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Gastric mucosal end-tidal $P\mathrm{CO}_2$ difference as a continuous indicator of splanchnic perfusion

A. Uusaro*, P. Lahtinen, I. Parviainen and J. Takala[1]

Critical Care Research Program, Department of Anesthesiology and Intensive Care, Division of Critical Care, Kuopio University Hospital, Kuopio, Finland

[1]Present address: Department of Intensive Care Medicine, University Hospital of Bern (Inselspital), Bern, Switzerland

**Corresponding author: Department of Anesthesiology and Intensive Care, Division of Critical Care, Kuopio University Hospital, PO Box 1777, FIN-70211 Kuopio, Finland*

Gastric mucosal and arterial blood $P\mathrm{CO}_2$ must be known to assess mucosal perfusion by means of gastric tonometry. As end-tidal $P\mathrm{CO}_2$ ($P\mathrm{E}'_{\mathrm{CO}_2}$) is a function of arterial $P\mathrm{CO}_2$, the gradient between $P\mathrm{E}'_{\mathrm{CO}_2}$ and gastric mucosal $P\mathrm{CO}_2$ may reflect mucosal perfusion. We studied the agreement between two methods to monitor gut perfusion. We measured the difference between gastric mucosal $P\mathrm{CO}_2$ (air tonometry) and $P\mathrm{E}'_{\mathrm{CO}_2}$ (=$D\mathrm{PCO}_{2\mathrm{gas}}$) and the difference between gastric mucosal $P\mathrm{CO}_2$ (saline tonometry) and arterial blood $P\mathrm{CO}_2$ (=$D\mathrm{PCO}_{2\mathrm{sal}}$) in 20 patients with or without lung injury. $D\mathrm{PCO}_{2\mathrm{gas}}$ was greater than $D\mathrm{PCO}_{2\mathrm{sal}}$ but changes in $D\mathrm{PCO}_{2\mathrm{gas}}$ reflected changes in $D\mathrm{PCO}_{2\mathrm{sal}}$. The bias between $D\mathrm{PCO}_{2\mathrm{gas}}$ and $D\mathrm{PCO}_{2\mathrm{sal}}$ was 0.85 kPa and precision 1.25 kPa. The disagreement between $D\mathrm{PCO}_{2\mathrm{gas}}$ and $D\mathrm{PCO}_{2\mathrm{sal}}$ increased with increasing dead space. We propose that the disagreement between the two methods studied may not be clinically important and that $D\mathrm{PCO}_{2\mathrm{gas}}$ may be a method for continuous estimation of splanchnic perfusion.

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Gastrointestinal hypoperfusion may lead to organ dysfunction, increased mortality and increased cost of care of critically ill patients.[1–3] However, we do not have a practical method for assessment of gut mucosal perfusion.[4–6] Gastrointestinal saline tonometry is still controversial and not routinely used in critical care, for several reasons. Originally the gastric tonometer was designed to measure gastric mucosal $P\mathrm{CO}_2$ which was then used to calculate gastric mucosal pH ($\mathrm{pH_i}$).[7 8] Gastric mucosal pH was assumed to reflect splanchnic perfusion and oxygenation. However, the calculation of $\mathrm{pH_i}$ necessitates both taking arterial blood sample to measure bicarbonate concentration and the use of a cumbersome formula. In addition, experimental and clinical studies have shown that the calculation of $\mathrm{pH_i}$ using arterial blood bicarbonate concentration may be incorrect, the use of $\mathrm{pH_i}$ alone ignores the effects of systemic acid–base status on gastric mucosal pH and there is also a potential bias from the measurement of saline $P\mathrm{CO}_2$ with different blood gas analysers.[9–11]

The measurement of gastric mucosal $P\mathrm{CO}_2$ has become more popular in experimental and clinical studies and avoids the potential problems of $\mathrm{pH_i}$. An automated gas tonometer was developed to measure gastric mucosal $P\mathrm{CO}_2$, so that repeated analysis of saline samples for $P\mathrm{CO}_2$ and the potential errors of analysis are eliminated and the measurements are now easier.[10 12 13] Clinical and experimental studies have validated gas tonometry using conventional saline tonometry as a reference.[14–16] However, the gradient between systemic $P\mathrm{CO}_2$ and gastric mucosal $P\mathrm{CO}_2$ is the variable of interest that reflects mucosal perfusion.[4 17] Repeated arterial blood samples are needed to measure blood $P\mathrm{CO}_2$ which may not be feasible in clinical practice and may make clinicians unwilling to use gastric tonometry. On the other hand, without continuous or semi-continuous measurements important episodes of splanchnic hypoperfusion may not be noticed.

