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Subcutaneous oxygen tensions provide similar information to ileal luminal CO_2 tensions in an animal model of haemorrhagic shock

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Abstract *Objectives*: The cutaneous and splanchnic circulations undergo early vasoconstriction in shock. Methodological problems and insufficient information on subcutaneous carbon dioxide partial pressures limit the usefulness of previous studies on splanchnic and subcutaneous gas tensions in shock. Little comparative data exist on the responses of these tissues to shock and resuscitation. We therefore compared continuous subcutaneous PO_2 (PO_{2sc}) and PCO_2 (PCO_{2sc}) with simultaneous continuous gut luminal PCO_2 (PCO_{2gi}) in an animal model of haemorrhagic shock and resuscitation.
Design: Prospective observational study.
Setting: Intensive care laboratory in a teaching hospital.
Subjects: Five anaesthetised rats.
Interventions: Electrochemical-fiberoptic gas sensors inserted into Silastic tubing placed in the subcutaneous tissue and in the ileal lumen measured PCO_{2sc}, PO_{2sc} and PCO_{2gi} continuously in five anaesthetised rats. After steady state conditions, hypotension [mean arterial blood pressure (MAP) 40 mmHg] was induced by controlled haemorrhage. The rats were allowed to remain hypotensive for 15 min and then resuscitated with shed blood and crystalloids. Arterial plasma lactate concentrations were measured at defined periods during the study.
Measurements and main results: Hypovolaemia resulted in a significant decrease in PO_{2sc} ($P < 0.01$) and a significant increase in PCO_{2gi} and PCO_{2sc} ($P < 0.05$). These values returned to baseline with resuscitation. PO_{2sc} appeared to respond to haemorrhage earlier than PCO_{2gi} and PCO_{2sc} ($P = 0.02$). PO_{2sc} was inversely correlated with PCO_{2gi} (r^2 0.7, $P < 0.001$). There were no significant changes in arterial plasma lactate concentrations.
Conclusions: In our rat model, subcutaneous oxygen tension provided similar information to ileal luminal PCO_2 and was more rapidly responsive than subcutaneous carbon dioxide tensions and arterial lactate during evolving haemorrhagic shock and resuscitation.

Key words Shock · Tonometry · Mucosal · Subcutaneous · Oxygen · Carbon dioxide · Lactate · Haemorrhage · Resuscitation · Ischaemia

Introduction

In light of recent knowledge that tissue dysoxia may still exist in patients who would otherwise be considered adequately resuscitated by conventional clinical criteria and oxygen transport variables, considerable investigative interest has been directed at monitoring tissue oxygenation indices as an end point in resuscitation in

shock and in critical illness [1]. The compensatory neurohumoral mechanisms triggered during the evolution of shock lead to redistribution of blood flow away from the splanchnic and cutaneous circulations [2]. The gut mucosa is particularly vulnerable to oxygen lack owing to: (a) the presence of a countercurrent blood circulation in the villus leading to a progressive decrease in oxygen tension from the base to the tip of the villus [3]; and (b) the right-angle origin of the villus arterioles leading to plasma skimming. The enhanced susceptibility of the gut mucosa to an ischaemic insult from hypoperfusion formed the basis for the development of gastric tonometry as an early indicator of covert compensated shock [4, 5]. Gastric tonometry measures gastric mucosal carbon dioxide tension and facilitates calculation of intramucosal pH (pHi). Low pHi in the postoperative period and in critically ill patients has been associated with increased morbidity and mortality [6, 7, 8]. A pHi > 7.32 has been used as an end point to titrate resuscitation therapy [9, 10].

The cutaneous circulation is characterised by a rich adrenergic innervation, an extensive subdermal capillary and venous plexus blood reservoir, numerous arteriovenous anastomotic connections and a countercurrent arrangement of blood vessels in the form of venae comitantes [11]. These anatomical and physiological characteristics result in an increased responsiveness of the cutaneous circulation to a hypoxic and hypovolaemic insult. This augmented responsiveness has been confirmed in animal studies using transcutaneous and subcutaneous oxygen tension monitoring (PO_{2sc}) [12, 13]. Reductions in PO_2sc have been demonstrated to parallel changes in visceral gas tensions [14].

