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Automated Detection of Gastric Luminal Partial Pressure of Carbon Dioxide during Cardiovascular Surgery Using the Tonocap

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Background: **A new automated system of air tonometry (Tonocap; Datex Ohmeda, Helsinki, Finland) allows for frequent (every 15 min) measurement of gastric luminal partial pressure of carbon dioxide. Its use has not been described in cardiac surgical patients.**

Methods: **One hundred patients undergoing coronary artery bypass graft or cardiac valve surgery were enrolled in a prospective cohort study. After anesthetic induction and insertion of a TRIP NGS Catheter (Datex Ohmeda), measurements of gastric luminal partial pressure of carbon dioxide were obtained using the Tonocap, and gastric mucosal *p*H (*p*Hi) was calculated. The main outcome measure was postoperative complication, defined as either in-hospital death or prolonged postoperative hospitalization (> 14 days).**

Results: **Four patients (4%) died, all of multiple-system organ failure, one each on postoperative days 9, 26, 46, and 121. Postoperative complication occurred in 18 patients (18%), all of whom exhibited persistent dysfunction of at least one organ system. Perioperatively, an abnormal *p*Hi (< 7.32) and gastric luminal minus arterial partial pressure of carbon dioxide gap (> 8 mmHg) occurred in 66% and 70% of patients, respectively. Predictors of postoperative complication included postoperative pHi ($P = 0.001$), gastric luminal partial pressure of carbon dioxide ($P = 0.022$), and gastric luminal minus arterial partial pressure of carbon dioxide gap ($P = 0.013$). In contrast, arterial base excess ($P > 0.4$) and routinely measured hemodynamic variables (*e.g.*, heart rate, blood pressure) were either less predictive compared with Tonocap-derived variables or not predictive.**

Conclusions: **Despite a low mortality rate, patients undergoing cardiac surgery exhibited high incidences of prolonged hospitalization and postoperative morbidity. The Tonocap was easy to use, particularly compared with saline tonometry. Several Tonocap-derived variables were predictive of postoperative complications consistent with previously published data using saline tonometry. (Key words: Gastric; morbidity; organ dysfunction; prolonged hospitalization.)**

APPROXIMATELY 500,000 cardiac surgical procedures are performed annually in the United States at a cost exceeding $5 billion.[1] Significant healthcare resources are used to provide care to patients with prolonged postoperative hospitalization, often because of low-grade organ dysfunction.[2,3] Clinicians, hospitals, and healthcare payers are increasingly focused on reducing complications and "unnecessary" days of hospitalization after surgery. Hypoperfusion of the gastrointestinal tract in surgical patients has been associated with adverse postoperative outcome and increased length of stay.[4–9]

Gastric tonometry is the only clinically available U.S. Food and Drug Administration–approved method for detecting gastrointestinal hypoperfusion. The tonometer is a modified nasogastric tube with a balloon on the distal end that is permeable to carbon dioxide. After insertion into the stomach, the manufacturer recommends instilling either saline (saline tonometry) or air (air tonometry) into the tonometer's balloon. The balloon's contents are subsequently withdrawn after a period of equilibration and assayed for the partial pressure of carbon dioxide (P_{CO_2}) using a blood gas analyzer (for saline tonometry) or an infrared analyzer (for air tonometry). The P_{CO_2} measured from the catheter's balloon's contents is

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thought to be a reflection of the P_{CO_2} of the gastric lumen and gastric mucosa (Pg_{CO_2}). Gastrointestinal hypoperfusion and mucosal acidosis lead to an elevated Pg_{CO_2} out of proportion to the arterial P_{CO_2} (*i.e.*, P_{CO_2} gap). The traditional method for presenting tonometric data involves calculating the gastric intramucosal *p*H (*p*Hi); *p*Hi is calculated by inserting the Pg_{CO_2} and the arterial bicarbonate concentration into a modified Henderson–Hasselbalch equation:[10] $p\text{Hi} = 6.1 + \log_{10}$ (arterial $[HCO_3^-]/Pg_{CO_2}$). The *p*Hi should decrease, *i.e.*, move in the opposite direction of Pg_{CO_2}, during periods of gastric hypoperfusion.

