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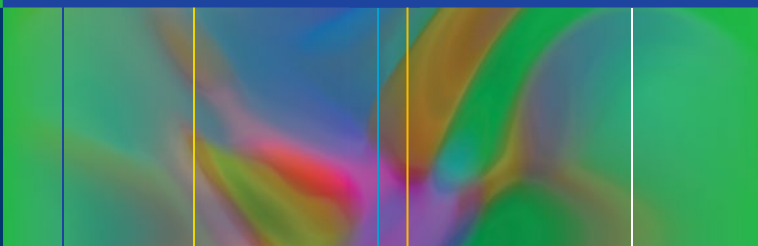

The SAGES Manual of Pediatric Minimally Invasive Surgery

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Preface

…find though she be but little, she is fierce.—Shakespeare

More than once pediatric surgeons have heard general surgeons comment on their "fear" of caring for pediatric surgical patients. The diminutive size of the patient can intimidate, but those of us flourishing in the pediatric world recognize a well-kept secret—infants and children are fierce in their desire to live, handling the surgical insults that would cause many adults to give out, with determination of sometimes Olympic proportions. While they tolerate large incisions for invasive procedures with aplomb, showing their scars as badges of courage on the playground, we believe our kids deserve to reap the same benefits from minimally invasive techniques that the adult population embraces. This book was developed to help current and future surgeons in advancing their comfort in approaching children with laparoscopy, thoracoscopy, and endoscopy.

The mission of the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) is to improve patient care through education, research, innovation, and leadership, principally in gastrointestinal endoscopic surgery. The pediatric surgery community within SAGES has been grateful that the leadership of SAGES has recognized the need to apply this mission to not only the adult general surgical population but to all patients, including our youngest and smallest. It is with this in mind that these authors set out to educate *ALL* surgeons, not just pediatric specialists, in the applications of minimally invasive surgery to children through this textbook.

The focus of this text is on the technical knowhow of these minimally invasive techniques. There are larger resources for detailed information on pathophysiology and others reviewing each and every alternative technique for managing a particular disorder. However, this publication is for providing a safe way of technically approaching a particular problem utilizing percutaneous or per-orifice methods in a concise compendium. It is appropriate for the trained professional looking for a refresher on a less commonly performed intervention, an adult MIS surgeon with a pediatric emergency unable to be transferred, or a surgical student or resident in need of critical teaching points for understanding.

This coeditor team greatly appreciates the support we have received from SAGES and Springer in making this endeavor come to fruition. We applaud the authors, colleagues, staff, families, and patients who contributed to this book through either time, effort, patience, or use of their surgical journey to build the knowledge and content within these pages. It is our hope that many a student of surgery will benefit from the herein pearls of wisdom as they endeavor to improve the care of a pediatric surgical patient.

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1. Physiologic Considerations for Minimally Invasive Surgery in Infants and Children

Brian T. Craig and Gretchen Purcell Jackson

Introduction

Laparoscopy and thoracoscopy have gained widespread acceptance in the surgical approach to infants and children. Minimally invasive procedures are routinely performed and often considered the standard of care for common pediatric operations, such as appendectomy, pyloromyotomy, and fundoplication. Many pediatric surgeons employ laparoscopy or thoracoscopy for advanced procedures including operations for duodenal atresia, malrotation, anorectal malformations, Hirschsprung's disease, congenital diaphragmatic hernia, and tracheoesophageal fistula [1, 2]. Additionally, there are case reports of minimally invasive pancreatectomy, hepatectomy, and resections for neuroblastoma and Wilms tumor in children. The general trend in pediatric surgical practice has been increased adoption of minimally invasive approaches.

Safe application of minimally invasive surgery in pediatric patients necessitates a thorough understanding of the physiologic effects of carbon dioxide (CO_2) insufflation in this population. Regardless of the operation being performed, two main effects produce the physiological consequences of insufflation: (1) increased intra-abdominal or intrathoracic pressure and (2) CO_2 absorption through the visceral and parietal peritoneum (Fig. 1.1). One series reported a 7 % rate of needing to stop insufflation either transiently or permanently for children undergoing laparoscopy [3, 4]. Patients who had insufflation-related incidents and needed the procedure halted were younger with lower immediate preoperative body temperature, and the operations were longer and had higher