The partial pressure of carbon dioxide (CO_2) of end expiratory gas (end tidal CO_2, $P\mathrm{E}'_{\mathrm{CO}_2}$) can be used to estimate arterial $P\mathrm{CO}_2$.[18] $P\mathrm{E}'_{\mathrm{CO}_2}$ is routinely monitored in intubated patients although $P\mathrm{E}'_{\mathrm{CO}_2}$ does not necessarily accurately represent arterial CO_2 if the proportion of dead space ventilation is increased as in patients with lung

injury.[19] However, the difference between $P\mathrm{E}'_{\mathrm{CO}_2}$ and gastric mucosal CO_2 (measured by gas tonometry) could reflect gastric mucosal perfusion continuously or semi-continuously without a need for laboratory testing. We hypothesized that this would be the case even in patients with increased physiologic dead space, providing that the dead space remains relatively constant. To our knowledge this possibility has not been tested. We designed our study to investigate if the gradient between gastric mucosal $P\mathrm{CO}_2$ and end-tidal CO_2 can be used to monitor gastric mucosal perfusion.

Patients and methods

The study was approved by the Ethics Committee of the Kuopio University Hospital and a written informed consent was obtained either from the patient (patients recovering from cardiac surgery), or from the relatives (patients with acute lung injury, ALI). We studied 10 patients who were recovering from cardiac surgery (and who did not have lung injury) and 10 patients who had ALI. We defined ALI as $P\mathrm{a}_{\mathrm{O}_2}/F\mathrm{I}_{\mathrm{O}_2}$ less than 200 mm Hg (26.7 kPa). We studied patients with ALI because increased dead space ventilation increases the difference between arterial CO_2 and $P\mathrm{E}'_{\mathrm{CO}_2}$ and this may reduce the accuracy of gastric-mucosal end-tidal $P\mathrm{CO}_2$ difference to indicate gastric-mucosal arterial $P\mathrm{CO}_2$ difference (gastric-mucosal end-tidal $P\mathrm{CO}_2$ tends to be higher than gastric-mucosal arterial $P\mathrm{CO}_2$ difference). All patients were intubated, mechanically ventilated (Servo 900C, Siemens AB, Solna, Sweden) and sedated as clinically appropriate during the measurements.

Two gastric tonometers, a gas and a saline tonometer, were inserted in each patient via mouth. The correct positions of the tips of the tonometers were confirmed by x-ray. We used continuous gastric suctioning but H_2-blockers were not given to any patient.[20,21] Gas tonometer (Tonocap®, Datex/Instrumentarium, Helsinki, Finland) was used to measure gastric mucosal partial pressure of carbon dioxide ($P\mathrm{r}_{\mathrm{CO}_2}$) in 15 min intervals during the 8 h study period. In Tonocap® the device fills the tonometer TRIP-catheter (Tonometrics, Datex/Instrumentarium, Finland) with 5 ml gas (air) and a sample of this gas is drawn after an equilibration period. The $P\mathrm{CO}_2$ of this sample is measured by Tonocap® using the same standard infra-red method that is used to measure the partial pressure of end-tidal CO_2 ($P\mathrm{E}'_{\mathrm{CO}_2}$). A time dependent correction factor of 1.12 (for incomplete equilibration time of 15 min) for the mucosal $P\mathrm{CO}_2$ ($P\mathrm{r}_{\mathrm{CO}_2}$) was used. The Tonocap® was calibrated before the measurements according to the manufacturer's recommendation using calibration gas ($5\pm0.03\%$ CO_2 in 95% oxygen, Datex/Instrumentarium, Helsinki, Finland). The mean value of $P\mathrm{r}_{\mathrm{CO}_2}$ was calculated each hour to allow comparison between gas and saline tonometers. End-tidal CO_2 was measured from the expired air immediately distal to the intubation tube using an AS3 monitor (Datex/Instrumentarium, Helsinki, Finland). The gastric-mucosal end-tidal $P\mathrm{CO}_2$ difference ($\mathrm{D}P\mathrm{CO}_{2\mathrm{gas}}$) was calculated by subtracting end tidal $P\mathrm{CO}_2$ from gastric mucosal $P\mathrm{CO}_2$ (as measured by Tonocap®).

We measured $P\mathrm{r}_{\mathrm{CO}_2}$ using conventional saline tonometry and arterial $P\mathrm{CO}_2$ each hour throughout the study. With the saline tonometry $P\mathrm{r}_{\mathrm{CO}_2}$ was measured using 2.5 ml of sodium chloride in the tonometer balloon. Both the saline and arterial blood samples were analysed within 2 min of withdrawal using a blood–gas analyser (ABL-520, Radiometer, Copenhagen, Denmark). We did not take into account the potential bias related to blood gas analyser.[10] A time dependent correction factor of 1.13 (for incomplete equilibration time of 60 min) for the $P\mathrm{r}_{\mathrm{CO}_2}$ was used with saline tonometry and the measurements were carried out according to the manufacturer's recommendations. Gastric-mucosal arterial $P\mathrm{CO}_2$ difference ($\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$) was calculated by subtracting arterial $P\mathrm{CO}_2$ from gastric mucosal $P\mathrm{CO}_2$ (as measured by saline tonometry). We regarded this difference ($\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$) as the reference to represent true systemic-gastric mucosal $P\mathrm{CO}_2$. In addition to the comparison between $\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$ and $\mathrm{D}P\mathrm{CO}_{2\mathrm{gas}}$, we also compared the differences between gastric mucosal $P\mathrm{CO}_2$ (measured using gas tonometry) and arterial blood $P\mathrm{CO}_2$ or end-tidal $P\mathrm{CO}_2$. This was done to eliminate potential errors in the saline technique, such as those related to blood–gas analyser bias, inappropriate equilibration factors and tonometer catheter dead space effects.

