CHAPTER 42

Pediatric Anesthesia

KEY CONCEPTS

1. Neonates and infants have fewer and smaller alveoli, reducing lung compliance; in contrast, their cartilaginous rib cage makes their chest wall very compliant. The combination of these two characteristics promotes chest wall collapse during inspiration and relatively low residual lung volumes at expiration. The resulting decrease in functional residual capacity (FRC) limits oxygen reserves during periods of apnea (eg, intubation attempts) and readily predisposes them to atelectasis and hypoxemia.
2. Compared with older children and adults, neonates and infants have a proportionately larger head and tongue, narrower nasal passages, an anterior and cephalad larynx, a longer epiglottis, and a shorter trachea and neck. These anatomic features make neonates and infants obligate nasal breathers until about 5 months of age. The cricoid cartilage is the narrowest point of the airway in children younger than 5 years of age.
3. Cardiac stroke volume is relatively fixed by a noncompliant and immature left ventricle in neonates and infants. The cardiac output is therefore very sensitive to changes in heart rate.
4. Thin skin, low fat content, and a greater surface area relative to weight promote greater heat loss to the environment in neonates. Heat loss is compounded by cold operating rooms, wound exposure, intravenous fluid administration, dry anesthetic gases, and the direct effect of anesthetic agents on temperature regulation. Hypothermia has been associated with delayed awakening from anesthesia, cardiac irritability, respiratory depression, increased pulmonary vascular resistance, and altered drug responses.
5. Neonates, infants, and young children have relatively greater alveolar ventilation and reduced FRC compared with older children and adults even after adjustment for weight. This greater minute ventilation-to-FRC ratio with relatively greater blood flow to vessel-rich organs contributes to a rapid increase in alveolar anesthetic concentration and speeds inhalation induction.
6. Minimum alveolar concentration (MAC) for halogenated agents is greater in infants than in neonates and adults. Unlike other agents, sevoflurane has the same MAC in neonates and infants. Sevoflurane appears to have a greater therapeutic index than halothane and has become the preferred agent for inhaled induction in pediatric anesthesia.
7. Children are more susceptible than adults to cardiac arrhythmias, hyperkalemia, rhabdomyolysis, myoglobinemia, masseter spasm, and malignant hyperthermia associated with succinylcholine. When a child experiences cardiac arrest following administration of succinylcholine, immediate

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treatment for hyperkalemia should be instituted.

8. Unlike adults, children may have profound bradycardia and sinus node arrest following the first dose of succinylcholine without atropine pretreatment.
9. A viral infection within 2–4 weeks before general anesthesia and endotracheal intubation appears to place the child at an increased risk for perioperative pulmonary complications, such as wheezing, laryngospasm, hypoxemia, and atelectasis.
10. Temperature must be closely monitored in pediatric patients because of their greater risk for malignant hyperthermia and the potential for both iatrogenic hypothermia and hyperthermia.
11. Meticulous attention to fluid intake and loss is required in younger pediatric patients because these patients have limited margins of error. A programmable infusion pump or a buret with a microdrip chamber is useful for accurate measurements. Drugs can be flushed through low dead-space tubing to minimize unnecessary fluid administration.
12. Laryngospasm can usually be avoided by extubating the patient either while awake or while deeply anesthetized; both techniques have advocates. Extubation during the interval between these extremes, however, is generally recognized as more hazardous.
13. Patients with scoliosis due to muscular dystrophy are predisposed to malignant hypertension, cardiac arrhythmias, and untoward effects of succinylcholine (hyperkalemia, myoglobinuria, and sustained muscular contractures).

Pediatric anesthesia involves more than simply adjusting drug doses and equipment for smaller patients. Neonates (0–1 months), infants (1–12 months), toddlers (12–24 months), and young children (2–12 years of age) have differing anesthetic requirements. Safe anesthetic management depends on full appreciation of the physiological, anatomic, and pharmacological characteristics of each group (Table 42–1). Indeed infants are at much greater risk of anesthetic morbidity and mortality than older children; risk is generally inversely proportional to age. In addition, pediatric patients are prone to illnesses that require unique surgical and anesthetic strategies.

