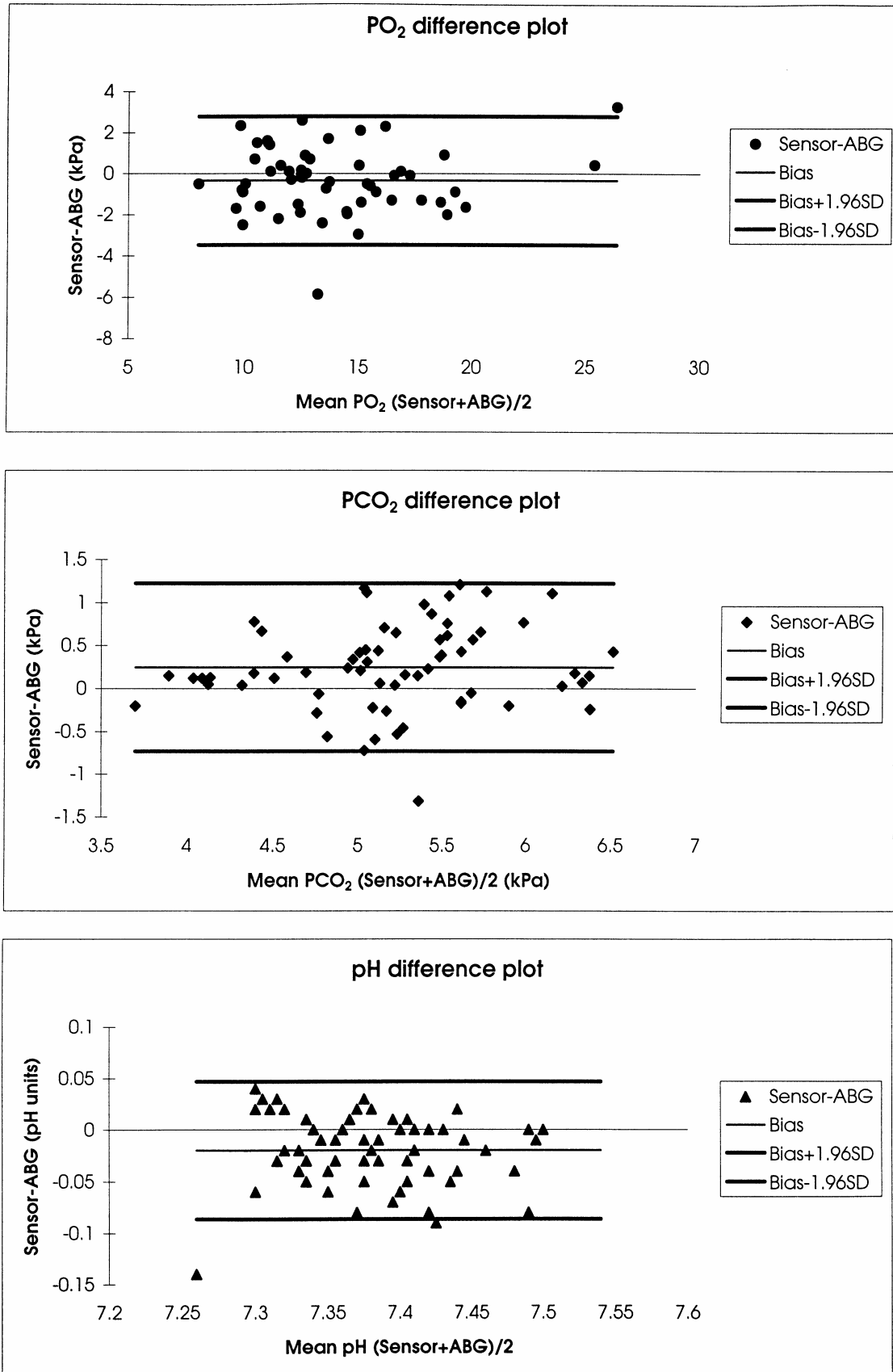


Fig. 2 Bland-Altman plots illustrating the performance of the Paratrend 7

This phenomenon should be considered when the PO₂ sensor tends to under-read.