Despite a large body of evidence supporting the usefulness of gastric tonometry and subcutaneous oxygen measurements in covert shock states, the data are partly limited by measurement inaccuracies associated with the use of saline in gastric tonometry [15] and the paucity of information on subcutaneous CO_2 tensions (PCO_{2sc}) in shock states. Also, the intermittent nature of the measurement techniques [13] and the use of slow response sensors [14] in some of the previous studies have made it difficult to characterise the time course of changes in gas tensions in response to shock and resuscitation. Although it has been shown that there is a semi quantitative elevation of ileal luminal PCO_2 to brief reductions in aortic pressure using an animal model [16], the technique of continuous ileal tonometry is unlikely to reach clinical application owing to technological and logistic problems. Reliable continuous monitoring of covert compensated shock and of the adequacy of resuscitation remains an important challenge. Despite some studies comparing subcutaneous and splanchnic gas tensions in shock, there is no information on which of the two beds is more responsive during shock and resuscitation [13, 14].

Using a rapidly responsive gas sensor, we therefore compared *continuous* subcutaneous PO_2 (PO_{2sc}) and PCO_2 (PCO_{2sc}) measurements with *continuous* gut luminal PCO_2 (PCO_{2gi}) measurements in an animal model of haemorrhagic shock and resuscitation, in order to: (1) examine the magnitude of changes in tissue gas tension and compare this with systemic acid-base indices in response to evolving shock and resuscitation; and (2) examine the time course of changes in these tissue gas tensions during evolving shock and resuscitation.

Materials and methods

The experimental protocol was approved by the Animal Experimentation Ethics Committee of the University of Queensland and the care and handling of animals were in accord with the guidelines for ethical animal research laid down by the National Health and Medical Research Council, Australia. Five female Sprague-Dawley rats weighing an average of 277 g (268–320 g) were anaesthetised with sodium pentobarbital (60 mg/kg IP) and ventilated via a tracheostomy with supplemental oxygen and isoflurane using a Harvard Rodent Ventilator (683, South Natick, Mass., USA). Heat loss was reduced by placing the anaesthetised rats on a warming pad under reflecting metal foil. A 10 cm length of Silastic tubing OD 1.5 mm, ID 0.9 mm, (Dow-Corning, Midland, Mich., USA) was attached to a straight needle and inserted in the subcutaneous tissue of the ventrolateral torso from the inguinal area to the axilla for a minimum of 8 cm. Following exit of the needle from the skin, the tubing was tied off with silk at its junction with the needle, cut free and retracted into the subcutaneous tissue. A sensor (Paratrend 7, Diametrics Medical, Bucks, UK) was inserted into the tubing through a 20-gauge cannula. A laparotomy was performed and another length of silastic tubing was placed in the proximal ileum via a small incision in the anti-mesenteric border. The air was then atraumatically expelled from the gut through the incision site by gentle milking and the incision closed with 3/0 silk. A second sensor was then passed into the silastic tubing in the ileum. Prior to commencement of the study, both the subcutaneous and the ileal sites were inspected to confirm the absence of tissue haematoma or gut ischaemia. Subcutaneous PO_2 and PCO_2 and ileal luminal PCO_2 measurements were recorded every 2 s and transferred as an ASCII file through an RS232 port to the Windows 3.1 Terminal Application (Microsoft, Redmond, Wash., USA) loaded on a 486 DX laptop computer (Roshtek, Brisbane, Queensland, Australia).

