Gastrointestinal Complications in the Perioperative Period

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James Pierce, Sylvia del Castillo, and Rula Harb

Abstract

Patients with congenital heart disease are prone to various gastrointestinal complications in the perioperative period including necrotizing enterocolitis, gastroesophageal reflux, intestinal perforation, protein-losing enteropathy, and liver dysfunction. The objective of this chapter is to discuss the various perioperative complications that can arise before or after surgical correction or palliation of different types of congenital heart disease. A review of the current literature is performed, and the management of patients from a surgical and intensive care perspective is addressed.

Keywords

Cardiac surgery • Congenital heart disease • Feeding intolerance • Focal intestinal perforation • Gastroesophageal reflux • Gastrointestinal dysfunction • Gastrointestinal • Intestinal ischemia • Intestinal perforation • Liver dysfunction • Necrotizing enterocolitis • Postoperative • Preoperative • Protein-losing enteropathy

J. Pierce (✉)
Pediatric General Surgery, USC Keck School of Medicine, Children's Hospital Los Angeles, Los Angeles, CA, USA
e-mail: JRPierce@chla.usc.edu

S. del Castillo
Critical Care, USC Keck School of Medicine, Children's Hospital Los Angeles, Los Angeles, CA, USA
e-mail: SdelCastillo@chla.usc.edu

R. Harb
USC Keck School of Medicine, Children's Hospital Los Angeles, Los Angeles, CA, USA
e-mail: RHarb@chla.usc.edu

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Introduction

It is well known that simply eating a meal has a profound effect on the human cardiovascular system [1, 2]. The earliest patients surviving with congenital and acquired cardiovascular disease often suffered with poor feeding and failure to thrive [3]. Indeed, poor feeding remains an independent predictor of congestive heart failure (CHF) even in the modern era [4]. Additionally, with increased survival of children with congenital heart defects, there are now more patients with both heart disease and congenital or acquired abnormalities of the gastrointestinal (GI) tract [5, 6]. GI complications include any acquired disease process arising in either the gastrointestinal tract or to solid organs supplied by the celiac artery (CA), superior mesenteric artery (SMA), or inferior mesenteric artery (IMA). Specifically, the hollow viscera include the esophagus, stomach, duodenum, jejunum, ileum, colon, rectum, and anus. Solid organs supplied by these arteries include the liver, spleen, and pancreas [7]. Every neonatal or pediatric patient with congenital heart disease (CHD) will require some form of medical management related to the gastrointestinal tract. Often, the most critical decision is related to the initiation of feeds. This is particularly true after complex congenital heart surgery. Patients with complicated cyanotic CHD, such as single-ventricle physiology or heterotaxy syndrome, will require multiple steps in their medical management to avoid gastrointestinal morbidity and mortality.

Both GI physiology and pathology are affected by cardiovascular function. Six broad categories of cardiac physiology should be considered when approaching GI pathophysiology: pulmonary overcirculation, left ventricular outflow tract obstruction, tetralogy of Fallot, transposition of the great arteries, obstructed pulmonary veins, and single ventricles (Table 168.1). This chapter will discuss the major decision points that can occur in these patients during the perioperative period.

Table 168.1 Six classes of cardiac physiology influencing gut perfusion

Pulmonary overcirculation
Left ventricular outflow tract obstruction
Tetralogy of Fallot
Transposition of the great arteries
Obstructed pulmonary veins
Single-ventricle physiology

Pulmonary Overcirculation

Pulmonary overcirculation, such as a ventricular septal defect (VSD), is the most common form of cardiac pathophysiology [8]. During the perinatal period, these defects are generally well tolerated due to elevated pulmonary vascular resistances (PVR). Nevertheless, there is a defined subset of patients who develop cardiopulmonary collapse during the transitional period shortly after the placental circulation is removed [9]. The main gastrointestinal morbidity for these neonates is the development of intestinal ischemia, often mistaken for necrotizing enterocolitis [10]. The best studied group in this category concerns premature babies with hemodynamically significant patent ductus arteriosus [11, 12]. These patients are at risk for both global ischemia associated with poor perfusion and focal ischemia related to exogenous administration of cyclooxygenase inhibitors and steroids [13]. The subtle differences between focal intestinal perforation, necrotizing enterocolitis, and intestinal ischemia are discussed below.

For those patients who survive to postnatal circulation, the subsequent weeks and months most commonly manifest as difficulty feeding [15, 16]. PVR drops significantly in the first week of life and can lead to progressive worsening of pulmonary overcirculation. In cases with a nonrestrictive left-to-right shunt, the lungs will become progressively congested resulting in heart failure. While mild to moderate heart failure may be managed with a combination of diuretics and high-density caloric feeds, some patients will continue to experience failure to

thrive. One strategy for managing these patients is early definitive cardiac repair, which generally requires full cardiopulmonary bypass and cardiac arrest. A second strategy is palliative surgery with pulmonary arterial banding to restrict pulmonary blood flow. This avoids both cardiopulmonary bypass surgery and cardiac arrest but has a profound impact on cardiac physiology prior to definitive repair. A third strategy is to postpone surgery and aggressively feed via the enteral route, thus avoiding increased work of oral intake and ensuring adequate caloric support.

Patients with overcirculation who become malnourished fall into two subgroups. The first group includes the patients with no other feeding issues and a significant amount of left-to-right shunt. These patients often have a low-velocity (nonrestrictive) ventricular septal defect or an endocardial cushion defect. The second category includes patients with an associated condition that hinders the ability to feed. The latter include craniofacial abnormalities such as cleft lip/palate or choanal atresia, tracheal abnormalities such as malacia or stenosis, neurologic dysfunction such as intraventricular hemorrhage or seizures, prematurity, and genetic/chromosomal disease. Initial assessment of both groups of patients involves utilizing gavage feedings. Patients who cannot be adequately fed despite high caloric intake should be evaluated for cardiac palliation or repair. The process for this decision is discussed in detail later in this chapter. Patients who can consistently gain weight with supplemental gavage feeds may benefit from placement of a gastrostomy tube (G-tube). This decision to proceed with a G-tube should be carefully balanced with consideration of ongoing feeding difficulties as well as the timing of cardiac surgery. At the authors' institution, patients with no significant comorbidities and a relatively short waiting time to surgery will continue nasogastric feeds. Patients with significant abnormalities that hinder feeding will usually receive a G-tube. Invariably, there are many considerations with this decision, particularly the fact of the family's comfort and ease with an additional invasive procedure. Fortunately, the morbidity and mortality of gastric access is relatively low [17].

