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# Comparison of Arterial Oxygen Tension with Continuous Transcutaneous and Intravascular PO<sub>2</sub> Sensors and Intermittent Blood Samples Taken from the Sampling Port of a Bubble Oxygenator

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**Keywords:** blood sample collection; PO<sub>2</sub>, monitoring; oxygenator, bubbler; PO<sub>2</sub>, transcutaneous

## Abstract

Measurements of transcutaneous PO<sub>2</sub> (tc PO<sub>2</sub>), intra-arterial PO<sub>2</sub> (PiO<sub>2</sub>) and PO<sub>2</sub> of blood samples taken from the sampling port of the oxygenator (PoO<sub>2</sub>) were compared with arterial blood PO<sub>2</sub> (PaO<sub>2</sub>) in 16 adult patients undergoing cardiopulmonary bypass. tcPO<sub>2</sub> and PiO<sub>2</sub> were recorded continuously using Roche-Kontron electrodes. PoO<sub>2</sub> and PaO<sub>2</sub> were measured intermittently on a Radiometer ABL<sub>2</sub> blood gas analyser.

A total of 86 observations were made on the 16 patients. The correlation coefficient (r) between transcutaneous and arterial PO<sub>2</sub> was 0.69 (p<0.001). The relationship between PoO<sub>2</sub> and PaO<sub>2</sub> was poor (r=0.45, p<0.01). The intra-arterial electrode readings showed no significant difference with the PO<sub>2</sub> measured on arterial blood samples (r=0.99, p<0.001).

## Introduction

The measurement of the arterial blood oxygen tension (PaO<sub>2</sub>) is a routine part of the assessment of patients'

oxygenation while undergoing open heart surgery. Samples for blood gas analysis are usually withdrawn from the sampling port of the oxygenator provided for this purpose. The PaO<sub>2</sub> changes rapidly during cardiopulmonary bypass (CPB) and the variations can only be detected by frequent or continuous monitoring. The current methods, based on intermittent blood sampling, have inherent limitations related to the frequency with which samples can be taken, their storage and their processing before analysis. However, with the development of transcutaneous PO<sub>2</sub>(tcPO<sub>2</sub>) sensors (1,2) and intra-arterial PO<sub>2</sub>(PiO<sub>2</sub>) electrodes (3,4) it has become possible to monitor PaO<sub>2</sub> continuously. This study compares tcPO<sub>2</sub>, PiO<sub>2</sub> and PO<sub>2</sub> of blood samples taken from the sampling port of the oxygenator (PoO<sub>2</sub>) with arterial blood PO<sub>2</sub> in adult patients.

## Materials and Methods

Measurements were made in 16 adult patients (Table 1) whose ages ranged from 37 to 76 years (mean ± SD, 53.8 ± 9.9). They were undergoing normothermic cardiopulmonary bypass for valvular or coronary arterial surgery. The extracorporeal circuit consisted of a Bentley BOS-10 bubble oxygenator<sup>a</sup> and a Gambro (Model H-10)

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<sup>a</sup> Bentley Laboratories Inc, Irvine, CA 92714, USA

**Table 1**  
**Clinical details of patients**

| Patient (number) | Sex (M/F) | Age (years) | Weight (kg) | Surface area (m <sup>2</sup> ) | Diagnosis* (operation) | Perfusion rate (ℓ/min) | Bypass time (min) |
|------------------|-----------|-------------|-------------|--------------------------------|------------------------|------------------------|-------------------|
| 1                | F         | 55          | 75          | 1.78                           | AVR                    | 4.2                    | 85                |
| 2                | M         | 57          | 68          | 1.76                           | SVG × 3                | 4.4                    | 165               |
| 3                | M         | 49          | 57          | 1.64                           | SVG × 2                | 3.9                    | 138               |
| 4                | M         | 37          | 72          | 1.82                           | SVG                    | 4.4                    | 75                |
| 5                | M         | 54          | 81          | 1.90                           | SVG                    | 4.5                    | 65                |
| 6                | F         | 76          | 63          | 1.75                           | AVR + SVG              | 4.2                    | 95                |
| 7                | F         | 64          | 48          | 1.40                           | MVR + TVR              | 3.4                    | 75                |
| 8                | M         | 50          | 64          | 1.77                           | SVG × 3                | 4.2                    | 90                |
| 9                | M         | 37          | 67          | 1.79                           | SVG                    | 4.2                    | 65                |
| 10               | M         | 54          | 68          | 1.76                           | SVG × 3                | 4.3                    | 125               |
| 11               | M         | 52          | 79          | 1.98                           | SVG × 2                | 4.9                    | 105               |
| 12               | F         | 49          | 57          | 1.64                           | AVR + MVR              | 3.8                    | 120               |
| 13               | F         | 62          | 71          | 1.82                           | SVG × 2                | 4.3                    | 80                |
| 14               | M         | 42          | 70          | 1.88                           | SVG                    | 4.5                    | 110               |
| 15               | M         | 54          | 74          | 1.90                           | SVG                    | 4.5                    | 78                |
| 16               | M         | 61          | 75          | 1.97                           | AVR                    | 4.7                    | 93                |