Arterial end-tidal $P\mathrm{CO}_2$ difference was calculated by subtracting end-tidal $P\mathrm{CO}_2$ from arterial blood $P\mathrm{CO}_2$. This gradient was calculated to indirectly estimate dead space ventilation of the lung. The higher the gradient between arterial ($P\mathrm{a}_{\mathrm{CO}_2}$) end-tidal $P\mathrm{CO}_2$ ($P\mathrm{E}'_{\mathrm{CO}_2}$), the higher is the dead space ventilation of the lung. The fraction (%) of dead space ventilation ($V\mathrm{D}/V\mathrm{T}$) was estimated using the following equation: $V\mathrm{D}/V\mathrm{T} = (P\mathrm{a}_{\mathrm{CO}_2} - P\mathrm{E}'_{\mathrm{CO}_2})/P\mathrm{a}_{\mathrm{CO}_2}$.

Statistical analysis

Our main interest in the analysis was to study the agreement between $\mathrm{D}P\mathrm{CO}_{2\mathrm{gas}}$ and $\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$. We studied this agreement using the method described by Bland and Altman.[22] In addition to graphical display we also calculated bias (the mean difference between the two measurements) and precision (SD of the bias) for this comparison. Because we repeated measurements, the effect of time, and particularly time by group ($\mathrm{D}P\mathrm{CO}_{2\mathrm{gas}}$ or $\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$) interaction, was analysed using general linear model with repeated measures option (statistical package SPSS for Windows, version 7.5). This analysis was carried out to test whether changes in gastric-mucosal systemic $P\mathrm{CO}_2$ difference during the study were similar for $\mathrm{D}P\mathrm{CO}_{2\mathrm{gas}}$ and $\mathrm{D}P\mathrm{CO}_{2\mathrm{sal}}$. We used regression analysis to study the correlation between two variables and *t*-test when appropriate. A *P*-value of <0.05 was considered statistically significant. Results are given as mean (SD).

Results

The fraction of dead space ventilation was 11 (7)% (mean (SD)) in CABG patients and 25 (12)% in patients with ALI ($P<0.001$). The mean values and standard deviations of gastric mucosal end tidal P_{CO_2} difference ($DP_{CO_{2gas}}$) and gastric mucosal arterial P_{CO_2} difference ($DP_{CO_{2sal}}$) for each hour during the whole study period are shown in Figure 1. When all patients were analysed together there was a significant effect of time ($P<0.01$) but no time by group interaction ($P=0.33$) indicating that the changes of gastric mucosal-systemic P_{CO_2} difference were similar for $DP_{CO_{2sal}}$ and $DP_{CO_{2gas}}$. Also in this analysis the group effect was not significant ($P=0.084$). $DP_{CO_{2gas}}$ tended to be greater that $DP_{CO_{2sal}}$ both in patients with ALI and in patients recovering from cardiac surgery. However, the difference between the two methods was greater in patients with ALI. Figure 2 shows that the agreement between the two methods to reflect gastric mucosal systemic P_{CO_2} is reasonably good, except for higher mean gastric mucosal systemic P_{CO_2} differences. With greater mean gastric mucosal-systemic P_{CO_2} differences, $DP_{CO_{2gas}}$ tends to overestimate $DP_{CO_{2sal}}$ (Fig. 2). The bias and the precision of this comparison are 0.85 and 1.25 kPa, respectively. The comparison between gastric mucosal P_{CO_2} (measured by gas tonometry) and arterial blood P_{CO_2} or end-tidal CO_2 is shown in Figure 3. The difference between gastric mucosal P_{CO_2} (gas tonometry) and end-tidal CO_2 was higher ($P=0.022$, 'group' effect) than the difference between gastric mucosal P_{CO_2} (gas tonometry) and arterial blood P_{CO_2}. In addition, the effect of time was significant ($P<0.001$) but there was no time by group interaction ($P=0.9$). In Bland and Altman analysis the bias and the precision of this comparison are 1.08 and 0.85 kPa, respectively (figure not shown).

As expected, the difference between $DP_{CO_{2gas}}$ and $DP_{CO_{2sal}}$ increased with increasing arterial end-tidal P_{CO_2} difference (Fig. 4). Figure 5 shows a reasonable correlation between the maximum change from baseline in $DP_{CO_{2sal}}$ and the corresponding change in $DP_{CO_{2gas}}$. The correlation in gastric mucosal P_{CO_2}, when it was measured both by saline and by gas tonometry, is shown in Figure 6 and the Bland–Altman plot for the same comparison in Figure 7. The bias in this Bland–Altman analysis was –0.26 kPa and the precision 0.81 kPa. Finally, the correlation showing the mean gastric mucosal P_{CO_2} (measured by air and saline tonometry) for each patient during the whole study period is shown in Figure 8.

