

## Research

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**Urinary bladder partial carbon dioxide tension during hemorrhagic shock and reperfusion: an observational study**Arnaldo Dubin<sup>1</sup>, Mario O Pozo<sup>2</sup>, Vanina S Kanoore Edul<sup>3</sup>, Gastón Murias<sup>4</sup>, Héctor S Canales<sup>5</sup>, Marcelo Barán<sup>6</sup>, Bernardo Maskin<sup>7</sup>, Gonzalo Ferrara<sup>8</sup>, Mercedes Laporte<sup>9</sup> and Elisa Estenssoro<sup>10</sup><sup>1</sup>Medical Director, Intensive Care Unit, Sanatorio Otamendi y Miroli, Buenos Aires, Argentina<sup>2</sup>Staff physician, Intensive Care Unit, Clínicas Bazterrica y Santa Isabel, Buenos Aires, Argentina<sup>3</sup>Research Fellow, Cátedra de Farmacología, Facultad de Ciencias Médicas, Universidad Nacional de La Plata, La Plata, Argentina<sup>4</sup>Staff physician, Intensive Care Unit, Clínicas Bazterrica y Santa Isabel, Buenos Aires, Argentina<sup>5</sup>Staff physician, Intensive Care Unit, Hospital San Martín de La Plata, Argentina<sup>6</sup>Medical Director, Renal Transplantation Unit, CRAI Sur, CUCAIBA, Argentina<sup>7</sup>Medical Director, Intensive Care Unit, Hospital Posadas, Buenos Aires, Argentina<sup>8</sup>Resident, Intensive Care Unit, Hospital San Martín de La Plata, Argentina<sup>9</sup>Medical Director, Clinical Chemistry Laboratory, Hospital San Martín de La Plata, Argentina<sup>10</sup>Medical Director, Intensive Care Unit, Hospital San Martín de La Plata, ArgentinaCorresponding author: Arnaldo Dubin, [arnaldodubin@speedy.com.ar](mailto:arnaldodubin@speedy.com.ar)

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*Critical Care* 2005, **9**:R556-R561 (DOI 10.1186/cc3797)This article is online at: <http://ccforum.com/content/9/5/R556>© 2005 Dubin *et al.*; licensee BioMed Central Ltd.This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/2.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.**Abstract**

**Introduction** Continuous monitoring of bladder partial carbon dioxide tension (PCO<sub>2</sub>) using fibreoptic sensor technology may represent a useful means by which tissue perfusion may be monitored. In addition, its changes might parallel tonometric gut PCO<sub>2</sub>. Our hypothesis was that bladder PCO<sub>2</sub>, measured using saline tonometry, will be similar to ileal PCO<sub>2</sub> during ischaemia and reperfusion.

**Method** Six anaesthetized and mechanically ventilated sheep were bled to a mean arterial blood pressure of 40 mmHg for 30 min (ischaemia). Then, blood was reinfused and measurements were repeated at 30 and 60 min (reperfusion). We measured systemic and gut oxygen delivery and consumption, lactate and various PCO<sub>2</sub> gradients (urinary bladder-arterial, ileal-arterial, mixed venous-arterial and mesenteric venous-arterial). Both bladder and ileal PCO<sub>2</sub> were measured using saline tonometry.

**Results** After bleeding systemic and intestinal oxygen supply dependency and lactic acidosis ensued, along with elevations in

PCO<sub>2</sub> gradients when compared with baseline values (all values in mmHg; bladder ΔPCO<sub>2</sub> 3 ± 3 versus 12 ± 5, ileal ΔPCO<sub>2</sub> 9 ± 5 versus 29 ± 16, mixed venous-arterial PCO<sub>2</sub> 5 ± 1 versus 13 ± 4, and mesenteric venous-arterial PCO<sub>2</sub> 4 ± 2 versus 14 ± 4; *P* < 0.05 versus basal for all). After blood reinfusion, PCO<sub>2</sub> gradients returned to basal values except for bladder ΔPCO<sub>2</sub>, which remained at ischaemic levels (13 ± 7 mmHg).

