Catheter deadspace: a source of error during tonometry


Summary
Tonometry of $P_{CO_2}$ is a promising method for assessing the oxygen supply to demand ratio of the gastrointestinal mucosa in critically ill patients. A balloon-tipped tonometer is introduced into the stomach or sigmoid colon, and saline is instilled into the balloon. After a time to allow partial equilibration with intraluminal $P_{CO_2}$, saline is aspirated and $P_{CO_2}$ is measured. Intermittent instillation and aspiration of saline allows serial $P_{CO_2}$ measurements, provided correction factors are used to calculate the $P_{CO_2}$ value expected at full equilibration from the $P_{CO_2}$ values measured after short dwell times. The technique is not yet widely applied, partly because of methodological controversies. We evaluated the role of the catheter deadspace as a source of error during $P_{CO_2}$ tonometry. The increase in $P_{CO_2}$ in sigmoid-type tonometers with a normal length (normal tonometer (NT)) and in those with a 50% increase in length and thus deadspace (extended tonometer (ET)), in a saline bath at a $P_{CO_2}$ of 4.8 kPa was assessed. Saline dwell times were 10, 20, 30, 45, 60 and 90 min and the time-dependent $P_{CO_2}$ increase was determined at deadspace $P_{CO_2}$ values of approximately 4.0 and 8.0 kPa following contamination of the catheter deadspace after immersion in saline baths at $P_{CO_2}$ values of 4.8 and 9.6 kPa, respectively, before each measurement cycle. In another experiment, the tonometer was rinsed between measurement cycles to remove deadspace saline containing carbon dioxide and to obviate contamination of instilled saline. $P_{CO_2}$ was measured in a blood-gas analyser, taking into account measurement bias in saline. Failure to remove deadspace saline between measurement cycles resulted in an overestimation of 10% and 6% for the NT and 16% and 10% for the ET, at saline dwell times of 10 and 20 min, respectively, at a deadspace $P_{CO_2}$ of approximately 4.0 kPa. At a deadspace $P_{CO_2}$ of approximately 8.0 kPa, $P_{CO_2}$ was overestimated by 17%, 11% and 5% for the NT and 31%, 20% and 11% for the ET, at dwell times of 10, 20 and 30 min, respectively. Rinsing the NT/ET resulted in accurate assessment of $P_{CO_2}$ at all dwell times, but the dwell time-dependent increase in $P_{CO_2}$ was slightly slower in the ET, particularly at 10 min, after a sink effect of the increased deadspace. Hence, a previously unrecognized deadspace effect caused error during $P_{CO_2}$ tonometry, particularly with short dwell times. This potentially large error can be avoided by rinsing the tonometer before each measurement cycle, allowing accurate $P_{CO_2}$ tonometry even at 10-min saline dwell times, provided that correction factors are used that are specific for catheter size. These findings may help to widen the clinical applicability of tonometry. (Br. J. Anaesth. 1998; 80: 337–341)

Keywords: carbon dioxide, partial pressure; airway, deadspace; monitoring, tonometry

The tonometry of intraluminal $P_{CO_2}$ in the gastrointestinal tract and calculation of intramucosal pH may be useful in assessing the prognosis and guiding treatment of critically ill patients. During tonometry, saline instilled into the tonometer balloon is allowed to equilibrate with intraluminal $P_{CO_2}$. After a certain dwell time, saline is aspirated and $P_{CO_2}$ is measured in a conventional blood-gas analyser.

There are various problems with the methods for this technique that may lead to errors. First, carbon dioxide may be lost from the aspirate during transport and second, most blood-gas analysers underestimate $P_{CO_2}$ measured in saline. Finally, a major disadvantage of tonometry is its relative slowness, as complete equilibration between balloon and intraluminal $P_{CO_2}$ may require 60 min. As this is impractical for clinical purposes, correction factors have been provided to calculate steady state $P_{CO_2}$ when short dwell times are applied. Even with the use of these factors, dwell times of less than 30 min are discouraged as they are believed to yield inaccurate results.