ANATOMIC & PHYSIOLOGICAL DEVELOPMENT

Respiratory System

The transition from fetal to neonatal physiology is reviewed in Chapter 40. Compared with older children and adults, neonates and infants have weaker intercostal muscles and weaker diaphragms (due to a paucity of type I fibers) and less efficient ventilation, more horizontal and pliable ribs, and protuberant abdomens. Respiratory rate is increased in neonates and gradually falls to adult values by adolescence. Tidal volume and dead space per kilogram are nearly constant during development. The presence of fewer, smaller airways produces increased airway resistance. The alveoli are fully mature by late childhood (about 8 years of age). The work of breathing is increased and respiratory muscles easily fatigue.

1. Neonates and infants have fewer and smaller alveoli, reducing lung compliance; in contrast, their cartilaginous rib cage makes their chest wall very compliant. The combination of these two characteristics promotes chest wall collapse during inspiration and relatively low residual lung volumes at expiration. The resulting decrease in functional residual capacity (FRC) limits oxygen reserves during periods of apnea (eg, intubation attempts) and readily predisposes neonates and infants to atelectasis and hypoxemia. This may be exaggerated by their

TABLE 42–1 Characteristics of neonates and infants that differentiate them from adult patients.[1]

Physiological
Heart-rate-dependent cardiac output
Increased heart rate
Reduced blood pressure
Increased respiratory rate
Increased metabolic rate
Reduced lung compliance
Increased chest wall compliance
Reduced functional residual capacity
Increased ratio of body surface area to body weight
Increased total body water content
Anatomic
Noncompliant left ventricle
Residual fetal circulation
Difficult venous and arterial cannulation
Relatively larger head and tongue
Narrower nasal passages
Anterior and cephalad larynx
Relatively longer epiglottis
Shorter trachea and neck
More prominent adenoids and tonsils
Weaker intercostal and diaphragmatic muscles
Greater resistance to airflow
Pharmacological
Immature hepatic biotransformation
Decreased blood protein for drug binding
More rapid rise in F_A/F_I and more rapid induction and recovery from inhaled anesthetics
Increased minimum alveolar concentration
Relatively larger volume of distribution for water-soluble drugs
Immature neuromuscular junction

[1] F_A/F_I, Fractional alveolar concentration/fractional inspired concentration.

relatively higher rate of oxygen consumption. Moreover, hypoxic and hypercapnic ventilatory drives are not well developed in neonates and infants. In fact, unlike in adults, hypoxia and hypercapnia may depress respiration in these patients.

2 Neonates and infants have, compared with older children and adults, a proportionately larger head and tongue, narrower nasal passages, an anterior and cephalad larynx (the glottis is at a vertebral level of C4 versus C6 in adults), a longer epiglottis, and a shorter trachea and neck (Figure 42–1). These anatomic features make neonates and young infants obligate nasal breathers until about 5 months of age. **The cricoid cartilage is the narrowest point of the airway in children younger than 5 years of age; in adults, the narrowest point is the glottis**. One millimeter of mucosal edema will have a proportionately greater effect on gas flow in children because of their smaller tracheal diameters.

Cardiovascular System

3 Cardiac stroke volume is relatively fixed by a noncompliant and immature left ventricle in neonates and infants. The cardiac output is therefore very sensitive to changes in heart rate (see Chapter 20). Although basal heart rate is greater than in adults (Table 42–2), activation of the parasympathetic nervous system, anesthetic overdose, or hypoxia can quickly trigger bradycardia and profound reductions in cardiac output. Sick infants undergoing emergency or prolonged surgical procedures appear particularly prone to episodes of bradycardia that can lead to hypotension, asystole, and intraoperative death. The sympathetic nervous system and baroreceptor reflexes are not fully mature. The infant cardiovascular system displays a blunted response to exogenous catecholamines. The immature heart is more sensitive to depression by volatile anesthetics and to opioid-induced bradycardia. The vascular tree is less able to respond to hypovolemia with compensatory vasoconstriction. Intravascular volume depletion in neonates and infants may be signaled by hypotension without tachycardia.

Metabolism & Temperature Regulation

Pediatric patients have a larger surface area per kilogram than adults (or a smaller body-mass index). Metabolism and its associated parameters (oxygen consumption, CO_2 production, cardiac output, and alveolar ventilation) correlate better with surface area than with weight.