Low *p*Hi has been shown to be associated with the subsequent development of complications in both high-risk surgical patients and those in the intensive care unit.[4–15] All of these previous studies used saline tonometry, which is cumbersome to use and requires a long equilibration period (30–90 min), making it less suitable for use in the perioperative setting.[16] A new automated system of air tonometry (Tonocap, Datex Ohmeda, Helsinki, Finland) allows for the measurement of Pg_{CO_2} up to every 15 min. The Tonocap has been validated *in vitro* and *in vivo*.[17–23] Its use in surgical patients has not been well described.

Using this automated recycling air tonometer, we sought to determine the incidence of abnormal tonometric measurements in the perioperative period and their association with the development of postoperative complications.

Methods

Patient Selection

After institutional review board approval and informed consent were obtained, patients undergoing isolated coronary artery bypass graft or cardiac valve surgery were enrolled at The Mount Sinai Medical Center (New York, NY) in a prospective, cohort, observational study.

Exclusion criteria included age younger than 18 yr, emergency surgery, any religious or ethical prohibition from receiving blood products, contraindication to placement of a nasogastric tube, concomitant surgical procedures (*e.g.*, aortic surgery, closure of atrial or ventricular septal defects, placement of pacemaker), and procedures requiring circulatory arrest.

Patient Care and Monitoring

After oral benzodiazepine premedication, venous and radial arterial catheters were inserted. A pulmonary artery catheter was inserted after anesthetic induction. Maintenance of general anesthesia was accomplished using a balanced technique of midazolam hydrochloride, fentanyl citrate, and isoflurane. Patients underwent standard nonpulsatile hypothermic (23–32°C) cardiopulmonary bypass with a membrane oxygenator and hemodilution using a crystalloid prime. Porcine heparin was administered as a bolus of 300 U/kg and supplemented as necessary to maintain a kaolin-activated coagulation time of > 450 s during cardiopulmonary bypass. Heparin was neutralized with 1 mg protamine per 100 U heparin. After cardiopulmonary bypass, fluids were administered to optimize intravascular volume, inotropic agents to maintain an adequate cardiac index, and vasoactive agents to maintain a mean systemic blood pressure between 50 and 90 mmHg.

Gastrointestinal Tonometry

After induction of anesthesia a TRIP NGS Catheter (Datex Ohmeda) was placed *via* the mouth into the stomach and its position confirmed by aspiration of gastric contents or auscultation. Measurements of regional Pg_{CO_2} were obtained every 15 min using air tonometry with the Tonocap monitor. The Tonocap device automatically fills the tonometer catheter balloon with 5 ml of room air, which is kept in the balloon for a preselected equilibration period to allow carbon dioxide diffusion from the gastric lumen. The sample then is emptied back into an infrared measuring chamber for analysis. The air is recycled to the catheter balloon to avoid carbon dioxide depletion in the catheter system, thereby decreasing subsequent equilibration times. During steady-state conditions there is a permanent correction factor of about 2% to allow for catheter dead space.

In addition to intraoperative measurements, tonometric data were collected postoperatively in a subset of patients until the patient was extubated (up to a maximum of 12 h postoperatively). Arterial blood samples were obtained at least every hour and were withdrawn at the same time as a corresponding Pg_{CO_2} measurement. All arterial blood P_{CO_2} measurements were corrected for esophageal temperature to compensate for the low temperatures frequently encountered during cardiac surgery.[24] *p*Hi was calculated according to the manufacturer's guidelines, *i.e.*, by inserting the values for gastric tonometer P_{CO_2} and the arterial bicarbonate levels, which were determined by arterial blood gas analysis, into the modified Henderson–Hasselbalch equation described previously. The gastric P_{CO_2} gap was calculated by subtracting the temperature-corrected arterial P_{CO_2}