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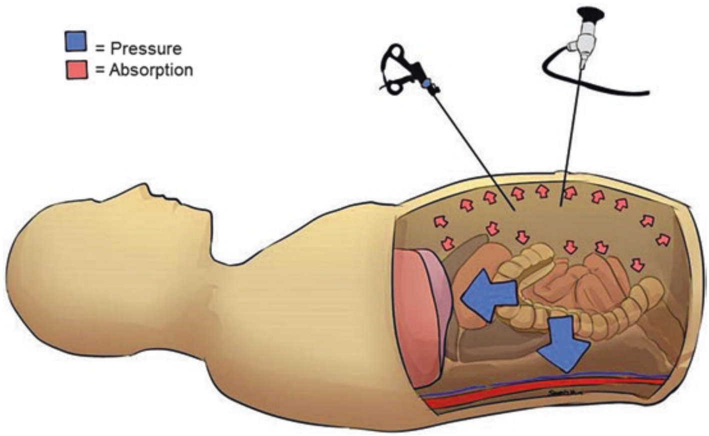

Fig. 1.1. Two major stimuli produce the observed physiologic changes during abdominal insufflation for laparoscopy: (1) increased intra-abdominal pressure (*blue arrows*), which impedes full lung expansion and can decrease flow through the aorta and vascular system, and (2) enhanced CO_2 absorption (*red arrows*) by the visceral and parietal peritoneum, which increases the necessary minute ventilation to maintain acid-base balance. Figure courtesy of Sarah Hua.

insufflation pressures. Therefore, during minimally invasive operations, pediatric surgeons and anesthesiologists frequently contend with acute physiologic changes from abdominal or thoracic insufflation that may significantly change the course of the procedure. They should anticipate such changes and be prepared to manage them.

This chapter describes the effects of abdominal and thoracic insufflation on the cardiovascular, pulmonary, metabolic, and immune/inflammatory systems, with a special emphasis on neonates and infants, as these patients differ significantly from adults and older children both anatomically and physiologically. General principles for preoperative preparation and postoperative care are addressed. Physiologic sequelae of abdominal insufflation are discussed in context of the organ systems affected.

Preoperative Evaluation

As with any pediatric or neonatal operation, general fitness for a planned minimally invasive operation is of paramount importance. Appropriate history related to nutritional status and growth should be obtained for every patient, and any symptoms or signs that could suggest cardiac or pulmonary impairment must be elicited. Anesthetic management plans need to be carefully formulated, especially in neonatal cases with extended procedures, reverse Trendelenburg positioning, and higher insufflation pressures [5]. General endotracheal anesthesia remains the standard for pediatric laparoscopic and thoracoscopic operations to allow the anesthesiologist to contend with the physiologic effects of hypercarbia and increased intra-abdominal or intrathoracic pressures [2].

Several specific comorbidities warrant special consideration in preoperative planning. Minimally invasive procedures are increasingly being performed in infants with congenital heart disease. These patients may be more susceptible to changes in preload due to impaired venous return or changes in systemic resistance associated with increased intra-abdominal pressure [6]. Laparoscopic and thoracoscopic operations can be done safely in these patients in experienced centers with dedicated pediatric cardiac anesthesia teams [6–8].

Underlying pulmonary disease is another important comorbidity to consider before undertaking a minimally invasive procedure in a child. Excretion of excess CO_2 that is absorbed through the visceral and parietal peritoneum is a primary concern of the anesthesiologist managing the infant undergoing laparoscopic or thoracoscopic surgery. Increasing minute ventilation is the primary tool used to remove excess CO_2. Any pulmonary condition that may limit the ability to increase minute ventilation or impair gas exchange could rapidly lead to a respiratory acidosis. If laparoscopy is to be undertaken in a patient with baseline pulmonary dysfunction, intensive postoperative monitoring should be utilized to limit risks of hypoventilation from retained hypercarbia. A related problem is portal hypertension, which has been shown to accelerate absorption of CO_2 to a level twice that of the already increased absorption displayed in children [9]. Similar to the patient with pulmonary disease, patients with portal hypertension should be managed with increased vigilance to limit the negative effects of hypercarbia in the postoperative period.

