Descending aortic blood flow during aortic cross-clamp indicates postoperative splanchnic perfusion and gastrointestinal function in patients undergoing aortic reconstruction

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Editor’s key points
- The relationship between splanchnic and renal blood flow during infrarenal aortic cross-clamp (XC) and postoperative gastrointestinal perfusion and function was studied.
- Cardiac output (CO) and gastric intramucosal pH (pHi) significantly decreased during XC.
- The gastric pHi remained decreased after XC release, despite increased CO.
- There was a critical threshold of descending aortic blood flow (DABF) during XC to prevent gastric pHi decrease after XC release.
- DABF during XC was inversely correlated with recovery of postoperative gastrointestinal function.

Background. The purpose of this observational study was to investigate the relationship between splanchnic and renal blood flow during infrarenal aortic cross-clamp (XC) and postoperative gastrointestinal perfusion and function.

Methods. Descending aortic blood flow (DABF) was continuously monitored with an oesophageal Doppler monitor (Cardio-Q, Deltex Ltd, Chichester, UK) in 31 patients undergoing elective abdominal aortic aneurysm repair. Cardiac output (CO) was determined by indocyanine green dilution before, during, and after XC. Perioperative gastrointestinal perfusion was assessed by gastric intramucosal pH (pHi, Tonocap, GE Healthcare, Helsinki, Finland). Postoperative gastrointestinal recovery was assessed by the number of postoperative days until the patient successfully resumed solid food intake. The relationship between the mean DABF during XC and gastric pHi after XC release and postoperative gastrointestinal recovery was analysed with Spearman’s correlation coefficient.

Results. DABF accounted for ~55% of CO during XC and significantly decreased during XC, despite arterial pressure remaining within an optimal range. There were two distinct relationships between DABF during XC and gastric pHi after XC release. Gastric pHi steeply and linearly declined when indexed DABF was below 0.82 litre min$^{-1}$ m$^{-2}$. Above this critical value, there was no linear relationship between them. The duration of postoperative gastrointestinal dysfunction was inversely correlated with the mean DABF during XC. The best cut-off value of the mean indexed DABF during XC to prevent prolonged gastrointestinal dysfunction was 1.2 litre min$^{-1}$ m$^{-2}$.

Conclusions. Decreased DABF during XC associates splanchnic hypoperfusion after XC release and delayed recovery of gastrointestinal function.

Keywords: aortic Doppler; arteries, aortic clamp; cardiovascular anaesthesia; gastrointestinal tract, bowel function; gastrointestinal tract, pH

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Infrarenal aortic reconstruction is a high-risk procedure and requires careful anaesthetic management. Although myocardial and large bowel ischaemia contribute to the majority of mortality and morbidity, renal and hepatic injuries are also implicated in morbidity after aortic reconstruction. Previous experimental studies demonstrated increased blood flow through the superior mesenteric artery during infrarenal aortic cross-clamp (XC). However, other clinical studies have found that splanchnic blood flow is compromised during XC or after XC release.

Oesophageal Doppler monitor (ODM) is a less-invasive cardiac output (CO) monitor and is based on the following principles. The Doppler technology is used to measure descending aortic blood flow (DABF) typically at the Th 5 or 6 level. During XC, DABF equals the sum of splanchnic, renal, and blood flow through the intercostal artery. With this method, we can reasonably estimate splanchnic and renal blood flow by DABF during infrarenal aortic XC, assuming that the blood flow through the intercostal artery is negligible. Therefore, the relationship between systemic
and regional blood flow during XC can be evaluated with this technique.

We hypothesized that there was a critical threshold of DABF during aortic XC below which postoperative gastrointestinal and renal dysfunction may occur. The purpose of this prospective, observational study was to investigate the relationship between splanchnic blood flow during XC and postoperative gastrointestinal, hepatic, and renal function in patients undergoing abdominal aortic reconstruction.