A hitherto overlooked source of error is the carbon dioxide impermeable deadspace of the catheter, which may have two consequences. First, with each measurement, saline that contains carbon dioxide is retained in the deadspace after aspiration and then flushed into the balloon at the next saline instillation, thereby increasing balloon $P_{CO_2}$ before each measurement cycle. This may lead to saline $P_{CO_2}$ overestimation, particularly at short dwell times. Second, the deadspace may serve as a sink for $P_{CO_2}$.
increase in the saline of the balloon, so that the correction factors may depend on the size and thus the deadspace volume of the catheter used. Conversely, this may help to explain the differences in correction factors between gastric- and sigmoid-type tonometers of different lengths.\textsuperscript{17} Successful elimination of sources of error may widen the clinical applicability of manual tonometry in centres where the recently introduced, semi-continuous and automated air tonometry, a technique of proven reliability, is not available.\textsuperscript{18,19} 

Therefore, we studied \textit{in vitro} the effect of the catheter deadspace on $P_{CO_2}$ tonometry. $P_{CO_2}$ was measured after various saline dwell times using a normal tonometer and an extended tonometer with an increased deadspace, both with and without rinsing the carbon dioxide containing deadspace of the tonometer before each measurement cycle.

**Materials and methods**

A steady state $P_{CO_2}$ in a 3-litre, temperature-controlled (mean 37.0 (sd 0.2) °C) saline bath was achieved by bubbling carbon dioxide calibration gases (4.98% and 9.98% in nitrogen, both with an accuracy of 1% NTG, Tilburg, The Netherlands) at a flow rate of 5 litre min\textsuperscript{-1}. Bath $P_{CO_2}$ was assumed to have reached steady state when five consecutive measurements at 5-min intervals differed by less than 5%.

Bias and precision of $P_{CO_2}$ measurements in saline with the blood-gas analyser (ABL 505, Radiometer, Copenhagen, Denmark) were derived from comparison of the measured bath $P_{CO_2}$ at steady state with the expected bath $P_{CO_2}$ calculated from the carbon dioxide content of the calibration gas, bath temperature and barometric pressure ($P_{bar}$), according to $P_{CO_2} = (P_{bar} - 47) \times 100 \times x%$ carbon dioxide content.

The measured bath $P_{CO_2}$ at steady state underestimated the expected $P_{CO_2}$: mean 4.5 (sd 0.2) kPa ($n = 32$) vs 4.8 kPa ($P < 0.0001$), and 8.8 (0.2) vs 9.6 kPa ($P < 0.0001$), respectively. The bias of the $P_{CO_2}$ measurements, defined as the mean percentage difference between measured and expected $P_{CO_2}$, was thus −6.8%. Precision, the sd of bias, was 3.0%. Bias and precision were independent of bath $P_{CO_2}$.

Underestimation of $P_{CO_2}$ measured in saline with the type of blood-gas analyser used is in agreement with the literature.\textsuperscript{13,16} Thus all $P_{CO_2}$ measurements in saline were multiplied by a factor of 1.07 (= 109.9/3.2).

For our \textit{in vitro} study we used TRIP Sigmoid tonometers (Tonometrics, Inc., Bethesda, MD, USA), as applied previously for gastric tonometry in healthy volunteers.\textsuperscript{20} We did not compare sigmoid (length 202 cm) with gastric (length 150 cm) tonometers, which have different deadspaces, because the catheters not only differ in length but also in external diameter, at similar balloon properties. The correction factors for the increase in $P_{CO_2}$ in the tonometer types differ, as stated by the manufacturer,\textsuperscript{17} and this may indicate that the increase in $P_{CO_2}$ as a function of time may be slower in the sigmoid-type tonometer, but the reason is not given. To evaluate the effect of deadspace on the increase in $P_{CO_2}$ in the balloon saline as a function of time, we decided to use tonometers of the same type with different lengths and thus deadspace volumes, and the manufacturer kindly supplied sigmoid-type tonometers that were extended to 300 cm. All tonometers had identical stopcocks, balloons and tube material. The deadspace was assessed with a micro-syringe, after cutting the tube at balloon entry. The deadspace volume was 1.07±0.02 ml in the normal sigmoid-type tonometer (normal tonometer (NT), $n = 10$) and 1.71±0.03 ml in the extended sigmoid-type tonometer (extended tonometer (ET), $n = 10$). Carbon dioxide permeability of the tube was also assessed ($n = 6$). After cutting off the balloon and stopcock, the tubes were filled with saline, sealed and placed in a saline bath with a $P_{CO_2}$ value of 9.6 kPa for 24 h at 37°C. The tube was then opened, saline aspirated immediately and $P_{CO_2}$ measured in a blood-gas analyser. $P_{CO_2}$ increased by only 0.5±0.2 kPa at 24 h.