Physiologic Effects of Pneumoperitoneum by System

Cardiovascular System

Several studies have examined the cardiovascular effects of pneumoperitoneum in children. Direct measurement of flow in the thoracic aorta by transesophageal echocardiography (TEE) in healthy 6- to 30-month-old infants and children undergoing laparoscopic assisted orchiopexy for undescended testicles with a maximum insufflation pressure of 10 mmHg showed significantly decreased flow, decreased stroke volume, and increased systemic resistance. However, these changes resolved completely after desufflation of the abdominal cavity. Significant changes in mean arterial pressure (MAP) or end-tidal CO_2 were not observed during these relatively short procedures, nor were any clinically important sequelae [10]. In another study of healthy 2- to 6-year-old children undergoing laparoscopic inguinal herniorrhaphy, an initial insufflation to an abdominal pressure of 12 mmHg decreased cardiac index (CI) as measured by TEE [11]. Interestingly, CI returned to baseline with a decrease in insufflation pressure to 6 mmHg and did not decrease with a subsequent increase in abdominal pressure to 12 mmHg, suggesting an adaptation to the change in afterload induced by abdominal insufflation. A recent study exposed neonatal and adolescent piglets to 180 min of abdominal insufflation, which caused a decrease in CI and MAP that persisted well into the recovery period after insufflation ended. This effect was more pronounced in the neonates [12]. The extended response to the pressure stimulus suggests a need for vigilant monitoring in the postoperative period to ensure that hypotension does not ensue. Prolonged exposure to higher insufflation pressures (>8–10 mmHg) may also induce capillary microcirculatory changes and impair venous return [1]. In contrast, a study using low-pressure insufflation no greater than 5 mmHg combined with reverse Trendelenburg positioning in children ages 6 to 36 months undergoing laparoscopic fundoplication actually increased CI, heart rate, and MAP [13].

In summary, in the otherwise healthy infant or child, abdominal insufflation pressures of 12 mmHg or less for short- to medium-length procedures may cause changes in CI, MAP, or systemic resistance when specifically measured but rarely (3.2 % of cases) produce clinically significant effects requiring intervention [4]. The location of monitoring may not affect the accuracy of blood pressure measurements. In a piglet model, no difference was found between measured carotid and femoral arterial blood pressures with up to 24 mmHg abdominal insufflation, a level nearly twice that of the highest commonly used clinically [14].

Pulmonary System

The pulmonary effects of pneumoperitoneum in pediatric patients are the result of anatomic and physiologic differences between adults and children. The alveolar surface area to body surface area ratio in infants and children is smaller than that of adults. Therefore, children have a significantly higher minute ventilation and oxygen consumption (up to twice that of an adult) *even at baseline* to maintain $PaCO_2$ in the normal range [1]. In patients younger than 1 year of age, the space-occupying effects of abdominal insufflation lead to increased peak inspiratory pressure, reduced tidal volume, and decreased compliance [15]. These changes in turn produce decreased functional residual capacity (FRC), increased pulmonary vascular resistance, and increased shunt fraction, which in combination with the increased CO_2 absorption can lead to hypercarbia if the minute ventilation is not increased concomitantly [15].

Hypercapnia is a significant concern in minimally invasive surgery, especially in children with underlying pulmonary disease. In one series of laparoscopic and thoracoscopic procedures performed in neonates (i.e., <1 month of age), hypercapnia >45 mmHg was reported in 2.3 % of cases [4]. The degree of hypercapnia depends on insufflation pressure and duration of pneumoperitoneum. In piglet models, $PaCO_2$ has been shown to increase 25 % with stepwise increases in insufflation pressure with associated increases in mortality from CO_2 embolism [16]. In a study of low-pressure (i.e., maximum 5 mmHg) insufflation for fundoplication, CO_2 rose 28 % on average when patients up to 3 years of age were exposed for more than an hour [17]. Careful monitoring for hypercapnia is warranted for all pediatric minimally invasive procedures, and laparoscopic insufflation pressures should be limited, with a maximum recommended pressure of 12 mmHg for neonates [15].

An important consideration for respiratory monitoring is that a gradient will develop between the $PaCO_2$ and the end-tidal CO_2 after abdominal insufflation because of an increased CO_2 and diminished functional residual volume. This gradient has been documented to increase significantly in adults during the first 60 min of insufflation for laparoscopic colorectal surgery but to stabilize or decrease thereafter [18]. In young children with cyanotic congenital heart disease undergoing laparoscopic fundoplication, the gradient increased by a factor of nearly 2.5 soon after initial insufflation of the abdomen [19]. This gradient was shown to be as high as 8 mmHg in one study of laparoscopic fundoplication in children without underlying cardiac or respiratory disease; as in other studies, the gradient decreased with longer insufflation stimulus [20]. Measuring CO_2 elimination has also been used to monitor this process. End-tidal CO_2 increases disproportionately for younger patients compared to older children with the same insufflation pressures and duration, and it remains elevated even after the conclusion of the procedure [15]. For these reasons, postoperative monitoring of respiratory rate is critical to safely performing laparoscopy in infants and neonates.

Another potential problem in infants undergoing laparoscopy is hypoxemia. In neonates and infants, there is a close relationship between functional residual capacity (FRC) and airway closing pressure. When FRC decreases in response to the increased intra-abdominal pressure, airway closure will exacerbate right-to-left intrapulmonary shunt and can lead to hypoxemia [5].