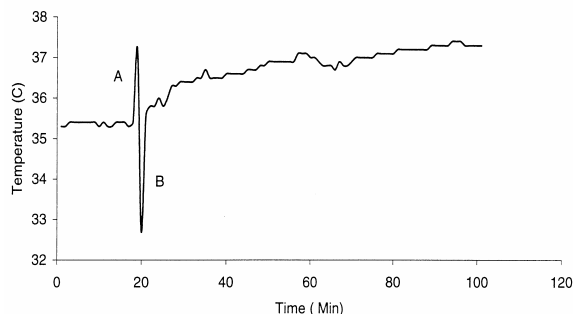


Fig. 3 Temperature changes in the radial artery during blood sampling and heparinised saline flushing. A – temperature rise with sampling, B – temperature drop with flushing

Flush effect: The continuous heparinised saline flush used to maintain the patency of arterial cannulae can potentially affect sensor data. The flush solution, at room temperature, contains dissolved oxygen and carbon dioxide at partial pressures similar to that of the atmosphere. If the sensing elements of the device are not inserted to an adequate distance past the tip of the arterial cannula, then they may measure the blood gases in the flush solution resulting in erroneous 'blood gas measurements'. The effect of the flush is two fold: the first is to alter the local gas tensions, and the second is to induce a change in temperature of the blood flowing past the sensor. Although the significance of this phenomenon in clinical practice is not clear, the author has observed that a longer insertion length of the sensor past the tip of the cannula often results in improved sensor performance.⁵⁴

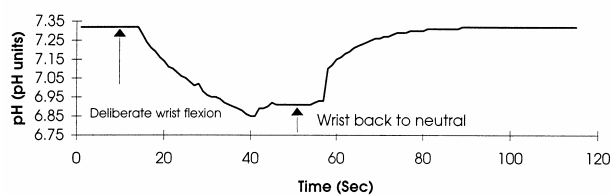
Impact of wrist position: The radial artery is the most commonly used site for arterial cannulation in intensive care practice. An intra-arterial sensor placed in the radial artery may be prone to wrist movement artefacts (Figures 4a and 4b). Bending of the wrist can compromise radial arterial flow and interfere with light transmission to and from the optodes to varying degrees. This effect is clinically relevant because patients in the ICU who are restless, may not always maintain their wrists in a neutral position.

From the above it is evident that the performance of an intravascular sensor is confounded by a number of clinical variables, which are commonly seen in the critical care setting and therefore it is unrealistic to expect a consistent degree of correlation between the sensor and the blood gas analyser in every instance.

Limitations and problems of indwelling sensors

The technology of intra-arterial blood gas monitoring has been developed, by necessity, in the laboratory, where the sample containing the analyte is in a stable environment with a fixed volume, in contrast to the clinical situation where there is a constantly changing 'environment'. Host response to the sensor in the form of macrophage deposition on the external surface and thrombogenicity are well recognised problems with many commercially available intravascular catheters.⁵⁵ The former can lead to a reduction in the time period of response, whereas the latter has been minimised by the use of heparinised saline flush, selection of biocompatible materials and heparin bonding of sensors. Failure of electrical and optical circuitry, often induced by user-patient insult, can also result in erroneous sensor measurements. Finally interference with arterial waveform and sampling of blood from the arterial line are other potential problems which may arise during the use of these monitors.