4 Thin skin, low fat content, and a greater surface area relative to weight promote greater heat loss to the environment in neonates. This problem is compounded by inadequately warmed operating rooms, prolonged wound exposure, administration of room temperature intravenous or irrigation fluid, and dry anesthetic gases. Of course, there are also effects of anesthetic agents on temperature regulation (see Chapter 52). Even mild degrees of hypothermia can cause perioperative problems,

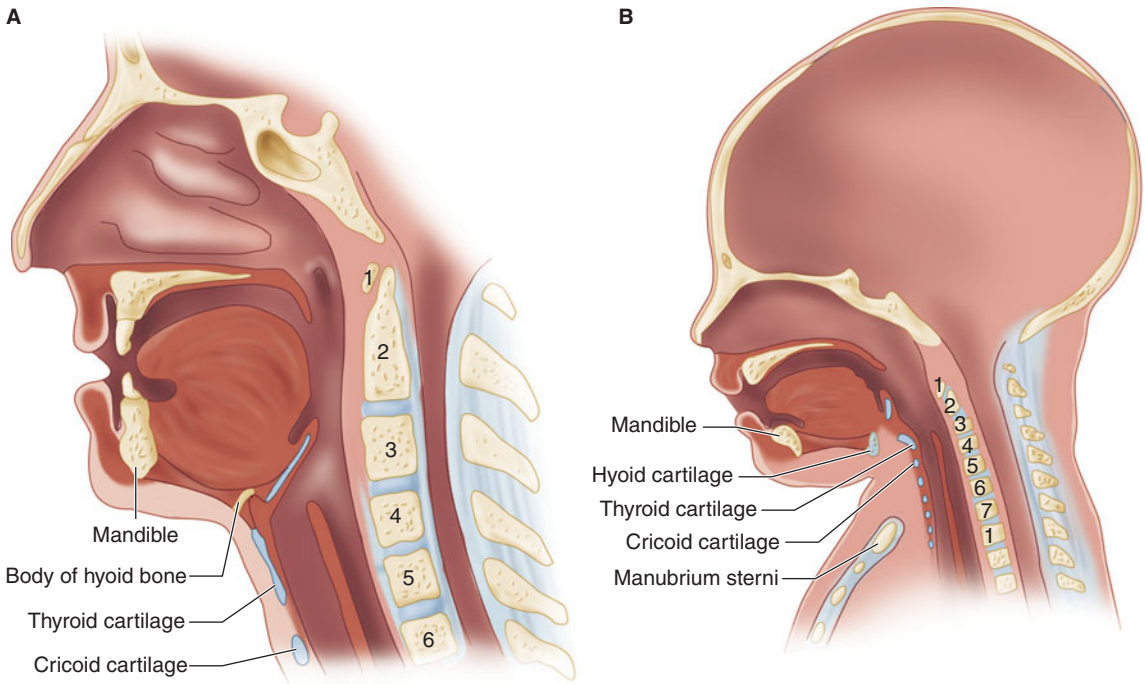

FIGURE 42–1 Sagittal section of the adult (**A**) and infant (**B**) airway. (Reproduced, with permission, from Snell RS, Katz J: *Clinical Anatomy for Anesthesiologists*. Appleton & Lange, 1988.)

including delayed awakening from anesthesia, cardiac irritability, respiratory depression, increased pulmonary vascular resistance, and altered responses to anesthetics, neuromuscular blockers, and other agents. The more important mechanisms for heat production in neonates are nonshivering thermogenesis by metabolism of brown fat and shifting of hepatic oxidative phosphorylation to a more thermogenic pathway. Yet, metabolism of brown fat is severely limited in premature infants and in sick neonates who are deficient in fat stores. Furthermore, volatile anesthetics inhibit thermogenesis in brown adipocytes.

TABLE 42–2 Age-related changes in vital signs.[1]

Age	Respiratory Rate	Heart Rate	Arterial Blood Pressure	
			Systolic	*Diastolic*
Neonate	40	140	65	40
12 months	30	120	95	65
3 years	25	100	100	70
12 years	20	80	110	60

[1]Values are mean averages derived from numerous sources. Normal ranges may include measurements that deviate from these as much as 25–50%.