\*Legend: AVR = Aortic Valve Replacement; SVG = Saphenous Vein Graft; MVR = Mitral Valve Replacement; TVR = Tricuspid Valve Replacement.

roller pump<sup>b</sup>. It was primed with 2ℓ of 5% dextrose solution. The mean perfusion rate was  $4.3 \pm 0.4\ell \text{ min}^{-1}$  and the mean bypass time was  $97.8 \pm 27.9 \text{ min}$ .

Patients were premedicated about an hour before leaving the ward. They were anesthetized and after an Allens' test (5), to demonstrate ulnar artery patency, radial artery cannulation was performed using an 18 gauge Abbocath cannula<sup>c</sup> for continuous blood pressure (BP) monitoring. The PiO<sub>2</sub> (Module 636) electrode<sup>d</sup>, which had been pre-treated with heparin, was inserted through the cannula using an aseptic technique. It was calibrated in-situ by withdrawing a blood sample from the arterial line and analyzing this sample with a conventional blood gas analyser. The catheters were perfused with a solution of 0.18% saline and 4% dextrose using a continuous flushing device. The temperature of the tcPO<sub>2</sub> (module 632) sensor was set at 44°C during calibration in room air and throughout all measurements. The shoulder was used as the tcPO<sub>2</sub> monitoring site, instead of the usual chest location, to prevent the disruption of the sensor during surgery. The blood pressure, the PiO<sub>2</sub> and the tcPO<sub>2</sub> signals were continuously recorded on a constant speed chart recorder. Although patients were not actively cooled during the operation, mean skin and nasopharyngeal temperatures fell to  $31.2 \pm 1.4^\circ\text{C}$  and  $35.6 \pm 1.2^\circ\text{C}$  respectively.

<sup>b</sup> Gambro Heart Lung Products AB, PO Box 10101, Lund 09-1982, Sweden

<sup>c</sup> Abbott Laboratories Inc, North Chicago, IL 60064, USA

<sup>d</sup> Kontron Instruments Ltd, Watford, Herts, WD1 8HQ, UK

Blood samples were taken simultaneously from the cannulated radial artery and the sampling port of the oxygenator, and analysed immediately in duplicate using a Radiometer-ABL2 blood gas analyser<sup>e</sup>.

Data were expressed as the mean  $\pm$  standard deviation. Statistical analysis was performed by means of a least square regression analysis and Students' t-test, with  $P < 0.05$  considered significant.

## Results

A total of 86 sets of observations were made on 16 patients and PaO<sub>2</sub> values were used as reference standard for statistical comparison. Overall, the PiO<sub>2</sub> readings were lower than the PaO<sub>2</sub> (Table 2), giving mean  $\Delta(\text{PaO}_2 - \text{PiO}_2) = 12.2 \pm 8.9 \text{ mm Hg}$ , but a paired t-test showed that this difference was not statistically significant. The tcPO<sub>2</sub> and the PoO<sub>2</sub>, however, were statistically different to PaO<sub>2</sub>. The mean differences were  $\Delta(\text{PaO}_2 - \text{tcPO}_2) = 108.9 \pm 71.8 \text{ mm Hg}$  and  $\Delta(\text{PaO}_2 - \text{PoO}_2) = 89.9 \pm 67.7 \text{ mm Hg}$ . Linear regression analysis (Table 3) of the data yielded for (1) intravascular electrode (Figure 1): PiO<sub>2</sub> =

