Gastric tonometry: in vivo comparison of saline and air tonometry in patients with cardiogenic shock

U. JANSSENS, J. GRAF, K. C. KOCH AND P. HANRATH

Summary
Measurement of gastric intramucosal pH (pHi) has been advocated to assess gastric perfusion. Regional $P_{\text{CO}_2}$ ($rP_{\text{CO}_2}$) values are measured using saline tonometry ($rsP_{\text{CO}_2}$) and more recently using air tonometry ($raP_{\text{CO}_2}$). We compared 237 measurements of saline and air tonometry in 19 consecutive, severely ill patients (mean age 59 (range 31–76) yr, 19 males, APACHE II 22±7) with cardiogenic shock. Equilibration period was set to 90 min. Nineteen independent paired samples were compared with saline tonometry at high $rP_{\text{CO}_2}$ and mean $rsP_{\text{CO}_2}$ of each patient showed good correlation ($r=0.93$, $P<0.001$). Mean $raP_{\text{CO}_2}$ was 6.5 (1.8) kPa and mean $rsP_{\text{CO}_2}$ 6.8 (2.4) kPa. $P_{\text{CO}_2}$ measured by saline was significantly higher than that measured by air ($P<0.05$). Bland and Altman analysis showed a bias (mean $rsP_{\text{CO}_2}$–mean $raP_{\text{CO}_2}$) of 0.3 kPa and a precision of 1.2 kPa. Agreement between the two methods decreased with increasing $rP_{\text{CO}_2}$ concentrations. Although air tonometry of $rP_{\text{CO}_2}$ is a promising technique, a systematic disagreement with saline tonometry at high $rP_{\text{CO}_2}$ values requires further investigation and cautious interpretation of these values. (Br. J. Anaesth. 1998; 81: 676–680).

Keywords: gastrointestinal tract, mucosal perfusion; gastrointestinal tract, pH; measurement techniques, tonometry

Gastric tonometry for estimation of intramucosal pH (pHi) in severely ill patients is becoming increasingly used in intensive care units. Low pH is thought to indicate gastrointestinal ischaemia, identifying those patients at risk of developing complications attributable to mucosal disruption in critical illness. Determination of pHi has been used to guide treatment of critically ill patients and as a measure of outcome prediction. The value of pH in the mucosa is obtained indirectly by measuring the regional partial pressure of carbon dioxide ($rP_{\text{CO}_2}$) in the lumen of the stomach with a saline-filled silicone balloon tonometer and the bicarbonate ($\text{HCO}_3^-$) concentration in arterial blood, and substituting these two values in the Henderson–Hasselbalch equation. It is assumed that the $\text{HCO}_3^-$ concentration in the intra-cellular fluid of the tissue is in equilibrium with the $\text{HCO}_3^-$ concentration in mucosal capillary blood which is further presumed to be the concentration found in blood.

Until recently $rP_{\text{CO}_2}$ was determined by analysing saline from the tonometer balloon, a method suggested to be a source of several errors. Depending on design features of the blood-gas analyser, varying amounts of carbon dioxide are lost from the sample because of the low stability of carbon dioxide in saline before carbon dioxide analysis by the carbon dioxide electrode is completed. Differences in blood-gas analysers which indicate different $P_{\text{CO}_2}$ values from identical samples may contribute to erroneous intramucosal pH values. Further, tonometry does not allow rapid assessment of $rP_{\text{CO}_2}$. Because of these concerns a continuous air tonometric monitoring system was developed.

In this study, we have compared the (semi-) automatic air tonometry method with conventional saline tonometry in critically ill patients in terms of accuracy and precision.

Patients and methods
The study was approved by the local Ethics Committee of the University Hospital of Aachen and conducted according to the principles of the Helsinki Declaration.