**Methods**

**Patients**

The study protocol was approved by the institutional review board. Thirty-one patients undergoing elective abdominal aortic aneurysm repair were enrolled in this study. Written informed consent was obtained from each participant. Standard monitoring, including ECG, non-invasive arterial pressure, pulse oximetry, and end-tidal gas monitor, was applied in each case. Additionally, arterial pressure and central venous pressure were continuously monitored. An epidural catheter was inserted at either the Th 9/10 or the Th 10/11 interspace. Identiﬁed anaesthetic management was used in all cases. Anaesthesia was induced with i.v. fentanyl, propofol, and vecuronium bromide, and the trachea was intubated and mechanically ventilated. Anaesthesia was maintained with sevoflurane in an oxygen–air mixture and supplemented with i.v. vecuronium and fentanyl. Intermittent boluses of 0.5% ropivacaine were epidurally administered during surgery. During XC, systolic arterial pressure was maintained between 100 and 140 mm Hg by continuous infusion of vasoactive agents. Acetate Ringer’s solution was administered during anaesthesia and the stay in the intensive care unit (ICU). Two grams per kilogram of mannitol solution was also administered before XC. Other medications were at the discretion of the attending anaesthetist. After operation, the trachea was extubated, and the patient was transferred to a 14-bed multidisciplinary ICU for overnight observation. Haemodynamic management during the ICU stay was at the discretion of the ICU physicians and cardiovascular surgeons.

**Measurement of DABF**

After tracheal intubation, the ODM probe (Cardio-Q, Deltex Ltd, Chichester, UK) was inserted, and blood flow at the descending aorta was continuously monitored. The probe position was adjusted to obtain an optimal Doppler signal by one of the investigators (Y.K.) who had performed more than 100 measurements. In this study, we used a typical assumption that 70% of CO accounts for DABF; the following formula was used to calculate descending aortic blood flow index (DABFi).\(^12\) \(^\text{–}^14\)

\[
DABFi = \text{cardiac index obtained from ODM (CI-ODM)} \times 0.7
\]

**Measurement of CO by dye dilution**

Additionally, cardiac index (CI-PDD) and plasma disappearance rate of indocyanine green (ICG-PDR) were measured with the pulse dye densitometric method (DDG-2001, Nihon Kohden Corp., Tokyo, Japan) at the following periods: after surgical exposure of the infrarenal abdominal aorta (before XC), 30 min after XC of the abdominal aorta (during XC), and 60 min after release of the XC (after XC release).\(^15\) \(^\text{–}^17\)

**Measurement of gastrointestinal, hepatic, and renal function**

Gastric transluminal CO\(_2\) was continuously measured with a balloon-tipped gastric catheter (Tonometer, GE Healthcare, Helsinki, Finland).\(^9\) \(^\text{–}^13\) Gastric intramucosal pH (pHi) was calculated by entering arterial blood gas data obtained from the blood gas analyzer (Stat Profile M, Nova Biomedical, Waltham, MA, USA). Perioperative hepatic and renal functions were assessed with serum aspartate aminotransferase (AST), alanine aminotransferase (ALT), and creatinine. Urine samples were collected after anaesthetic induction and at the end of the surgery. Urinary N-acetyl-β-D-glucosaminidase activity (NAG) and creatinine concentration were spectrophotometrically determined (NAG test, Shionogi, Osaka, Japan, and Creatinine Test L-type Wako, Wako Pure Chemicals, Osaka, Japan).\(^2\) \(^\text{–}^20\) The results were expressed as urinary NAG creatinine ratio.

To evaluate gastrointestinal function, the duration of nasogastric tube placement and the day when the patient successfully tolerated solid food was recorded. The decision to remove the nasogastric tube and provide solid food was made by cardiovascular surgeons who were blinded to the measurements.

**Statistical analysis**

Data were expressed as mean (SD) unless otherwise specified. To evaluate blood flow distribution before, during, and after XC, the relationship between CI-PDD and instantaneous DABFi was analysed with linear regression. The slope of the regression line was used to define the ratio between cardiac index and DABFi. To evaluate the effects of DABFi during XC on gastrointestinal, hepatic, and renal functions, data were analysed if there was a threshold of mean DABFi during XC to prevent clinically relevant morbidity. Morbidity was defined as follows: ICG-PDR < 0.15 min\(^{-1}\), postoperative serum Cr > 1.3 mg dl\(^{-1}\), urinary NAG Cr ratio > 2 or need for renal replacement therapy, elevated postoperative serum AST or ALT activity, increased duration of nasogastric tube placement, or increased number of postoperative days before the patient was able to tolerate solid food. A P-value of < 0.05 was used for statistical significance. We estimated the standard deviation of DABFi and days before the patient was able to tolerate solid food as 0.6 litre m\(^{-2}\) and 1 day, respectively, and found that the sample size was enough to demonstrate a significant correlation at \(\alpha=0.05\) and \(\beta=0.8\).\(^21\)

