Gastric Tonometry*

The Hemodynamic Monitor of Choice (Pro)

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Controversy exists as to the best means to monitor the critically ill patient and the appropriate end points of therapy. Use of global hemodynamic or metabolic parameters may be normal in the patient who has not been completely or adequately resuscitated. Decreased perfusion to the gut is not well tolerated and may contribute to the development of the multiple organ dysfunction syndrome. Gastric tonometry is a minimally invasive way to monitor splanchnic perfusion in the critically ill patient. Data suggest that tonometry is useful for outcome prognostication and for detection of early hypovolemia. In addition, use of gastric intramucosal pH or mucosal-arterial CO₂ gap as end points of resuscitation may be superior to other conventional whole-body parameters. For these reasons, gastric tonometry must be considered the hemodynamic monitor of choice. (CHEST 2003; 123:469S–474S)

Key words: gastric tonometry; hemodynamic; hypoperfusion; hypovolemia

Abbreviations: Do₂ = oxygen delivery; PHi = intramucosal pH

INTRODUCTION: TRADITIONAL MONITORING

Critically ill patients are most often monitored by measuring vital signs, urine output, indexes of cardiac performance and oxygen transport, and chemical indicators of metabolic activity, such as lactate. These methods are sometimes inadequate for a number of reasons, including the following: (1) BP may be normal despite a low blood volume or cardiac index; (2) heart rate can be affected by multiple variables that are not germane to the adequacy of resuscitation (eg, pain); (3) urine output can be confounded by the hormonal milieu of the patient, including antidiuretic hormone and aldosterone; and (4) measurements of central filling pressures, cardiac index, oxygen transport variables, arterial blood gases, and serum lactate assess global perfusion and will not always identify localized peripheral organ hypoperfusion.

A monitor is still needed to identify earlier, and more accurately, those patients at highest risk of ischemic organ failure and death, especially when conventional indicators are normal. Such a monitor should also be able to guide resuscitation and provide better information on those interventions most able to prevent the complications of inadequate perfusion. Gastric tonometry is a minimally invasive means to determine perfusion to the stomach and is the only one of a few clinical organ-specific monitors to help guide resuscitation.

THE THEORY BEHIND GASTRIC TONOMETRY

The gut is sensitive to ischemia. Periods of hypoperfusion may cause the release of inflammatory cytokines and bacterial translocation, thereby causing damage in remote organs. Monitoring perfusion to the gut may help minimize or prevent episodes of mesenteric ischemia and improve the outcome of critically ill patients. The stomach is a relatively easy organ to access and may provide crucial information about perfusion to the rest of the splanchnic bed.

Gastric tonometry attempts to determine the perfusion status of the gastric mucosa using measurements of local Pco₂. CO₂ diffuses from the mucosa into the lumen of the stomach and subsequently into the silicone balloon of the tonometer (Fig 1). The Pco₂ within the balloon serves as a proxy for gastric mucosal CO₂ and can be measured by one of two means: (1) saline tonometry, where saline solution is anaerobically injected into the balloon, withdrawn after an equilibration period and measured using a blood gas analyzer; or (2) air tonometry, where air is pumped through the balloon and the Pco₂ is determined by an infrared detector on a semicontinuous basis. As blood flow to the stomach decreases, the Pco₂ will increase due to a decrease in bulk removal of CO₂ produced by normal respiration. When oxygen delivery (Do₂) to the mucosa is reduced below metabolic demand (ie, anaerobiosis), acidosis ensues. The hydrogen ions that are produced are titrated with bicarbonate, and (by mass action: H⁺ + HCO₃⁻ ⇌ H₂CO₃ ⇌ CO₂ + H₂O) even more CO₂ will accumulate than would be expected by a reduction in blood flow. By assuming that arterial (art) bicarbonate equals mucosal bicarbonate, intramucosal pH (pHi) can be calculated using the Henderson-Hasselbalch equation:

\[
\text{pHi} = \log([\text{HCO}_3^-]_{\text{art}}/0.03(\text{Pco}_2\text{muc}))
\]

where Pco₂muc is gastric mucosal Pco₂.

In addition to many animal investigations, support for the notion that gastric pH assesses perfusion comes from a study of 17 patients receiving mechanical ventilation. A low gastric pH in these patients was associated with a lower mucosal blood flow as determined by laser Doppler flowmetry compared to patients with a normal pH.

Unfortunately, the critical assumption—that arterial bicarbonate equals mucosal bicarbonate—is flawed. Simulations of mesenteric ischemia indicate that use of the arterial bicarbonate will result in errors in the determination of gastric pH. In addition, respiratory acid/base disturbances will introduce errors in the calculation of pH. Consequently, pH has been replaced by the Pco₂ or the Pco₂ gap (the difference between gastric mucosal and arterial Pco₂) as a better way to determine perfusion to the stomach.

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Dedicated in memory of Robert Schlichtig, MD.

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There are a number of factors that may cause errors in the determination of gastric pH or PCO₂, and these must be taken into account. If saline tonometry is used, some blood gas analyzers will consistently and dramatically underestimate the PCO₂ in the saline solution. Use of buffered saline solutions will improve the accuracy of the PCO₂ determination, but the time for a steady state to be reached in the tonometer is increased. Gastric acid
secretion may also increase CO₂ production by titration of luminal acid with bicarbonate in the gastric mucus or refluxed duodenal contents, thereby introducing additional errors into determination of the Pco₂ gap. Use of histamine type-2 receptor antagonists will reduce this error. Sucralfate does not appear to interfere with determination of gastric pH. Gastric but not duodenal feedings will cause a factitious reduction in gastric pH.