A 20-gauge cannula was placed in the left carotid artery via a small neck incision, and the mean arterial blood pressure (MAP) was monitored continuously using a pressure transducer (Model 43–212, Baxter Edwards Critical-Care, Irvine, Calif., USA) which was calibrated to zero at the mid-axillary line and displayed the output on a portable monitor (1275A, Hewlett-Packard, Waltham, Mass., USA). The MAP was recorded at 1-min intervals throughout the experiment. Minute ventilation was adjusted until the $PaCO_2$ was in the range of 40–60 torr as determined by blood gas analysis. Normal saline was infused into the carotid artery at 3 ml/h, and the inspired isoflurane concentration was adjusted to maintain an initial mean aortic pressure of 90–110 mmHg. The ileal temperature measured by the sensor was kept within the range of 35–38 °C.

Experimental protocol

After surgical dissection and insertion of lines and sensors, the experiment was performed in four phases.

Control phase: On reaching steady state conditions as indicated by an ileal temperature of 36 °C or above, the animals were observed without intervention for 15 min during which time tissue gas tension data were collected continuously.

Haemorrhage phase: During this phase, arterial blood was withdrawn into a heparin-coated syringe at a rate of 0.4 ml /min until the MAP reached 40 mmHg.

Shock phase: The rats were allowed to remain hypotensive for a period of 15 min without any intervention.

Resuscitation phase: At the end of the shock phase the shed blood was reinfused over 1 min. Subcutaneous and luminal data were collected for a further 15 min following reinfusion, and during this time 0.25 ml boluses of normal saline were administered if the MAP fell below 90 mmHg.

Plasma lactate concentrations and arterial blood gases were measured at the end of each phase in a standard blood gas and lactate analyser (ABL 625, Radiometer, Copenhagen, Denmark) [17]. At the end of the resuscitation phase, the animals were killed under anaesthesia by bilateral thoracotomy.

Paratrend 7 sensor

The Paratrend 7 (Diametrics Medical, Bucks, UK) is a multiparameter sensor comprised of a Clark electrode for the measurement of PO_2, optodes for the measurement of pH and PCO_2 and a thermocouple for the measurement of temperature. Before use, the sensor was calibrated with precision gases bubbled in sequence through the tonometer under microprocessor control. The mean 90 % in vitro response times of the pH, PCO_2 and PO_2 sensors are 70, 143 and 76 s, respectively [18] and the corresponding in vivo drift characteristics are 0.001 pH units/h, 0.15 torr/h and 0.03 torr/h, respectively [19].

Data analysis

A generalised estimating equations approach was taken to fitting multiple linear regression models of torr as a function of site, gas, and time. Model error structures were specified to account for the repeated measures nature of the collected data. Despite the small sample size, the data met the assumptions of normality and equality of variances adequately for the valid application of these models. The baseline gas tension in each vascular bed was defined as the mean of the values in the minute preceding the onset of the bleed. The nadir PCO_2 and PO_2 values during the shock phase were defined as the mean of the values in the minute where the greatest deviation (nadir) from baseline was observed. The magnitude of change in tissue gas tensions during haemorrhage and shock was calculated as the difference between the baseline and nadir values. Paired t-tests were used to compare tissue gas tensions at the nadir with the baseline. Analysis of variance for repeated measures was used to determine: (1) the time point at which gas tensions changed significantly from baseline during haemorrhage; and (2) the time point at which gas tensions changed significantly from the last mean in shock phase during resuscitation. Pearson correlation coefficients were used to examine the relationship between PO_{2sc} and PCO_{2gi}. Statistical significance was defined to be at the conventional 95 % level (two-tailed).

Results

Control phase

The mean baseline MAP was 112 ± 11 mmHg. The coefficient of variation of gas tensions during the 15 min preceding the onset of haemorrhage, used as an indicator of stability of experimental conditions, was calculated to be 0.8 % for PO_{2sc}, 3 % for PCO_{2sc} and 2 % for PCO_{2gi}. The mean subcutaneous and ileal luminal temperatures at the commencement of haemorrhage were 38.3 ± 0.3 °C and 37.4 ± 0.6 °C, respectively.

Haemorrhage, shock and resuscitation phases

Haemodynamic data

The mean volume of blood loss was 3.5 ± 0.2 ml (approximately 20 % of total blood volume). The time to induce hypotension to a MAP of 40 mmHg through controlled haemorrhage was consistently between 8 and 9 min.