The initial postoperative period for these patients may be complicated by pulmonary hypertensive crises which can interfere with feeding secondary to low cardiac output and unstable hemodynamics. However, the postoperative period for this group of patients is usually uneventful, and they are able to resume enteral feeds soon after their repair [7].

Left Ventricular Outflow Tract Obstruction (LVOTO)

Significant left ventricular outflow tract obstruction and congenital abnormalities of the aortic arch comprise the second physiology group in patients with acyanotic congenital heart disease. With the advancement of fetal echocardiography, many of these patients are diagnosed prenatally. Early initiation of prostaglandin maintains fetal circulation, optimizing systemic blood flow and gut perfusion. However, many patients in this category present with either acute left heart failure (true LVOTO) or loss of distal systemic blood flow (aortic arch abnormalities). In these cases, surgical management of the cardiac lesion may be the only option to establish gut perfusion. The acute insult to the GI tract in these patients usually results in ischemic injury. It can lead to gut gangrene in as many as 11 % of patients with coarctation of the aorta [18] but remains an uncommon complication of critical aortic stenosis [19, 20]. Endovascular approaches to aortic valve and arch abnormalities generally do not aggravate gastrointestinal dysfunction. Surgical intervention for aortic valvar and especially for aortic arch defects, however, can be associated with significant postoperative gastrointestinal issues. Recurrent laryngeal nerve injury occurs in approximately 5 % [21] of aortic arch reconstructions and can lead to aspiration and inability to safely feed by mouth. This often requires feeding through a nasogastric or surgical G-tube. Operations within the posterior mediastinum, such as aortic coarctation repair and interrupted aortic arch, can injure both the thoracic duct and the vagus nerve. Thoracic duct injury can result in chylothorax or chylopericardium.

Vagal neuropraxia presents as esophageal dysfunction, delayed gastric emptying, and significant gastroesophageal reflux. In most cases, these are transient processes that can be managed conservatively. In severe cases, interventional radiology, endoscopy, or surgical repair are required.

Tetralogy of Fallot

Tetralogy of Fallot (TOF) is traditionally described as a cyanotic congenital heart lesion associated with decreased pulmonary blood flow. There are several other lesions which have a similar physiology. These include pulmonary stenosis or atresia with an ASD or VSD, double outlet right ventricle (DORV) with pulmonary stenosis, and lesions palliated with a pulmonary artery band such as a large VSD.

During early transition to extrauterine circulation, the patent ductus arteriosus allows left-to-right shunting to increase pulmonary blood flow. Ductal closure is associated with acutely worsening cyanosis which may, in the setting of cardiovascular collapse, lead to ischemic bowel. Thus, while presentation of decreased pulmonary blood flow physiology in the first 2 weeks of life is usually hypercyanosis and shock, presentation in the first several months is usually failure to thrive in patients who have not been repaired or palliated. Other factors contributing to poor feeding include prolonged ventilatory support, need for cardiopulmonary bypass, and prematurity [22, 23]. Patients with TOF or other conotruncal abnormalities have a higher incidence of a right-sided aortic arch or vascular ring which may cause dysphagia. The clinician must therefore have a high index of suspicion in this population when reviewing the echocardiogram in patients who present with dysphagia. Following complete repair, recurrent laryngeal nerve dysfunction can lead to primary aspiration. Contrast studies such as modified barium swallow study (for evaluation of oropharyngeal function) and esophagram (for extrinsic lesions obstructing the foregut) are useful in further dysphagia work-up.

Conotruncal abnormalities are associated with congenital anomalies of the gastrointestinal tract and hepatobiliary system or with heterotaxy syndromes and malrotation.

Parallel Circulation

The second major group of cyanotic congenital heart disease patients presents with increased pulmonary blood flow, but inadequate mixing of saturated and desaturated blood at the atrial or ductal level. The classic example of this type of lesion is *d*-transposition of the great arteries (TGA), although any twisting lesion with streaming dependent parallel circulations can produce transposition-like physiology. In the presence of streaming, double outlet right ventricle (DORV) can result in this physiology, as can truncus arteriosus and nonobstructed total anomalous pulmonary venous return (TAPVR).

Because these lesions are mixing dependent, adequate perfusion is reliant on shunting at multiple levels, and patients lacking this characteristic may present in complete cardiovascular collapse and develop bowel ischemia. Patients with adequate mixing may tolerate extrauterine life but are at higher risk for necrotizing enterocolitis and gastrointestinal dysfunction leading to feeding intolerance. Currently, most surgeons prefer the arterial switch operation for TGA with or without VSD within the first 2 weeks of life to minimize the systemic adverse effects of either congestive heart failure or prolonged cyanosis, both of which can lead to poor GI perfusion and feeding intolerance [24]. These lesions, with complex truncal anatomy, are also at high risk for extrinsic compression of the esophagus (vascular ring) and recurrent laryngeal nerve or vagal nerve injury during definitive repair.

