Continuous intra-jugular venous blood-gas monitoring with the Paratrend 7 during hypothermic cardiopulmonary bypass²

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We measured the accuracy of the continuous intra-vascular blood-gas monitoring system (Paratrend 7, PT7) placed in the jugular venous bulb in 18 adult patients having cardiac or aortic surgery with hypothermic cardiopulmonary bypass (CPB). After induction of anaesthesia, a PT7 sensor was inserted through a 20-gauge venous catheter into the right jugular venous bulb. Blood samples were drawn from the venous catheter and measured with a blood gas analyser (BGA). Five to eight paired measurements using the PT7 and blood samples were made per patient, and bias and precision were calculated for each patient using the Bland-Altman method. The ranges for the blood sample measurements were: pH 7.12 to 7.59, P\textsubscript{CO\textsubscript{2}} 3.7 to 9.6 kPa, P\textsubscript{O\textsubscript{2}} 3.5 to 16.0 kPa, oxygen saturation 40 to 99%, bicarbonate 18.6 to 34.4 mmol l\textsuperscript{-1}, and base excess –7.8 to 12.5 mmol l\textsuperscript{-1}. Bias and precision values were 0.014/0.071 for pH, 0/0.90 kPa for P\textsubscript{CO\textsubscript{2}}, and ±0.16/1.18 kPa for P\textsubscript{O\textsubscript{2}}. These values were comparable with those previously made on arterial blood. However, precision for oxygen saturation in each patient varied 2.3 to 23.6% (95% CI: 6.3 to 12.9%), which was unsatisfactory for clinical measurements. Deep hypothermia (~19.6 °C) and marked haemodilution (~13.5%) during CPB did not influence the reliability of the PT7 sensor. Thus, we concluded that continuous intra-jugular venous blood-gas monitoring is clinically feasible using the PT7 and may provide valuable information during CPB.

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Brain injury is a serious adverse complication following cardiac surgery with cardiopulmonary bypass (CPB). Several aetiologies have been proposed; an imbalance between cerebral oxygen supply and demand during CPB may contribute to brain injury. Continuous measurement of jugular venous oxygen saturation using a fiberoptic oximetric catheter has been used during or after CPB to assess cerebral oxygen balance.¹⁻³

When increased oxygen extraction by the brain can no longer completely compensate for decreased oxygen supply, cerebral oxygen consumption will decrease and anaerobic metabolism with lactate production will result.⁴ These features may not be detected adequately by measuring changes in oxygen saturation or oxygen tension (P\textsubscript{O\textsubscript{2}}); measurements of pH and carbon dioxide tension (P\textsubscript{CO\textsubscript{2}}) in the jugular venous blood may more completely indicate changes in brain oxygenation.

The Paratrend 7 system (PT7) (Biomedical Sensors, High Wycombe, UK) incorporates four different sensors: P\textsubscript{O\textsubscript{2}} is measured with a miniaturized Clark-type electrode, P\textsubscript{CO\textsubscript{2}} and pH are measured with two optical fibres, and blood temperature is determined by a thermocouple. In addition, oxygen saturation, bicarbonate, and base excess are automatically computed from these variables. The four sensor elements are housed in a heparin-coated microporous polyethylene tubing approximately 0.5 mm in diameter, which can be passed through a 20-gauge catheter.

Acceptable accuracy and good clinical performance of the PT7 sensors in arterial blood have been demonstrated during surgery⁵⁻¹⁰ and in the intensive care unit.¹¹⁻¹⁵ We know of only one anecdotal report that describes the use of the PT7 in the jugular bulb of a patient with subarachnoid haemorrhage.¹⁶ We evaluated the accuracy and clinical feasibility of continuous intra-jugular blood-gas monitoring

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with the PT7 in adult patients undergoing cardiac or aortic surgery with hypothermic CPB.