At the end of the haemorrhage phase, this dropped to 40 mmHg as per the protocol and increased to 96 ± 32 mmHg at the end of resuscitation phase. There was no significant difference in the MAP between baseline values and those at the end of resuscitation.

Blood gas data

The haemoglobin and the arterial blood gas data are presented in Table 1. There were no significant changes in arterial pH, PaO_2, haemoglobin or plasma lactate concentrations between the baseline, shock and resuscitation phases of the study. $PaCO_2$ was significantly lower at the end of haemorrhage phase as compared to baseline ($P < 0.05$).

Table 1 Arterial gas tensions, haemoglobin and acid-base data

	Baseline	Haemorrhage	Shock	Resuscitation
pH	7.28 ± 0.06	7.32 ± 0.08	7.26 ± 0.06	7.22 ± 0.09
PCO_2 (torr)	51 ± 7.6	41 ± 8.7*	47 ± 6	51 ± 7
PO_2 (torr)	234 ± 43	211 ± 73	224 ± 62	241 ± 59
Hb (G%)	14.7 ± 0.1	12.9 ± 1.1	13 ± 0.7	12.6 ± 3.4
Lactate (mmol/L)	1.7 ± 0.6	1.8 ± 0.3	2.3 ± 0.3	1.7 ± 0.6

* $P < 0.05$ different from baseline

Table 2 Tissue gas tensions during the various phases of the study

	Baseline	Nadir	Resuscitation
PO_{2sc} (torr)	70 ± 16	35 ± 18*	75 ± 31
PCO_{2sc} (torr)	75 ± 9	85 ± 8**	79 ± 10
PCO_{2gi} (torr)	65 ± 8	88 ± 19**	70 ± 9

* $p < 0.01$ (statistically significant as compared to baseline)
** $p < 0.05$ (statistically significant as compared to baseline)

Tissue gas tensions

The gas tensions in the subcutaneous tissue and in the ileal lumen (the grouped data of the five animals) during shock and resuscitation are outlined in Table 2 and Fig. 1.

Tissue O_2 tensions

Hypovolaemia resulted in a statistically significant decrease in PO_{2sc} ($P < 0.005$) during haemorrhage. The oxygen tensions were restored to baseline values with resuscitation.

Tissue CO_2 tensions

Haemorrhage resulted in a statistically significant increase in PCO_{2gi} ($P < 0.01$) and PCO_{2sc} ($P < 0.05$). The magnitude of change in PCO_{2sc} was less than that of PCO_{2gi} during haemorrhage and resuscitation.

The tissue gas tensions for each of the individual rats are presented in Fig. 2. Inspection of the individual rat data reveals that in all five animals haemorrhage resulted in a decrease in PO_{2sc} and an increase in PCO_{2gi}, which returned to baseline with resuscitation, although the magnitude of the responses were different in each of the animals.

Relationship between arterial and tissue gas tensions

There was a significant increase in the mean tissue CO_2 gap (PCO_{2gi}–PCO_{2art}) from 14 ± 4 torr at baseline to 30 ± 8 torr with shock ($P < 0.01$) and a return towards baseline with resuscitation.

Time course of changes

In the haemorrhage phase, PO_{2sc} change was the first to reach statistical significance (4 min, $P = 0.02$) followed by CO_2 tensions in both beds (PCO_{2gi} 8 min and PCO_{2sc} 9 min, $P < 0.05$). During the resuscitation phase PO_{2sc} was also the first to respond (7 min, $P = 0.02$) followed by PCO_{2gi} (9 min, $P = 0.05$).

Relationship between the subcutaneous and ileal luminal gas tensions

Mean PO_{2sc} was inversely correlated with mean PCO_{2gi} ($r^2 = 0.7$, $P < 0.001$). This relationship is illustrated in Fig. 3. PCO_{2sc} was less strongly correlated with PCO_{2gi} ($r^2 = 0.4$). Analysis of the relationship in individual animals also revealed a strong correlation (Table 3) between PO_{2sc} and PCO_{2gi} in four of the five animals.