Renal & Gastrointestinal Function

Kidney function approaches normal values (corrected for size) by 6 months of age, but this may be delayed until the child is 2 years old. Premature neonates often demonstrate multiple forms of renal immaturity, including decreased creatinine clearance; impaired sodium retention, impaired glucose excretion, and impaired bicarbonate reabsorption; and reduced diluting and concentrating ability. These abnormalities underscore the importance of appropriate fluid administration in the early days of life.

Neonates also have a relatively increased incidence of gastroesophageal reflux. The immature liver conjugates drugs and other molecules less readily early in life.

Glucose Homeostasis

Neonates have relatively reduced glycogen stores, predisposing them to hypoglycemia. Impaired glucose excretion by the kidneys may partially offset this tendency. In general, neonates at greatest risk for hypoglycemia are either premature or small for gestational age, receiving hyperalimentation, and the offspring of diabetic mothers.

PHARMACOLOGICAL DIFFERENCES

Pediatric drug dosing is typically adjusted on a per-kilogram basis for convenience (Table 42–3). In early childhood a patient's weight can be approximated based on age:

$$\text{50th percentile weight (kg)} = (\text{Age} \times 2) + 9$$

TABLE 42–3 Pediatric drug dosages.

Drug	Comment	Dosage
Acetaminophen	Rectal	40 mg/kg
	PO	10–20 mg/kg
	IV (age > 2 y)	15 mg/kg
	Maximum (per day)	60 mg/kg
Adenosine	Rapid IV bolus	0.1 mg/kg
	Repeat dose	0.2 mg/kg
	Maximum dose	12 mg
Albuterol	Nebulized	1.25–2.5 mg in 2 mL saline
Alfentanil	Anesthetic supplement (IV)	20–25 mcg/kg
	Maintenance infusion	1–3 mcg/kg/min
Aminophylline	Loading dose administered over 20 min (IV)	5–6 mg/kg
	Maintenance dose (therapeutic level: 10–20 mg/mL)	0.5–0.9 mg/kg/h
Amiodarone	Loading dose (IV)	5 mg/kg
	Repeat dose (slowly)	5 mg/kg
	Infusion	5–10 mcg/kg/min
	Maximum dose	20 mg/kg/day
Amoxicillin	PO	50 mg/kg
Ampicillin	IV	50 mg/kg
Ampicillin/sulbactam	IV	25–50 mg/kg
Atracurium	Intubation (IV)	0.5 mg/kg
Atropine	IV	0.01–0.02 mg/kg
	IM	0.02 mg/kg
	Minimum dose	0.1 mg
	Premedication (PO)	0.03–0.05 mg/kg
Bretylium	Loading dose (IV)	5 mg/kg
Caffeine	IV	10 mg/kg
Calcium chloride	IV (slowly)	5–20 mg/kg
Calcium gluconate	IV (slowly)	15–100 mg/kg
Cefazolin	IV	25 mg/kg
Cefotaxime	IV	25–50 mg/kg
Cefotetan	IV	20–40 mg/kg
Cefoxitin	IV	30–40 mg/kg
Ceftazidime	IV	30–50 mg/kg
Ceftriaxone	IV	25–50 mg/kg
Cefuroxime	IV	25 mg/kg
Chloral hydrate	PO	25–100 mg/kg
	Rectal	50 mg/kg
Cimetidine	IV or PO	5–10 mg/kg
Cisatracurium	Intubation (IV)	0.15 mg/kg
Clindamycin	IV	20 mg/kg
Dantrolene	Initial dose (IV)	2.5 mg/kg
	Maximum dose	10 mg/kg
	Subsequent attempts	4 J/kg
Desmopressin	IV	0.2–0.4 mcg/kg
Dexamethasone	IV	0.1–0.5 mg/kg
Dextrose	$D_{25}W$ or $D_{50}W$ (IV)	0.5–1 g/kg
Digoxin	IV	0.1–0.2 mg/kg
	Three divided doses over 24 h (IV)	15–30 mcg/kg
Diltiazem	IV over 2 min	0.25 mg/kg
Diphenhydramine	IV, IM, or PO	1 mg/kg
Dobutamine	Infusion	2–20 mcg/kg/min
Dolasetron	IV	0.35 mg/kg
Dopamine	Infusion	2–20 mcg/kg/min
Droperidol	IV	50–75 mcg/kg
Edrophonium	Depends on degree of paralysis (IV)	0.5–1 mg/kg
Ephedrine	IV	0.1–0.3 mg/kg
Epinephrine	IV bolus	10 mcg/kg
	Endotracheal dose	100 mcg/kg
	Infusion	0.05–1 mcg/kg/min
Epinephrine, 2.25% racemic	Nebulized	0.05 mL/kg in 3 mL saline
Esmolol	IV bolus	100–500 mcg/kg
	IV infusion	25–200 mcg/kg/min
Famotidine	IV	0.15 mg/kg
Fentanyl	Pain relief (IV)	1–2 mcg/kg
	Pain relief (Intranasal)	2 mcg/kg
	Premedication (Actiq PO)	10–15 mcg/kg
	Anesthetic adjunct (IV)	1–5 mcg/kg
	Maintenance infusion	2–4 mcg/kg/h
	Main anesthetic (IV)	50–100 mcg/kg