**Methods**

After institutional approval, patients undergoing coronary artery bypass graft (CABG) surgery \( (n=12) \) or aortic surgery \( (n=8) \) under hypothermic CPB were enrolled. Written informed consent was obtained directly from 19 patients, and a close relative gave assent for one patient because the patient was intubated and sedated. Patients with cerebrovascular disease, uncontrolled hypertension (systolic pressure >150 mm Hg and/or diastolic pressure >95 mm Hg), or diabetes mellitus were excluded from the study. Premedication consisted of intramuscular atropine 0.5 mg and morphine 0.1 mg \( \text{kg}^{-1} \) for elective cases or intramuscular atropine 0.5 mg for emergency cases, given 45–60 min before transfer to the operating room. Anaesthesia was induced with midazolam 0.1–0.2 mg \( \text{kg}^{-1} \) i.v., fentanyl 30 \( \mu \text{g} \) \( \text{kg}^{-1} \), and pancuronium bromide 0.15 mg \( \text{kg}^{-1} \) and maintained with a continuous infusion of fentanyl (10 \( \mu \text{g} \) \( \text{kg}^{-1} \) \( \text{h}^{-1} \)), supplemented with sevoflurane (0.5–1.0 MAC). Muscular relaxation was maintained with intermittent doses of 4 mg pancuronium bromide i.v. The trachea was intubated, and the lungs were mechanically ventilated to maintain normocapnia with a mixture of oxygen and air \( (F_{\text{IO}_2} 0.5–0.85) \). At the beginning of CPB, midazolam 0.2 mg \( \text{kg}^{-1} \) and pancuronium bromide 4 mg were administered. During CPB, no anaesthetics were given. A radial artery catheter was inserted to measure arterial pressure and sample arterial blood. Electrocardiogram, pulmonary artery pressure, oesophageal and bladder temperature, pulse oximeter saturation, and end-tidal \( \text{CO}_2 \) and sevoflurane concentration (Capnomac Ultima, Datex-Ohmeda, Helsinki, Finland) were measured.

After induction of anaesthesia, a 8.0Fr introducer sheath (Arrow International, Inc., Reading, PA, USA) for a 7.5Fr pulmonary artery catheter (Arrow International, Inc.) and a 7Fr triple lumen catheter (Arrow International, Inc.) were inserted through the right internal jugular vein. In addition, a 5.1 cm long, 20-gauge venous catheter (Insysy, Becton Dickinson Inc., Franklin Lakes, NJ, USA) was inserted cephalad more than 2 cm apart from the insertion sites of the above two catheters. For continuous monitoring of jugular venous blood, the PT7 sensor was advanced more than 15 cm through the catheter into the jugular bulb, and adjusted to lie in the jugular bulb using fluoroscopy. In vitro calibration was performed before the insertion. After stabilization of the sensor in the jugular bulb, in vivo calibration between the sensor and the blood gas analyser (BGA) was carried out, and no further calibrations were done. Blood samples (0.5 ml) were drawn via a Y-connection attached to the venous catheter at a rate of 1 ml \( \text{min}^{-1} \) regardless of body temperature or the status of CPB and measured with a blood gas analyser (Corning 280 with Corning 2500 co-oximetry, Bayer Medical Ltd, Tokyo, Japan) within 2 min. According to the manufacturer, when used with the usual calibration frequencies (one-point calibrations every 30 min and two-point calibrations every 2 h) the precision expected is 0.002 pH units, 0.25 kPa, 0.17 kPa, and 0.58% for \( \text{pH} \), \( \text{PCO}_2 \), \( \text{PO}_2 \), and oxygen saturation, respectively, over the following range of measurements: pH 7.0–7.6 pH units, \( \text{PCO}_2 \) 2.7–13.2 kPa, and \( \text{PO}_2 \) 2.7–20.0 kPa.

All data are presented at 37°C without temperature correction, and the PT7 data were stored in a personal computer (Macintosh PowerBook 5300cs, Apple Computer, Tokyo, Japan) via a RS-232C port every 1 min for subsequent analysis.