**Conclusion** Tissue and venous hypercapnia are ubiquitous events during low flow states. Tonometric bladder PCO<sub>2</sub> might be a useful indicator of tissue hypoperfusion. In addition, the observed persistence of bladder hypercapnia after blood reinfusion may identify a territory that is more susceptible to reperfusion injury. The greatest increase in PCO<sub>2</sub> gradients occurred in gut mucosa. Moreover, the fact that ileal ΔPCO<sub>2</sub> was greater than the mesenteric venous-arterial PCO<sub>2</sub> suggests that tonometrically measured PCO<sub>2</sub> reflects mucosal rather than transmural PCO<sub>2</sub>. Ileal ΔPCO<sub>2</sub> appears to be the more sensitive marker of ischaemia.

**Introduction**

Monitoring the adequacy of tissue oxygenation in critically ill patients is a challenging task [1]. Despite extensive research, tissue capnometry remains the only clinically relevant

approach to monitoring regional perfusion and oxygenation. Elevation in tissue partial carbon dioxide tension (PCO<sub>2</sub>) might represent a better surrogate of hypoperfusion than other systemic and regional parameters [2,3].

CaO<sub>2</sub> = arterial oxygen content; Cv<sub>m</sub>O<sub>2</sub> = mesenteric venous oxygen content; CvO<sub>2</sub> = mixed venous oxygen content; DO<sub>2</sub> = oxygen transport; PCO<sub>2</sub> = partial carbon dioxide tension; PO<sub>2</sub> = partial oxygen tension; P<sub>v-a</sub>CO<sub>2</sub> = mixed venous-arterial PCO<sub>2</sub> difference; P<sub>v<sub>m</sub>-a</sub>CO<sub>2</sub> = mesenteric venous-arterial PCO<sub>2</sub> difference; Q = cardiac output; VO<sub>2</sub> = oxygen consumption.

During the past 20 years a large body of clinical evidence was developed supporting the usefulness of gastrointestinal PCO<sub>2</sub> tonometry for the monitoring of tissue perfusion [4]. Gastric tonometry can readily be performed in the critically ill and gives significant information on outcomes [5,6]. It may also be a helpful guide in therapeutic decision making [7]. Nevertheless, technical difficulties and frequent artefacts have dampened the initial enthusiasm [8]. In an attempt to overcome the limitations of gastric tonometry, sublingual capnometry was then developed [9]. Despite initial interest and potential advantages, this technique has neither been completely validated nor widely used [10].

More recently, tissue perfusion has been assessed with continuous monitoring of bladder PCO<sub>2</sub> using fibreoptic sensor technology [11,12], yielding interesting findings in experimental models of ischaemia/reperfusion. Although the equipment required may be expensive, bladder PCO<sub>2</sub> can readily be measured via a urinary catheter incorporating a silicone balloon. Our goal in the present study was to compare bladder PCO<sub>2</sub> measured using saline tonometry versus other tissue and venous PCO<sub>2</sub> values. Our hypothesis was that bladder PCO<sub>2</sub> will track ileal PCO<sub>2</sub> during ischaemia and reperfusion.

## Materials and methods

### Surgical preparation

Six sheep were anaesthetized with 30 mg/kg sodium pentobarbital, intubated and mechanically ventilated (Harvard Apparatus Dual Phase Control Respirator Pump Ventilator; South Natick, MA, USA) with a tidal volume of 15 ml/kg, a fractional inspired oxygen of 0.21, and positive end-expiratory pressure adjusted to maintain arterial oxygen saturation above 90%. The respiratory rate was set to keep the end-tidal PCO<sub>2</sub> at 35 mmHg. Neuromuscular blockade was applied with intravenous pancuronium bromide (0.06 mg/kg). Additional pentobarbital boluses (1 mg/kg per hour) were administered.

Catheters were advanced through the left femoral vein to administer fluids and drugs, and through left femoral artery to measure blood pressure and obtain blood gases. A pulmonary artery catheter was inserted through the right external jugular vein (Flow-directed thermodilution fibreoptic pulmonary artery catheter; Abbott Critical Care Systems, Mountain View, CA, USA).