Inflammatory/Immune System

In children, data from a study of procedures for acute abdominal pain suggested that laparoscopic compared to open operations did not result in differences in major inflammatory mediators such as cortisol and IL-6 [21]. However, several subsequent studies have demonstrated a lesser degree of increase in inflammatory mediators including IL-6, CRP, TNF-α, and cortisol with laparoscopy compared to open approach for a variety of operations [22–25]. Cellular responses are also affected by laparoscopy, in a manner similar to the cytokine responses. Both macrophages and neutrophils are recruited to the peritoneal cavity with insufflation, though the numbers are lower with CO_2 insufflation compared to air [26].

Other

Compared with adults, children have a greater body surface area to volume ratio [27] and thus are at increased risk for hypothermia. During minimally invasive surgical procedures in infants and children, hypothermia is reported to occur in 1.8 % of cases [4]. Temperature monitoring is especially important in newborns. Dry CO_2 insufflation on continuous flow of 5–8 L/min will lead to massive evaporative losses relative to body size, and the accompanying heat loss can approach 40 % of a neonate's metabolic power capacity, despite their higher-per-kilogram power capacity compared to adults [3]. Additionally, gas leaks around port sites in a neonate can result in a much greater loss of insufflation gas, thereby requiring higher flow rates and potentially exacerbating hypothermia if non-humidified CO_2 is used.

Reversible anuria during laparoscopy is a consistent observation in the literature, occurring in 88 % of neonates and 14 % in older children. Up to one-third of older children will experience oliguria [28]. Interestingly, these decreases in urine output are not responsive to volume challenge and do not reflect decreases in renal blood flow. Thus, intraoperative fluid resuscitation during laparoscopic procedures should not be governed by urine output alone.

Finally, potential catastrophic events can occur during laparoscopy, and some of these severe complications may be more likely in children. Venous air embolism due to cannulation and insufflation of a patent umbilical vein has been reported in several instances and has sometimes led to cardiac arrest [1]. CO_2 pneumothorax is another rare complication that has been reported in children. In one case, it was discovered at the end of the procedure when the infant did not resume spontaneous respirations with reversal of anesthesia, although the child eventually recovered with no reported long-term effects [29].

Thoracoscopic Surgery Considerations

Many of the major pediatric thoracic operations have been performed thoracoscopically, including resection for congenital pulmonary airway malformation, repair of congenital diaphragmatic hernia, and repair of esophageal atresia with and without concomitant tracheoesophageal fistula [1]. Thoracoscopy is routinely employed in pediatric surgical practice for other procedures such as decortication, sympathectomy, and lung biopsies or resections. A knowledge of the physiology of minimally invasive chest procedures is essential for their safe application.

Two potential effects of thoracoscopic surgery merit consideration. First, single-lung ventilation produces ventilation/ perfusion (V/Q) mismatch, which is most pronounced in neonates. Several factors make neonates particularly susceptible to V/Q mismatch: a narrower window between FRC and residual volume, a compliant chest wall, a lateral decubitus positioning, and a neuromuscular blockade [5]. The end result is hypoxia.

Second, there is a widely held belief that CO_2 absorption is greater during thoracoscopy compared to laparoscopy, which could lead to metabolic acidosis, as reported during congenital diaphragmatic hernia repair [1]. In support of this hypothesis, end-tidal CO_2 has been shown to increase significantly after chest insufflation and persist after desufflation, and these changes are greater in younger patients and larger than those observed during laparoscopy [30]. The data on these two responses are far from conclusive, and more work is needed to identify specific situations that will produce clinically important changes in CO_2 level and acid-base status.

Postoperative Care

The most important consideration in the postoperative care of children undergoing minimally invasive procedures is respiratory monitoring in the first several hours after abdominal desufflation, when residual hypercarbia may be present and the potential for hypoventilation persists. This risk is especially important in neonates, infants, and young children, and we recommend these patients be monitored with continuous pulse oximetry for at least the first several hours after laparoscopy. Further work will be needed to accurately determine if a predefined, mandatory length of stay in the anesthesia recovery area or in a monitored hospital unit is necessary to prevent life-threatening hypoventilation.

Summary

- Laparoscopy is physiologically safe and effective approach in pediatric patients of all ages and for many pediatric abdominal surgical procedures.
- Increased intra-abdominal pressure leading to impaired pulmonary mechanics and increased CO_2 absorption are the two primary stimuli that lead to the array of physiologic sequelae during and after laparoscopy.
- Cardiac index, mean arterial pressure, and aortic blood flow decrease during abdominal insufflation but rarely with important clinical consequences.
- Increased minute ventilation must be achieved during minimally invasive surgery, especially in neonates, to prevent hypercarbia and subsequent acidosis.
- Reversible anuria and oliguria occur with laparoscopy, and this effect is more pronounced in younger patients.
- Increases in inflammatory mediators and cellular responses are decreased during laparoscopic compared to open operations in children.
- Vigilant postoperative monitoring for neonates should be employed as CO_2 retention may persist after abdominal desufflation.

