Clinical assessment of a continuous intra-arterial blood gas monitoring system

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We evaluated the clinical performance of a continuous intra-arterial blood gas monitoring (CIABG) system which includes a fluorometric intravascular sensor. Seventeen patients undergoing elective surgery were monitored perioperatively with the CIABG system (PB3300; Puritan Bennett, Carlsbad, CA). Conventional laboratory blood gas analyses (BGA) were performed simultaneously whenever indicated, and the values were compared with those obtained from the CIABG system. Monitoring time ranged from 24 to 72 hr. The biases (average error between PB3300 and BGA) of pH, PCO₂ and PO₂ were 0.003 pH unit, -2.8 mmHg, and 0.9 mmHg in the operating room (OR), and 0.005 pH unit, 3.9 mmHg, and 8.5 mmHg in the intensive care unit (ICU), respectively. The precision (standard deviation of the bias) of pH, PCO₂ and PO₂ were 0.030 pH unit, 2.1 mmHg, and 29.9 mmHg in the OR and 0.035 pH unit, 3.8 mmHg, and 14.7 mmHg in the ICU, respectively. Although the PB3300 system was clinically useful as a trend monitor, the system's precision and reliability were unacceptable for estimation of true blood gas values.

Nous évaluons en clinique la performance d'un système de monitoring continu des gaz artériels (CIABG) qui contient un senseur fluorométrique intravasculaire. Dix-sept patients subissant une chirurgie programmée sont monitorisés pendant la période périopératoire avec le système CIABG (PB 3300; Puritan Bennett, Carlsbad, Californie). Des mesures conventionnelles de laboratoire (BGA) sont réalisées simultanément lorsqu'indiquées

et les résultats sont comparés avec ceux obtenus par le système CIABG. La durée du monitoring se situe entre 24 et 72 heures. Le biais (l'erreur moyenne entre PB 3300 et BGA) du pH, de la PCO₂ et de la PO₂ est de 0,003 unité de pH, -2,8 mmHg et 0,9 mmHg en salle d'opération (SO); de 0,005 unité de pH, 3,9 mmHg et 8,5 mmHg à l'unité de soins intensifs (USI). La précision (écart-type du biais de la moyenne) du pH, de la PCO₂ 0,030 unité de PH, 2,1 mmHg et 29,9 mmHg en SO et de 0,035 par unité de PH, 3,8 mmHg et 14,7 mmHg à l'USI. Bien que le système PH 3300 soit cliniquement utile comme moniteur de tendance, sa précision et sa fiabilité sont inacceptables pour l'estimation des valeurs absolues des gaz sanguins.

The analysis of arterial blood gas values (pH, PaCO₂, PaO₂) is essential for the perioperative management of critically ill patients. Current analysis is periodic, because it is based on intermittent arterial sampling and *in vitro* measurements. Many clinicians have been looking forward to continuous monitoring, because it may improve patient care by allowing earlier detection of developing abnormalities in critical situations.

Placing a sensor into the patient, instead of drawing blood from the patient, is one of the approaches which enables continuous arterial blood gas monitoring. In the 1970's, miniaturized electrochemical pH, PCO₂, and PO₂ electrodes were developed for intravascular placement, but they had some problems. First, they tended to show calibration drift. Second, because of technical limitations of miniaturization, it was difficult to make a single sensor package capable of measuring all three variables.¹

Recently, optical fibre techniques and pH/oxygen sensitive dyes have been important in overcoming such hurdles. Since the mid-1970's, several types of fluorometric intra-arterial blood gas sensors have been developed and their accuracy has been verified both *in vitro* and *in vivo*. Among them, the CDI System 1000 (CDI-3M Healthcare, Irvine, CA), was the prototype three component blood gas sensor which contains optical fibres to measure pH, PCO₂, and PO₂. It was 0.6 mm in diameter and easy to insert through a 20-ga. cannula. Although *in vitro*

Key words

ACID-BASE EQUILIBRIUM: measurement;
EQUIPMENT: analyzer, oxygen, carbon dioxide, pH;
MEASUREMENT: acid-base, gas tensions.