An orogastric tube was inserted to allow drainage of gastric contents. Then, a midline laparotomy and splenectomy were performed. An electromagnetic flow probe was placed around the superior mesenteric artery to measure intestinal blood flow. A catheter was placed in the mesenteric vein through a small vein proximal to the gut to draw blood gases. Tonometers (TRIP Sigmoid Catheter; Tonometrics, Inc., Worcester, MA, USA) were inserted through small ileotomy and cystostomy to measure ileal and urinary bladder intramucosal PCO<sub>2</sub>. A second catheter was placed through the same cyst-

ostomy to drain urine. Finally, after careful haemostasis, the abdominal wall incision was closed.

### Measurements and derived calculations

Arterial, systemic, pulmonary and central venous pressures were measured using corresponding transducers (Statham P23 AA; Statham, Hato Rey, Puerto Rico). Cardiac output was measured by thermodilution with 5 ml saline solution at 0°C (HP OmniCare Model 24 A 10; Hewlett Packard, Andover, MA, USA). An average of three measurements taken randomly during the respiratory cycle was considered and was referenced to body weight to yield the cardiac output (Q). Intestinal blood flow was measured with the electromagnetic method (Spectramed Blood Flowmeter model SP 2202 B; Spectramed Inc., Oxnard, CA, USA) with *in vitro* calibrated transducers of 5–7 mm diameter (Blood Flowmeter Transducer; Spectramed Inc.). Occlusive zero was controlled before and after each experiment. Non-occlusive zero was corrected before each measurement. Superior mesenteric blood flow was referenced to gut weight (Q<sub>intestinal</sub>).

Arterial, mixed venous and mesenteric venous partial oxygen tension (PO<sub>2</sub>), PCO<sub>2</sub> and pH were measured using a blood gas analyzer (ABL 5; Radiometer, Copenhagen, Denmark), and haemoglobin and oxygen saturation were measured using a co-oximeter calibrated for sheep blood (OSM 3; Radiometer). Arterial oxygen content (CaO<sub>2</sub>), mixed venous oxygen content (CvO<sub>2</sub>) and mesenteric venous oxygen content (CvmO<sub>2</sub>) were calculated as follows: haemoglobin × 1.34 × oxygen saturation + PO<sub>2</sub> × 0.0031. Systemic and intestinal oxygen delivery (DO<sub>2</sub>) and oxygen consumption (VO<sub>2</sub>) were calculated as follows: systemic DO<sub>2</sub> = Q × CaO<sub>2</sub>; systemic VO<sub>2</sub> = Q × (CaO<sub>2</sub> - CvO<sub>2</sub>); intestinal DO<sub>2</sub> = Q<sub>intestinal</sub> × CaO<sub>2</sub>; and intestinal VO<sub>2</sub> = Q<sub>intestinal</sub> × (CaO<sub>2</sub> - CvmO<sub>2</sub>).

Arterial lactate concentration was measured using an automatic analyzer (Hitachi 912; Boehringer Mannheim Corporation, Indianapolis, IN, USA).

Bladder and ileal intramucosal PCO<sub>2</sub> were measured using a tonometer filled with 2.5 ml saline solution. Of the solution, 1.0 ml was discarded after an equilibration period of 30 min, and PCO<sub>2</sub> was measured in the remaining 1.5 ml. These values were corrected for the equilibration period and were used to calculate intramucosal-arterial gradients (bladder and ileal ΔPCO<sub>2</sub>). Mixed venous-arterial PCO<sub>2</sub> (Pv-aCO<sub>2</sub>) and mesenteric venous-arterial PCO<sub>2</sub> differences (Pvm-aCO<sub>2</sub>) were also calculated.