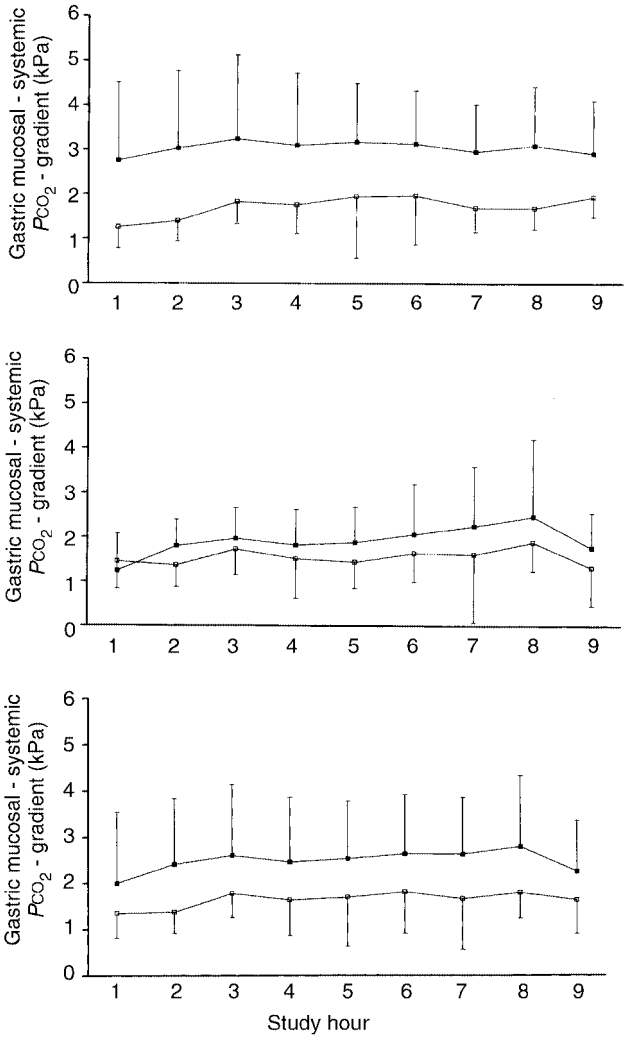

Fig 1 Gastric mucosal end tidal P_{CO_2} difference ($DP_{CO_{2gas}}$) and gastric mucosal-arterial P_{CO_2} difference ($DP_{CO_{2sal}}$) (mean (SD)) during the 8 h study period. (Top) Patients with ALI; (middle) patients recovering from cardiac surgery; (bottom) all patients combined. When all patients were analysed together (bottom) using general linear model there was a significant effect of time ($P<0.01$) but no time by group ($DP_{CO_{2gas}}$ or $DP_{CO_{2sal}}$) interaction ($P=0.33$).

Discussion

We found that the difference between gastric mucosal P_{CO_2} (measured by gas tonometry) and end-tidal P_{CO_2} ($DP_{CO_{2gas}}$) reflects the difference between gastric mucosal P_{CO_2} (measured by saline tonometry) and arterial P_{CO_2} ($DP_{CO_{2sal}}$). We also found that $P_{CO_{2gas}}$ systematically overestimated $DP_{CO_{2sal}}$ and that $DP_{CO_{2gas}}$ has some obvious limitations. However, the agreement between the two methods is acceptable and allows $DP_{CO_{2gas}}$ to be used in clinical practice as a semi-continous indicator of the adequacy of splanchnic perfusion.

The advantage of $DP_{CO_{2gas}}$ is that it reflects the adequacy of gastric mucosal perfusion continuously. A monitor is a warning device that reveals progressive change, e.g. perfusion abnormalities, promptly, and continuous monitoring is the best option in clinical practice. The gastric mucosal systemic P_{CO_2} (arterial blood) gradient best reflects mucosal perfusion. Also, gut perfusion decreases early in shock, often when systemic haemodynamics are stable.[23] Saline tonometry, and gas tonometry, both need repeated samples for arterial blood or saline P_{CO_2}. It is not feasible in

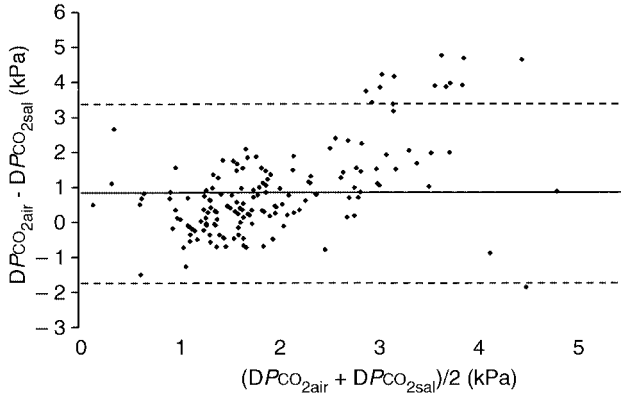

Fig 2 The agreement between $D(P_{CO_{2gas}})$ and $D(P_{CO_{2sal}})$ analysed using the method by Bland and Altman.[20] $D(P_{CO_{2air}})$=gastric mucosal end-tidal P_{CO_2} difference when mucosal P_{CO_2} was measured using gas tonometry. $D(P_{CO_{2sal}})$=gastric mucosal arterial P_{CO_2} difference when mucosal P_{CO_2} was measured using saline tonometry. Solid line indicates bias of this comparison and dotted lines indicate ±2 SD of the bias.