(*continued*)

TABLE 42–3 Pediatric drug dosages. (continued)

Drug	Comment	Dosage
Flumazenil	IV	0.01 mg/kg
Fosphenytoin	IV	15–20 mg/kg
Furosemide	IV	0.2–1 mg/kg
Gentamicin	IV	2 mg/kg
Glucagon	IV	0.5–1 mg
Glucose	IV	0.5–1 g/kg
Glycopyrrolate	IV	0.01 mg/kg
Granisetron	IV	0.04 mg/kg
Heparin	IV (not for cardiac surgery)	100 units/kg
	Cardiac surgery dose	300–400 units/kg
Hydrocortisone	IV	1 mg/kg
Hydromorphone	IV	15–20 mcg/kg
Ibuprofen	PO	4–10 mg/kg
Imipenem	IV	15–25 mg/kg
Inamrinone	Loading (IV)	1.5 mg/kg
	Maintenance	5–10 mcg/kg/min
Insulin	Infusion	0.02–0.1 units/kg/h
Isoproterenol	Infusion	0.1–1 mcg/kg/min
Ketamine	Induction (IV)	1–2 mg/kg
	Induction (IM)	6–10 mg/kg
	Induction (per rectum)	10 mg/kg
	Maintenance infusion	25–75 mcg/kg/min
	Premedication (PO)	6–10 mg/kg
	Sedation (IV)	0.5–1 mg/kg
Ketorolac	IV	0.5–0.75 mg/kg
Labetalol	IV	0.25 mg/kg
Lidocaine	Loading	1 mg/kg
	Maintenance	20–50 mcg/kg/min
Magnesium sulphate	IV (slowly)	25–50 mg/kg
	Maximum single dose	2 g
Mannitol	IV	0.25–1 g/kg
Meperidine	Pain relief (IV)	0.2–0.5 mg/kg
Methohexital	Induction (IV)	1–2 mg/kg
	Induction (per rectum)	25–30 mg/kg
	Induction (IM)	10 mg/kg
Methylprednisolone	IV	2–4 mg/kg
Metoclopramide	IV	0.15 mg/kg
Metronidazole	IV	7.5 mg/kg
Midazolam	Premedication (PO)	0.5 mg/kg
	Maximum dose (PO)	20 mg
	Sedation (IM)	0.1–0.15 mg/kg
	Sedation (IV)	0.05 mg/kg
Milrinone	Loading (IV)	50–75 mcg/kg
	Maintenance	0.375–0.75 mcg/kg/min
Morphine	Pain relief (IV)	0.025–0.1 mg/kg
	Premedication (IM)	0.1 mg/kg
Naloxone	IV	0.01 mg/kg
Neostigmine	Depends on degree of paralysis (IV)	0.04–0.07 mg/kg
Nitroglycerin	IV	0.5–3 mcg/kg/min
Nitroprusside	Infusion	0.5–4 mcg/kg/min
Norepinephrine	Infusion	0.05–2 mcg/kg/min
Ondansetron	IV	0.1 mg/kg
Oxacillin	IV	50 mg/kg
Pancuronium	IV	0.1 mg/kg
Penicillin G	IV	50,000 units/kg
Pentobarbital	Premedication (IM)	1–2 mg/kg
Phenobarbital	Anticonvulsant dose (IV)	5–20 mg/kg
Phentolamine	IV	30 mcg/kg
Phenylephrine	IV	1–10 mcg/kg
Phenytoin	Slowly IV	5–20 mg/kg
Physostigmine	IV	0.01–0.03 mg/kg
Prednisone	PO	1 mg/kg
Procainamide	Loading dose (IV)	15 mg/kg
Propofol	Induction (IV)	2–3 mg/kg
	Maintenance infusion	60–250 mcg/kg/min
Propranolol	IV	10–25 mcg/kg
Prostaglandin E_1	Infusion	0.05–0.1 mcg/kg/min
Protamine	IV	1 mg/100 units heparin
Ranitidine	IV	0.25–1.0 mg/kg
Remifentanil	IV bolus	0.25–1 mcg/kg
	IV infusion	0.05–2 mcg/kg/min
Rocuronium	Intubation (IV)	0.6–1.2 mg/kg
Sodium bicarbonate	IV	1 mEq/kg
Succinylcholine	Intubation (IV)	1–2mg/kg
	Intubation (IM)	4 mg/kg
Sufentanil	Premedication (Intranasal)	2 mcg/kg
	Anesthetic adjunct (IV)	0.5–1 mcg/kg
	Maintenance infusion	0.5–2 mcg/kg/h
	Main anesthetic (IV)	10–15 mcg/kg
Thiopental	Induction (IV)	5–6 mg/kg
Trimethoprim/sulfamethoxazole	IV	4–5 mg/kg
Vancomycin	IV	20 mg/kg
Vecuronium	IV	0.1 mg/kg
Verapamil	IV	0.1–0.3 mg/kg

