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Stephen O. Heard

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A M E R I C A N C O L L E G E O F



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Gastric Tonometry*

The Hemodynamic Monitor of Choice (Pro)

Stephen O. Heard, MD, FCCP

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: $\dot{V}O_2$ = 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.^{1–4} 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 PCO₂.⁵ 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 ($\dot{V}O_2$) to the mucosa is reduced below metabolic demand (ie, anaerobiasis), acidosis ensues. The hydrogen ions that are produced are titrated with bicarbonate, and (by mass action: $H^+ + HCO_3^- \rightleftharpoons H_2CO_3 \rightleftharpoons CO_2 + H_2O$) 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:

$$pHi = \log\left(\frac{[HCO_3^-]_{art}}{0.03(PCO_{2muc})}\right)$$

where PCO_{2muc} is gastric mucosal PCO₂.

In addition to many animal investigations, support for the notion that gastric pHi assesses perfusion comes from a study of 17 patients receiving mechanical ventilation.⁶ A low gastric pHi in these patients was associated with a lower mucosal blood flow as determined by laser Doppler flowmetry compared to patients with a normal pHi.

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 pHi.⁷ In addition, respiratory acid/base disturbances will introduce errors in the calculation of pHi.⁸ Consequently, pHi 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.⁹

*From the University of Massachusetts Medical School, Worcester, MA.

Dedicated in memory of Robert Schlichtig, MD.

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Correspondence to: Stephen O. Heard, MD, FCCP, Department of Anesthesiology, 55 Lake Ave North, University of Massachusetts Medical School, Worcester, MA 01655; e-mail: stephen.heard@umassmed.edu

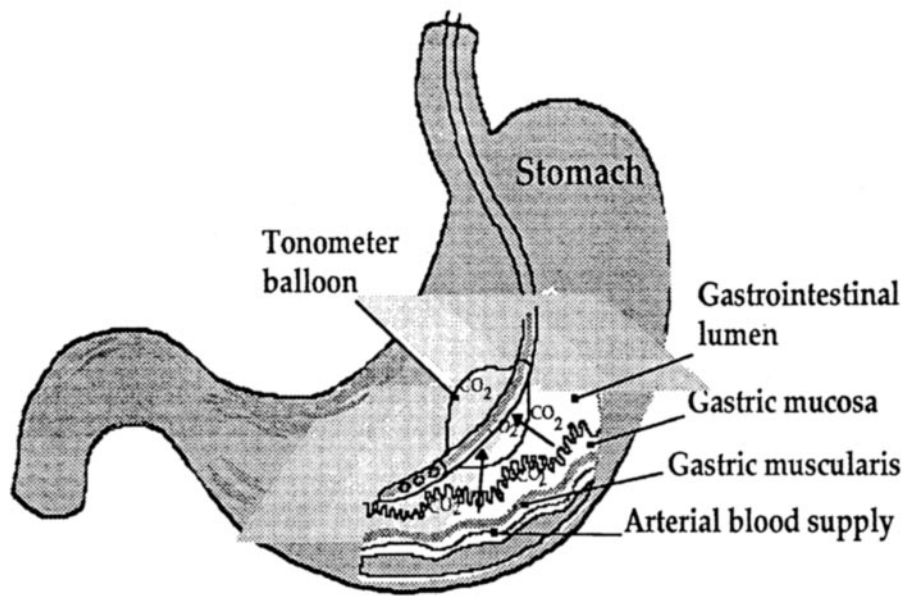


FIGURE 1. Schematic depicting the movement of CO₂ from the mucosa of the stomach into the gastric lumen and tonometer balloon. Reprinted with permission from Mythen et al.⁵

There are a number of factors that may cause errors in the determination of gastric pHi 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.¹⁰ 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.¹¹ Gastric acid