We studied prospectively 19 consecutive patients (mean age 59 (31–76) yr, 19 males, APACHE II 22±7) admitted to the cardiology intensive care unit of the University Hospital of Aachen with cardiogenic shock. All patients were sedated and underwent mechanical ventilation. Therefore, informed consent was obtained from the closest relatives. Cardiogenic shock was caused by anterior myocardial infarction in 10 of 19 patients, posterior myocardial infarction in four of 19 patients, ischaemic cardiomyopathy in four of 19 patients and dilated cardiomyopathy in one patient. Eleven of the 19 patients (58%) died. Haemodynamic values of all patients before study entry are shown in table 1. No patient received enteral nutrition and famotidine 20 mg (Pepdul, MSD Chibropharm, München, Germany) was administered i.v. twice daily.

Two gastric tonometer catheters (TRIP NGS catheter, Tonometric Division, Instrumentarium, Helsinki, Finland) were placed in the stomach via the nasogastric route. Correct placement of the tubes was verified radiologically. Measurements of $rP_{\text{CO}_2}$ were performed 90, 180 and 270 min after entry to the study and thereafter three times daily with saline ($rsP_{\text{CO}_2}$) and air ($raP_{\text{CO}_2}$) tonometry. The equilibration period was 90 min for each measurement. The end of study was defined as removal of gastric
tonometers for clinical reasons (e.g. extubation) or if death occurred. Arterial blood-gas analysis was carried out simultaneously using a standard blood-gas analyser (ABL 505 blood gas analyser, Radiometer, Copenhagen, Denmark).

An automated gas analyser (Tonocap TC 200, Tonometric Division, Instrumentarium, Helsinki, Finland) was connected to one of the gastric tonometer catheters. This monitor supplies the tonometer balloon with room air. The gas is held in the catheter balloon for a set period of time for diffusion to take place. This equilibration period may be predefined (10, 15, 30 or 60 min) or is set manually. With each measurement cycle, 6 ml of air are pumped into the balloon. A sample is then obtained automatically after the selected cycle period. The first 1.2 ml, equivalent to the deadspace of the system, are discarded. PCO2 is measured in the remainder with an infrared sensor. Using an internal nafion tube (used in the Tonocap) water vapour partial pressure of the vapour partial pressure. The technology of the Tonocap in respect to management of different water vapour partial pressures is comparable with the standard technique applied in other systems, such as capnography, where carbon dioxide is determined by infrared absorbance.

pHi is calculated from arterial pH (pHa), arterial PCO2 (PaCO2) and raPCO2:

\[
pHi = pHa + \log_{10}(PaCO2/raPCO2)
\]

The second tonometer balloon was primed following the manufacturer’s guidelines and filled with 2.5 ml of 0.9% saline. After 90 min of equilibration, anaerobic samples of the tonometer saline were obtained, discarding the deadspace volume of 1 ml. The saline samples were handled in capped syringes to avoid or minimize any possible equilibration with room air. All samples were analysed immediately and discarded if a delay during the sample process occurred. rsPCO2 was determined using the same blood-gas analyser as for arterial blood-gas analysis, and pHi was calculated:

\[
pHi = 6.1 + \log_{10}(\text{arterial HCO}_3^-/1.120 \times 0.3 \times \text{rsPCO}_2)
\]

The term 1.12 is a time-dependent equilibration factor from in vitro studies where the tonometer was exposed for ≈90 min to a physiological saline solution with a known PCO2, and “0.3” is the solubility coefficient of carbon dioxide in saline.