clinical practice to draw and analyse arterial blood and gastric tonometer saline samples at frequent, e.g. 10–15 min intervals, if patients are clinically stable. However, because splanchnic perfusion deteriorates early in shock, this clinically stable phase of critical illness would be ideal to monitor gastrointestinal perfusion. The measurement of gastric mucosal-end-tidal CO_2 is a convenient method to continuously monitor gastric mucosal perfusion without a need to repeatedly analyse saline or arterial blood samples. Because no laboratory work is needed, several potential errors and problems related with sample handling and analysis are avoided. We used a separate monitor to analyse end-tidal CO_2 but a newer version of Tonocap® automatically analyses and displays both gastric mucosal and end-tidal P_{CO_2}. Tonocap® (both mucosal P_{CO_2} and end-tidal P_{CO_2}) has to be calibrated once every 2 months with a gas of known P_{CO_2}. There is no need for recalibration after ventilatory adjustments and also temperature has no effect on the measurements. The potential problem of water evaporation in the tubing of capnograph is avoided because Tonocap® includes a water separation system which is based on a hydrophilic membrane.

We are not aware of any studies that have evaluated the gastric-mucosal end-tidal P_{CO_2} difference to assess splanchnic perfusion. There are several studies that examined the agreement between gastric mucosal P_{CO_2} measured by saline and gas tonometry.[14–16] In our study the correlation between gastric mucosal P_{CO_2} measured by saline and gas tonometry was not as good as has been reported elsewhere. We do not have a clear explanation for this discrepancy. Also, we do not know why gas tonometry systematically gave higher values than saline tonometry (Figs 6 and 8). We did not use H_2-blockers in our patients but this should not affect the agreement between the two methods. It is not clear if H_2-blockers are needed in critically ill patients to improve the performance of gastric tonometry.[20 21 24 25] In patients

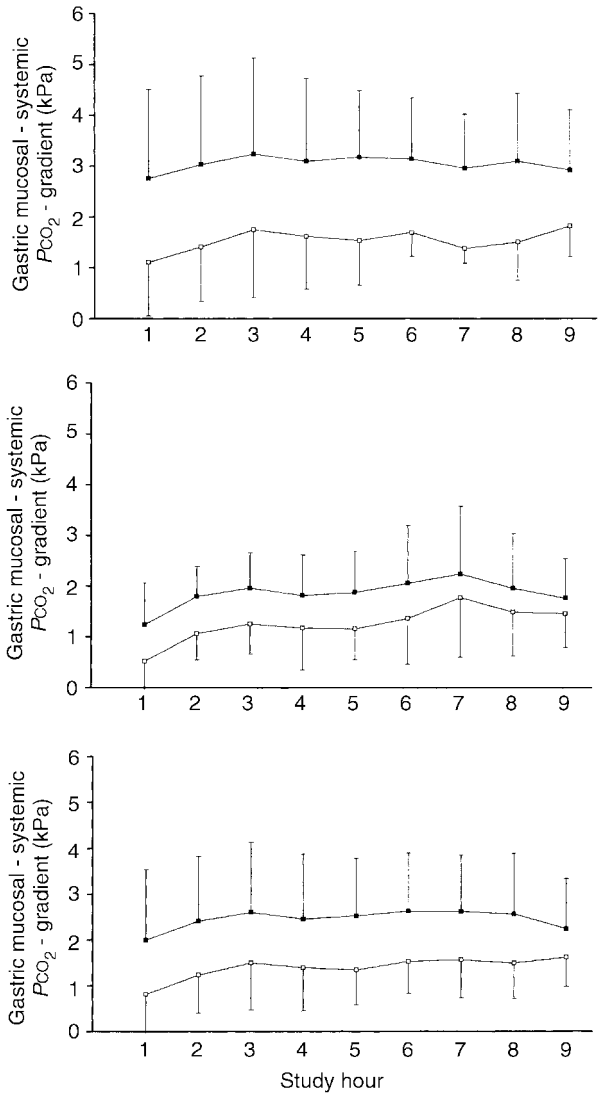

Fig 3 Gastric mucosal-systemic P_{CO_2} difference (mean (SD)) during the 8 h study period. Gastric mucosal P_{CO_2} was measured using Tonocap®. Open symbols = gastric mucosal-arterial blood P_{CO_2}, closed symbols = gastric mucosal-end-tidal P_{CO_2}. (Top) Patients with ALI; (middle) patients recovering from cardiac surgery; (bottom) all patients combined. When all patients were analysed together (bottom) using general linear model there was a significant effect of time (P<0.001) and group (P=0.02) but no time by group (arterial blood P_{CO_2} or end-tidal P_{CO_2}) interaction (P=0.9).