Obstructed Pulmonary Veins

Obstructed total anomalous pulmonary venous return (TAPVR) is one of the true emergent surgical lesions in congenital heart disease. Similar to other repaired physiologies, there are associated feeding issues that go along with neurologic dysfunction from perioperative stroke

or hypothermic arrest, and like other operations posterior to the heart (distal arch reconstruction, the atrial switch procedures now out of favor), there are associated risks of recurrent laryngeal nerve and vagal injury. These situations are unrelated to physiology; instead, they are postoperative complications of the cardiac surgery. Regardless of postsurgical complications, TAPVR has two important effects on the gastrointestinal tract. First, the obstructed veins can lead to significant chronic lung disease, which is a known risk factor for poor feeding [25]. Secondly, TAPVR is more commonly associated with the patterning disorders classified as heterotaxy and abnormalities of hepatobiliary and duodenal development. The initial echocardiogram can help provide the diagnosis of heterotaxy as suggested by bilateral superior vena cava, interrupted inferior vena cava with azygous return, transverse position of the liver, and atrial isomerism or inversion.

Single-Ventricle Physiology

There is a heterogeneous group of complex congenital heart abnormalities which are simply not amenable to either primary or staged biventricular repair. The majority of these patients have either inadequate ventricular mass or multiple VSD; they are only candidates for single-ventricle palliation via the Fontan pathway or heart transplant. Long-term gastrointestinal issues in one and a half ventricle palliation are not yet well described.

Patients with ductal-dependent systemic or pulmonary blood flow who are placed on prostacyclin occasionally need surgery for noncardiac congenital disorders, such as obstructing imperforate anus or tracheoesophageal fistula. There is a growing body of data that suggests that these operations are well tolerated on prostacyclin and these congenital disorders do not affect overall mortality or survival to discharge. Patients who have inadequate systemic blood flow are more likely to develop intestinal ischemia and sometimes necrosis. This is a difficult group of patients, as abdominal catastrophes portend a significant mortality, although if systemic oxygen delivery can be improved after management of the ischemia, postoperative survival increases [9, 26–28].

The impact of single-ventricle physiology on the gastrointestinal tract is based on three aspects: (1) manipulation of the aortic arch, (2) amount of pulmonary blood flow, and (3) the amount of continuous arterial shunt versus oscillatory shunt through the ductus arteriosus.

For patients requiring operation on the ventricular outflow tract to achieve adequate systemic perfusion, the postoperative effects on the gastrointestinal tract are similar to those individuals with biventricular physiology who have LVOTO and require repair. Recurrent laryngeal nerve neuropraxia, occurring in ~5 % [9, 26, 27] of Damus-Kaye-Stansel or Norwood-type procedures, can lead to aspiration and inability to safely take oral intake, mandating need for feeding access. With more posterior operations such as repair of aortic arch or coarctation of the aorta, injury to the thoracic duct or vagus nerve can also occur. Vagal neuropraxia appears to lead to esophageal dysfunction, delayed gastric emptying, and significant gastroesophageal reflux. These issues can be much more significant in the single-ventricle patient as they have significantly less reserve, and chronic reflux or aspiration can prevent pulmonary vascular remodeling and lead to persistently elevated pulmonary vascular resistances (PVR).

Pulmonary blood flow has a delicate relationship with feeding in this population of patients. Those patients who do not require palliation in the neonatal period because of apparently balanced pulmonary blood flow are at higher risk of feeding and growth delays because of progressive high-output congestive heart failure as the PVR decreases. Patients who are palliated with a systemic-to-pulmonary artery shunt in the neonatal period will have a different set of complications to consider. Early following the first stage of palliation, neonates are in severe high-output heart failure because the shunt size is too large relative to their weight, which makes feeding and growing difficult. As these children "grow into" their shunt, the overcirculation

improves and feeding/growing becomes easier. Unfortunately, as they start to "grow out of" their shunt, they will develop progressive hypoxia due to decreased pulmonary blood flow, which will also affect feeding and growing. One of the theoretical advantages to a right ventricle-to-pulmonary artery shunt is lack of diastolic runoff, which theoretically may lead to more uniform systemic-to-pulmonary (Qp:Qs) ratios and lessen the impact on feeding and growing. In all cases, decisions about feeding access must be made with a good understanding of what the pulmonary blood flow is expected to progress as the child grows.

During the interstage period, gastrointestinal infection plays an important role in survival. Acute gastroenteritis, leading to dehydration via significant vomiting and diarrhea, can lead to shunt failure and cardiovascular collapse. Overly aggressive resuscitation can lead to pulmonary edema and congestive heart failure, particularly in patients known to have increased risk factors for interstage mortality, such as those presenting with an intact atrial septum or older age prior to their palliation [29]. Furthermore, many of these events occur very rapidly making interstage patients a fragile population. Given these circumstances, more centers are now using interstage monitoring programs to keep track of the patient's weight and oxygen saturations to help reduce interstage mortality [30].

Patients can become remarkably stable once they undergo stage II palliation with a bidirectional Glenn, which results in ventricular unloading and stabilization of saturations. Following this, it may be the optimal time to accomplish definitive management of associated gastrointestinal congenital anomalies. Patients can undergo, with reasonably safe anesthetic risk, repair of cleft lips and palates, resection and pull through for Hirschsprung's disease, posterior sagittal anorectoplasty for imperforate anus, removal of gastrostomy tubes, and take-down of emergently placed stomas for perforation or obstruction. These patients are relatively resilient when they endure the various acute viral gastroenteritides of childhood. By the time of Fontan completion, the main postoperative issue is related to elevated systemic and mesenteric pressures. Chylothorax, ascites, and protein-losing enteropathy (PLE) are the primary sources of post-Fontan morbidity.

Ductal-Dependent Physiology and Feeding

In neonatal patients with ductal-dependent congenital heart disease (CHD), there is no general agreement among critical care providers regarding the safety or risks of preoperative enteral feeding while on continuous prostaglandin (PGE_1) therapy. It is a common practice by many physicians to refrain from feeding a patient who is awaiting surgical palliation while on PGE_1 because of the concern for the development of necrotizing enterocolitis (NEC) secondary to poor bowel perfusion. In one survey of critical care providers, up to 54 % of those surveyed stated that enteral feeds are never started on patients preoperatively, while 37 % reported either sometimes, always, or frequently starting either oral or nasogastric feeds [31, 32]. One small study of 34 neonates with ductal-dependent CHD found that enteral feeding was well tolerated in all but one of the patients regardless of the cardiac defect or ductal-flow pattern and did not seem to be related to the presence of an umbilical arterial or venous catheter [31].