### Experimental procedure

Basal measurements were taken after a stabilization period longer than 30 min. Then, sheep were bled to a mean arterial blood pressure of 40 mmHg for 30 min (ischaemia). This degree of arterial hypotension was maintained by extracting or returning blood, as necessary. Collected blood was

**Table 1****Haemodynamic and oxygen transport parameters at basal conditions, during ischaemia, and after 30 and 60 min of reperfusion**

Parameter	Basal	Ischemia	Reperfusion	
			30 min	60 min
Mean arterial blood pressure (mmHg)	87 ± 14	38 ± 4	105 ± 10*	104 ± 10*
Cardiac output (ml/min per kg)	138 ± 10	70 ± 17*	136 ± 17	137 ± 16
Intestinal blood flow (ml/min per kg)	787 ± 181	272 ± 100*	890 ± 278	756 ± 134
Systemic oxygen transport (ml/min per kg)	19.5 ± 2.7	7.8 ± 1.9*	18.8 ± 2.8	19.3 ± 3.2
Systemic oxygen consumption (ml/min per kg)	6.8 ± 1.0	5.7 ± 1.5*	7.4 ± 1.2*	7.2 ± 0.9*
Systemic oxygen extraction ratio	0.35 ± 0.06	0.72 ± 0.08*	0.40 ± 0.09*	0.39 ± 0.09
Intestinal oxygen transport (ml/min per kg)	112.5 ± 35.2	31.1 ± 14.0*	126.1 ± 51.1	107.8 ± 28.7
Intestinal oxygen consumption (ml/min per kg)	30.3 ± 4.6	19.3 ± 7.1*	31.3 ± 6.9	31.5 ± 6.6
Intestinal oxygen extraction ratio	0.29 ± 0.09	0.65 ± 0.12*	0.28 ± 0.11	0.31 ± 0.10

\**P* < 0.05 versus basal.**Table 2****Arterial, mixed venous and mesenteric venous blood gases, and arterial lactate at basal conditions, during ischemia and after 30 and 60 minutes of reperfusion**

Parameter	Basal	Ischaemia	Reperfusion	
			30 min	60 min
Arterial pH	7.37 ± 0.03	7.36 ± 0.05	7.33 ± 0.05*	7.36 ± 0.04
Arterial PCO <sub>2</sub> (mmHg)	38 ± 4	35 ± 5*	36 ± 4	36 ± 5
Arterial PO <sub>2</sub> (mmHg)	77 ± 9	80 ± 15	75 ± 10	78 ± 8
Arterial HCO <sub>3</sub> <sup>-</sup> (mmol/l)	22 ± 3	19 ± 2*	19 ± 2*	20 ± 2*
Arterial base excess (mmol/l)	-3 ± 3	-5 ± 2*	-6 ± 2*	-4 ± 3*
Mixed venous pH	7.34 ± 0.03	7.26 ± 0.03*	7.28 ± 0.04*	7.32 ± 0.04
Mixed venous PCO <sub>2</sub> (mmHg)	43 ± 4	48 ± 5*	43 ± 4	42 ± 3
Mixed venous PO <sub>2</sub> (mmHg)	38 ± 4	23 ± 3*	37 ± 4	39 ± 4
Mixed venous HCO <sub>3</sub> <sup>-</sup> (mmol/l)	23 ± 3	21 ± 3	20 ± 2	21 ± 2
Mixed venous base excess (mmol/l)	-3 ± 3	-6 ± 3*	-7 ± 2*	-5 ± 2*
Mesenteric venous pH	7.34 ± 0.03	7.26 ± 0.03*	7.30 ± 0.05*	7.32 ± 0.04
Mesenteric venous PCO <sub>2</sub> (mmHg)	42 ± 5	49 ± 5*	41 ± 4	41 ± 4
Mesenteric venous PO <sub>2</sub> (mmHg)	43 ± 7	26 ± 3*	42 ± 6	43 ± 5
Mesenteric venous HCO <sub>3</sub> <sup>-</sup> (mmol/l)	23 ± 3	22 ± 2	20 ± 2*	21 ± 2
Mesenteric venous base excess (mmol/l)	-3 ± 3	-5 ± 2*	-6 ± 2*	-5 ± 2*
Arterial lactate (mmol/l)	1.6 ± 0.5	3.7 ± 1.7*	3.9 ± 2.0*	3.2 ± 1.5*

Values are expressed as mean ± standard deviation. \**P* < 0.05 versus basal. PCO<sub>2</sub>, partial carbon dioxide tension; PO<sub>2</sub>, partial oxygen tension.

heparinized (5,000 U/l) and stored in a warmed water bath (37.5°C). Then, blood was reinfused and measurements were repeated at 30 and 60 min (reperfusion).