with cardiogenic shock, a systematic disagreement between saline and gas tonometry was found.[26] Under-correction of saline samples may be responsible although correction was done according to manufacturer's recommendations. We regarded saline technique as a gold standard but this may not necessarily be true.[27 28] *In vivo*, gas tonometry gave a closer agreement with the P_{CO_2} of the test solution.[27] Also, the bias between gas and saline tonometry was reduced by replacing saline by buffered electrolyte solutions.[27] We used saline with our conventional tonometry and this may have contributed to the differences in our study. The degree of clinically important disagreement between different

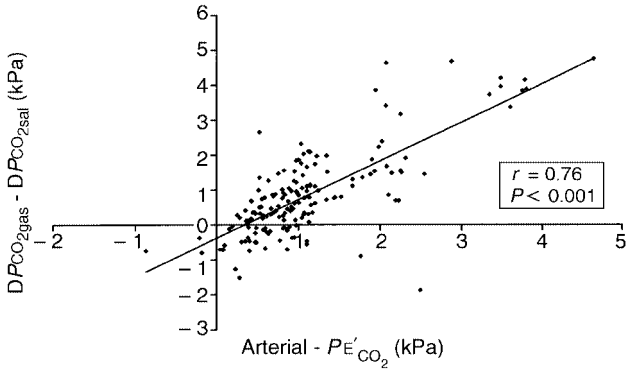

Fig 4 Correlation between arterial end-tidal P_{CO_2} difference (=arterial–$P_{E'CO_2}$) and $DP_{CO_{2gas}}$–$DP_{CO_{2sal}}$ difference. $DP_{CO_{2gas}}$=gastric mucosal P_{CO_2}-end-tidal P_{CO_2} when gastric mucosal P_{CO_2} is measured using gas tonometry. $DP_{CO_{2sal}}$=gastric mucosal P_{CO_2}–arterial P_{CO_2} when gastric mucosal P_{CO_2} is measured using saline tonometry.

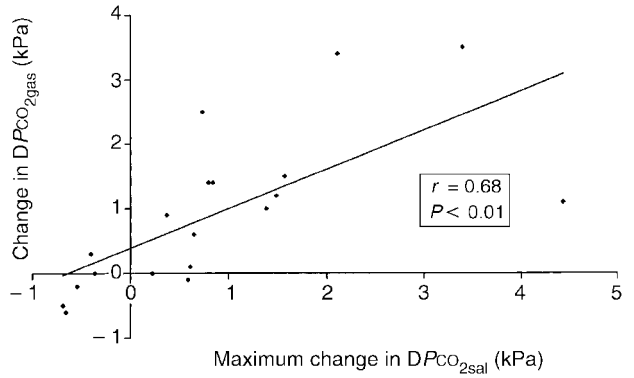

Fig 5 The maximum change from baseline in $DP_{CO_{2sal}}$ and the corresponding change in $DP_{CO_{2gas}}$. $DP_{CO_{2gas}}$=gastric mucosal P_{CO_2}–end-tidal P_{CO_2} when gastric mucosal P_{CO_2} is measured using gas tonometry. $DP_{CO_{2sal}}$=gastric mucosal P_{CO_2}–arterial P_{CO_2} when gastric mucosal P_{CO_2} is measured using saline tonometry.

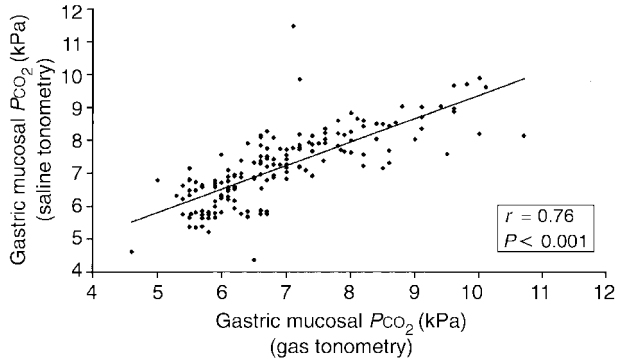

Fig 6 Correlation between paired gastric mucosal P_{CO_2} measurements when P_{CO_2} was measured simultaneously using both saline and gas tonometry.

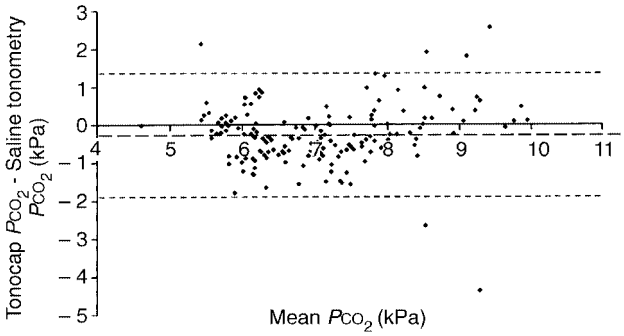

Fig 7 The agreement between simultaneous gastric mucosal P_{CO_2} measurements when both air (Tonocap®) and saline tonometry were used. Mean P_{CO_2}=(Tonocap® P_{CO_2}+saline tonometry P_{CO_2})/2. Analysis was done using the method by Bland and Altman.[20] Solid line indicates bias of this comparison and dotted lines indicate ±2 SD of the bias.

methods to estimate mucosal perfusion is more important than the disagreement *per se*.