(a) Effect of flexion of the wrist on sensor pH measurements



(b) Effect of wrist flexion on sensor PCO₂ measurement

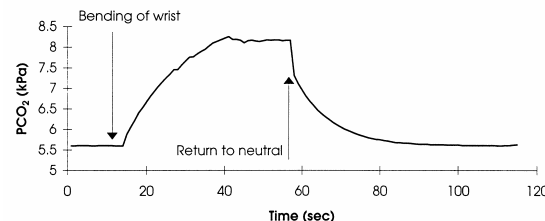


Fig. 4 Aberrant pH (a), and pCO₂ (b) data resulting from bending of the wrist

Robustness of intra-arterial sensors

A number of design features have been developed to increase the robustness of intra-arterial sensors and sensor longevity without causing arterial occlusion, interference with waveform or blood sampling. These include the use of flexible fiberoptics, employment of glass (Puritan Bennet, Optex) and plastic fibers (Paratrend 7) to minimise size (yielding sensor diameters between 0.5 to 0.62mm) and supporting the fibers with Kevlar strips. Despite the above design characteristics, if sufficient care is not taken, the sensors

are prone to damage during medical and nursing maneuvers. Damage to the sensor can lead to sensor malfunction, if there is damage to the optical fibers or the conducting wires. The recently developed systems display alarm signals which alert the user to such sensor insults. The use of wrist splints recommended by various manufacturers in the case of radial arterial sensors appears to have minimised some reports of sensor damage.

There is no report of any of the devices currently marketed having issues of sensor structural integrity problems that might be a threat to patient safety.

Clinical Applications of Continuous Intra-arterial blood gas monitoring

The proposed advantages of CIABGM in comparison with intermittent measurements include availability of continuous data, decrease in the laboratory turnaround time, decrease in the amount of blood lost through sampling, decrease in the exposure of personnel to potentially infected blood, reduction in infection risk, alarm availability and decrease in therapeutic decision time (Table 7). However, none of these proposed advantages have been proven by controlled outcome studies. While most of the published data on CIABGMs testify to the accuracy of these systems in various clinical groups, little published data exist on their usefulness in the management of critically ill patients. The evidence for the latter is largely anecdotal.⁵⁶⁻⁵⁹

Table 7. Advantages of a CIABGM over intermittent blood gas analysis

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- 1) Availability of continuous data
 - 2) Earlier detection of deleterious events
 - 3) Potential for trend analysis
 - 4) Decrease in blood loss
 - 5) Decrease in laboratory turnaround time
 - 6) Decrease in exposure of staff to potentially infected blood
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Intensive Care

The ability to trend arterial blood gases with CIABGM should potentially facilitate management of patients with severe ARDS and other forms of respiratory failure, requiring high levels of inspired oxygen, PEEP and other adjunctive therapy (e.g. NO, prone positioning, surfactant therapy, liquid ventilation and tracheal gas insufflation). Airway pressure therapy could be titrated more rapidly using CIABGM. Likewise, procedures such as tracheal suctioning,

physiotherapy and change of patient position could be performed under closer observation.

The continuous measurement of pH and PCO₂ might also provide useful information during permissive hypercapnia.⁶⁰ It might be possible to 'fine tune' nitric oxide and prostacyclin therapy for ARDS with these systems.⁵⁶ The trending ability of CIABGMs would alert the clinician to any evolving deleterious changes in respiratory function, not otherwise detected by intermittent blood gas analysis and therefore enhance therapeutic decision making. The indications for performing arterial blood gas analyses in ICU patients are still unclear and study of trends in stable and unstable patients using these monitors might help to determine the optimum frequency of and intervals between, blood gas analyses. From a practical point of view, a case for using CIABGM can be made in patients in whom pulse oximetry monitoring is either technically difficult (e.g. severe burn injury) or unreliable (e.g. severe circulatory failure).

Anaesthesia

Major surgical procedures such as cardiac bypass, thoracotomies, major laparotomies and transplant surgery are accompanied by profound changes in blood gases in the perioperative period, particularly in patients with borderline preoperative respiratory function. Elective CIABGM in these patients may lead to earlier detection and treatment of severe derangement in acid-base balance and arterial blood gases. The use of these monitors during total hip replacement has allowed the elucidation of PaO₂ changes during cement implantation.⁶¹ Elective monitoring of the blood gas status on a continuous basis in high-risk patients might also facilitate patient management during the postoperative period.