Whether or not a patient is fed, studies have shown that up to 47 % of neonates with CHD who developed NEC had diastolic runoff in the descending/abdominal aorta regardless of gestational age or anatomic type of CHD [33]. Other studies, however, refute the diastolic steal hypothesis by observation of patients with significant left-to-right shunting through the patent ductus arteriosus (PDA) without an associated higher incidence of NEC [27]. Although not all studies agree on the theory of diastolic steal, most conclude the highest risk factors for mesenteric ischemia are (1) earlier initiation of feeds correlating with earlier diagnosis of NEC [34], (2) hypoperfusion or shock from a closing ductus [35], or (3) apnea and hypotension associated with the use of PGE_1

Table 168.2 Ductal-dependent congenital heart lesions associated with persistent retrograde diastolic aortic flow

TAPVR
Coarctation of the aorta
Aortic stenosis
Truncus arteriosus
Ebstein's anomaly

TAPVR total anomalous pulmonary venous return

preoperatively [10, 27, 33]. Lower fasting SMA Doppler velocities in neonates with CHD compared to neonates without CHD may also increase their risk of mesenteric ischemia [36, 37]. Several varieties of ductal-dependent CHD with retrograde diastolic aortic flow are shown in Table 168.2. Until there are more definitive studies indicating the risks and benefits of feeding preoperative patients with ductal-dependent CHD on PGE_1, the decision to provide enteral nutrition preoperatively remains at the discretion of the team caring for the patient.

Heterotaxy Syndrome

Heterotaxy syndrome refers to any patient with abnormal patterning of left-right symmetry. In early descriptions of patterning and handedness, patients with normal left-right patterning were deemed *situs solitus*, or "usual arrangement." Patients with complete inversion of right and left (i.e., mirror image) were referred to as *situs inversus totalis*, or "completely inverse arrangement." The majority of patients with abnormal patterning failed to be completely reversed. These patients, who often had some organs in *solitus* and others in *inversus*, were named situs ambiguus, or "unclear arrangement."

These patients came to the attention of physicians, particularly Bjorn Ivemark, a Swedish pathologist, who, in 1955, coined the term right atrial isomerism after multiple autopsies he performed revealed abnormalities in the segmental arrangement and patterning of the heart. It became increasingly clear that jumbled viscera, especially intra-abdominal organs, frequently accompanied abnormalities of viscero-atrial arrangement. During the 1950s, a pair of syndromes, now often referred to as "asplenia syndrome" and "polysplenia syndrome," represented around 80 % of these patients with mixed patterning abnormalities. Further work at that time noted that many patients with asplenia had right atrial isomerism and those with polysplenia often had left atrial isomerism. Figure 168.1a demonstrates GI findings in asplenia, and Fig. 168.1b demonstrates findings in polysplenia.

Ciliary Dysfunction in Heterotaxy

In heterotaxy patients, there are often abnormalities of cilia function which can result in ramifications for the gastrointestinal tract such as hepatobiliary and pancreaticoduodenal complications. In addition to increased frequency of annular pancreas, duodenal atresia, and preduodenal portal vein, these patients also have higher rates of inspissated bile syndrome and biliary tract obstruction. Several reports have identified perforated gall bladder following complete obstruction of the biliary duct [38].

Additionally, as many of these patients have intestinal malrotation and undergo a Ladd's procedure, the incidence of adhesive small bowel obstruction is twice that of non-heterotaxy patients and is extremely poorly tolerated, leading to operation and bowel resection in up to 75 % of acute obstructions.

Malrotation and Duodenal Disease

Heterotaxy patients have a number of different potential anatomic arrangements of the stomach, small bowel, and colon. For the gut, situs solitus is a left upper quadrant stomach, duodenal *c*-loop that crosses the spine to the right and returns to turn up to a duodenal-jejunal junction that is posterior to the stomach, jejunum that travels inferiorly and posteriorly to the transverse mesocolon, jejunum and ileum that progress from left upper quadrant to right lower quadrant, and colon that continues clockwise around the

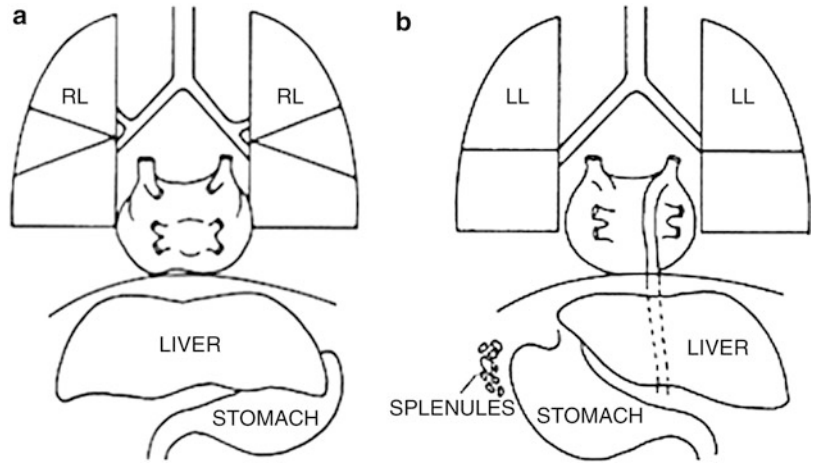

Fig. 168.1 (**a**) Schematic representing the abnormal anatomic features seen with right isomerism (asplenia); *RL* right lung. (**b**) Schematic representing the abnormal anatomic features seen with left isomerism (polysplenia); *LL* left lung

abdomen from right lower quadrant all the way around to the rectum in the pelvis. This arrangement involves a 270° counterclockwise rotation around the superior mesenteric artery. Amazingly, situs inversus totalis is the complete mirror image including the 270° clockwise rotation.