The normal gastric mucosal systemic P_{CO_2} difference is not known and more importantly we do not know how large a difference is clinically important in critically ill patients. In our previous study with healthy volunteers, the gastric mucosal arterial P_{CO_2} gap varied between 1.4 and 3 kPa depending on whether nasogastric suction or H_2-blockers were used.[20] A more recent study in healthy volunteers suggested a normal threshold value of <1.1 kPa for a gastric mucosal arterial P_{CO_2} difference.[29] Gastric mucosal P_{CO_2} depends on several factors such as aerobic and anaerobic production of CO_2 and also on perfusion of the gastric mucosa,[17] and it is not clear to what extent increased gastric mucosal P_{CO_2} indicates tissue hypoxia or decreased mucosal perfusion. A recent experimental study suggested that gastric mucosal P_{CO_2} has to increase to >13 kPa to indicate tissue hypoxia.[30] In our study the bias and the precision of the agreement between $DP_{CO_{2gas}}$ and $DP_{CO_{2sal}}$ were 0.85 and 1.25 kPa, respectively. Therefore, we propose, that the small disagreement between these methods may not be clinically important.

One obvious problem with the use of the gastric mucosal end-tidal P_{CO_2} difference is that in patients with impaired gas exchange, end-tidal CO_2 does not represent arterial (and hence systemic) P_{CO_2}.[19] In patients who do not have ALI this is not a large problem but in patients who have lung injury, end-tidal CO_2 may underestimate systemic P_{CO_2}. We found that in patients who have ALI, $DP_{CO_{2gas}}$ overestimated $DP_{CO_{2sal}}$ more than in patients who do not have ALI. Figure 3 also shows that the disagreement between $DP_{CO_{2gas}}$ and $DP_{CO_{2sal}}$ increases as the arterial end-tidal P_{CO_2} difference increases (indicating increased dead space ventilation). However, for at least two reasons the potential overestimation of the gastric mucosal systemic P_{CO_2} difference is not a major clinical problem. First, it is physiologically obvious and easily recognizable. A significant difference between arterial blood P_{CO_2} and end-tidal CO_2, can be easily measured and used to interpret $DP_{CO_{2gas}}$.

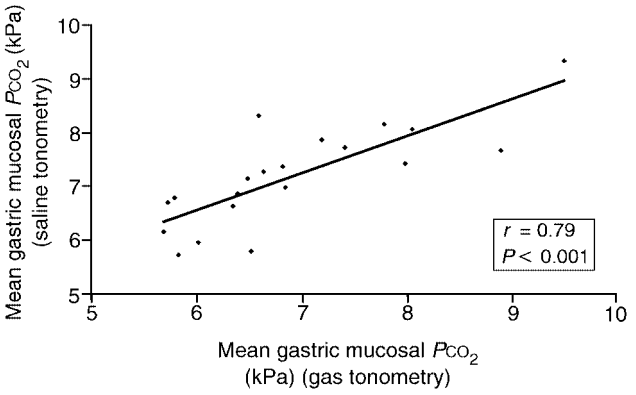

Fig 8 Correlation between the mean gastric mucosal P_{CO_2} values calculated for each patient during the 8 h study period. Measurements were done simultaneously both by air and saline tonometry.

Secondly, an overestimate of the gastric mucosal systemic P_{CO_2} difference using $D P_{CO_{2gas}}$ means that truly increased P_{CO_2} differences will not be left undetected. We found that changes in $D P_{CO_{2gas}}$ reflected changes in $D P_{CO_{2sal}}$ during our study period, but the time period for our study was relatively short and probably was during steady state CO_2 production, lung function and dead space ventilation. Therefore, we cannot address the potential impact of changes in these variables during the progression of critical illness.

The difference between gastric mucosal end tidal P_{CO_2} is a potentially useful method for continuous monitoring of splanchnic perfusion. It is easy to use and it does not require much additional work from staff, and the limits of the method are easy to assess and they do not jeopardize patient care. Studies of clinical outcome, based on interventions using this information are needed.

References

1 *Gut*ierrez G, Palizas F, Doglio G *et al.* Gastric intramucosal pH as a therapeutic index of tissue oxygenation in critically ill patients. *Lancet* 1992; **339**: 195–9

2 Marik PE. Gastric intramucosal pH. A better predictor of multiorgan dysfunction syndrome and death than oxygen-derived variables in patients with sepsis. *Chest* 1993; **104**: 225–9

3 Mythen MG, Webb AR. Intra-operative gut mucosal hypoperfusion is associated with increased post-operative complications and cost. *Intensive Care Med* 1994; **20**: 99–104

4 Russell JA. Gastric tonometry: does it work? *Intensive Care Med* 1997; **23**: 3–6

5 Mythen MG, Webb AR. Gastrointestinal tonometry comes of age? *Br J Anaesth* 1998; **81**: 667–8

6 Keenan SP, Guyatt GH, Sibbald WJ *et al.* How to use articles about diagnostic technology: gastric tonometry. *Crit Care Med* 1999; **27**: 1726–31