Arterial HCO3− is calculated by the blood-gas analyser:

\[
\text{HCO}_3^- = 0.23 \times PaCO2 \times \text{antilog}(pH – pK); \quad pK = 6.125 - \log_{10}(1+\text{antilog}(pH-8.7))
\]

All probes were analysed by the blood-gas analyser at 37°C and thereafter corrected for the patient’s actual body temperature using internal software because PCO2 in a saline sample which is kept anaerobic changes with temperature; the equation used for internal temperature correction, according to the manufacturer’s handbook was:

\[
P_{\text{CO}_2}(\text{temp}) = P_{\text{CO}_2}(37\,\text{C}) \times 10^{0.021(\text{temp}-37\,\text{C})}
\]

Statistical analysis was with a microcomputer using the Statistical Package for the Social Sciences (SPSS, SPSS Inc., Chicago, IL, USA). All data are given as mean (SD). The Wilcoxon signed rank test and Pearson’s correlation coefficient were performed with pooled data. Simple linear regression analysis was applied to each patient’s mean rsPCO2 and raPCO2 values. Agreement between saline samples and Tonocap measurements were analysed according to the method of Bland and Altman.7 Bias is the mean difference between rsPCO2 and raPCO2 and precision the SD of the differences.

Results

We obtained 237 paired samples (table 2). Mean duration of tonometry was 77 (49) h. We did not observe any complication associated with the two tonometer probes (e.g. nasopharyngeal injuries, oesophageal or gastric bleeding). Mean air PCO2 was 6.5 (1.8) kPa and mean saline PCO2 6.8 (2.4) kPa.

There were no negative PCO2 differences in either saline tonometry (rsPCO2−PaCO2 = −2.3 (2.3) kPa) or in air tonometry (raPCO2−PaCO2 = −2.3 (2.3) kPa). PCO2 values from both methods were highly correlated (n = 19, Pearson’s r = 0.93; P < 0.0001 (two-tailed)). Figure 1 shows regression analysis of each patient’s mean raPCO2 and rsPCO2 values. PCO2 measured by saline tonometry was significantly higher than that from the Tonocap (P < 0.05 (two-tailed)). Mean pH calculated from the Tonocap was 7.29 (0.11) while with the saline method it was 7.20 (0.12). A Bland and Altman plot showed a bias of 0.3 kPa and a precision of 1.2 kPa (fig. 2).

Agreement between the two methods decreased at greater rsPCO2 values. Using an arbitrary difference of 7.3 kPa, paired samples with rsPCO2 values greater than 7.3 kPa had a bias of 1.2 kPa and a precision of 1.8 kPa. Below 7.3 kPa, bias was −0.04 kPa and precision was 0.7 kPa (fig. 3).

Table 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac index (litre min−1 min−2)</td>
<td>1.63 (0.27)</td>
</tr>
<tr>
<td>Heart rate (beat·min−1)</td>
<td>126 (17)</td>
</tr>
<tr>
<td>Systolic arterial pressure (mmHg)</td>
<td>90 (11)</td>
</tr>
<tr>
<td>Mean arterial pressure (mmHg)</td>
<td>62 (7)</td>
</tr>
<tr>
<td>Diastolic arterial pressure (mmHg)</td>
<td>48 (7)</td>
</tr>
<tr>
<td>PCWP (mmHg)</td>
<td>20 (4)</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaCO2 (kPa)</td>
<td>4.7 (0.7)</td>
</tr>
<tr>
<td>HCO3− (mmol litre−1)</td>
<td>22.2 (3.2)</td>
</tr>
<tr>
<td>Arterial pH</td>
<td>7.42 (0.05)</td>
</tr>
<tr>
<td>rsPCO2 (kPa)</td>
<td>6.8 (2.4)</td>
</tr>
<tr>
<td>raPCO2 (kPa)</td>
<td>6.5 (1.8)</td>
</tr>
<tr>
<td>pHair</td>
<td>7.20 (0.12)</td>
</tr>
<tr>
<td>pHsaline</td>
<td>7.29 (0.11)</td>
</tr>
<tr>
<td>rsPCO2−PaCO2 (kPa)</td>
<td>2.3 (2.3)</td>
</tr>
<tr>
<td>raPCO2−PaCO2 (kPa)</td>
<td>1.9 (1.6)</td>
</tr>
</tbody>
</table>
paired samples. Obtained by air tonometry (ra \( CO_2 \)) with a 90-min cycle time. Bias in 
\[ r^2 = 0.86 \]
\[ P = <0.0001 \]
\[ Y = 2.15 + 0.66 \times \]

Figure 1 Scatter plot showing relationship between mean regional \( PCO_2 (rPCO_2) \) obtained by air tonometry (ra\( PCO_2 \)) and saline tonometry (rs\( PCO_2 \)) in 19 patients. Solid line = regression line; broken line = 95% confidence interval around the regression line. \( r^2 \) = coefficient of determination.