**Results**

The flow diagram of this study is demonstrated in Figure 1. The patient characteristic and operative data are
summarized in Table 1. The median (range) DABFi during XC was 1.02 (0.48–1.88) litre min\(^{-1}\) m\(^{-2}\), and DABF was highly variable during XC, despite maintenance of systolic arterial pressure between 100 and 140 mm Hg during XC. Time-dependent changes of CI-PDD, ICG-PDR, instantaneous DABFi, and gastric pHi are summarized in Table 2. There was a linear relationship between CI-PDD and instantaneous DABFi at the three measurement periods (Fig. 2). The relationship between CI-PDD and instantaneous DABFi was as follows: DABFi = 0.69 × CI-PDD (\(r^2 = 0.70, P < 0.01\)) before XC, DABFi = 0.55 × CI-PDD (\(r^2 = 0.59, P < 0.01\)) during XC, and DABFi = 0.73 × CI-PDD (\(r^2 = 0.28, P < 0.01\)) after XC release. The relationship between the mean DABFi during XC and gastric pHi after XC release is demonstrated in Figure 3. The data suggest that two distinct relationships exist between them, depending on the mean DABFi value. The mean DABFi and pHi after XC release significantly correlated if the mean DABFi during XC was below 1.0 litre min\(^{-1}\) m\(^{-2}\) (\(r^2 = 0.74, P < 0.01\)). On the contrary, there is no significant correlation when the mean DABFi during XC was more than 1.0 litre min\(^{-1}\) m\(^{-2}\). The critical value of the mean DABFi during XC where steep decline in pH starts is estimated as 0.82 litre min\(^{-1}\) m\(^{-2}\). To investigate the effects of duration below the critical DABFi value on the pH after XC release, time-flow integral of DABFi below 0.82 litre min\(^{-1}\) m\(^{-2}\) in each subject was calculated and plotted against pH after XC release (Fig. 4). There is an inverse linear relationship between time-flow integral and pH (\(r^2 = 0.65, P < 0.01\)).

*Table 1* Patient characteristics. Data are expressed as mean (range), mean (so), or number of subjects. *Either 6% HES 70/0.5 (Saline-HES, Fresenius-Kabi, Japan) or Dextran 40 (Otsuka Pharmaceuticals, Japan).* \(^1\)Blood products include intraoperatively salvaged autologous blood processed with CellSaver 5 Plus (Haemonetics, Braintree, MA, USA) or allogeneic packed red cell concentrate, fresh-frozen plasma, and platelet concentrates. \(^2\)Multiple interventions were used in several cases.

| Age (yr) | 71 (40–89) |
| Gender (M/F) | 27/4 |
| Height (cm) | 163 (7) |
| Weight (kg) | 63 (10) |
| Duration of surgery (min) | 232 (57) |
| Preoperative medication (n) |  |
| \(\beta\)-Blocker | 24 |
| Ca-channel blocker | 9 |
| Other anti-anginal drugs | 19 |
| Diuretics | 6 |
| Duration of aortic cross-clamp (min) | 56 (16) |
| Intraoperative blood loss (ml) | 1040 (560) |
| Intraoperatively administered acetate Ringer’s solution (ml) | 3260 (1180) |
| Intraoperatively administered colloid* (ml) | 720 (510) |
| Intraoperatively administered blood products† (ml) | 480 (240) |
| Vasoactive agents used during aortic cross-clamp‡ |  |
| Nitroglycerin infusion | 7 |
| Nicardipine infusion | 16 |
| Phenylephrine bolus | 9 |
| Dopamine infusion | 5 |
| Dobutamine infusion | 3 |

*Table 2* Summary of heart rate, mean arterial pressure, cardiac index, ICG-PDR, DABFi index, and gastric intramucosal pH. Data are expressed as mean (so). \(*P < 0.05\) vs before XC. MAP, mean arterial pressure measured at brachial artery; CI-PDD, cardiac index measured with pulse dye densitometry; ICG-PDR, plasma disappearance rate of indocyanine green. DABFi, descending aortic blood flow index calculated with oesophageal Doppler monitor; pH, gastric intramucosal pH; XC, aortic cross-clamp.