**DETERMINATION OF CRITICAL CO₂ VALUE**

One of the problems that has plagued gastric tonometry is that the value for pH or Pco₂ where dysoxia (DO₂ is insufficient to meet metabolic demand) occurs is unknown. In a canine model of cardiac tamponade, Schlichtig and Bowles measured intestinal DO₂, pHᵢ, and tonometric CO₂ in the jejunum and ileum. They determined that dysoxia occurred around a Pco₂ value of 65 mm Hg and a Pco₂ gap of 25 to 35 mm Hg (Fig 2). These data suggest that the critical Pco₂ values currently being used for humans—in the range of 48 mm Hg for Pco₂ and 8 mm Hg for the corresponding Pco₂ gap—are unnecessarily low.

**INDICATIONS FOR THE USE OF GASTRIC TONOMETRY**

Since tonometry will provide information about levels of CO₂ (ie, blood flow) only in tissue, use of this monitor in shock states where blood flow is normal or elevated may not be particularly helpful. Patients with hypovolemia from any cause (eg, hemorrhagic shock or septic shock before fluid resuscitation) or who suffer from cardiac failure will benefit the most from the use of this monitor. The tonometer has been shown to be useful as a prognosticating tool, to detect hypovolemia, and as a guide for therapy.

**Prognostic Capability of Gastric Tonometry**

In a study of 83 critically ill patients (Figs 3, 4), Maynard and colleagues demonstrated that gastric tonometry can predict outcome with better accuracy than other standard hemodynamic or metabolic variables (arterial pH, serum lactate, base excess, DO₂ and oxygen consumption, cardiac index, mean arterial BP, and heart rate).

In a study of multiple-trauma patients, Kirton and colleagues demonstrated the superiority of gastric tonometry over other clinical variables in predicting death. Other clinical studies have confirmed these findings, and investigators have found gastric tonometry to be useful as a predictor for the development of multiple organ dysfunction syndrome and successful extubation.

**Detection of Hypovolemia**

To examine the utility of gastric tonometry in detecting hypovolemia, Hamilton-Davies and colleagues removed and replaced 25% of the blood volume of six volunteers while measuring their gastric pH and the mucosal-arterial Pco₂ gap. Heart rate, BP, base excess, and lactate varied insignificantly during the experiment, but pH and the Pco₂ gap showed dramatic and significant changes (Fig 5).

**Gastric Tonometry as a Guide to Therapy**

A number of studies have examined the utility of gastric tonometry as a guide to therapy. Unfortunately, most of these studies did not have the statistical power to detect differences in resuscitation strategies.

In a large, multicenter investigation, Gutierrez and colleagues stratified 260 patients with APACHE (acute physiology and chronic health evaluation) II scores between 15 and 25 according to their hospital admission pH. Those patients with an initial pHi ≥ 7.35 and whose resuscitation was guided by pHi had a higher 28-day survival compared to those individuals who were resuscitated according to standard protocols (Fig 6). Of interest, there was no difference between groups if the initial pHi was < 7.35.

A small study of major trauma patients compared the utility of resuscitation to a gastric pH of > 7.3 with resuscitation to global oxygen transport variables (DO₂ > 600 mL/min/m² or oxygen consumption > 150 mL/min/m²). There was a statistically insignificant trend (p = 0.16) toward increased survival (90% vs 74%) and a reduced incidence of multiple organ dysfunction syndrome (10% vs 26%) in those patients whose treatment end point was pHi. Other small studies with inadequate statistical power also failed to demonstrate a benefit of using pHi as...
a therapeutic end point. In addition, a more recent, larger prospective, randomized study of critically ill patients with diverse illnesses did not detect a difference in outcome when resuscitation to a gastric pH of > 7.35 was compared to a standard resuscitation protocol. The authors recruited 210 patients into the study and hoped to detect a reduction in mortality from 40 to 30%. It appears, however, that this study may also have lacked statistical power as calculations by this author indicate a sample size of > 350 patients per group would be needed to detect such a change in mortality. A consistent observation in all of these studies has been that a low gastric pH correlates with outcome. Failure to demonstrate an improvement in survival or a decrease in organ dysfunction by guiding therapy to gastric pH may very well be the result of the failure of the therapeutic intervention protocols to raise gastric pH.

Gastric tonometry has been shown to be useful in
titrating vasopressor support and determining which vasoactive agent or vasoactive drug combination improves gastric perfusion in critically ill patients. Several studies have demonstrated that dobutamine, dobutamine/norepinephrine combinations, or dopexamine will increase gastric pHi or decrease Pco2 gap compared to other agents or placebo in patients with sepsis or septic shock (Fig 7) or high-risk surgical patients.

Limitations of Tonometry

Recent clinical data cast doubt on the validity that gastric tonometry can be used as a proxy for monitoring perfusion to the rest of the hepatosplanchnic bed. Creteur and colleagues11 measured gastric Pco2 gap, hepatosplanchnic blood flow (via indocyanine green infusion), hepatic venous saturation, and hepatic venoarterial Pco2 gradient in 36 patients with severe sepsis and found that the gastric Pco2 did not correlate with the other indexes of hepatosplanchnic blood flow. Similar findings have been found in cardiac surgery patients treated with dobutamine.32,33

Summary

Despite the limitations of gastric tonometry, this minimally invasive monitor remains one of a few organ-specific monitors approved for clinical use. The tonometer remains valuable as a prognostic tool and to detect hypovolemia before it can be identified by global hemodynamic variables. Its use as a guide for therapy remains controversial, but it has fared no worse than other common monitors utilized in the care of critically ill patients.34,35 Indeed, the use of the tonometer has not been associated with an increase in mortality.36

Active investigation into other noninvasive monitors continues. Sublingual Pco2 monitoring37 and near infrared spectroscopy38 may prove to be more useful than gastric tonometry in the monitoring and treatment of our critically ill patients.

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