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2. Pediatric Laparoscopic and Thoracoscopic Instrumentation

Sarah Gilmore and Colin A. Martin

Early Experience

Pediatric minimally invasive surgery (MIS) has lagged behind its adult counterpart. In 1973, a report in the Journal of Pediatric Surgery by Gans and Berci described 16 early laparoscopic pediatric cases [1]. These early advances were possible in part by the Hopkins rod-lens optical system (Fig. 2.1). However, widespread adoption of pediatric laparoscopy was initially met with criticism. The first adult laparoscopic cholecystectomy was performed in 1985 [2] and was widely regarded as experimental and dangerous. There has been no single procedure that has propelled the advance of MIS in pediatric patients the way laparoscopic cholecystectomies did with adult MIS. Training modules for teaching laparoscopic cholecystectomy to adult surgeons were not well suited for teaching the advanced skills required for pediatric surgery [3]. This procedure was not considered standard of care in pediatrics until many years later. However, great strides have been made within the last 20 years. Today, it is common practice for neonates to undergo minimally invasive surgery. A study conducted by Rothenberg et al. over a 51-month period with 183 infants weighing 1.3–5.0 kg who underwent 195 procedures using minimally invasive techniques “demonstrates that advanced endosurgical techniques in infants is safe, effective, and associated with the same benefit as that seen in older patients” [4].

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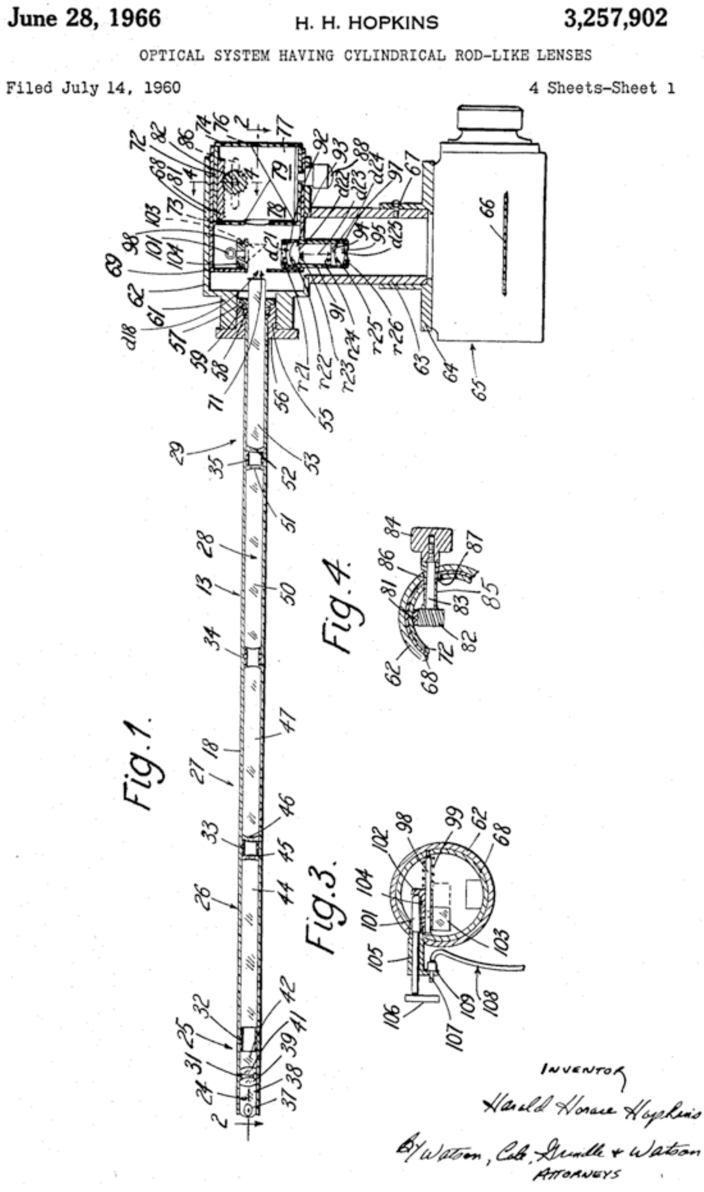

Fig. 2.1. Hopkins rod-lens optical system.