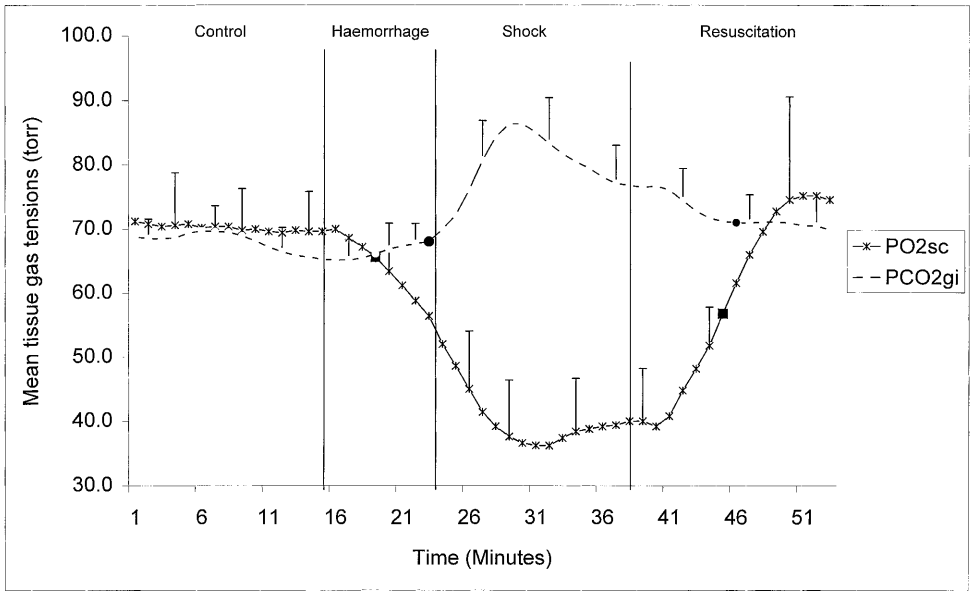

Fig. 1 Subcutaneous oxygen and ileal luminal carbon dioxide tensions during haemorrhage, shock and resuscitation. PO_{2sc} (*stars*), PCO_{2gi} (*open circles*). Representative SEMs have also been illustrated. The highlighted data labels in black reflect time points of significant change during haemorrhage and resuscitation