**Table 2**  
**Comparison of PO<sub>2</sub> values**

| Description            | Mean  | Range  | S.D   | S.E  |
|------------------------|-------|--------|-------|------|
| PaO <sub>2</sub> mmHg  | 226.4 | 64-395 | 107.0 | 11.5 |
| PiO <sub>2</sub> mmHg  | 224.4 | 57-369 | 102.9 | 11.9 |
| tcPO <sub>2</sub> mmHg | 114.5 | 34-275 | 64.3  | 6.9  |
| PoO <sub>2</sub> mmHg  | 226.1 | 79-398 | 96.0  | 10.4 |

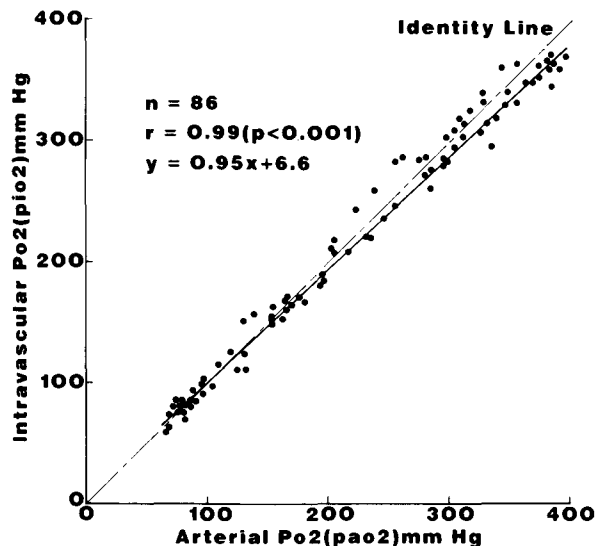
<sup>e</sup> Radiometer A/S, Emdrupvej 72, Copenhagen DK 2400, Denmark

0.95 PaO<sub>2</sub> + 6.6 with a correlation coefficient (r) = 0.99 (p<0.001), (2) transcutaneous sensor (Figure 2): AcPo<sub>2</sub> = 0.42 PaO<sub>2</sub> + 17.9 with r = 0.69 (p<0.001) and (3) samples from the oxygenator (Figure 3): PoO<sub>2</sub> = 0.41 PaO<sub>2</sub> + 173.1 with r = 0.45 (p<0.01).