Table 1. Postoperative Morbidity Survey

Morbidity Type	Criteria
Pulmonary	*De novo* requirement for supplemental oxygen or other respiratory support (*e.g.,* mechanical ventilation or CPAP)
Infectious	Currently on antibiotics or temperature > 38°C in the last 24 h
Renal	Presence of oliguria (< 500 ml/day), elevated serum creatinine (> 30% from preoperative value), or urinary catheter in place for a nonsurgical reason
Gastrointestinal	Unable to tolerate an enteral diet (either by mouth or *via* a feeding tube) for any reason, including nausea, vomiting, and abdominal distention
Cardiovascular	Diagnostic tests or therapy within the last 24 h for any of the following: *de novo* myocardial infarction or ischemia, hypotension (requiring pharmacologic therapy or fluid therapy > 200 ml/h), atrial or ventricular arrhythmias, or cardiogenic pulmonary edema
Neurologic	Presence of a *de novo* focal deficit, coma, or confusion and delirium
Wound complication	Wound dehiscence requiring surgical exploration or drainage of pus from the operation wound, with or without isolation of organisms
Hematologic	Requirement for any of the following within the last 24 h: packed erythrocytes, platelets, fresh-frozen plasma, or cryoprecipitate
Pain	Surgical wound pain significant enough to require parenteral opiates or regional analgesia
Free text entry	Any other possible reason that could explain prolonged hospitalization

CPAP = continuous positive airway pressure.

from the Pg_{CO_2}. In general, previous studies have shown that the air and saline tonometry exhibit good correlation, the air technique in particular demonstrating low levels of bias, good precision, and shorter equilibration times.

There are no validated cutoffs for abnormal values of *p*Hi and P_{CO_2} gap using the Tonocap. Thus, initial analyses of these potential predictors did not assume a threshold of normality for these values. To see how our results compared with previous literature using saline tonometry, we also conducted separate analyses using reported values of abnormality for *p*Hi (< 7.32) and P_{CO_2} gap (> 8 mmHg).[7]

Other Potential Predictor Variables

Preoperative and intraoperative patient characteristics were recorded. Routinely recorded cardiovascular variables (*e.g.*, blood pressure, heart rate, blood oxygen saturation, hematocrit) as well as indices of organ perfusion (*e.g.*, arterial base excess, arterial *p*H, urine flow rate) were recorded. Patients were assigned a preoperative risk score using the validated Parsonnet method.[25] This model sums the assigned values for 19 factors known to increase mortality and morbidity rates after cardiac surgery and generates a score between 0 (*i.e.*, no risk factors) and 148; most patients in the original series by Parsonnet *et al.* (n = 4,832) were assigned a score between 0 and 30, with approximately 50% of patients assigned a score between 0 and 9.[24]

Outcomes

Patients were prospectively followed from the day of surgery until either discharge from the hospital or death. Postoperative length of stay was defined as the number of days from the day of operation (day 0) to hospital discharge or death. Postoperative complication was the primary outcome of this study and was defined as either in-hospital death or postoperative length of stay greater than 14 days. Fourteen days was chosen as a reasonable cutoff for the following reasons: A retrospective analysis at The Mount Sinai Medical Center of these procedures revealed that the median postoperative duration of hospitalization was 7 days, a week less than the duration used in our study. Furthermore, in this retrospective analysis, all patients with a postoperative length of stay > 14 days exhibited persistent dysfunction of at least one organ system.

To characterize postoperative complications, hospitalized patients were evaluated using a postoperative morbidity survey described in table 1. In addition to being assessed on the day corresponding to the study's primary outcome (*i.e.*, postoperative day 15), patients were also assessed 10 and 21 days after surgery to characterize complications associated with shorter and longer periods, respectively, of prolonged hospitalization. The criteria in this survey were selected to identify both severe complications (*e.g.*, pulmonary failure, acute respiratory distress syndrome) and more subtle complications that could delay discharge from the hospital (*e.g.*, moderate pulmonary dysfunction necessitating supplemental oxy-

Table 2. Patient Demographics

Age (yr)	65.6 ± 11.6
Gender (% male)	70
CABG procedure (%)	70
Valve procedure (%)	22
CABG + valve procedure (%)	8
Parsonnet risk score	10.9 ± 7.6
Operative duration (h)	4.6 ± 1.2
CPB duration (min)	129 ± 44
AoXC duration (min)	99 ± 30

Data are mean ± SD, where appropriate.

CABG = coronary artery bypass graft surgery; CPB = cardiopulmonary bypass; AoXC = aortic cross-clamp.

gen therapy). In addition, other possible reasons for delay in hospital discharge were recorded as a free-text entry. Inclusion of this free-text entry space on the data sheet was done to avoid a bias toward only recording predefined complications.