At the end of the experiment the animals were killed with an additional dose of pentobarbital and a KCl bolus. A catheter was inserted into the superior mesenteric artery and Indian ink

was instilled. Dyed intestinal segments were dissected, washed and weighed to calculate gut indices.

The local Animal Care Committee approved the study. Care of animals was in accordance with US National Institute of Health guidelines.

### Statistical analysis

Data were assessed for normality and expressed as mean  $\pm$  standard deviation. Differences were analyzed using repeated measures analysis of variance and Dunnett's multiple comparisons test to compare each time point with baseline. One-time comparisons between different PCO<sub>2</sub> gradients were tested using one-way analysis of variance and Newman-Keuls multiple comparisons test.

## Results

### Haemodynamic and oxygen transport effects

Mean arterial pressure decreased during bleeding, as did Q, Q<sub>intestinal</sub> and systemic and intestinal DO<sub>2</sub> and VO<sub>2</sub>. These variables returned to basal values after reinfusion of blood, with the exception of mean arterial pressure and systemic VO<sub>2</sub>, which remained higher than basal values (Table 1).

### Metabolic effects

Metabolic acidosis and hyperlactataemia developed during ischaemia, and persisted after reinfusion (Table 2).

### Effects on partial carbon dioxide tension gradients

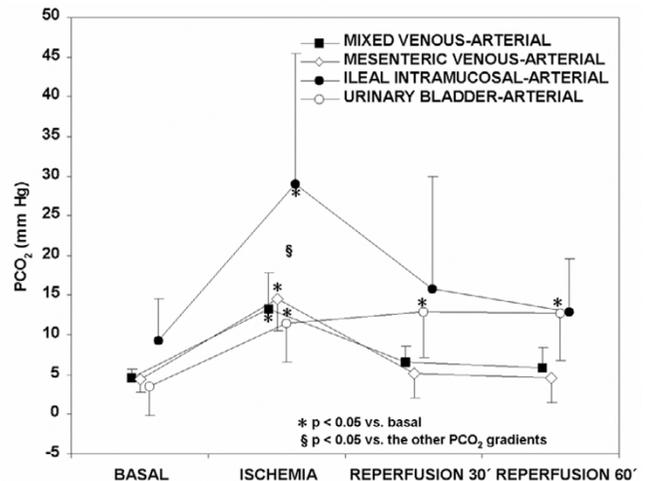
Mixed and mesenteric venoarterial and urinary bladder and ileal  $\Delta$ PCO<sub>2</sub> differences increased during ischaemia. Ileal  $\Delta$ PCO<sub>2</sub> was higher than other PCO<sub>2</sub> gradients during ischaemia (Fig. 1). The change in ileal  $\Delta$ PCO<sub>2</sub> ( $20 \pm 10$  mmHg) during ischaemia was greater than that in bladder  $\Delta$ PCO<sub>2</sub> ( $8 \pm 7$  mmHg) and in Pv-aCO<sub>2</sub> ( $9 \pm 5$  mmHg) and Pvm-aCO<sub>2</sub> ( $10 \pm 3$  mmHg;  $P < 0.05$  for bladder  $\Delta$ PCO<sub>2</sub>, Pv-aCO<sub>2</sub> and Pvm-aCO<sub>2</sub> versus ileal  $\Delta$ PCO<sub>2</sub>). However, all PCO<sub>2</sub> gradients returned to basal values after reperfusion, except for bladder  $\Delta$ PCO<sub>2</sub>, which remained elevated (Fig. 1).

## Discussion

The main finding in the present study is the consistent expression of hypercapnia during low flow states. High PCO<sub>2</sub> values were evident in veins, ileum and even urinary bladder. In contrast to the other carbon dioxide gradients, bladder  $\Delta$ PCO<sub>2</sub> remained elevated after reperfusion.