The time-dependent increase in $P_{CO_2}$ in the balloons of the tonometers ($n = 6$ NT, $n = 12$ ET) at saline dwell times of 10, 20, 30, 45, 60 and 90 min was determined in two experiments for each type of tonometer. Each measurement cycle consisted of introducing 2.5 ml of saline into the tonometer balloon, a certain dwell time for (partial) equilibration, and aspiration. The first 1.1 ml aspirated in the NT and 1.7 ml in the ET was considered to represent the deadspace and was discarded. The final aspirate was introduced into the blood-gas analyser for $P_{CO_2}$ measurements. In experiment I, the effect of carbon dioxide contamination of the deadspace saline on the time-dependent increase in $P_{CO_2}$ in a bath of $P_{CO_2}$ 4.8 kPa was evaluated. Before each measurement cycle, the following were performed: (1) rinsing of the tonometer with fresh saline; (2) filling of the tonometer with saline 2.5 ml and immersion in a saline bath at a $P_{CO_2}$ of 4.8 kPa or 9.6 kPa for 30 min; (3) aspiration and disposal of saline 2.5 ml, thereby retaining the deadspace volume with an estimated $P_{CO_2}$ of approximately 4.0 kPa and 8.0 kPa, respectively; and (4) placing the tonometer in a saline bath at a $P_{CO_2}$ of 4.8 kPa for a measurement cycle. In experiment II, the increase in $P_{CO_2}$ was determined in saline baths at $P_{CO_2}$ values of 4.8 and 9.6 kPa, and all residual carbon dioxide in the deadspace saline was removed by rinsing the tonometer three times with 2.5 ml of fresh saline, before each measurement cycle.

**Statistical analysis**

For experiment II, the increase in $P_{CO_2}$ in the tonometer balloon, in terms of $P_{CO_2}(ss)$ (steady state $P_{CO_2}$) and $T_{1/2}$ (half-time), was assessed by non-linear regression analysis according to: $P_{CO_2}(t) = (P_{CO_2}(ss) \times t)/(T_{1/2} + t)$, where $P_{CO_2}(t) = P_{CO_2}$ at $t$ (min) dwell time. Mean data were used to plot the regression curve. The characteristics of the increase in $P_{CO_2}$ in the NT and ET were compared using Student’s $t$ test. Correction factors for calculation of $P_{CO_2}(ss)$ from $P_{CO_2}(t)$ at each dwell time were calculated for each tonometer type. To judge the accuracy of $P_{CO_2}(ss)$ estimated using the correction factors at each dwell time in predicting bath $P_{CO_2}$, we calculated the bias and precision for $P_{CO_2}(ss)$ for each dwell time. The bias represents the percentage difference in $P_{CO_2}(ss)$ and bath $P_{CO_2}$ and precision is the sd
of bias. For experiment I, $P_{CO_2}$ after each dwell time was expressed as the percentage difference in $P_{CO_2}$ measured at corresponding dwell times in experiment II. For graphical presentation, non-linear regression curves were calculated using mean values and a one-phase exponential decay. Data are expressed as mean (SD). $P<0.05$ was considered statistically significant.

**Results**

**EXPERIMENT I**

At a deadspace $P_{CO_2}$ of approximately 4.0 kPa (bath $P_{CO_2}$ 4.8 kPa), the increase in $P_{CO_2}$ was different from that in experiment II, as $P_{CO_2}$ measured at short dwell times was increased, especially in the ET (fig. 1A). With the NT, $P_{CO_2}$ was significantly overestimated at dwell times of 10 and 20 min by mean 10% and 6%, respectively. With the ET, $P_{CO_2}$ overestimation after 10, 20 and 30 min was 16%, 10% and 5%, respectively. At a deadspace $P_{CO_2}$ of approximately 8.0 kPa (bath $P_{CO_2}$ 9.6 kPa), overestimation of $P_{CO_2}$ at short dwell times was even greater and more pronounced with the ET (fig. 1B). In the NT, mean $P_{CO_2}$ overestimation after 10, 20 and 30 min was 17%, 11% and 5%, respectively. In the ET, $P_{CO_2}$ overestimation at 10, 20, 30 and 45 min was 31%, 20%, 11% and 5%, respectively.