**Cardiopulmonary bypass**

A non-pulsatile pump flow rate of 2.2–2.6 litres \( \text{min}^{-1} \) \( \text{m}^{-2} \) was maintained using a membrane oxygenator and a 40-\( \mu \text{m} \) arterial filter. Perfusion pressure was maintained at 50–90 mm Hg using either chlorpromazine 0.3–1.0 mg \( \text{kg}^{-1} \) i.v. or phenylephrine 0.1–0.5 mg i.v. Oesophageal temperature during aortic cross-clamp was maintained in the range of 25 to 30°C for CABG surgery or 15 to 20°C for aortic surgery. \( P_{\text{A} \text{CO}_2} \) was adjusted to 4.5–5.3 kPa without temperature correction. Selective cerebral perfusion was maintained at a flow rate of 5–10 ml \( \text{kg}^{-1} \) \( \text{min}^{-1} \) for all patients who underwent aortic surgery.

**Statistical analysis**

We used a statistical package (SPSS 9.0 for Windows, Base and Advanced models; SPSS Inc., Chicago, IL, USA). All data are presented as mean and SD. Hydrogen ion concentration \( ([H^+] \text{ nmol litre}^{-1}) \) was calculated from the value of \( \text{pH} \). Bias (mean of the differences of the values measured by the PT7 minus the blood sample values) and precision values (1.96 SD of the differences) for each variable were calculated for each patient by the Bland-Altman method. Simple linear regression analysis of each variable was made using a statistical package (SPSS 9.0 for Windows, Base and Advanced models; SPSS Inc., Chicago, IL, USA). All data are presented as mean and SD. Hydrogen ion concentration \( ([H^+] \text{ nmol litre}^{-1}) \) was calculated from the value of \( \text{pH} \). Bias (mean of the differences of the values measured by the PT7 minus the blood sample values) and precision values (1.96 SD of the differences) for each variable were calculated for each patient by the Bland-Altman method. Simple linear regression analysis of each variable was made using a least-squares method. The paired data were then divided into three subgroups according to the value of bladder temperature or haematocrit. Bias and precision for each variable were also calculated in each of the three subgroups, and the bias values were compared using one-way analysis of variance. When significance was found, Fisher’s protected least significant difference test was used as a post hoc comparison procedure. \( P \) values <0.05 were considered significant.

**Results**

Data from two patients who underwent aortic surgery were excluded because of sensor malfunction, and results from 18 patients are reported (mean age 66 yr (range 44–79); female/male ratio 5:13). One patient who underwent aortic replacement remained comatose and died on the second postoperative day. There were no complications related to
insertion of the sensor. All other patients survived and were discharged without clinically obvious brain injury. The mean durations of CPB, surgery, and anaesthesia were 181 min (range 109–353), 353 min (range 247–545), and 464 min (range 315–690), respectively.

Five to eight paired measurements with the PT7 and blood samples were made on each patient, with a total of 101 paired measurements. The ranges of each variable measured from the blood sample were: pH 7.12 to 7.59, $P_{\text{CO}_2}$ 3.7 to 9.6 kPa, $P_{\text{O}_2}$ 3.5 to 16.0 kPa, oxygen saturation 40–99%, bicarbonate 18.6 to 34.4 mmol litre$^{-1}$, and base excess $-7.8$ to 12.5 mmol litre$^{-1}$. Bias and precision values for each variable in each patient and overall bias, precision, and regression values are given in Table 1.

During this study, bladder temperature and haematocrit varied between 19.6 and 37.4°C, and between 13.5 and 41.1%, respectively. Bias and precision values for each variable in the three subgroups are given in Table 2. Bias values were not significantly different, and precision values were comparable in all three subgroups (Table 2).

A trace of the jugular venous measurements by the PT7 in a 65-year-old, female patient (patient 4 in Table 1) who underwent CABG surgery is given in Fig. 1.