The prevention, detection and correction of tissue dysoxia are main goals in the management of critically ill patients [1]. Gastric tonometry has been considered the only available method to track tissue oxygenation in the clinical arena [1]. However, tissue hypercapnia is not just a marker of dysoxia but is also an indicator of hypoperfusion. Tissue and venous PCO<sub>2</sub> remain unchanged in states of tissue dysoxia with preserved blood flow, such as hypoxic and anaemic hypoxia [13-15]. On the

**Figure 1**



Behaviour of PCO<sub>2</sub> gradients. Shown are the various partial carbon dioxide tension (PCO<sub>2</sub>) gradients in basal conditions, during ischaemia and after reperfusion.

other hand, in a high flow state, such as sepsis, measurements of intramucosal acidosis remain helpful because of the frequent presence of microcirculatory derangements [16]. Moreover, increased blood flow may correct tissue hypercapnia in endotoxaemia [17].

Although most studies dealing with tissue capnometry have focused on the gastrointestinal tract, others have been performed in muscle [18,19], renal parenchyma [20,21] and subcutaneous tissue [22]. Few studies have assessed urinary PCO<sub>2</sub> for the monitoring of tissue oxygenation. Lin and coworkers [23] measured urinary PCO<sub>2</sub> in critically ill patients to evaluate the adequacy of perfusion. Urinary PCO<sub>2</sub> was higher in shock than in control patients ( $79 \pm 10$  mmHg versus  $43 \pm 2$  mmHg;  $P < 0.0001$ ). Lang and colleagues [11] measured urinary bladder gases using a fiberoptic sensor in a swine model of ischaemia/reperfusion. After 30 min of aortic clamping bladder PCO<sub>2</sub> increased from  $57 \pm 5$  mmHg to  $117 \pm 7$  mmHg, and it returned to baseline after 60 min of reperfusion. Clavijo-Alvarez and coworkers [12] studied this issue in a model of haemorrhagic shock in which pigs were bled and kept at a mean arterial pressure of 40 mmHg until decompensation. Animals were then resuscitated with shed blood plus lactated Ringer's solution and observed for 2 hours. In contrast to our findings, those investigators found greater increases in bladder PCO<sub>2</sub>; basal PCO<sub>2</sub> was  $49 \pm 6$  mmHg and increased to  $71 \pm 7$  mmHg at the end of shock. Jejunal intramucosal PCO<sub>2</sub> exhibited similar behaviour.

These differences might be related to the use of different animal species but also, and primarily, to the longer period of shock. Because the pigs in the study by Clavijo-Alvarez and coworkers [12] reached a lower cardiac output than did the

sheep in our study, changes in surrogates of hypoperfusion such as base excess bicarbonate and bladder  $\text{PCO}_2$  were more pronounced. Nevertheless, gut intramucosal acidosis was similar in both studies, which might be related to the greater vulnerability of sheep intestinal mucosa to hypoperfusion. In addition, differences might be explained by diverse surgical preparations and methods for measuring intramucosal  $\text{PCO}_2$ . Clavijo-Alvarez and coworkers completely isolated the bladder, and the  $\text{PCO}_2$  sensor was encased within the mucosa so that they could avoid interference. In this way, the measurements should reflect those from the bladder wall more accurately. Furthermore, they used a more sensitive method to measure  $\text{PCO}_2$ . Nevertheless, it is difficult to reproduce this type of measurement in patients, and our methodology seems more suitable for clinical application.