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Accepted for publication 12th September, 1993.

TABLE 1 Patients' data

No	Age (yr)	Operation	Duration (hr)	Reasons for sensor removal
1	30	Renal artery reconstruction	24	Discharge from ICU
2	63	OWRT	72	72 hr*
3	71	OWRT	47	Discharge from ICU
4	67	OWRT	50	Inadequate AP monitoring†
5	56	Right nephrectomy	49	Discharge from ICU
6	65	OWRT	47	Discharge from ICU
7	62	OWRT	72	72 hr*
8	64	OWRT	72	72 hr*
9	71	OWRT	72	72 hr*
10	21	OWRT	50	Discharge from ICU
11	44	OWRT	21	Inadequate AP monitoring†
12	74	OWRT	24	Inadequate AP monitoring†
13	54	OWRT	24	Inadequate AP monitoring†
14	70	Oesophageal bypass	22	Discharge from ICU
15	50	OWRT	23	Inadequate AP monitoring†
16	67	Aortofemoral bypass	35	Discharge from ICU
17	65	OWRT	72	72 hr*

OWRT: Oesophagectomy with right thoracotomy.

*Monitoring duration >72 hr.

†Arterial pressure wave became over-damped and accurate arterial pressure monitoring was not possible.

FIGURE 1 The intravascular sensor.

studies in tonometered bovine blood showed high accuracy, the data from patients gave relatively poor results.¹⁻³ Recent reports have introduced new devices and verified their clinical accuracy.^{4,5}

The PB3300 (Puritan Bennett, Carlsbad, CA) is a new fluorometric continuous intra-arterial blood gas monitoring (CIABG) system. One of the new features is its sensor configuration. While the prototype sensors had the dyes fixed at the tip of the fibre, the PB3300 system have the dyes immobilized along the exterior circumference of the fibre⁶ (Figure 1). Such a configuration enables a larger total signal because of its much larger surface area. *In vitro* tests with tonometered whole blood or pH buffers have already shown its accuracy. In this report, we present the results of a clinical study of the performance of the CIABG system.

Methods

With institutional approval and individual informed consent, the study was performed in 17 patients undergoing elective surgery. Surgical procedures included oesophagectomy with right thoracotomy (13 of 17 patients) which required differential lung ventilation (DLV) (Table I).

After arrival of the patient in the operating room (OR), the radial artery was cannulated with a 20-gauge intra-vascular catheter (Becton Dickinson Insyte® ArtCath™ arterial catheterization unit) under local anaesthesia. Through it, a sensor (PB-FOx Intra-Arterial Blood Gas Sensor, Puritan Bennett, Carlsbad, CA) was inserted into the artery. Arterial blood pressure was monitored by connecting the conventional pressure transducer to the side port of the catheter (Figure 1). Then pH, PaCO₂, and PaO₂ were automatically measured every 20 sec. Blood samples were drawn from the arterial sampling port into dry heparinized syringes whenever the physician ordered blood gas analysis. In the operating room, arterial blood gas analyses were performed every 30–60 min. All samples were analyzed within a few minutes by a laboratory blood gas analyzer (BGA) (STAT Profile™; NOVA biomedical, Waltham, MA). After the end of the surgical procedure, the sensor cable was disconnected from the monitor, and the patient was transferred to the intensive care unit (ICU) with the sensor *in situ*. In the ICU, the sensor cable was reconnected to the monitor, and monitoring was resumed. Continuous intra-arterial blood gas monitoring lasted for up to 72 hr. All values (pH, PaCO₂, and PaO₂) were printed out with the on-board printer. In ten of 17 patients, data were also recorded with a

personal computer (Pc-9801 NT/S, NEC, Tokyo) connected to the PB3300 system through an RS-232C serial communication port.

Sensor calibration

THE PB3300 SYSTEM

Before insertion of the sensor into the arterial cannula, *in vitro* two-point calibration was carried out with two calibrating gas mixtures (the first gas contained 7% O₂, 2.8% CO₂ and the balance N₂; the second gas contained 21% O₂ and 8.4% CO₂ and balance N₂). The monitor was not recalibrated until the end of the monitoring.