Weight-adjustment of drug dosing is incompletely effective because it does not take into account the disproportionately larger pediatric intravascular and extracellular fluid compartments, the immaturity of hepatic biotransformation pathways, increased organ blood flow, decreased protein for drug binding, or higher metabolic rate.

Neonates and infants have a proportionately greater total water content (70–75%) than adults (50–60%). Total body water content decreases while fat and muscle content increase with age. As a direct result, the volume of distribution for most intravenous drugs is disproportionately greater in neonates, infants, and young children, and the optimal dose (per kilogram) is usually greater than in older children and adults. A disproportionately smaller muscle mass in neonates prolongs the clinical duration of action (by delaying redistribution to muscle) of drugs such as thiopental and fentanyl. Neonates also have a relatively decreased glomerular filtration rate, hepatic blood flow, and renal tubular function, and immature hepatic enzyme systems. Increased intraabdominal pressure and abdominal surgery further reduce hepatic blood flow. All these factors may impair renal drug handling, hepatic metabolism, or biliary excretion of drugs in neonates and young infants. Neonates also have decreased protein binding for some drugs, most notably thiopental, bupivacaine, and many antibiotics. In the case of thiopental, increased free drug enhances potency and reduces the induction dose in neonates compared with older children. An increase in free bupivacaine might increase the risk of systemic toxicity.

Inhalational Anesthetics

5 Neonates, infants, and young children have relatively greater alveolar ventilation and reduced FRC compared with older children and adults. This greater minute ventilation-to-FRC ratio with relatively greater blood flow to vessel-rich organs contributes to a rapid increase in alveolar anesthetic concentration and speeds inhalation induction. Furthermore, the blood/gas coefficients of volatile anesthetics are reduced in neonates compared with adults, resulting in even faster induction times and potentially increasing the risk of accidental overdosage.

TABLE 42–4 Approximate MAC[1] values for pediatric patients reported in % of an atmosphere.[2]

Agent	Neonates	Infants	Small Children	Adults
Halothane	0.90	1.1–1.2	0.9	0.75
Sevoflurane	3.2	3.2	2.5	2
Isoflurane	1.6	1.8–1.9	1.3–1.6	1.2
Desflurane	8–9	9–10	7–8	6

[1]MAC, minimum alveolar concentration.
[2]Values are derived from various sources.