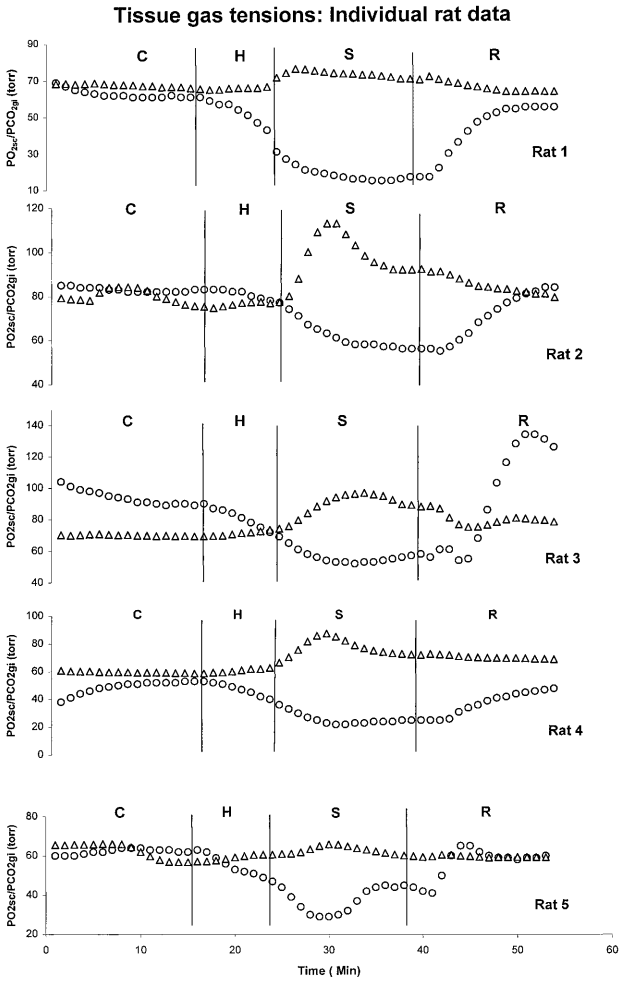

Fig. 2 Subcutaneous and ileal luminal gas tension data of the individual animals. PO_{2sc} in *open circles*, PCO_{2gi} in *open triangles*. The phases of the experiment are indicated as follows: *C* – Control, *H* – Haemorrhage, *S* – Shock, *R* – Resuscitation

There was a significant overshoot response of PO_{2sc} in animal number 3 with resuscitation, which would explain the poor correlation (Fig. 2, Table 3).

Discussion

The primary finding in this study was that subcutaneous oxygen tensions responded as rapidly as gut luminal CO_2 tensions to haemorrhage and volume restoration. Although responses were brisk with regard to all three measured gas tensions, PO_{2sc} and PCO_{2gi} responded more rapidly than PCO_{2sc}.

The baseline tissue CO_2 tensions observed in this study were slightly higher than previously published data in rodent and porcine models [16, 20]. Although this raises the question of baseline tissue hypoperfusion,

Table 3 Relationship between PO_{2sc} and PCO_{2gi} – regression data for each animal

Animal number	r^2	P value
1	0.8	$P < 0.001$
2	0.54	$P < 0.001$
3	0.21	$P < 0.05$
4	0.7	$P < 0.001$
5	0.7	$P < 0.001$

the normal baseline tissue oxygen tensions [21, 22] and plasma lactate concentrations [23] and the presence of haemodynamic stability make tissue hypoxia or tissue damage unlikely contributors to the baseline tissue hypercapnia. We attribute the slightly elevated levels of baseline tissue PCO_2 to the higher baseline $PaCO_2$ in this set of experiments.

The fall in tissue oxygen tension with haemorrhage is a result of reduction in oxygen delivery to but continuing oxygen consumption by the tissue. The increase in tissue PCO_2 reflects a combination of flow stagnation and anaerobic metabolism [24]. The reason for the less rapid response of tissue CO_2 tensions to haemorrhage and resuscitation is unclear but could be attributed in part to the longer response time of the PCO_2 optode [18], the difference in variance of PCO_2 as compared to PO_2 (Table 2), the lower level of $PaCO_2$ in the haemorrhage phase and in part to the rapid diffusibility [25], the larger volume of distribution and the larger stores of carbon dioxide in the body as compared to oxygen [26]. The inert metabolic nature of the skin as compared to that of the gut mucosa [11, 27] may explain the differences in CO_2 response between the two tissues to shock and resuscitation. It is also noteworthy that PCO_{2gi} started to decrease in the latter half of the shock phase even before resuscitation. This is probably due to a combination of: (a) deactivation of homeostatic mechanisms because of cessation of haemorrhage; and (b) the phenomenon of autoregulatory escape whereby myogenic and chemical factors produce splanchnic vasodilatation to ameliorate hypoperfusion induced by sympathetic stimulation [28].

Comparison with previously published data

The close correlation between PO_{2sc} and PCO_{2gi} for both grouped and individual values (Table 3, Fig. 2) through all the phases of the study suggests that PO_{2sc} closely reflects changes in intestinal mucosal perfusion. It is also noteworthy that the temporal profile of changes in gas tensions in both circulatory beds were similar in our study, which is in keeping with data published by Makisalo et al., who demonstrated a close relationship between PO_{2sc} and liver tissue PO_2 in an animal model