BGA SYSTEM (STAT PROFILE[®])

With the BGA system both one-point and two-point calibration were performed using the standard gas mixtures (the standard gas A contains 20.0% O₂, 5.0% CO₂ and balance N₂; the standard gas B contains 10.0% CO₂ and balance N₂). A two-point calibration using both gas A and B, was initiated automatically at intervals of several hours. A one-point calibration was performed using gas A at approximately 30 min intervals.

Data analysis

Data were divided into OR and ICU data groups.

CORRELATION ANALYSIS

Correlation analysis was performed between the corresponding data of PB3300 and BGA and correlation was described by Pearson's *r* value.

ACCURACY AND REPEATABILITY

Accuracy was quantified by the bias which is the averaged difference between PB3300 and BGA measurements. Repeatability was assessed by precision, which is the standard deviation (SD) of the bias. We also constructed Bland-Altman diagrams,⁷ by plotting the error on the ordinate and the mean of two methods on the abscissa, to represent the relationship between the measurement error and the true value.

STABILITY ANALYSIS

For stability analysis, the data were divided into six groups at 12 hr sampling intervals. Intergroup differences were analyzed using ANOVA. If *F* was <0.05, Scheffe *F* test was performed as a *post hoc* evaluation.

Results

Twenty-one sensors were used in the study. During setup and calibration, three sensors were found to have "sensor fault" and were discarded. We failed to insert one sensor into the radial artery because of anatomical variation.

TABLE II Correlation analysis and accuracy

	OR	ICU
<i>pH</i>		
Pearson's <i>r</i> value	0.77	0.79
Bias (pH unit)	0.003	0.005
Precision (pH unit)	0.030	0.035
<i>PCO₂</i>		
Pearson's <i>r</i> value	0.77	0.8
Bias (mmHg)	-2.8	3.9
Precision (mmHg)	2.1	3.8
<i>PO₂</i>		
Pearson's <i>r</i> value	0.95	0.98
Bias (mmHg)	0.9	8.5
Precision (mmHg)	29.9	14.7
<i>PO₂ < 200 mmHg</i>		
Bias (mmHg)	0.6	7.0
Precision (mmHg)	18.1	12.0

Monitoring time ranged from 24 to 72 hr (mean 46 hr). Five patients were monitored for 72 hr, and then according to the manufacturer's recommendation, the sensors were withdrawn. In five patients CIABG monitoring was interrupted because arterial pressure monitoring was interfered with by the sensor (arterial pressure wave was restored by the sensor removal). In the other cases CIABG monitoring was interrupted because patients left the ICU (Table I). No complications (e.g., vessel thrombus, haematoma formation, postoperative pain at insertion site, loss of pulse) were found in this study.

Arterial blood sampling and BGA were performed 196 times in the OR, and 151 times in the ICU. Scattergrams of the compared data from PB3300 and BGA are shown in Figure 2. Pearson's *r* values for pH, PCO₂, and PO₂ are shown in Table II. There was no difference between the *r* values obtained in the OR and those from the ICU.

The bias and precision of each variable are shown in Table II. Bland-Altman diagrams for pH, PCO₂, and PO₂ are shown in Figures 3-6. In addition, the accuracy of PO₂ values <200 mmHg was analyzed separately (Table II and Figure 6).

The results of the stability analysis are shown in Figure 7. Although the PO₂ sensor was almost stable throughout the study, pH and PCO₂ sensors showed considerable bias drift. Compared with the first 12 hr, the pH sensor tended to show higher values after 24 hr, and the PCO₂ sensor tended to show higher values after 36 hr.