For patients with situs ambiguus, there are several possible anatomic orientations, but most commonly, there are abnormalities of the foregut and midgut. Each of these abnormalities can be screened for by a complete abdominal ultrasound, and if malrotation or other abdominal anomaly is found, a general surgery consult should be considered prior to initiating feeds depending on each institution's preference.

Specific Gastrointestinal Diseases

Necrotizing Enterocolitis and Intestinal Ischemia

Necrotic bowel is a catastrophic situation that occurs as the final common pathway of several distinct disease entities. In all cases, there is clinical deterioration and evidence of an intra-abdominal source. For this reason, these processes are often incorrectly lumped together – both via using denominations interchangeably and also by applying similar treatment plans. It must be emphasized, however, that at the root of these different diseases, there are two main contributing mechanisms. The first is bowel ischemia due to inadequate oxygen delivery which requires emergent intervention to reestablish adequate bowel perfusion, whether by addressing the primary cardiac lesion (LVOTO) or addressing a specific obstructive cause of ischemia (malrotation with volvulus and obstruction of superior mesenteric artery). Conservative therapy will fail because the ischemia will progress to dead bowel. The second main contributing mechanism is not from ischemia but rather inflammation or infection. In these cases, most commonly necrotizing enterocolitis, the inflammation or infection leads to patchy mucosal injury, which may go on to develop congestion, ischemia, full-thickness necrosis, and perforation. In these cases, however, a conservative approach of reducing tissue oxygen demand via bowel rest with gastric drainage and broad spectrum antibiotics to treat infection is often successful. Emergent intervention is only indicated if there is a frank surgical indication: perforation or complete obstruction. Thus, the first step in evaluation of an abdominal catastrophe is to identify ischemic from nonischemic causes [39], which requires a thorough understanding of the underlying cardiac pathology. As discussed above, ischemia can occur following a decrease in systemic blood flow, as occurs at ductal closure in lesions with ductal-dependent systemic blood flow or critical

LVOTO. Ischemia can also occur with adequate blood flow but profound hypoxia, as in *d*-TGA physiology with inadequate mixing. Additionally, ischemia occurs during cardiopulmonary collapse and during periods of cardiogenic shock (from dysrhythmias, cardiac stun, myocardial ischemia, acute valve failure, and other situations). In all of these situations, the bowel ischemia is a symptom, and the primary focus should be on resuscitation and management of the cardiac lesion. Simultaneously, patients should be made nil per os, receive a Salem Sump style gastric drainage tube, have all enteral access (gastrostomy, jejunostomy) placed to gravity, and receive intermittent abdominal films looking for evidence of perforation – specifically, free air. As long as no absolute surgical indication develops (i.e., perforation), continued focus should remain on the cardiac lesion.

In patients without a recent change in cardiac status, acute ischemia is unusual but not impossible. The most common extra-cardiac cause of primary ischemia is acute volvulus. Superior mesenteric artery or aortic thrombosis is rare but can be associated with prolonged use of umbilical arterial lines or primary hypercoagulable states [40–42]. Acute mesenteric ischemia of embolic origin has only been reported in adults. Assessment of the aorta and superior mesenteric artery can be done via Doppler ultrasonography, although without predisposing risk factors, the extremely low pretest probability makes this study unlikely to be useful.

True necrotizing enterocolitis (NEC) is a multifactorial disease process that involves an immature intestinal barrier that is "primed" for mucosal damage by a perinatal or transient hypoxic/ischemic insult. This allows indigenous organisms to breach the damaged mucosa and initiate a cycle of inflammation, worsening mucosal integrity, and increased translocation [43]. Figure 168.2 shows a patient diagnosed with tetralogy of Fallot and pulmonary stenosis who presented with pneumatosis intestinalis after being fed following the closure of the ductus arteriosus. Feeding is a requirement (to facilitate intestinal colonization), and aggressive feeding is a known risk factor for NEC [44]. The timing of NEC is later than ischemia but before a more mature gut flora colonization, suggesting that it is a different group of transient bacteria that may participate in this process. In any event, patients with CHD developing NEC generally are postoperative (palliative or definitive repair), receive an aggressive feeding advancement because they look clinically well, and develop severe sepsis and decompensation with evidence of an abdominal source. This is in stark contrast to primary ischemia as discussed above.

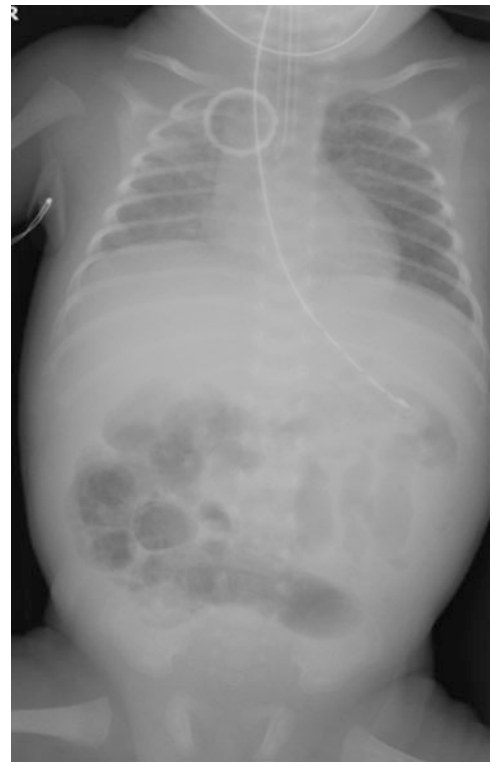

Fig. 168.2 Pneumatosis intestinalis

Necrotizing enterocolitis has a variable clinical picture ranging from very mild to full arrest. Symptoms include feeding intolerance, heme-positive or bloody stools, temperature instability, lethargy, and lability of vitals. Physical exam often shows poor perfusion with mottled skin and central-peripheral temperature gradient. The abdominal exam can range from mild distention to discolored and tense.