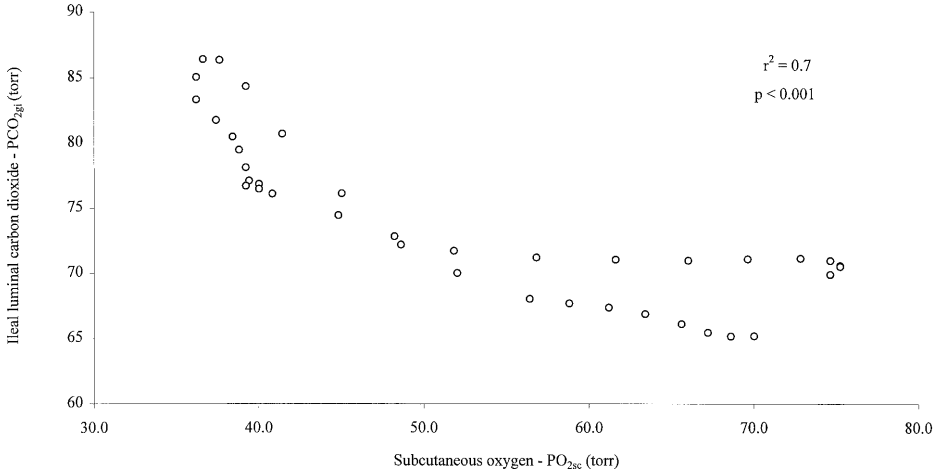

Fig. 3 An X-Y scatter plot of the mean subcutaneous oxygen and ileal luminal carbon dioxide tensions. The corresponding values of PO_{2sc} and PCO_{2gi} are shown in *open circles*

of haemorrhage and resuscitation [12], and Nordin et al., who have shown that changes in liver and subcutaneous oxygenation and pHi parallel each other in an animal model of haemorrhagic shock [29]. Whilst this contrasts with the data of Edouard et al., who have demonstrated prolonged splanchnic vasoconstriction even after restoration of global perfusion in human volunteers, we suggest that the differences in results could be related to species differences and partly due to differences in the mode of induction, duration and severity of ischaemia [30]. Other investigators have demonstrated a close correlation between cardiac output, oxygen delivery and subcutaneous oxygen tension [13, 14]. The results obtained in this study with regard to PO_{2sc} are also in accordance with those of Hunt et al., and Kwan et al. [31, 32], who showed a decrease in subcutaneous oxygen tensions with haemorrhage. Owing to the paucity of published literature on continuous CO_2 measurements in the gut and the subcutaneous tissue, similar comparisons are not possible.

In keeping with previously published data, arterial blood pH, arterial blood gases and plasma lactate concentrations were found to be poor indicators of evolving shock in this study [12, 33]. The lack of significant elevations in plasma lactate concentrations might suggest either: (a) the ischaemic insult was not severe enough; (b) regional production of lactate in ischaemic tissues was diluted by venous effluent from well perfused tissues; (c) the liver, kidney [34] and possibly the muscle tissue [35] acted as efficient "sinks" for the lactate and prevented significant elevations in the plasma; or (d) intermittent measurements of lactate missed significant rises in plasma levels. Although the first three possibilities cannot be excluded, the fourth one is unlikely because the half life of plasma lactate in healthy humans is 15 min and is prolonged in the presence of liver dysfunction [36]. It is well recognised that an elevated plasma lactate level is a late finding in shock [33] and that a normal plasma lactate concentration does not imply adequate tissue oxygenation [37]. Irrespective of the reason for eulactataemia in this study, the results strongly reinforce the message that tissue gas tensions are earlier indicators of tissue hypoperfusion than arterial acid-base indices or arterial lactate concentration.

Muscle gas tensions and pH measurements have been proposed as an alternative mode of monitoring to that of the gut and the subcutaneous tissue in covert shock [38]. Muscle gas tension measurement is more invasive than the subcutaneous route and there is evidence to show that during evolving shock, there is a disproportionately greater reduction in cutaneous and adipose tissue blood flow than in muscle tissue [39].