An example of plots of CIABG values, with superimposed laboratory measurements, is shown in Figure 8. In this patient, hypoxaemia occurred during DLV and resolved with 5 cm H₂O CPAP to the nonventilated non-dependent lung. However, about three hours after the in-

FIGURE 2 Scattergrams of correlation analysis. (a) pH data collected in OR; (b) pH data collected in ICU; (c) PCO₂ data collected in OR; (d) PCO₂ data collected in ICU; (e) PO₂ data collected in OR; (f) PO₂ data collected in ICU. r: Pearson's r value.

section of the PB3300 sensor, hypoxaemia recurred and DLV was interrupted. In addition, 6.5 hr after sensor insertion, the airway pressure increased rapidly and the endotracheal tube was found to be obstructed. The PB3300 sharply responded to fluctuation of blood gas data and was useful for early detection of each episode.

Discussion

Continuous intra-arterial blood gas monitoring is theoretically useful in the perioperative patient management for several reasons.^{1,2,4} With such monitoring, physicians can detect abnormal blood gas data more quickly than with intermittent conventional laboratory measurement. They can also observe trends and evaluate treatments. Frequent blood sampling is not necessary and the possibility of infection can be reduced. In addition, the fluorometric method, which is used in the PB3300 system, is free from electrical hazard and is not interfered with

FIGURE 3 Bland-Altman diagrams of pH. Mean of PB3300 and laboratory blood gas analysis (BGA) are plotted on the X-axis and the difference between the two methods (error) on the Y-axis. Data were collected in (a) OR, and (b) ICU.

by electrical noise. Because the sensor is placed directly in the radial artery, intra-arterial blood gas monitoring is hardly influenced by poor peripheral circulation which occasionally interferes with pulse oximetry. Compared with end-tidal CO₂ for PaCO₂ monitoring, continuous intra-arterial blood gas monitoring is not influenced by ventilation-perfusion inequality. Moreover, sensors in the bloodstream enable direct measurement of arterial blood and exclude modifications which may occur during sampling and carrying. For example, it is difficult to measure high PO₂ values with current laboratory techniques, because oxygen in the sampled blood may be consumed by erythrocytes or diffused into the air during transport.

In this study, continuous intra-arterial blood gas monitoring with the PB3300 system was performed in 17 patients. The first purpose of the study was to investigate its *in vivo* accuracy in the perioperative period. The second purpose was to examine its clinical performance as a "continuous" monitor. To investigate the optode sensor accuracy, the values from the PB3300 were compared with the current laboratory electrode system. According to the instrument specifications of the Stat Profile system, its day-to-day precision is <0.009 for pH, <2.3 mmHg for PCO₂, and <3.4 mmHg for PO₂ with control so-

FIGURE 4 Bland-Altman diagrams of PCO_2 . Mean of PB3300 and BGA are plotted on the X-axis and the difference between the two methods on the Y-axis. Data were collected in (a) OR, or (b) ICU.

FIGURE 5 Bland-Altman diagrams of PO_2 . Mean of PB3300 and BGA are plotted on the X-axis and the difference between the two methods on the Y-axis. Data were collected in (a) OR, and (b) ICU.

FIGURE 6 Bland-Altman diagrams of PO_2 ($\text{PO}_2 < 200$ mmHg). Mean of PB3300 and BGA are plotted on the X-axis and the difference between the two methods on the Y-axis. Data were collected in (a) OR, and (b) ICU.

lutions. Thus the current electrode system can be regarded as an "established standard."

From this study, the PB3300 system fulfilled most requirements for trend monitoring. In particular during thoracotomy with differential lung ventilation, we consider that continuous intra-arterial blood gas monitoring is one of the most effective monitors. During differential lung ventilation, adequate oxygenation and appropriate ventilation are essential. Pulse oximetry and end-tidal CO_2 monitoring are currently used for estimation of arterial blood gas values. But during the anaesthetic management of thoracotomy, the efficacy of these techniques may be limited. Circulatory changes, often caused by mediastinal compression or relative hypovolaemia, may modify pulse oximetry. Also, large ventilation-perfusion inequality may increase the discrepancy between arterial and end-tidal CO_2 partial pressures. Monitoring with the PB3300 system enables information about arterial oxygenation and ventilation in real time. For example, Figure 8 clearly shows episodes such as hypoxaemia during differential lung ventilation, and hypercapnia caused by endotracheal tube obstruction.