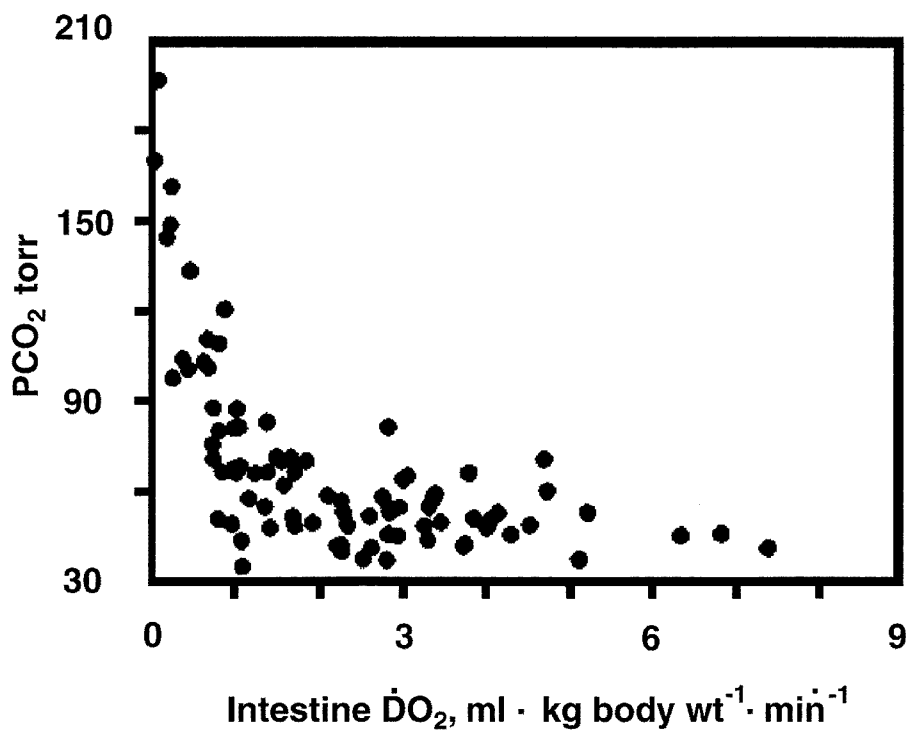


FIGURE 2. Relationship of jejunal mucosal PCO₂ and intestinal DO₂ in a canine model of cardiac tamponade. The estimated critical mucosal PCO₂ is 63 to 65 mm Hg. Reprinted with permission from Schlichtig and Bowles.¹⁶

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.¹² Sucralfate does not appear to interfere with determination of gastric pHi.¹³ Gastric but not duodenal feedings will cause a factitious reduction in gastric pHi.^{14,15}

DETERMINATION OF CRITICAL CO₂ VALUE

One of the problems that has plagued gastric tonometry is that the value for pHi or PCO₂ where dysoxia ($\dot{D}O_2$ is insufficient to meet metabolic demand) occurs is unknown. In a canine model of cardiac tamponade, Schlichtig and Bowles¹⁶ measured intestinal $\dot{D}O_2$, 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 colleagues¹⁷ demonstrated that gastric tonometry can predict outcome with better accuracy than other standard hemodynamic or metabolic variables (arterial pH, serum lactate, base excess, $\dot{D}O_2$ and oxygen consumption, cardiac index, mean arterial BP, and heart rate).

In a study of multiple-trauma patients, Kirton and colleagues¹⁸ demonstrated the superiority of gastric tonometry over other clinical variables in predicting death. Other clinical studies have confirmed these findings,¹⁹ and investigators have found gastric tonometry to be useful as a predictor for the development of multiple organ dysfunction syndrome²⁰ and successful extubation.²¹

Detection of Hypovolemia

To examine the utility of gastric tonometry in detecting hypovolemia, Hamilton-Davies and colleagues²² removed and replaced 25% of the blood volume of six volunteers while measuring their gastric pHi and the mucosal-arterial PCO₂ gap. Heart rate, BP, base excess, and lactate varied

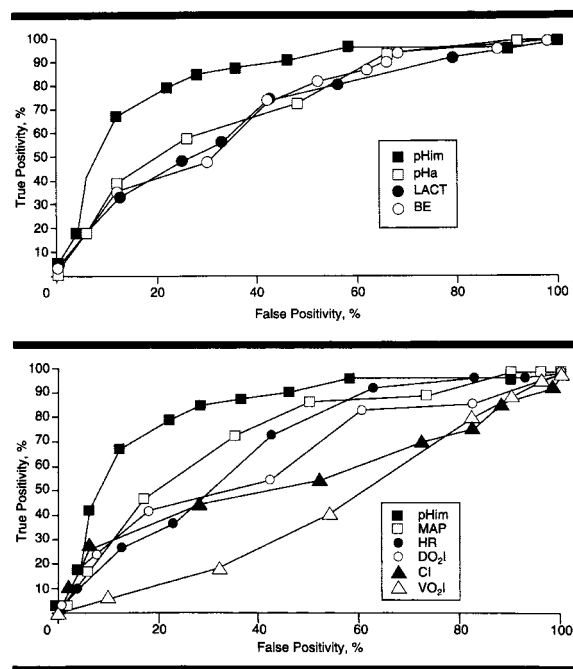


FIGURE 3. Receiver operating characteristic curves for the prediction of death: pHi (pHim), oxygen transport ($\dot{D}O_2I$), oxygen consumption ($\dot{V}O_2I$), mean arterial BP (MAP), heart rate (HR), cardiac index (CI), arterial pH (pHa), lactate (LACT), and base excess (BE) derived from 83 critically ill patients. The area under the curve for pHi is greater than the other variables, thereby signifying its utility as a prognostic indicator. Reprinted with permission from Maynard et al.¹⁷

insignificantly during the experiment, but pHi 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 colleagues²³ stratified 260 patients with APACHE (acute physiology and chronic health evaluation) II scores between 15 and 25 according to their hospital admission pHi. 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 study²⁴ of major trauma patients compared the utility of resuscitation to a gastric pHi of > 7.3 with resuscitation to global oxygen transport variables ($\dot{D}O_2 > 600$ mL/min/m³ 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 studies²⁵ with inadequate statistical power also failed to demonstrate a benefit of using pHi as