Critique of the study

The sensor used in this study was originally designed for continuous intra-arterial blood gas and pH measurement [18, 40]. It has since been validated and widely used experimentally for the measurement of tissue O_2 and CO_2 tensions [16, 41, 20, 42]. Ileal luminal PCO_2 was used as an indicator of mucosal PCO_2 based on theoretical considerations and experimental data: (a) CO_2 is highly diffusible and mucosal CO_2 tension would be expected to equilibrate rapidly with the lumen; and (b) data published recently have shown a close correlation between mesenteric venous and intestinal luminal gas tensions in a porcine model under physiological conditions [41] and during mesenteric ischaemia [20]. A number of factors may interfere with luminal PCO_2 measurement such as the presence of intestinal secretions, the presence of faecal material and feeds [43]. The use of silastic tubing was based on the methodology of Ninnikoski and Hunt [44, 45]. Silastic has a high O_2 and CO_2 permeability [44] and was used in order to maintain sensor stability, prevent host response to the sensor over

short periods of monitoring and prevent contact between luminal contents and the sensor. However, the lack of permeability of silastic to protons precluded the measurement of tissue pH despite the presence of a pH optode in the sensor. Placement of the silastic tubing can cause trauma, which may have influenced the accuracy of the results. Whilst we did not use a control bleed group, all the animals were observed for a period of time (15 min) during the control phase, prior to commencement of bleeding. During this phase of haemodynamic stability, there was marked stability of tissue gas tensions in the individual animals as evidenced by the low coefficient of variation (see the Results section). This confirmed the reliability and consistency of the measuring devices at the tissue sites. Gas tensions changed significantly from baseline only in response to a bleed and returned to near baseline values following return of haemodynamic parameters to baseline. Only five animals were studied but the sample size was adequate to demonstrate significant change in tissue gas tensions during the shock phase.

Supplemental oxygen was used in this study because we wanted to ensure that tissue hypoxaemia was not secondary to arterial hypoxaemia during shock. It may be argued that this manoeuvre may have artificially increased the responsiveness of PO_{2sc} as an indicator of evolving shock. However, other studies [12, 13, 14] have shown a similar PO_{2sc} responsiveness when experiments were performed on room air. Although minute ventilation was adjusted to maintain baseline $PaCO_2$ levels between 40 and 60 torr, only one rat was hypercapnic ($PaCO_2 > 60$ torr) at baseline. All the animals were normocapnic following the onset of the bleed. Hypercapnia would have increased both splanchnic and cutaneous blood flow and therefore the impact of this factor on the tissue responses would be expected to be similar in both circulatory beds [46, 47, 48, 49, 50]. The relevance of this animal model and its application to critical care patients deserves a brief mention. Whilst a number of studies using different types of haemorrhagic shock models have been published, such as controlled and uncontrolled haemorrhage [12, 31, 51], with and without sedation, constant volume and constant pressure haemorrhage [52], survival and non-survival, etc., all of them differ in the mode of induction, severity and duration of shock and resuscitation. It still remains to be determined which of those best represents the clinical situation [53]. The type of model is critical in a survival study. The purpose of our study was to examine tissue gas tensions during shock and resuscitation in a sedated animal and to that end we induced a discrete insult for a defined period followed by a fixed duration of resuscitation. Isoflurane was chosen as the maintenance anaesthetic agent in view of its favourable cardiovascular profile for the maintenance of perfusion to the splanchnic and the cutaneous circulations [54, 55].

In conclusion, we have demonstrated in this rat model that continuous subcutaneous oxygen tension monitoring, a minimally invasive technique, provides similar information to intestinal luminal carbon dioxide tension measurement as an indicator of evolving haemorrhagic shock, and that both monitoring modalities are superior to arterial plasma lactate concentrations. Subcutaneous carbon dioxide measurements were not found to be as sensitive an indicator of tissue hypoperfusion as PO_{2sc} and PCO_{2gi}. Whilst the results from this study are encouraging and the data adds to the growing literature on new techniques to monitor tissue oxygenation, this mode of monitoring requires further evaluation in different forms of shock in other animal models and in humans to assess its usefulness, safety and ability to predict outcome in critical illness.

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