<table>
<thead>
<tr>
<th>Before XC</th>
<th>During XC</th>
<th>After XC release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (beats min(^{-1}))</td>
<td>56 (8)</td>
<td>65 (11)</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>73 (12)</td>
<td>93 (17)</td>
</tr>
<tr>
<td>CI-PDD (litre min(^{-1}) m(^{-2}))</td>
<td>2.4 (0.8)</td>
<td>2.2 (0.6)</td>
</tr>
<tr>
<td>ICG-PDR (min(^{-1}))</td>
<td>0.16 (0.04)</td>
<td>0.25 (0.05)*</td>
</tr>
<tr>
<td>Instantaneous DABFi (litre min(^{-1}) m(^{-2}))</td>
<td>1.7 (0.5)</td>
<td>1.2 (0.5)*</td>
</tr>
<tr>
<td>pH</td>
<td>7.36 (0.06)</td>
<td>7.29 (0.10)*</td>
</tr>
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The median (range) duration of nasogastric tube placement was 1 (0–4) day. The relationship between the mean DABFi during XC and the duration of nasogastric tube placement did not achieve statistical significance (\(P = 0.059\)). The
The median (range) number of postoperative days until resumption of solid food intake was 3 (2–6) days. There was a modest but statistically significant inverse relationship between the mean DABFi during XC and the number of postoperative days until solid food intake ($r^2 = 0.35$, $P < 0.01$, Fig. 5). The area under the receiver operating characteristic curve was 0.75 ($P = 0.02$) and the best cut-off value of the mean DABFi during XC to resume solid food within 3 days was 1.2 litre min$^{-1}$ m$^{-2}$ with the sensitivity and the specificity of 86% and 53%.

Discussion

In this study, we found that CO and gastric pH remained decreased during aortic XC and that 55% of CO was distributed to the splanchnic region and kidney during infra renal aortic XC. The gastric pH remained decreased after XC release, despite increased CO. There was a critical threshold of DABFi during XC to prevent gastric pH decrease after XC release.
release and DABF during XC was inversely correlated with recovery of postoperative gastrointestinal function.

There are some conflicting reports about splanchnic perfusion during infrarenal aortic XC. Several animal studies demonstrated that splanchnic blood flow increases during infrarenal aortic XC due to its high vascular compliance. However, recent clinical investigations suggest that gastrointestinal hypoperfusion occurs during infrarenal aortic XC. For example, Pargger and colleagues found that more than 40% of patients have gastric intramucosal acidosis after elective abdominal aortic surgery, and prolonged intramucosal acidosis is an important risk factor for postoperative mortality and morbidity. Nakatsuka also reported that gastric pH significantly decreases during XC and 30 min after XC release. These findings indicate that splanchnic blood flow may be compromised during XC. Furthermore, Valentine and colleagues reported that gastrointestinal complications occur in 20% of the patients undergoing elective abdominal aortic aneurysm repair and is associated with increased morbidity, prolonged length of stay, and increased mortality. Although the pathophysiology of postoperative gastrointestinal dysfunction is multifactorial, several studies suggest that reduced splanchnic perfusion plays an important role in retarded gastrointestinal recovery. From these perspectives, we hypothesized that the relationship between reduced splanchnic perfusion and postoperative morbidity could be demonstrated by monitoring DABF with ODM.