Classic laboratory signs include thrombocytopenia, acidosis, and coagulopathy. Plane films of the abdomen in two views are performed looking for evidence of mucosal disease (pneumatosis intestinalis), which can progress to portal venous gas and even perforation (abdominal free air). While a full discussion of the nuances of surgical management is beyond the scope of this chapter, any concern for NEC (or ischemia) should prompt a general surgery consult to determine the frequency of imaging and examination, duration of therapy, and, in the event of perforation or obstruction, the surgical management.

Focal intestinal perforation (FIP, also referred to as single intestinal perforation) generally occurs in a premature newborn with a patent ductus arteriosus. Because of its association with prematurity and perforation, many patients with FIP are classified as one end of the spectrum of NEC. Unlike NEC, however, these patients lack global patchy mucosal disease. Instead, they have a very focal perforation of the terminal ileum, generally a few centimeters from the ileocecal valve. When cases of FIP are selected, independent risk factors for FIP include antenatal steroid administration and cyclooxygenase inhibition for medical closure of PDA. Clinically, patients are usually much more stable with FIP than NEC and lack the intensity of the inflammatory response, and the hallmark finding is massive free air on abdominal film. The current hypothesis is focal dysregulation of distal ileal mucosal blood flow – inhibited by NSAID and steroids, leading to perforation. Like all major abdominal catastrophes, prompt surgical evaluation is mandatory.

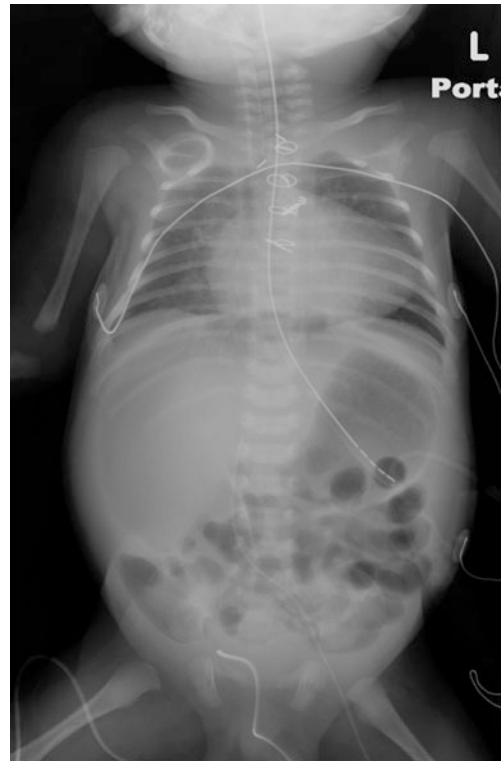

Fig. 168.3 Abdominal free air on KUB (kidney, ureter, bladder) radiograph

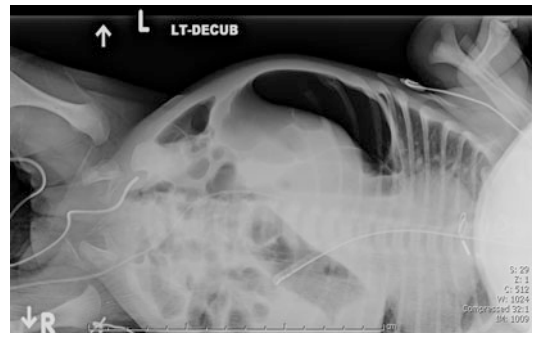

Fig. 168.4 Abdominal free air seen on lateral decubitus radiograph

Abdominal Free Air

Abdominal free air is actually "free gas" as it may not always be the air mixture of 79 % nitrogen and 21 % oxygen. Figures 168.3 and 168.4 demonstrate abdominal free air on kidneys, ureter, and bladder (KUB) and lateral decubitus films.

The most benign source of gas in the abdomen results from a hole in the diaphragm (congenital or iatrogenic). If a congenital diaphragmatic hernia exists without an hernia sac, any open heart operation that violates the pleural space will allow free air to travel through the hernia into the abdominal cavity. Most posterolateral diaphragm hernias (Bochdalek) are identified preoperatively on chest x-ray and, because of

the resulting pulmonary hypoplasia, are considered during operative planning for the cardiac defect. Anterior defects, Morgagni hernias, are usually recognized during operative exposure of the heart. Besides these congenital lesions, because of the limited space in the neonatal costal angle, occasionally mediastinal tubes graze the central tendon and pass through the abdominal cavity. When this occurs, free air can enter the abdomen prior to chest closure. Because these drainage tubes are often placed to suction, most abdominal air will be evacuated reasonably quickly; the remainder will reabsorb over 3–7 days much like free air from laparotomy.

Thoracic operations, particularly reoperations, can be associated with transient air leak from the lung surface. In the event that a congenital or iatrogenic diaphragm hole exists, the leaking air may preferentially drain intra-abdominally. Because of the speed at which postoperative air would be evacuated and the persistence of air in the abdomen in the setting of air leak, the first step in evaluating free abdominal air in the early postoperative period is to evaluate the patient for air leak, ensure all chest drains are unblocked and on suction, and then perform plane films of the chest and abdomen in two views. Generally speaking, in patients with good clinical status, no evidence of ischemia (normal lactate and pH), and an air leak or visible tube traversing the abdomen, there will be minimal suspicion of abdominal catastrophe. Expectant management and utilizing chest tubes to avoid tension physiology will generally allow resolution of the free gas. The late concern of transabdominal mediastinal tube placement is the development of a diaphragmatic or epigastric hernia requiring repair at a later date.