Figure 2 Bland and Altman analysis of regional \( PCO_2 (rPCO_2) \) obtained by air tonometry (ra\( PCO_2 \)) and saline tonometry (rs\( PCO_2 \)) with a 90-min cycle time. Bias = mean difference between ra\( PCO_2 \) and rs\( PCO_2 \), and precision = SD of the differences. \( n \) = Number of paired samples.

Discussion

Indirect estimation of gut wall intramucosal \( pH \) was popularized by the work of Fiddian-Green and co-workers who promoted this technique for the early detection of splanchnic ischaemia. Tonometry has been proposed to predict mortality and morbidity, provide a target in goal-directed therapy and to gauge therapeutic efficacy on splanchnic perfusion. Nevertheless, it remains a research method rather than a routine technique in the critically ill patient.

Until recently, tonometry was performed using 0.9% saline. Several authors have suggested the potential hazards, namely underestimation of \( PCO_2 \) by different blood-gas analysers and hence overestimation of \( pH_1 \). This bias is caused by a low stability of carbon dioxide in saline. Thus different constructions of blood-gas analysers can cause different carbon dioxide losses from the sample before it reaches the measuring electrode. The ABL 505 blood-gas analyser, which was used in our study, gives only minor underestimation of saline \( PCO_2 \) after equilibration with different gas mixtures compared with five other systems. Substituting a phosphate-buffered or colloid solution for saline may improve \( PCO_2 \) measurements in blood-gas analysers. However, the higher carbon dioxide-binding capacity of the buffer prolongs the equilibration time between tissue and sample carbon dioxide. Therefore, the ability of the saline method to detect rapid changes in regional carbon dioxide is not improved and remains a problem.

Moreover, saline tonometry is subject to several errors from variation in sample handling and time delay. The development of air tonometry provides the clinician with a feasible technique without the aforementioned limitations.

In our study, saline and air tonometry showed a good correlation. We chose a cycle time of 90 min to ensure a steady state between \( PCO_2 \) in the mucosa and in the saline filled tonometer balloon. To ensure comparability, the cycle time of the Tonocap device was set to 90 min also, although an equilibration time of 10 min may be sufficient for air tonometry. Saline tonometry seems to overestimate \( rPCO_2 \) after an equilibration period of 90 min as shown by the bias of 0.3 kPa. So far there are no data on \( rPCO_2 \) values obtained by saline tonometry commensurable with air tonometry at 90 min. Creter, De Backer and Vincent found a bias of 0.5 kPa in 84 paired measurements at 30 min and Heinonen and colleagues found a bias of 0.2 kPa in a small number of 14 paired \( rPCO_2 \) determinations at 60 min. Overestimation of \( rPCO_2 \) by saline in our study was attributable predominantly to 61 measurements of high \( rPCO_2 \) values greater than 7.3 kPa (fig. 3 A, B), which were detected in 16 of 19 patients. Excluding these values, a small bias of \(-0.04\) kPa with an acceptable precision of 0.7 kPa were found. Therefore, high regional \( PCO_2 \) concentrations are subject to inappropriate overestimation by saline tonometry.