Statistical Analysis

Statistical calculations and analyses were carried out using the SAS software system version 6.12 (SAS Institute, Cary, NC). Statistical significance (*P*) was set at $\alpha = 0.05$. Associations between categoric variables and the primary outcome were tested using the contingency table chi-square test. For the primary analysis, associations between continuous variables and the primary outcome were tested by means of a series of univariate (unadjusted) logistic regression models. The independent influences of selected variables with $P < 0.1$ were subsequently analyzed in a multivariate logistic regression model taking Parsonnet score into account. Given the fact that prior studies involving saline tonometry used cutoffs for tonometric variables, we also conducted a secondary analysis using established cutoffs, *i.e.*, *p*Hi < 7.32 and P_{CO_2} gap > 8 mmHg.

This study's objective was not to rigorously assess all of the possible perioperative predictors of postoperative complications; therefore, a full multivariate analysis was not deemed to be appropriate.

Results

A total of 100 patients were enrolled in the study. Preoperative demographics and intraoperative characteristics for the study population are presented in table 2. Intraoperative tonometric data were collected in 100 patients. Tonometric data were collected postoperatively in a subset of 44 patients based on logistics (*e.g.*, availability of the study nurse). There were no significant difference between patients in whom monitoring was continued postoperatively (n = 44) and patients in whom monitoring was not continued postoperatively (n = 56), *e.g.*, age (67 ± 12 *vs.* 64 ± 11 yr), preoperative left-ventricular ejection fraction (0.44 ± 0.16 *vs.* 0.42 ± 0.13), preoperative hematocrit level (0.39 ± 0.6 *vs.* 0.38 ± 0.5), cardiac reoperation (11 *vs.* 11%), cardiopulmonary bypass duration (121 ± 38 *vs.* 135 ± 48 min), minimum temperature (22 ± 4 *vs.* 23 ± 3°C), time to tracheal extubation (23 ± 22 *vs.* 25 ± 31 h), postoperative chest-tube drainage in the first 24 h (626 ± 323 *vs.* 593 ± 349 ml).

Overall, 82 patients (82%) were discharged to home alive within the first 2 weeks after surgery. Postoperative complication (death or prolonged hospitalization) occurred in 18 patients (18%). Overall, the mortality rate was 4%. These four patients all died of multiple-system organ failure, one each on postoperative days 9, 26, 46, and 121. The mean overall postoperative length of stay was 13.3 ± SD 20.7 days (median, 7 days; range, 3–128 days).

All of the patients with prolonged hospitalization (> 14 days) exhibited persistent dysfunction of at least one organ system. Complications in patients hospitalized for greater than 14 days are listed in table 3. Of note, complications involved multiple organ systems and were consistent with an injury from an exaggerated systemic inflammatory response.

In the primary statistical analysis, the validated Parsonnet risk score was predictive of postoperative complication ($P = 0.028$). *P* values for the associations between other perioperative variables and postoperative complication are shown in table 4. It is noteworthy that, in the intraoperative period, neither *p*Hi ($P = 0.165$) nor P_{CO_2}

Table 3. Postoperative Complications

Complication Type	% Complications on Postoperative Day 15*
Pulmonary	53
Infectious	59
Renal	24
Gastrointestinal	35
Cardiovascular	59
Neurologic	24
Wound complication	6
Hematologic	18
Pain	0

* Excludes one patient who died in the hospital on postoperative day 9. Complications do not add up to 100% because many patients had more than one type of complication.

Table 4. Univariate Associations between Predictors and Postoperative Complication

Predictor	*P:* Intraoperative Measurement	Effect Direction	*P:* ICU Measurement	Effect Direction
Gastric *p*Hi	NS		0.001	↓
Gastric P_{CO_2}	NS		0.022	↑
Gastric P_{CO_2} gap	NS		0.013	↑
Arterial P_{CO_2}	NS		NS	
End-tidal P_{CO_2}	NS		NS	
Arterial *p*H	NS		0.012	↓
Arterial P_{O_2}	NS		NS	
Arterial base excess	NS		NS	
Heart rate	NS		NS	
Systolic blood pressure	NS		NS	
PAD pressure	0.001	↑	0.05	↑
Urine flow rate	NS		NS	
Hematocrit	NS		NS	
Body temperature	0.001	↑	NS	

NS = $P < 0.05$.