Although tissue and venous hypercapnia is a widespread consequence of hypoperfusion, our experiments reveal that the increase in  $\text{PCO}_2$  is higher in ileal mucosa than in bladder mucosa and mixed and mesenteric venous blood. The underlying mechanism producing this preferential elevation in ileal  $\Delta\text{PCO}_2$  might be related to particular characteristics of villi microcirculation. Countercurrent circulation might induce a functional shunt that could place distal microvilli segments at ischaemic risk [24]. There is some controversy regarding the meaning of intramucosal  $\text{PCO}_2$ ; specifically, does it reflect whole wall or superficial mucosal perfusion? An ileal  $\Delta\text{PCO}_2$  greater than the  $\text{Pvm-aCO}_2$  suggests that tonometric  $\text{PCO}_2$  reflects mucosal rather than transmural  $\text{PCO}_2$ . On the other hand, the similar increase in bladder-arterial and systemic and intestinal venoarterial  $\text{PCO}_2$  gradients suggests the presence of similar degrees of hypoperfusion. As previously described [25], the fraction of cardiac output directed to gut (superior mesenteric artery blood flow/cardiac output) decreased during ischaemia (from  $0.23 \pm 0.06$  to  $0.16 \pm 0.07$ ; data not shown). However, this was not enough to produce differences between systemic and intestinal venoarterial  $\text{PCO}_2$  gradients.

Another interesting finding of this study lies in the persistence of bladder intramucosal acidosis during reperfusion. Recent studies indicated that ischaemia/reperfusion can cause acute inflammation and contractile dysfunction of the bladder [26]. Bajory and coworkers [27] demonstrated severe microcirculatory derangements such as decreased functional capillary density, red blood cell velocity, venular and arteriolar diameter, and enhanced macromolecular leakage after bladder ischaemia/reperfusion. We speculate that these microcirculatory alterations might lead to decreased carbon dioxide removal. Again, differential susceptibility to injury between species could explain differences from other studies [11,12].

Limitations of the present study could be related to the method of measurement of bladder  $\text{PCO}_2$ . First, tonometric measurement of  $\text{PCO}_2$  has drawbacks [8]. Second, urine itself could potentially influence tonometric  $\text{PCO}_2$  beyond perfusion defi-

cits. In fact, urine can have variable carbon dioxide content, resulting, for example, from different grades of carbonic anhydrase inhibition or from systemic bicarbonate administration [28]. Actually, failure to observe an appropriate increase in urinary-blood  $\text{PCO}_2$  during bicarbonate loading has been employed as an index of reduced distal nephron proton secretion in distal renal tubular acidosis [28]. Changes in systemic oxygenation can also modify urine composition. Moriguchi and coworkers [29] have showed that urinary bicarbonate, calculated from urinary  $\text{PCO}_2$  and pH, increases after anaerobic exercise. Those authors related these findings to systemic carbon dioxide production and later urinary excretion [29]. They also described a circadian rhythm in urinary bicarbonate elimination [30]. Moreover, an elevated bladder  $\Delta\text{PCO}_2$  could also represent a late manifestation of renal hypoperfusion. Further studies are needed to clarify the influence of renal carbon dioxide excretion on bladder  $\text{PCO}_2$ .

## Conclusion

Our data suggest that bladder  $\Delta\text{PCO}_2$  could be a useful indicator of tissue perfusion. However, intestinal  $\Delta\text{PCO}_2$  is the more sensitive carbon dioxide gradient for monitoring low flow states. Further studies are needed to establish the definitive monitoring value of urinary  $\text{PCO}_2$ .

### Key messages

- Urinary bladder  $\Delta\text{PCO}_2$  may be a useful indicator of tissue perfusion, but intestinal  $\Delta\text{PCO}_2$  is the more sensitive carbon dioxide gradient for the monitoring of low flow states.
- The fact that the observed ileal  $\Delta\text{PCO}_2$  was greater than  $\text{Pvm-aCO}_2$  suggests that tonometric  $\text{PCO}_2$  reflects mucosal rather than transmural  $\text{PCO}_2$ .

## Competing interests

The author(s) declare that they have no competing interests.

## Authors' contributions

AD was responsible for the study concept and design, analysis and interpretation of data, and drafting of the manuscript. MOP, VSKE, GM and HSC performed acquisition of data and contributed to drafting of the manuscript. BM and ML conducted blood determinations and contributed to drafting of the manuscript. MB and GF performed the surgical preparation and contributed to the discussion. EE helped in the drafting of the manuscript and conducted a critical revision for important intellectual content. All authors read and approved the final manuscript.

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