There are times, however, when the clinical status of the patient is questionable or worsening, and it is impossible to discern free gas from the causes above from hollow viscus perforation. In this case, there is generally simultaneous decline in cardiopulmonary function and evidence of abdominal catastrophe. Because these situations can result from both ischemic and nonischemic causes as discussed above, it is imperative that surgeons, cardiologists, and intensivists work together to ensure both cardiac function and abdominal disease are appropriately addressed. An ischemic bowel that perforates can be resected, but unless the cause of the ischemia is addressed, the outcome will be poor. Cardiac function can be supported during an episode of necrotizing enterocolitis, but without broad spectrum antibiotics and bowel rest, patients will succumb to progressive sepsis and disseminated intravascular coagulation.

Gastroesophageal Reflux

Adults and children have physiologic reflux that helps stimulate the esophagus to clear esophageal contents and facilitate evacuation of intragastric (swallowed) air. From birth until approximately 6 months of age, the esophagus has minimal intra-abdominal length, and therefore, neonates have greater reflux than infants who have more than toddlers. Teleologically, this can be explained by the need to evacuate significant gastric air from crying as neonates and infants have greater parasympathetic tone and are less tolerant of acute gastric distention. Severe reflux is associated with failure to thrive, apparent life-threatening events, increased airway reactivity by both reflux-mediated aspiration and parasympathetic reflex, laryngospasm and edema, exacerbation of chronic lung disease, aspiration pneumonias, interstitial pulmonary disease, and persistent pulmonary hypertension.

A number of different methods have been utilized to assess degree of reflux. Upper gastrointestinal fluoroscopy can demonstrate anatomic abnormalities associated with reflux, such as intrathoracic stomach, as well as functional abnormalities like poor esophageal motility and actual episodes of visualized reflux. Unfortunately, this study is limited by its short duration and the unpredictable nature of reflux. Gastric scintigraphy, a longer study, has slightly better predictive value than fluoroscopy but is still limited by averaging during the study. Excessive reflux can lead to an interpretation of delayed gastric emptying, and gastric outlet obstruction can minimize readings of reflux. In adults and

increasingly in children, pH probe is being used to standardize the diagnosis of GER. Although adults have [45, 46] standardized pH probe placement to 5 cm above the manometrically determined gastroesophageal sphincter, it has been difficult to standardize pH placement in children and impossible in infants because of the rapid change in sphincter location, esophageal length, and sphincter function. Different techniques have been tried including radiologic placement using the diaphragm, measurements using crown rump length, and even manometry; however, a pediatric and neonatal gold standard study is still lacking.

Nearly all patients who undergo distal aortic arch manipulation (especially coarctation and hypoplastic arch) vagal dysfunction, likely a neuropraxia due to moving the nerve out of develop at least a transient the way during operation. When significant vagal nerve dysfunction is present, patients manifest not only reflux but poor esophageal motility, proximal reflux, and significant delayed gastric emptying. Fortunately, rates of significant nerve dysfunction are low, estimated in the same range as recurrent laryngeal nerve or phrenic nerve injury, between 1 % and 5 %. In general, this transient reflux can be managed conservatively and resolves in 2–6 weeks.

Patients with single ventricles who require reconstruction of the ventricular outflow tract and arch (i.e., true Norwood procedure) have similar transient vagal dysfunction. In these patients, radiologic reflux is associated with failure to survive to bidirectional Glenn [28]. One hypothesis is that chronic reflux leads to persistently elevated pulmonary vascular resistance due to aspiration pneumonitis and pneumonia with pulmonary sepsis. Fortunately, the majority of these are transient neuropraxia which can be resolved with medical management or low-risk nasojejunal feeding. Several centers have achieved anti-reflux procedural mortality under 5 %; nevertheless, there is not yet a good method to identify which patients will have improved survival with fundoplication.

There is a very unique situation in these patients that deserves mention. Failure to survive to stage II palliation (cavopulmonary shunt/bidirectional Glenn) is increased in patients with severe GER, likely due to a combination of aspiration pneumonitis and elevated PVR which can lead to progressive cyanosis, which may be misinterpreted as shunt obstruction. These patients may undergo many negative evaluations for shunt obstruction via repeated echocardiograms or cardiac catheterization or may be subject to another operation to either upsize or place a second shunt to increase pulmonary blood flow, when in fact, the etiology is severe reflux. Rather than undergoing multiple shunt revisions or early bidirectional Glenn, these patients could benefit from aggressive control of reflux. Attempts to perform anti-reflux surgery after stage II palliation in the authors' institution have had unacceptably high mortality (three of four attempts died), as opposed to early fundoplication which has mortalities from 3 % to 8 % in skilled hands [28].

Protein-Losing Enteropathy After Fontan Operation

Protein-losing enteropathy (PLE) is defined as the abnormal loss of serum proteins into the lumen of the gastrointestinal (GI) tract. It is reported to occur in anywhere from 1 % to 15 % of patients who have received a Fontan operation [47, 48]. The onset of PLE after Fontan is reported to range from 2 months to 16.4 years, with a mean of about 2–3 years [47, 49]. It results in significant morbidity and mortality to the patient, with a reported 5-year survival rate of 50 % after onset of diagnosis [47, 49].

The diagnosis is suspected when patients present with symptoms of diarrhea, weight gain, and increased abdominal girth from peripheral edema and ascites. Often, GI symptoms such as abdominal pain and even diarrhea may not be present and the only symptoms are secondary to fluid accumulation that results from a low intravascular oncotic pressure due to the loss of serum proteins into the GI tract. Other clinical signs and symptoms may include breathing difficulties from pleural/pericardial effusions, failure to

thrive and short stature, and muscle tetany (secondary to low serum calcium). There are reports of acquired immunodeficiency associated with PLE post-Fontan [50, 51] as lymphocytes and immunoglobulins are also lost into the intestine. GI bleeding, where all testing failed to demonstrate GI pathology as a source of the bleeding, has also been reported [52]. Diagnosis is made by demonstrating low levels of serum albumin (<3.5 g/dL) and serum protein (<5.5 g/dL), as well as increased wasting of protein in the GI tract measured by an elevated stool alpha-1-antitrypsin. Primary renal disease (nephrotic syndrome) as well as hepatic disease should be ruled out.