Tonometric-derived variables were treated as continuous variables, *i.e.,* no cutoff for normality was assumed (*e.g., p*Hi < 7.32). Measurements reflect the most abnormal value observed during the period specified.

Gastric *p*Hi = derived from gastric luminal carbon dioxide partial pressure and arterial HCO_3; Gastric Pg_{CO_2} = gastric luminal carbon dioxide partial pressure; Gastric P_{CO_2} gap = difference between gastric luminal carbon dioxide partial pressure and arterial carbon dioxide partial pressure; PAD = pulmonary artery diastolic; ICU = intensive care unit.

gap ($P = 0.165$) was associated with postoperative complication. In contrast, in the group studied in the postoperative period, both *p*Hi ($P = 0.001$) and P_{CO_2} gap ($P = 0.013$) were strongly associated with postoperative complication. Low *p*Hi postoperatively was a predictor of postoperative complication independent of arterial HCO_3, arterial base excess, and Parsonnet risk score. In general, hemodynamic variables and other indices of organ delivery or perfusion were either less significant or not significant predictors of postoperative complication.

In a secondary analysis using published thresholds for abnormality (*i.e.*, *p*Hi < 7.32), the overall results for gastric *p*Hi were similar, *i.e.*, low *p*Hi continued to be a predictor ($P = 0.022$) of postoperative complication. In contrast, P_{CO_2} gap did not significantly predict postoperative complications ($P = 0.174$) if it was treated as a categoric variable with abnormality defined as P_{CO_2} gap > 8 mmHg.

It is noteworthy that intraoperatively at least one episode of low *p*Hi (< 7.32) or elevated P_{CO_2} gap (> 8 mmHg) occurred in 53% and 35% of patients, respectively. These episodes occurred infrequently in the period before cardiopulmonary bypass with only 6% and 24% of patients having an episode of low *p*Hi or elevated P_{CO_2} gap, respectively, in this period of surgery. Postoperatively, 66% and 70% of patients had at least one episode of, respectively, low *p*Hi or elevated P_{CO_2} gap.

Discussion

Consistent with previously published studies we have demonstrated that complications are common after routine cardiac surgery and involve multiple organ systems. This pattern of generalized organ dysfunction is consistent with exposure to endotoxin and a systemic inflammatory response.[26–32]

Gastric tonometry is the only clinically available U.S. Food and Drug Administration–approved method for monitoring gastrointestinal perfusion. Saline tonometry has been shown to be an effective clinical tool in intensive care unit and other high-risk patients.[15,33] Saline tonometry, however, is cumbersome to use, requires a long equilibration period, and cannot be used with all blood gas analyzers, making it less suitable for use in the perioperative setting.[16] A new automated system of air tonometry (Tonocap) allows for frequent measurements of gastric luminal P_{CO_2} up to every 15 min and does not require the use of a specific type of blood gas analyzer. We sought to determine the ease of use of this monitor as well as the predictive nature of tonometric measurements derived from it.

The Tonocap was easy to use, particularly compared with saline tonometry. We noticed that initial Pg_{CO_2} values measured immediately after insertion of the tonometer often appeared to be artifactually low. Within

15–30 min the Pg_{CO_2} values would approach those that would be expected, which is consistent with some published data.[19] Despite this brief period of "equilibration," air tonometry provides information more quickly than does saline tonometry.[16] In contrast to saline tonometry, air tonometry–derived Pg_{CO_2} measurements do not require temperature correction during hypothermic conditions, a fact which may be particularly useful for cardiac surgery.

Consistent with previously published data, a *p*Hi < 7.32 existed in the majority of patients undergoing cardiac surgery and, if noted postoperatively, was a predictor of prolonged hospitalization. In our study P_{CO_2} gap was a less robust predictor of adverse outcome than *p*Hi. This finding appears to be consistent with claims that *p*Hi is an inherently more sensitive measure than P_{CO_2} gap, perhaps because the equation from which *p*Hi is derived takes into account both global metabolic acidosis as well as regional gastrointestinal hypoperfusion. Nevertheless, the fact that postoperative *p*Hi and P_{CO_2} gap were predictive when both base excess and HCO_3 were not suggests that low *p*Hi is not solely a reflection of global metabolic abnormalities.