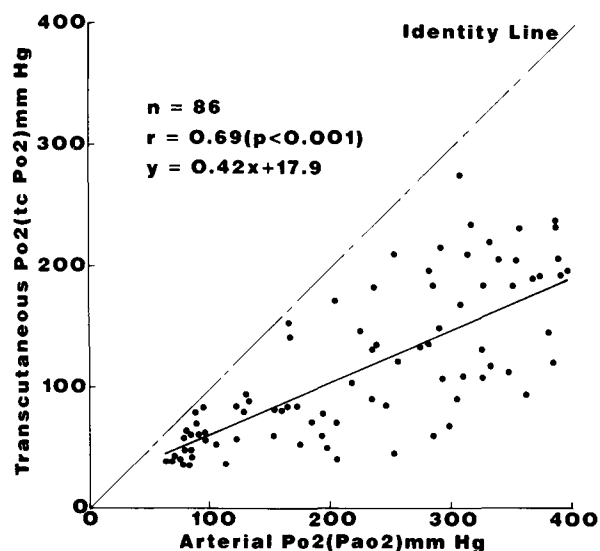
**Table 3**

Least Squares linear regression analysis of data

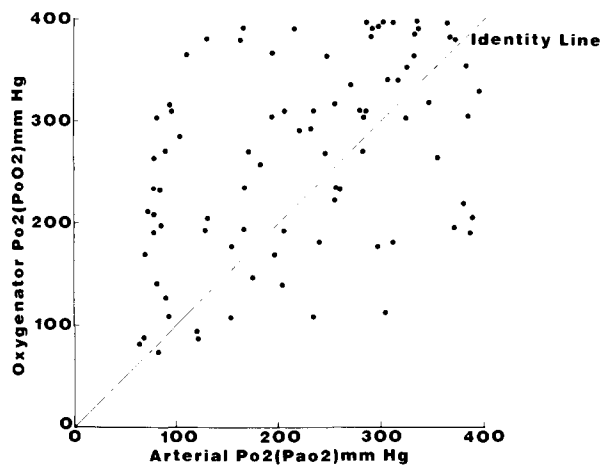
| Description            | Equation                        | r    | SEE  |
|------------------------|---------------------------------|------|------|
| PiO <sub>2</sub> mmHg  | 0.95(PaO <sub>2</sub> ) + 6.6   | 0.99 | 14.4 |
| tcPO <sub>2</sub> mmHg | 0.42(PaO <sub>2</sub> ) + 17.9  | 0.69 | 46.1 |
| PoO <sub>2</sub> mmHg  | 0.41(PaO <sub>2</sub> ) + 173.1 | 0.45 | 85.4 |



**Figure 1.** Comparison of simultaneous recordings of intravascular PO<sub>2</sub> and arterial blood PO<sub>2</sub>.



**Figure 2.** Comparison of simultaneous recordings of transcutaneous PO<sub>2</sub> and arterial blood PO<sub>2</sub>.



**Figure 3.** Comparison of simultaneous recordings of oxygenator sample PO<sub>2</sub> and arterial blood PO<sub>2</sub>. The equation of the regression line is PoO<sub>2</sub> = 0.41 PaO<sub>2</sub> + 173.1 (r = 0.45, p<0.01).

The intravascular electrodes were easy to insert through 18 gauge cannulae and they did not affect the intra-arterial blood pressure measurement. There were no complications with either the transcutaneous or the intravascular sensor system. The PiO<sub>2</sub> readings correlated extremely well with the PaO<sub>2</sub> measured in vitro. Directional changes of arterial oxygen tension were always in agreement with transcutaneous PO<sub>2</sub>. For all patients tcPO<sub>2</sub> values were lower than PaO<sub>2</sub>. There was wide discrepancy between arterial and oxygenator PO<sub>2</sub> values. The PoO<sub>2</sub> values did not follow any trend, as shown by a large scatter in Figure 3, but in 58 out of 86 observations they were higher than PaO<sub>2</sub>.

## Discussion

The PO<sub>2</sub> electrodes used in this study were Clarke type polarographic sensors (6). It is well known that measurement of blood oxygen tension by these electrodes depends on temperature (7), flow and presence of anaesthetic gases (8). The PO<sub>2</sub> is also affected by the influence of temperature on oxyhaemoglobin dissociation (9). Although PaO<sub>2</sub>, PoO<sub>2</sub> and PiO<sub>2</sub> are the measurements directly made in blood, tcPO<sub>2</sub> estimates blood PO<sub>2</sub> through the intact skin. The tcPO<sub>2</sub> measurement procedure itself is non-invasive and very simple but the readings are influenced by a variety of technical, methodological and physiological factors (10). Many variables, such as electrode temperature, peripheral perfusion and skin properties must be taken into account when the results are interpreted. The tcPO<sub>2</sub>, in fact, indicates mean PO<sub>2</sub> in the tissue beneath the sensor (11).

It is interesting to note that the correlation between tcPO<sub>2</sub> and PaO<sub>2</sub> (r = 0.69) is better than that between

PoO<sub>2</sub> and PaO<sub>2</sub> ( $r = 0.45$ ). Even at low cardiac flow rates changes in PaO<sub>2</sub> were reflected by similar directional variations in tcPO<sub>2</sub>. However, a wide discrepancy in (PaO<sub>2</sub> - tcPO<sub>2</sub>) shows that tcPO<sub>2</sub> values cannot be used as a substitute for PaO<sub>2</sub>. This difference is associated with reduced blood flow and the poor oxygenation in the cutaneous tissue (12,13) and probably in other organs (14). The ratio between tcPO<sub>2</sub> and PaO<sub>2</sub>, usually defined as the tcPO<sub>2</sub> index (15), varied from patient to patient. Shibutani et al. (16) have evaluated the usefulness of this parameter as a monitor of coming off bypass. A lower tcPO<sub>2</sub> has been always associated with poor peripheral perfusion (12,17).