![Figure 1](image1.png)  
**Figure 1** Effect of carbon dioxide contamination of deadspace on the increase in $P_{CO_2}$. A: Immersion for 30 min in a bath at a $P_{CO_2}$ value of 4.8 kPa (deadspace $P_{CO_2}$ approximately 4.0 kPa) before each measurement cycle of $P_{CO_2}$ increase. B: Immersion for 30 min in a bath at a $P_{CO_2}$ value of 9.6 kPa (deadspace $P_{CO_2}$ approximately 8.0 kPa) before each measurement cycle of $P_{CO_2}$ increase. Mean (SD) percentage difference in $P_{CO_2}$ at corresponding dwell times in figure 2 and non-linear regression curve for means for the normal tonometer and extended tonometer. **$P<0.01$; ***$P<0.001$** between tonometers.

![Figure 2](image2.png)  
**Figure 2** Increase in $P_{CO_2}$ as a function of saline dwell time, in the normal and extended tonometer balloons in a saline bath at a $P_{CO_2}$ value of 4.8 kPa (lower two curves) and 9.6 kPa (upper curves). Mean (SD) regression curve for means. **$P<0.01$** between tonometers.

**EXPERIMENT II**

The increase in $P_{CO_2}$ in the tonometer balloon was described adequately by a non-linear regression model (fig. 2). The increase in $P_{CO_2}$ in the NT was slightly faster than that in the ET, with an estimated $T/2$ of 4.4 (0.5) and 5.3 (0.6) min, respectively ($P<0.001$). Hence, the 10-min $P_{CO_2}$ value was significantly greater in the NT than in the ET at a bath $P_{CO_2}$ of 9.6 kPa and the 10-min correction factors for estimation of $P_{CO_2}(ss)$ from $P_{CO_2}(t)$ differed between catheter types (1.40 (0.02) and 1.48 (0.04) for both bath $P_{CO_2}$ values together, and for the NT and ET, respectively ($P<0.001$)). $P_{CO_2}(ss)$ in the NT and ET calculated from the non-linear regression equations did not differ from the bath $P_{CO_2}$: $P_{CO_2}(ss)$ was 4.8 (0.1) and 4.9 (0.1) kPa at a bath $P_{CO_2}$ of 4.8 kPa, and 9.5 (0.1) and 9.6 (0.1) kPa at a bath $P_{CO_2}$ of 9.6 kPa for the NT and ET, respectively (ns). Bias and precision for $P_{CO_2}(ss)$ estimates, calculated from $P_{CO_2}(t)$ and correction factors for the NT and ET, were independent of saline dwell times (table 1). The pooled bias was 0.0 (0.1) % and precision was 2.7 (0.7)% indicating accurate and reproducible $P_{CO_2}(ss)$ estimation.

**Discussion**

This study has indicated that a previously overlooked deadspace effect caused errors in $P_{CO_2}$ tonometry at dwell times of less than 30 min. If this error is prevented by removal of deadspace saline containing

<table>
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<th>Normal tonometer</th>
<th>Extended tonometer</th>
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<tbody>
<tr>
<td>10</td>
<td>−0.1</td>
<td>1.9</td>
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<tr>
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<td>30</td>
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<td>90</td>
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Table 1 Measuring bias and precision of $P_{CO_2}$ tonometry for each saline dwell time, at bath $P_{CO_2}$ values of 4.8 and 9.6 kPa. For measurement of bias and precision, the means of measurements at bath $P_{CO_2}$ values of 4.8 and 9.6 kPa in experiment II were used. Bias is the percentage difference between bath $P_{CO_2}$ and calculated $P_{CO_2}(ss)$, $P_{CO_2}(ss)=P_{CO_2}(t)\times$correction factor (t); precision is the SD of bias.
carbon dioxide before each dwell time, \( P_{\text{CO}_2} \) measurements at 10- and 20-min dwell times are as accurate as those obtained at longer dwell times, provided that correction factors are used that are specific for catheter size.