We found significantly decreased DABFi and cardiac index during XC. Increased afterload and myocardial dysfunction may be responsible for this finding since the majority of subjects had hypertension and were prescribed medications, including β-blockers. This finding also underscores the importance of CO monitoring in patients undergoing infra-renal aortic reconstruction. Our linear regression analysis demonstrated that DABF comprised 69% and 73% of CI before and after XC, respectively. This finding provides additional validation to the algorithm used in the ODM that 70% of CO is distributed through the descending aorta. Then, 55% of CI was directed to the gastrointestinal and renal regions during XC. To our knowledge, blood flow through the femoral artery in anaesthetized patients has not been reported in the literature. However, Uusaro and colleagues reported that 7% of CO is distributed to the ipsilateral femoral artery in patients after cardiac surgery. If this finding is applicable to anaesthetized patients, the blood flow to the gastrointestinal and renal regions can be assumed as about 55% (69–14%) of CO before XC and 59% (73–14%) after XC. These estimates suggest that the blood flow to the gastrointestinal tract and the kidney was around 55–60% range during abdominal aortic aneurysm repair and was fairly constant before, during, and after infrarenal aortic XC.

Additionally, we found an interesting relationship between the mean DABFi during XC and pH after XC release. This relationship is very similar to the one between systematic oxygen delivery and oxygen consumption. We also found an inverse linear relationship between the mean DABFi during XC and the duration required to recover gastrointestinal function. These findings underscore the importance of maintaining DABF during XC on postoperative recovery of gastrointestinal function. Obviously, DABF can only be measured by ODM, our data suggest that other CO monitors can be used to prevent gastrointestinal hypoperfusion and subsequent gastrointestinal dysfunction since the aforementioned relationship between DABF and CO is fairly stable. The critical value of CI during XC to prevent steep decline in pH after XC release corresponds to 1.5 (0.82/0.55) litre min⁻¹ m⁻². Clinically, we believe that higher CI should be targeted since several individuals in our study showed clinically significant decrease in pH even when DABF was maintained over this threshold value (Fig. 4). The findings of Nakatsuka where the mean gastric pH was 7.37 (0.8) while the mean CO was 4.0 (1.0) litre min⁻¹ may also support this assumption.

Interestingly, no relationship between DABF during XC and renal and hepatic functions was demonstrated. Previous studies demonstrate significantly reduced renal blood flow during XC. However, modern anaesthetic agents better preserve hepatic and renal blood flow. We speculate that hepatic and renal blood flow was relatively preserved with current anaesthetic management, while gastrointestinal perfusion was significantly compromised when DABF was reduced. It is well known that renal perfusion is controlled by intrinsic autoregulatory mechanisms, and prophylactic measures such as mannitol administration before XC to prevent renal dysfunction was used in all cases. Also, the liver has a dual supply of blood flow, and blood flow through the hepatic artery is governed by hepatic arterial buffer response. These protective mechanisms might have attenuated the possible deleterious effects of reduced DABF on renal and hepatic function, but the gastrointestinal region might have been inadequately perfused during XC, since this region supposedly lacks protective mechanisms.

This study obviously has several limitations. First, this study is an observational study and involves a limited number of subjects. The clinical relevance of our finding must be prospectively confirmed. Secondly, the influence of the epidural block is not known. The epidural block inhibits sympathetic control in the splanchnic region and may increase blood flow. On the contrary, epidural block-induced circulatory depression may decrease CO and splanchnic perfusion. These complex interactions may influence our results, and it remains to be seen whether our findings are applicable to patients undergoing different anaesthetic management. Thirdly, the accuracy of ODM is also a concern. One of the disadvantages of ODM is that the accuracy is operator-dependent. Additionally, the aortic diameter may increase during aortic XC and may cause additional inaccuracy. However, Lafanechere and colleagues reported minimal change of abdominal aortic diameter during aortic XC and we assume the change of aortic diameter during...
XC contributes minimally to the inaccuracy of ODM measurement during XC. Despite these limitations, our study revealed that DABF during aortic XC plays an important role in the postoperative recovery of gastrointestinal function and provides further rationale for a prospective study to investigate the effectiveness of haemodynamic management during XC on postoperative morbidity.

In conclusion, we found reduced DABFi during aortic XC despite the maintenance of arterial pressure within the normal range in patients undergoing abdominal aortic reconstruction. Reduced CO during aortic XC is responsible for this finding since the percentage of splanchnic blood flow remained stable. We also found association between reduced DABFi during aortic XC and gastric hypoperfusion after XC release, and also the delayed recovery of gastrointestinal function. The result of this study suggests the importance of maintaining CO and DABF during aortic XC to avoid splanchnic hypoperfusion and its clinical consequences such as postoperative gastrointestinal dysfunction.

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