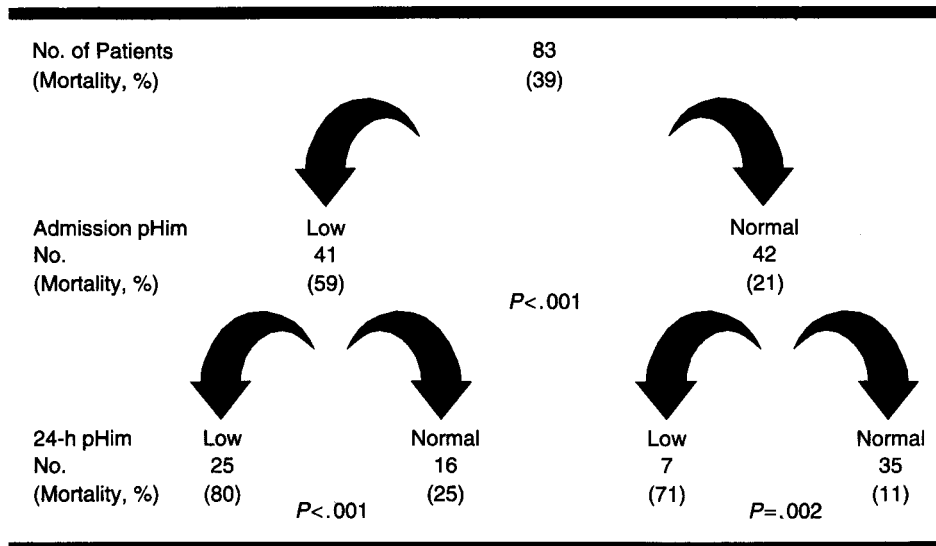


FIGURE 4. Mortality according to pHi on hospital admission and at 24 h. Reprinted with permission from Maynard et al.¹⁷ See Figure 3 legend for expansion of abbreviation.

a therapeutic end point. In addition, a more recent, larger prospective, randomized study²⁶ of critically ill patients with diverse illnesses did not detect a difference in outcome when resuscitation to a gastric pHi 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 pHi correlates with outcome. Failure to demonstrate an improvement in survival or a decrease in organ dysfunction by guiding therapy to gastric pHi may very well be the result of the failure of the therapeutic intervention protocols to raise gastric pHi.

Gastric tonometry has been shown to be useful in

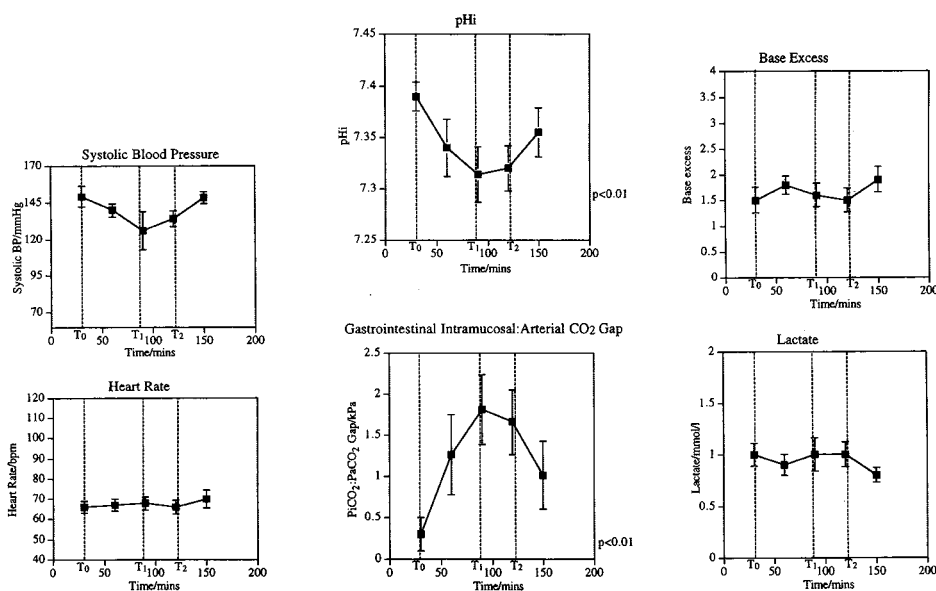


FIGURE 5. Responses to acute hemorrhage in human volunteers. T₀ = baseline; T₁ = end of hemorrhage; T₂ = prior to reinfusion of shed blood. There are significant decreases in gastric intramucosal pH (pHi) and increases in gastric intramucosal:arterial CO₂ gap compared to baseline analysis of variance. There are no significant changes in BP, heart rate, base excess, or lactate. Reprinted with permission from Hamilton-Davies et al.²²