The longer \( T/\delta \) using the ET in experiment II, with an almost 50% larger deadspace than the NT, was probably a result of the deadspace acting as a sink for the increase in \( P_{\text{CO}_2} \) in the tonometer balloon. However, the effect is only detectable at short dwell times and is probably small, as a 50% increase in deadspace reduced \( P_{\text{CO}_2} \) at the 10-min dwell time by only 5%. The sink effect can be explained by diffusion of carbon dioxide into the saline of the balloon and, subsequently, into the catheter lumen and deadspace, so that the correction factors would become dependent, for a given balloon volume, on the deadspace and thereby on the length and diameter of the tonometer. With a larger sized catheter, more carbon dioxide diffuses into the deadspace and subsequently the increase in \( P_{\text{CO}_2} \) in the balloon is slower. The sink effect may thus explain how measured \( P_{\text{CO}_2} \), even after rinsing, is dependent on the deadspace, particularly at short dwell times and high surrounding \( P_{\text{CO}_2} \) values. Indeed, the carbon dioxide diffusion rate, which depends on the pressure gradient, would be greater and therefore more dependent on the sink effect at a high surrounding \( P_{\text{CO}_2} \) and a low \( P_{\text{CO}_2} \) in the saline of the deadspace, that is shortly after introduction of fresh saline and start of a new measurement sequence. Conversely, reliable \( P_{\text{CO}_2} \) measurements would be independent of the (size of) deadspace acting as a sink, at dwell times exceeding 10 min (fig. 2). A sink effect that depends on the ratio between catheter length and balloon volume may partly explain the difference in correction factors for gastric- and sigmoid-type tonometers provided by the manufacturer. A reduction in catheter volume to reduce the sink effect would be impracticable, as this would reduce the working length of the tonometer, and increasing balloon volume would further slow the increase in \( P_{\text{CO}_2} \) in the balloon.

The most apparent effect of the tonometer deadspace on \( P_{\text{CO}_2} \) measurements relates to recharging of the balloon saline by carbon dioxide-enriched deadspace saline. Failure to remove this deadspace saline before each measurement cycle resulted in overestimation of \( P_{\text{CO}_2} \) particularly with the ET (experiment I) at saline dwell times of less than 30 min. This effect can be calculated, knowing the ratio of deadspace vs balloon volume (0.44 for the NT and 0.68 for ET), diffusion rate into the tonometer balloon and surrounding \( P_{\text{CO}_2} \) using the formula: measured \( P_{\text{CO}_2} = (\text{ratio} \times (\text{deadspace } P_{\text{CO}_2})) + (% \text{ diffusion} \times \text{surrounding } P_{\text{CO}_2} - \text{balloon } P_{\text{CO}_2}) \). The calculated overestimate for a 10-min dwell time, at steady state surrounding \( P_{\text{CO}_2} \) would be 15% for NT and 21% for ET, which is in close agreement with our results. Similarly, it can be calculated that dwell times >30 min eliminate the effect, as equilibration is almost complete by this time. Prolonged dwell times are therefore unaffected by deadspace errors. In most clinical situations, the interval between measurement cycles can vary considerably and therefore the deadspace \( P_{\text{CO}_2} \) is unpredictable, as is the way it may influence subsequent \( P_{\text{CO}_2} \) determinations. There are two practicable options to eliminate the deadspace effect. Dwell times >30 min are chosen or the tonometer is rinsed before each measurement cycle. The results of experiment II (table 1) indicate that even dwell times of 10 min result in an estimation of surrounding \( P_{\text{CO}_2} \) with similar bias and precision to those obtained after longer dwell times if the tonometer is rinsed before each measurement cycle. This may widen the clinical applicability of manual tonometry by allowing short-term evaluation of therapeutic interventions.

In summary, our study indicated that saline dwell times of less than 30 min yielded reliable results during \( P_{\text{CO}_2} \) tonometry provided that the tonometer was rinsed before each measurement cycle and correction factors were used that were specific for catheter size. Failure to recognize the deadspace as a source of error may have affected results in recent studies on the value of splanchnic tonometry.\(^6\)\(^7\)

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References