Discussion
This study found good accuracy of the PT7 in the jugular venous bulb during hypothermic CPB; overall bias and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Bias and precision values for each variable in each patient and overall bias, precision, and regression values</th>
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<tbody>
<tr>
<td>Patient number</td>
<td>Samples</td>
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<td>1</td>
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<td>18</td>
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<tr>
<td>Overall bias/precision</td>
<td></td>
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<tr>
<td>Regression ($R^2$)</td>
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<table>
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<tr>
<th>Table 2</th>
<th>Bias and precision values for each variable in the three different subgroups based on bladder temperature (A) or haematocrit (B) ($n$=101). All values are expressed as bias/precision (1.96SD)</th>
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<tr>
<td>A</td>
<td>Bladder temperature (°C)</td>
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<td>$&gt;35$</td>
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<tr>
<td>Samples ($n$=101)</td>
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<tr>
<td>Temperature (°C)</td>
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<td>$p$H (pH units)</td>
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<td>$P_{\text{CO}_2}$ (kPa)</td>
<td>0.02/0.96</td>
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<tr>
<td>$P_{\text{O}_2}$ (kPa)</td>
<td>-0.12/1.17</td>
</tr>
<tr>
<td>B</td>
<td>Haematocrit (%)</td>
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<td></td>
<td>$&gt;25$</td>
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<tr>
<td>Samples ($n$=101)</td>
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<tr>
<td>Temperature (°C)</td>
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precision values for pH, $PCO_2$, and $PO_2$ were comparable with previous studies made on arterial blood (Table 3).\textsuperscript{5-14} In addition, a better bias or precision value for $PO_2$ was observed in this study, which may be attributable to a narrow range of jugular venous $PO_2$. Indeed, several studies have demonstrated a high accuracy of the $PO_2$ sensor when it is placed in a radial artery with a range of $PO_2$ less than 20 kPa.\textsuperscript{7,11,12} Furthermore, the 95\% confidence intervals (CI) for bias and precision for each variable were 0.006 to 0.022 and 0.058 to 0.084 pH units for pH, $-0.14$ to 0.14 and 0.73 to 1.06 kPa for $PCO_2$, and $-0.32$ to 0 and 0.90 to 1.45 kPa for $PO_2$, respectively; these values were satisfactory for clinical

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<th>Author</th>
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<th>Samples</th>
<th>Clinical setting</th>
<th>pH (pH units)</th>
<th>$PCO_2$ (kPa)</th>
<th>$PO_2$ (kPa)</th>
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<td>Venkatesh and colleagues\textsuperscript{5}</td>
<td>Artery</td>
<td>157</td>
<td>Cardiac surgery with CPB</td>
<td>0.01/0.06</td>
<td>0.53/0.35</td>
<td>0.5/6.0</td>
</tr>
<tr>
<td>Zollinger and colleagues\textsuperscript{6}</td>
<td>Artery</td>
<td>138</td>
<td>Differential lung ventilation</td>
<td>$-0.017/0.065$</td>
<td>0.31/0.76</td>
<td>0.38/9.52</td>
</tr>
<tr>
<td>Ishikawa and colleagues\textsuperscript{7}</td>
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<td>84</td>
<td>Differential lung ventilation</td>
<td>0.000/0.2</td>
<td>0.12/0.41</td>
<td>$-0.13/5.33$</td>
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<td>Myles and colleagues\textsuperscript{10}</td>
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<td>55</td>
<td>Lung transplantation</td>
<td>0.006/0.10</td>
<td>$-0.21/1.57$</td>
<td>$-2.93/14.4$</td>
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<td>Venkatesh and colleagues\textsuperscript{11}</td>
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<td>158</td>
<td>Intensive care unit</td>
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<td>0.2/1.4</td>
<td>0.4/6.8</td>
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<tr>
<td>Nunomiya and colleagues\textsuperscript{12}</td>
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<td>62</td>
<td>Intensive care unit</td>
<td>0.002/0.018</td>
<td>0.07/0.27</td>
<td>$-0.21/2.67$</td>
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<td>Weiss and colleagues\textsuperscript{13}</td>
<td>Artery</td>
<td>150</td>
<td>Pediatric intensive care unit</td>
<td>0.006/0.224</td>
<td>$-0.10/0.62$</td>
<td>0.25/2.28</td>
</tr>
<tr>
<td>Hatherill and colleagues\textsuperscript{14}</td>
<td>Artery</td>
<td>100</td>
<td>Pediatric intensive care unit</td>
<td>0.020/0.06</td>
<td>$-0.44/0.74$</td>
<td>0.04/0.87</td>
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<tr>
<td>Present study</td>
<td>Jugular vein</td>
<td>101</td>
<td>Cardiac surgery with CPB</td>
<td>0.014/0.071</td>
<td>0.00/0.90</td>
<td>$-0.16/1.18$</td>
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</table>