As is obvious from Table II, the errors (difference of the values obtained by the two methods) of the pH and PCO_2 sensor were less than 0.07 pH unit and 7.8 mmHg

FIGURE 7 The results of stability analysis. The data were divided into six groups at 12 hr sampling intervals. The differences between PB3300 and BGA in each period are shown with mean $\pm$ SD.

respectively with 95% reliability. This may be acceptable for most clinical situations but such errors may still lead clinicians to erroneous evaluations in critically ill patients. On the contrary, the error of the PO₂ sensor was <60 mmHg with 95% reliability. In the Bland-Altman diagram of PO₂, plots exceeding 200 mmHg are more scattered. For plots of PO₂ <200 mmHg, the error was less than 36 mmHg with 95% reliability. This is still inadequate for clinical application. For example, if the PB3300 system indicates the PO₂ to be 70 mmHg, the true PO₂ may be 34–106 mmHg. Interpretation of such a value is difficult.

These results were similar to reports of other intra-vascular optode systems.^{1,2,4} Several factors may influence the accuracy of the intravascular sensor.^{1–4} First, the intravascular site of the sensor limits its accuracy. Because it is placed in the artery, contact with the vessel wall

FIGURE 8 The intraoperative trend of Patient #9. This patient had a radical resection of the thoracic oesophagus. During thoracotomy, differential lung ventilation was attempted, but was interrupted because of hypoxaemia. Although 5 cm H₂O CPAP to the non-dependent lung relieved the first hypoxic event, recurrence of hypoxia could not be prevented. During neck surgery, the endotracheal tube (single lumen) was obstructed because of malposition. The PB3300 showed gradual rise of PCO₂ and drop of pH. After correcting the position, hypercapnia was rapidly restored. DLV: Differential lung ventilation; ETT: Endotracheal tube.

and/or clot formation may be inevitable. Mahutte *et al.* reported a "wall effect" of the CDI system 1000 intra-arterial blood gas sensor.² When the sensor tip touches the arterial wall, it measures intracellular pH, PCO₂ or PO₂ of vascular wall cells. As a result, pH and PO₂ decreased and PCO₂ increased. Although the PB3300 sensor unit (PB3Fox) has each sensor at a different angle and location (Figure 1), the wall effect may not be overcome completely. Clots also consume oxygen and produce CO₂. Although we have never observed clot formation on the sensor tip after its removal, micro clot formation during monitoring could not be excluded. Clots might be formed easily if the sensor tip touches the wall. In order to avoid these problems, wrist extension (stretching radial artery) and continuous flushing with heparinized saline is helpful but not sufficient. In particular for patients who have atherosclerotic and tortuous arteries,

relocation of the sensor might be necessary. Another possibility of overcoming such problems is with the extra-arterial fluorescent optode system.⁵ Although its clinical accuracy is better, it loses some features of continuous monitoring system.

Second, calibration methods have some problems. Because calibration gases of PB3300 system consist of CO₂ 2.8%, O₂ 7.0% and CO₂ 8.4%, O₂ 21%, the reliable range for accuracy is limited. Especially for PO₂, the more the actual value exceed these values, the less reliable is the measurement. Moreover, once the sensor is placed in the blood stream, its calibration cannot be adjusted except by making comparisons with a simultaneous blood sample.⁸ Two-point *in vivo* calibration is also difficult and, therefore, conventional quality control procedures, which are used in current laboratory analyzers and include frequent two-point calibrations, are not applicable to intravascular sensors.

According to the results of the study, calibration drift of the pH and PCO₂ sensors occurs after 24 hr (Figure 7). The causes of this phenomenon are unknown, but frequent *in vivo* calibration may be required to overcome this problem.

In conclusion, we used the PB3300 system in 17 patients and analyzed its clinical performance. From the viewpoint of trend monitoring, it gives much useful information in the perioperative period. However, because of its limited accuracy, estimating individual blood gas values with this system is unacceptable: occasional comparison with current blood gas analysis is preferable. Further refinement of the accuracy of such system is desirable before its substitution for current blood gas analyzers.

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