The pathophysiology of PLE after Fontan remains uncertain. PLE is usually seen in primary GI disease, such as Crohn's disease, with an inflammatory component, as well as in primary diseases of the lymphatic system such as intestinal lymphangiectasia. Why it occurs following Fontan operation remains poorly understood although a few studies have been aimed at trying to understand the pathophysiologic mechanisms. The presence of elevated systemic venous pressure leading to lymphatic and vascular engorgement and subsequent protein loss into the GI lumen is the most prevalent theory, although a direct association between elevated systemic venous pressure and PLE has not been found [47]. In their international, multicenter study of PLE after Fontan, Mertens et al. found that although patients with Fontan had elevated systemic venous pressures compared to patients with two-ventricle physiology, it was not significantly different in patients with PLE versus those who did not develop PLE. They did however find that patients after Fontan had low cardiac output, with those with PLE having even lower cardiac output [47]. In 2002, Rychik et al. demonstrated that mesenteric vascular resistance (MVR) was elevated in patients after Fontan and that patients with PLE had increased MVR compared to those without PLE. They postulated that low cardiac output after Fontan leads to elevated MVR and subsequent mesenteric hypoperfusion, contributing to the development of PLE [53]. PLE after Fontan is also thought to have an inflammatory component as it does respond to steroid treatment. In their study of 62 patients post-Fontan, Ostrow et al. found that these patients had elevated C-reactive protein (CRP) and one third had elevated tumor necrosis factor alpha (TNF-a), but these levels were not significantly more elevated in patients with PLE [54]. The authors felt that the number of patients they had with PLE (7 of a total of 62) was too small to see a significant trend. Studies on an in vitro model of PLE by Freeze et al. have shown that there is greater albumin flux across a monolayer of intestinal mucosal cells when it is treated with TNF-a and heparanase (to digest heparan sulfate) and that this increase is additive [55]. So Rychik, in his review article in 2006, postulates that the mechanism for developing PLE post-Fontan involves a low cardiac output that results in increased MVR, causing hypoperfusion of the intestine, subsequent inflammation, and loss of intestinal mucosal integrity, leading to protein loss.

Treatment options of this condition are shown in Table 168.3 and depend upon the severity of hypoalbuminemia and the patient's symptoms. In mild cases, the symptoms can be controlled with a high protein diet, containing medium chain fats (MCT) and diuretics (spironolactone and furosemide). Intermittent intravenous infusions (IV) of 25 % albumin followed by IV furosemide will also control symptoms for a short period of time but do not resolve the underlying problems. Treatment with heparin (5,000 units/m^2 subcutaneously) has been effective in some more moderate to severe cases [56]. Systemic corticosteroids are also effective in moderate to severe disease at a dose of 1–2 mg/kg/day orally [57]. Intravenous administration may be necessary in cases where the intestine is too edematous to be able to absorb oral prednisone, with subsequent transition to oral prednisone once symptoms improve. Sildenafil, at a starting dose of 0.5 mg/kg/dose four times a day, has also been used in patients with satisfactory Fontan pathways and baseline hemodynamics, but when signs of increased pulmonary and mesenteric and vascular resistance are noted [58]. Occasionally, if malabsorption is severe, patients may

Table 168.3 Management options of PLE

Mild	Moderate	Severe
High protein diet with MCT 25 % albumin IV	Heparin (5,000 U/m^2 SQ)	Systemic steroids
IV diuretics	Sildenafil (0.5 mg/kg/dose qid)	Bowel rest/TPN
		Transcatheter Fontan fenestration Surgical revision of Fontan
		Cardiac transplantation

MCT medium chain triglycerides, *IV* intravenous, *SQ* subcutaneous, *mg* milligram, *kg* kilogram, *qid* four times a day, *TPN* total parental nutrition

benefit from bowel rest and total parenteral nutrition (TPN) to replenish the electrolytes and protein that are being lost in the gut. Interventional treatment is reserved for severe cases and usually consists of transcatheter Fontan fenestration or surgical revision. Cardiac transplantation has also been reported to successfully resolve the PLE but is considered a last resort option for treatment [59].

Liver Disease

Ischemic hepatitis, also known as shock liver, results from acute hypoperfusion of the liver [60]. It presents with marked elevation of serum alanine aminotransferase (ALT), aspartate aminotransferase (AST), and lactate dehydrogenase (LDH) and has been reported in children post cardiac surgery [61–63]. These patients may also have hepatomegaly, jaundice/conjugated hyperbilirubinemia, and coagulopathy, consistent with acute liver failure. The pathophysiology is thought to result from a marked reduction in blood pressure, leading to hepatic hypoperfusion and hepatocyte injury. Seeto et al. investigated the pathogenesis of ischemic hepatitis and found that in their series of patients, those who developed the condition all had underlying organic heart disease. They postulate that these patients with underlying cardiac disease had decreased cardiac output leading to hepatic congestion that may predispose the liver to injury precipitated by hypotension [64]. AST and ALT become elevated in the perioperative period after cardiac surgery, usually within the first 48 h. Shteyer et al. retrospectively reviewed the charts of 384 children post cardiac surgery over a 10-year period and found that 11.9 % of them had elevated transaminases, with extreme AST and ALT elevations (>20× normal) found in about 3–5 %. They also found that elevated transaminases were primarily found in those with right-sided heart dysfunction (TOF, DORV) and that there was a significant increase in the overall mortality of patients with extreme transaminase elevation [62]. Despite the fairly classic presentation, it is important to rule out other possible underlying causes of liver disease (infectious, metabolic, toxic, autoimmune). It is also important to rule out other syndromes that may encompass both abnormalities of the heart and the liver such as Alagille syndrome and congenital biliary atresia. Treatment is supportive and is aimed at maximizing cardiac output and improving blood flow to the liver. Prognosis is usually dependent on the severity of the underlying cardiac condition.

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