\textbf{Fig 1} A tracing of the jugular venous oxygen saturation (A), $PO_2$ (B), pH (C), $PCO_2$ (D), and temperature (E) measured by the Paratrend 7 in a 65-yr-old, female patient who underwent coronary artery bypass grafting surgery with an uneventful clinical course. Open circles represent the corresponding values of jugular venous blood measured by a blood gas analyser, closed circles represent the values of arterial blood measured by a blood gas analyser, and open squares represent values of bladder temperature. CPB=cardiopulmonary bypass.

Table 3 Comparison of bias and precision values between the Paratrend 7 and blood gas analyser with other published data. CPB=cardiopulmonary bypass.
measurements. However, overall bias and precision values for oxygen saturation were −1.8±9.6%, and the precision for each patient varied from 2.3 to 23.6% (95% CI: 6.3 to 12.9%), which is not clinically acceptable. Similarly, Hatherill and colleagues\textsuperscript{14} reported poor precision for oxygen saturation (9.5%) despite the smallest bias and precision for PO\textsubscript{2} in children with cyanotic heart disease. The PT7 does not measure oxygen saturation directly, but calculates it from PO\textsubscript{2}, resulting in the significant discrepancy of precision between PO\textsubscript{2} and oxygen saturation.

During this study, bladder temperature and haematocrit varied from 19.6°C to 37.3°C and from 13.5 to 41.1%, respectively. However, these large changes in temperature or haematocrit did not influence the reliability of the intra-jugular pH, PO\textsubscript{2}, or PCO\textsubscript{2} sensor (Table 2). These findings support those of Venkatesh and colleagues\textsuperscript{5} who showed that the PT7 in a radial artery functioned well during CPB; unfortunately, ranges of temperature and haematocrit during CPB were not shown in their study.

The threshold value for the jugular venous PO\textsubscript{2} has not yet been determined. In volunteers breathing 100% nitrogen, slowing of EEG was observed when the jugular venous PO\textsubscript{2} decreased to 2.5 kPa.\textsuperscript{18} Taking the difference between normal jugular venous PO\textsubscript{2} (4.7–6.2 kPa) and the critical level described above (≥2.2 kPa), the bias, precision, and 95% CI for PO\textsubscript{2} presented in this study are acceptable for clinical decision making. Similarly, there are no available human data describing critical values for jugular venous pH and PCO\textsubscript{2}. However, in several human studies when the PT7 was inserted into brain tissue\textsuperscript{19,20} or in cerebrospinal fluid,\textsuperscript{21} trends showed a concomitant increase in PCO\textsubscript{2} and decrease in pH, along with a decrease in PO\textsubscript{2} during sustained brain ischemia\textsuperscript{19,20} or after brain death.\textsuperscript{21} Continuous measurement of jugular venous pH and PCO\textsubscript{2} together with PO\textsubscript{2} using the PT7 may give more information on the balance between brain oxygen supply and demand than the currently used fibroptic oximetric catheter.

Sensor malfunction occurred in two of eight patients who underwent aortic surgery with selective cerebral perfusion, but not in 12 patients who underwent CABG surgery. Postoperative fluoroscopy showed kinking of the sensors, which had not been seen preoperatively. All malfunctions occurred before the start of selective cerebral perfusion, and perfusion itself did not contribute to malfunctions. However, the patient’s head was moved for surgical positioning, presumably resulting in deflection of the sensors.

In conclusion, we describe good accuracy of the pH, PO\textsubscript{2}, and PCO\textsubscript{2} sensors of the PT7 in the jugular venous bulb, comparable to previous findings with arterial blood. Mild to deep hypothermia and marked haemodilution during CPB did not affect the reliability of the sensors. There were no complications attributable to the insertion of the sensor. Thus, continuous jugular venous blood-gas monitoring is clinically feasible using the PT7 and may provide valuable information during hypothermic CPB. However, large studies would be needed to demonstrate clinical improvement.

Acknowledgements
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