7 Fiddian-Green RG, Pittenger G, Whitehouse WM Jr. Back-diffusion of CO_2 and its influence on the intramural pH in gastric mucosa. *J Surg Res* 1982; **33**: 39–48

8 Antonsson JB, Boyle III CC, Kruithoff KL *et al.* Validation of tonometric measurement of gut intramural pH during endotoxemia and mesenteric occlusion in pigs. *Am J Physiol* 1990; **259**: G519–23

9 Desai VS, Weil MH, Tang W, Yang G, Bisera J. Gastric intramural PCO_2 during peritonitis and shock. *Chest* 1993; **104**: 1254–8

10 Takala J, Parviainen I, Siloaho M, Ruokonen E, Hämäläinen E. Saline PCO_2 is an important source of error in the assessment of gastric intramucosal pH. *Crit Care Med* 1994; **22**: 1877–9

11 Fiddian-Green RG. Gastric intramucosal pH, tissue oxygenation and acid–base balance. *Br J Anaesth* 1995; **74**: 591–606

12 Kolkman JJ, Zwarekant Lj, Boshuizen K, Groeneveldt ABJ, Steverink PJGM, Meuwissen SGM: Type of solution and PCO_2 measurement errors during tonometry. *Intensive Care Med* 1997; **23**: 658–63

13 Knichwitz G, Mertes N, Kuhmann M. Improved PCO_2 measurement in six standard blood gas analysers using a phosphate-buffered solution for gastric tonometry. *Anaesthesia* 1995; **50**: 532–4

14 Knichwitz G, Rotker J, Brussel T, Kuhmann M, Mertes N, Möllhoff T. A new method for continuous intramucosal PCO_2 measurement in the gastrointestinal tract. *Anesth Analg* 1996; **83**: 6–11

15 Heinonen PO, Jousela IT, Blomqvist KA, Olkkola KT, Takkunen OS. Validation of air tonometric measurement of gastric regional concentrations of CO_2 in critically ill septic patients. *Intensive Care Med* 1997; **23**: 524–9

16 Creteur J, De Backer D, Vincent J-L. Monitoring gastric mucosal carbon dioxide pressure using gas tonometry. *Anesthesiology* 1997; **87**: 504–10

17 Schlichtig R, Bowles SA. Distinguishing between aerobic and anaerobic appearance of dissolved CO_2 in intestine during low flow. *J Appl Physiol* 1994; **76**: 2443–51

18 Morley TF, Giaimo J, Maroszan E *et al.* Use of caphography for assessment of the adequacy of alveolar ventilation during weaning from mechanical ventilation. *Am Rev Respir Dis* 1993; **148**: 339–44

19 Nunn JF. *Applied Respiratory Physiology*, 4th edn. Butterworth-Heinemann: Oxford, 1993

20 Parviainen I, Väisänen O, Ruokonen E, Takala J. Effect of nasogastric suction and ranitidine on the calculated gastric intramucosal pH. *Intensive Care Med* 1996; **22**: 319–23

21 Väisänen O, Ruokonen E, Parviainen I, Bocek P, Takala J. Ranitidine or dobutamine alone or combined has no effect on gastric intramucosal-arterial PCO_2-difference after cardiac surgery. *Intensive Care Med* 2000; **26**: 45–51

22 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; **i**: 307–10

23 Price HL, Deutsch S, Marshall BE, Stephen GW, Behar MG, Neufeld GR. Hemodynamic and metabolic effects of hemorrhage in man with particular reference to the splanchnic circulation. *Circ Res* 1966; **18**: 469–74

24 Calvet X, Baigorri F, Duarte M *et al.* Effect of ranitidine on gastric intramucosal pH in critically ill patients. *Intensive Care Med* 1998; **24**: 12–7

25 Bams JL, Kolkman JJ, Roukens MP *et al.* Reliable gastric tonometry after coronary artery surgery: need for acid secretion suppression despite transient failure of acid secretion. *Intensive Care Med* 1998; **24**: 1139–43

26 Janssens U, Graf J, Koch KC, Hanrath P. Gastric tonometry: *in vivo* comparison of saline and air tonometry in patients with cardiogenic shock. *Br J Anaesth* 1998; **81**: 676–80

27 Temmesfeld-Wollbrück B, Szalay A, Olschewski H, Grimminger F, Seeger. Advantage of buffered solutions or automated

capnometry in air-filled balloons for use in gastric tonometry. *Intensive Care Med* 1997; **23**: 423–7

28 Taylor DE, Gutierrez G, Clark C, Hainley S. Measurement of gastric mucosal carbon dioxide tension by saline and air tonometry. *J Crit Care* 1997; **12**: 208–13

29 Kolkman JJ, Steverink PJGM, Groeneveld ABJ, Meuwissen SGM. Characteristics of time-dependent PCO_2 tonometry in the normal human stomach. *Br J Anaesth* 1998; **81**: 669–75

30 Rozenfeld RA, Dishart MK, Tonnessen TI, Schlictig R. Methods for detecting local intestinal ischemic anaerobic metabolic acidosis by PCO_2. *J Appl Physiol* 1996; **81**: 1834–42