In vitro air tonometry with the Tonocap, performed in a gas chamber fully saturated with five different carbon dioxide concentrations, showed comparable \( PCO_2 \) values except for the first 10-min cycle, but these authors did not give bias and precision values from their in vitro experiments. Recently, Creter, De Backer and Vincent reported on their in vitro validation studies for air and saline tonometry. For an equilibration time of 10 min at a water bath \( PCO_2 \) concentration of 5.3 kPa, air tonometry gave a bias of \(-0.04\) kPa and a precision of 0.09 kPa, whereas bias and precision of saline tonometry were \(-0.9\) kPa and 0.4 kPa, respectively. Increasing the equilibration time of the Tonocap did not improve the precision or decrease the bias. Their in vitro experiments further support the conclusion that equilibration times of 30 min cannot be recommended for saline tonometry.

Thirty minutes after increasing the water bath \( PCO_2 \) concentration from 5.3 to 10.7 kPa, \( PCO_2 \) measured by saline and air tonometry was 7.3 (0.3) kPa and 10.8 (0.1) kPa, respectively. Taken together with our results, comparison of both methods at different cycle times must be interpreted with caution. Equilibration periods of less than 30 min inevitably underestimate \( rPCO_2 \) determined by saline tonometry. Moreover, long cycle times \( >90\) min may fail to detect rapid changes in \( rPCO_2 \) by saline tonometry. As yet there is no explanation for overestimation of \( rPCO_2 \) by saline tonometry compared with air tonometry at high \( rPCO_2 \) concentrations. Neglecting high saline \( rPCO_2 \) values eliminated this presumed error in
In vivo comparison of saline and air tonometry

679

Further in vitro studies should aim to elucidate this discrepancy between the methods at high rPaco2 levels.

There are no published data on differences between the behaviour of saline and blood in blood-gas analysers at different temperatures. Although we corrected Pco2 for patient temperature using the internal software of the blood-gas analyser, it should be emphasized that the equation provided by the manufacturer does not apply directly to saline, and may result in a systematic error.

When computing pH from rsPco2 and raPco2, mean pH showed a mean difference of 0.09 although mean rsPco2 differed by only 0.3 kPa from mean rsPco2. This is mainly attributable to the two different formulae applied for calculation pH. Saline tonometry uses arterial HCO3− which is calculated automatically by the blood-gas analyser from arterial pH and PaCO2, whereas air tonometry computes pH making use of arterial pH and PaCO2. Further, the equilibration time dependent factor and the solubility coefficient in the saline tonometry equation may add to a systematic bias in computing pH by both methods thus causing a higher pH calculated using air tonometry. Assuming equal rPaco2 concentrations measured by saline and air tonometry and a constant equilibration time in saline tonometry, the difference in pH is governed exclusively by arterial pH and may range from 0.06 at a given arterial pH of 6.8, to 0.03 at a given arterial pH of 7.6.

Our study population consisted of severely ill patients in cardiogenic shock with a mortality of 58%. Concordantly pooled data of rsPco2−PaCO2 difference as an index of gut ischaemia were remarkably high (table 2) suggesting severe local tissue dysoxia. We did not assess rPaco2 and pH as predictors of morbidity and mortality in our investigation. However, several studies have shown that pH values have prognostic value after both cardiac and major vascular surgery and also in general critical care patients.2 11 12 22 23

Normal values for pH and the rsPco2−PaCO2 difference have not been established so far. Air tonometry offers potential measurement of Pco2 values with less sources of errors than saline tonometry, and may allow early recognition of splanchnic ischaemia. Future research may focus on this method to assess rPaco2, pH and rPaco2−PaCO2 indices of gastric oxygenation and predictors of mortality. Furthermore,
therapeutic interventions to improve oxygen delivery may be judged more quickly and accurately than that with saline tonometry.

In summary, we found a good correlation between air tonometry and saline tonometry. Overestimation of rPCO2, at high regional carbon dioxide concentrations by saline tonometry compared with air tonometry remains unexplained and requires (in vitro) further investigation. Air tonometry may become the standard means of assessing rPCO2. Discrepancies from saline tonometry, particularly at high PCO2 concentrations, should lead the clinician to interpret these values with caution.

References