Paediatric and neonatal intensive care

The CIABGMs have been validated for use in the paediatric population and published data are available relating to their use in anaesthesia and intensive care.⁴¹ A multiparameter sensor for use in the umbilical artery of neonates has been developed (Neocath) and is undergoing preliminary evaluation.

Why hasn't the technology been universally adopted?

A major factor determining the widespread acceptance of this technology is the issue of cost effectiveness, particularly in the current climate of escalating health care costs. The cost of a CIABGM in Australia is about \$ 25,000 for the monitor and about \$ 350 for the single use sensor. The cost of a blood gas

analysis has been reported to be between \$25 - \$150 in a North American ICU. In contrast, most European and Australasian ICUs possess their own blood gas analyser, thus significantly decreasing the cost of an individual blood gas analysis. Although an argument may be made on the savings made by the reduced number of conventional blood gas analyses performed, a significant reduction in costs is not achieved in most ICU patients because a minimum number of two blood gas analyses per day are required to perform a 12 hourly in vivo calibration.

The other important issue to examine is whether the regular use of these systems would lead to an improvement in patient outcome in terms of a reduction in the number of adverse events, ventilator days or duration of weaning. The data are currently non-existent, and would be difficult and costly to provide. To decipher the exact contribution of one monitoring system within a plethora of monitoring modalities, together with the numerous variables which influence patient outcome would be a very complex task.

It is important to note that cost effectiveness data do not exist for many of the standard monitoring techniques used in the ICU despite their widespread use in clinical practice (e.g. pulse oximetry, pulmonary artery catheterisation). Nevertheless, while the usage of CIABGMs is increasing, it is likely that their wholesale acceptance will ultimately be determined by outcome studies.

Extracorporeal on demand Blood Gas Monitor

Some of the problems encountered with intra-arterial sensors, particularly the effects of flow and position, have prompted the development of continuous extracorporeal monitors. The CDI 2000 is an example of an extracorporeal, optode based, on demand blood gas monitor and results from a four centre trial demonstrate a consistent level of accuracy equivalent to that of a blood gas analyser.⁶² When a blood gas measurement is desired, a sample is drawn into a sensing cassette located externally and the results are available in two minutes. Although the need to sample blood is obviated, it is still an intermittent measuring system and does not provide real time data.

Continuous extracorporeal blood gas monitoring systems

Other examples of extracorporeal blood gas monitoring systems include those designed for use in the extracorporeal circuit for use during cardiopulmonary bypass (Gas STAT, Cardiomet 4000).^{63,64} Nevertheless, while they provide reliable trend monitoring, the bias and precision data are not consistent when compared to continuous intravascular blood gas systems.³⁷ This

combined with the need for anticoagulation with the use of extracorporeal systems makes their role in ICU patients limited.

Applications of continuous blood gas monitoring systems

Although these systems were designed initially for continuous blood gas monitoring, they have found greater application in the continuous monitoring of tissue oxygenation and tissue perfusion. Our group have demonstrated the usefulness of the Paratrend 7 system for the measurement of subcutaneous and gut oxygenation in an animal model of haemorrhagic shock.⁶⁵ We have also validated the usefulness of continuous gut luminal PCO₂ measurements as a sensitive indicator of splanchnic ischaemia.⁶⁶ The Paratrend 7 system has also been adapted for the monitoring of cerebral oxygenation.^{67, 68} Although only one published study examined the usefulness of continuous arterial-end tidal CO₂ gradient as a trend of continuous cardiac output in the presence of stable ventilatory parameters and found a poor correlation,⁶⁹ this measurement offers a novel method of titrating inotropic therapy with minimally invasive technology. A recent modification to the design of the Paratrend 7 system has been the development of a pure optode based multiparameter sensor.

In 1980, Eberhart stated that continuous blood gas monitoring was an elusive ideal;⁷⁰ in the nineties, it has become a reality. Further refinements to this technology and data on cost effectiveness are required before it finds widespread application in intensive care practice. Physiological studies to define the interaction between the probe and the host environment will enable us to develop and apply this exciting technology further.

Received: 17 December 1998

Accepted: 22 January 1999

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