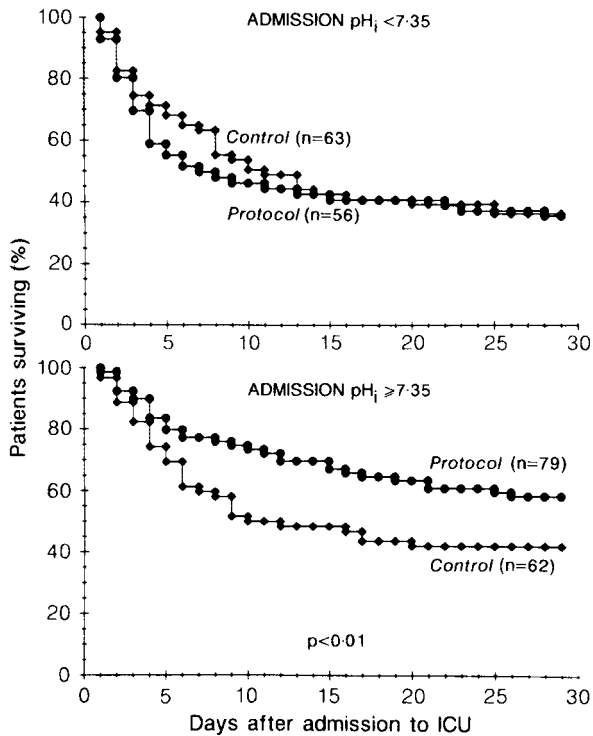


FIGURE 6. Kaplan-Meier hospital survival curves stratified according to admission gastric pH in 260 critically ill patients. There is a significant difference in survival between those patients resuscitated according to gastric pH compared to control patients if the hospital admission pH was ≥ 7.35 . There is no difference in mortality if the admission pH was < 7.35 . Reprinted with permission from Gutierrez et al.²³

titrating vasopressor support and determining which vasoactive agent or vasoactive drug combination improves gastric perfusion in critically ill patients.²⁷⁻²⁹ Several studies have demonstrated that dobutamine,²⁸ dobutamine/norepinephrine combinations,²⁹ or dopexamine³⁰ will increase gastric pH 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 colleagues³¹ 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 re-

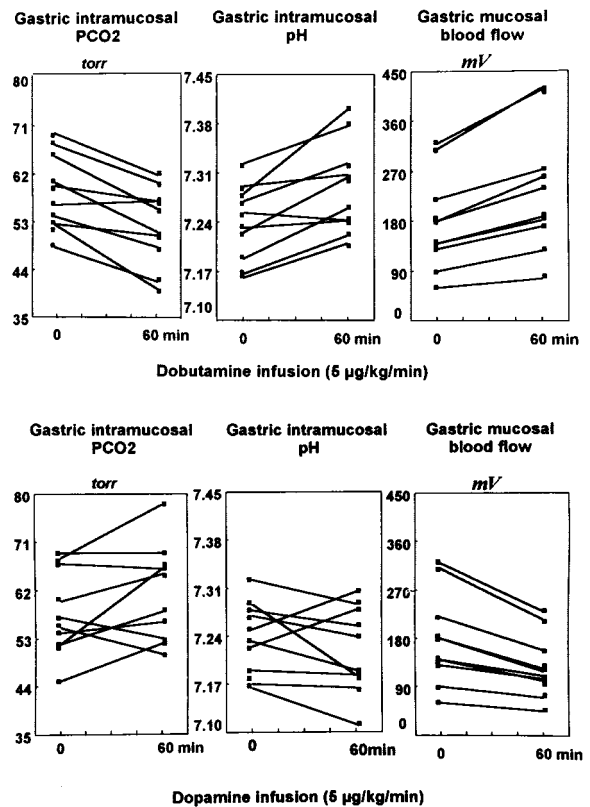


FIGURE 7. The contrasting effects of a 60-min infusion of dobutamine (5 $\mu\text{g}/\text{kg}/\text{min}$) [top] or dopamine (5 $\mu\text{g}/\text{kg}/\text{min}$) [bottom] on gastric intramucosal CO₂, intramucosal pH, and mucosal blood flow (as determined by laser Doppler flowmetry) in 10 septic patients. Note there is an inverse relationship between mucosal blood flow and gastric intramucosal PCO₂. Reprinted with permission from Nevière et al.²⁵

mains 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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