Gastric *p*Hi and P_{CO_2} gap measured during the postoperative period were predictive of adverse outcome. In contrast, although there was a trend toward significance, these same variables measured intraoperatively were not predictive of adverse outcome. This finding suggest that tonometry may have limited value for guiding the care of cardiac patients if used solely during the intraoperative period. We believe that any interventional clinical trials that evaluate gastric tonometry should use the Tonocap to guide care in the entire perioperative period, with particular emphasis on the postoperative period.

Nevertheless, there are several possible reasons why tonometric variables may not have been predictive of outcome if used in the intraoperative setting:

1. Gastric *p*Hi may be a good predictor if measured at the end of surgery and in the intensive care unit but may provide less useful information if measured intraoperatively. The predictive ability of intraoperative measurements might have become statistically significant with larger patient numbers, but clearly the effect we observed was less then that described in other studies using saline tonometry. In these previous studies *p*Hi was measured at the end of surgery. In contrast, in our study, tonometric measurements were made frequently (every 30–60 min), but the protocol did not call *per se* for a measurement at the end of surgery. It is possible that severe and long-lasting episodes of gastric hypoperfusion, as might be manifested by low *p*Hi at the end of surgery and postoperatively, may be more robust predictors of postoperative complications than transient episodes. Although it is known that gastric tonometry can detect gastric hypoperfusion within minutes,[34] there is no evidence that brief transient episodes of low *p*Hi are clinically relevant. This issue requires further study.
2. Profound hypothermia during cardiac surgery may have effects on gastric mucosal perfusion or the methodology of gastric tonometry that are not understood.[9] The effects of low temperature on carbon dioxide production, solubility, and diffusion of carbon dioxide through tissues and the tonometer balloon are not well understood. This issue may be of particular relevance at our hospital, where patients are cooled markedly. In fact, the minimum temperature during cardiopulmonary bypass in this study's patients was mean 22.5 ± SD 3.8°C. Moreover, patients at our center are warmed routinely to a bladder or rectal temperature of only 31 or 32°C before separation from cardiopulmonary bypass and thus are still relatively "hypothermic" in the entire post–cardiopulmonary bypass period. It is only in the intensive care unit that these patients' temperatures approach 37°C. Therefore, even though we corrected all arterial P_{CO_2} measurements for temperature, it is unknown whether this correction makes the monitor's information any more or less predictive at these low temperatures. The effect of hypothermia on the ability of gastric tonometry to predict adverse outcome warrants further study.
3. Another possible explanation for the lack of predictability of intraoperative measurements may relate to the use of H_2-receptor antagonists, *e.g.*, ranitidine.[7] Use of H_2-receptor antagonists theoretically improves the reliability of gastric tonometry by eliminating the occurrence of false positive elevations of Pg_{CO_2} caused by mixing of gastric acid with refluxed duodenal bicarbonate. Our study protocol did not mandate the use of H_2-receptor antagonists, because we do not believe that it has been proven that they improve the clinical reliability of Pg_{CO_2} measurements during surgery. Only 20% of patients received H_2-receptor antagonists preoperatively in our study. It is reassuring that this infrequent use of H_2-receptor antagonists did not effect the predictive ability of postoperative tonometric measurements. Nevertheless,

we cannot rule out the possibility that 100% use of H2-receptor antagonists may have improved the predictive ability of intraoperative measurements.

In summary, despite a low mortality rate, patients undergoing cardiac surgery exhibited high incidences of prolonged hospitalization and postoperative morbidity. The Tonocap was easy to use, particularly compared with saline tonometry. Several Tonocap-derived variables, if noted during the early postoperative period, were predictive of postoperative complications consistent with previously published data using saline tonometry. Gastric *p*Hi was a more robust predictor compared with P_{CO_2} gap, and both were more predictive if measured postoperatively. Randomized clinical trials are needed to assess whether the Tonocap can be used to improve end organ perfusion and improve postoperative outcome.

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