In a recent study, Green et al. (18) compared artificial blood gas with continuous intra-arterial and transcutaneous PO<sub>2</sub> sensors in adult critically ill patients. On the basis of standard error of estimate (SEE) alone, they concluded that tcPO<sub>2</sub> monitoring is as valuable as PiO<sub>2</sub> in assessing PaO<sub>2</sub>. We do not believe that their claim is based on sound physiological premises, however useful those who use transcutaneous technique in adults may claim it to be, and we think that tcPO<sub>2</sub> should not be interpreted as a direct reflection of PaO<sub>2</sub>. On the other hand, as our results show an excellent correlation ( $r = 0.99$ ), the intravascular PO<sub>2</sub> sensor, when properly made and correctly calibrated, provides true PO<sub>2</sub> values in the artery itself and not just a trend of PaO<sub>2</sub>. Whilst the exact relationship between the blood and transcutaneous PO<sub>2</sub> may remain unknown, PiO<sub>2</sub> represents absolute PaO<sub>2</sub> values in the artery. Unfortunately, for initial in-situ calibration, PiO<sub>2</sub> electrode requires a measurement on arterial blood in vitro. The intravascular electrode readings, therefore, can only be as accurate as the PaO<sub>2</sub> measured initially on the blood gas machine. Furthermore, the problems, limitations and contra-indications with the use of PiO<sub>2</sub> electrodes are similar to those of arterial cannulation for monitoring cardiovascular function (19), and include infection and thrombosis.

In practice, blood sampling from the oxygenator was simple and easy. The procedure was also completely under the control of the perfusionist. However, the use of the sampling port is only of value if the PoO<sub>2</sub> correlates well with PaO<sub>2</sub>. Relationship between these two variables as shown in Figure 3, has a large scatter and poor correlation coefficient ( $r = 0.45$ ). In the majority of cases the oxygenator values overestimated the arterial PO<sub>2</sub> and the mean difference,  $89.9 \pm 67.7$  mmHg, was unacceptably large. Since both the PaO<sub>2</sub> and PoO<sub>2</sub> samples were withdrawn simultaneously and analysed on the same blood gas machine, the differences between the two variables could not have occurred due to measurement errors. The wide discrepancy between the oxygenator and arterial values is probably due to the presence of microbubbles of oxygen which equilibrate with arterial blood after leaving the oxygenator, and inadequate mixing of blood

at the sampling port. Based on the results of the present investigation as well as a previous report (20), we believe that the use of samples taken from the Bentley bubble oxygenator for assessment of PaO<sub>2</sub> is not an adequate alternative. The question as to whether this is true for other blood gas parameters, such as PCO<sub>2</sub> and pH, and other bubble oxygenators will remain unanswered until they are similarly evaluated, but the general criticisms and deductions are relevant to them.

Several workers (21,22) have suggested that microembolism is an important cause of brain damage during open heart surgery. Using continuous readings of the numbers of gaseous microemboli and PO<sub>2</sub> in the arterial line of an extracorporeal circuit, Pearson et al. (23) have demonstrated a direct relationship between the two measurements. It has also been established that hyperoxia can cause vasoconstriction and ischemia damage (24) to the retina, brain, heart and kidney. Various researchers (25) have recommended a range of PaO<sub>2</sub> between 100 and 200 mmHg during CPB. However, our observations and those of others (26) have shown that patients are exposed to unnecessarily high levels of oxygen. In order to avoid the risks of tissue hypoxaemia, the perfusionists are more inclined to run hyperoxic perfusions. This trend is likely to continue until the establishment of a clinically acceptable and reliable continuous blood gas monitoring system.

The following conclusions can be drawn from this study:

- (1) The intravascular PO<sub>2</sub> electrodes are accurate and can be easily used without disturbing the measurement of intra-arterial blood pressure.
- (2) Measurement of transcutaneous PO<sub>2</sub> cannot be considered as a substitute for PaO<sub>2</sub> monitoring in patients during CPB.
- (3) The PO<sub>2</sub> of blood samples taken from the sampling port of a bubble oxygenator is a misleading and poor indicator of arterial oxygen tension.

## Acknowledgments

We wish to thank the surgeons and physicians for permission to study their patients, Paul Bosworth for his help and Norah Virtue for her secretarial assistance.

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