6 The minimum alveolar concentration (MAC) for halogenated agents is greater in infants than in neonates and adults (Table 42–4). In contrast to other agents, no increase in sevoflurane MAC can be demonstrated in neonates and infants. Nitrous oxide does not appear to reduce the MAC of desflurane or sevoflurane in children to the same extent as it does for other agents.

The blood pressure of neonates and infants appears to be especially sensitive to volatile anesthetics. This clinical observation has been attributed to less-well-developed compensatory mechanisms (eg, vasoconstriction, tachycardia) and greater sensitivity of the immature myocardium to myocardial depressants. Halothane (now much less commonly used) sensitizes the heart to catecholamines. The maximum recommended dose of epinephrine in local anesthetic solutions during halothane anesthesia is 10 mcg/kg. Cardiovascular depression, bradycardia, and arrhythmias are less frequent with sevoflurane than with halothane. Halothane and sevoflurane are less likely than other volatile agents to irritate the airway or cause breath holding or laryngospasm during induction (see Chapter 8). In general, volatile anesthetics appear to depress ventilation more in infants than in older children. Sevoflurane appears to produce the least respiratory depression. The risk for halothane-induced hepatic dysfunction appears to be much reduced in prepubertal children compared with adults. There are no reported instances of renal toxicity attributed to inorganic fluoride production during sevoflurane anesthesia in children.

Overall, sevoflurane appears to have a greater therapeutic index than halothane and has become the preferred agent for inhaled induction in pediatric anesthesia.

Emergence is fastest following desflurane or sevoflurane, but both agents are associated with a greater incidence of agitation or delirium upon emergence, particularly in young children. Because of the latter, some clinicians switch to isoflurane for maintenance anesthesia following a sevoflurane induction (see below).

Nonvolatile Anesthetics

After weight-adjustment of dosing, infants and young children require larger doses of propofol because of a larger volume of distribution compared with adults. Children also have a shorter elimination half-life and higher plasma clearance for propofol. Recovery from a single bolus is not appreciably different from that in adults; however, recovery following a continuous infusion may be more rapid. For the same reasons, children may require increased weight-adjusted rates of infusion for maintenance of anesthesia (up to 250 mcg/kg/min). Propofol is not recommended for prolonged sedation of critically ill pediatric patients in the intensive care unit (ICU) due to an association with greater mortality than other agents. Although the "propofol infusion syndrome" has been reported more often in critically ill children, it has also been reported in adults undergoing long-term propofol infusion (>48 h) for sedation, particularly at increased doses (>5 mg/kg/h). Its essential features include rhabdomyolysis, metabolic acidosis, hemodynamic instability, hepatomegaly, and multiorgan failure.

Children require relatively larger doses of thiopental compared with adults. The elimination half-life is shorter and the plasma clearance is greater than in adults. In contrast, neonates, appear to be more sensitive to barbiturates. Neonates have less protein binding, a longer half-life, and impaired clearance. The thiopental induction dose for neonates is 3–4 mg/kg compared with 5–6 mg/kg for infants.

Opioids appear to be more potent in neonates than in older children and adults. Unproven (but popular) explanations include "easier entry" across the blood–brain barrier, decreased metabolic capability, or increased sensitivity of the respiratory centers. Morphine sulfate, particularly in repeated doses, should be used with caution in neonates because hepatic conjugation is reduced and renal clearance of morphine metabolites is decreased. The cytochrome P-450 pathways mature at the end of the neonatal period. Older pediatric patients have relatively greater rates of biotransformation and elimination as a result of high hepatic blood flow. Sufentanil, alfentanil, and, possibly, fentanyl clearances may be greater in children than in adults. Remifentanil clearance is increased in neonates and infants but elimination half-life is unaltered compared with adults. Neonates and infants may be more resistant to the hypnotic effects of ketamine, requiring slightly higher doses than adults (but the "differences" are within the range of error in studies); pharmacokinetic values do not appear to be significantly different from those of adults. Etomidate has not been well-studied in pediatric patients younger than 10 years of age; its profile in older children is similar to that in adults. Midazolam has the fastest clearance of all the benzodiazepines; however, midazolam clearance is significantly reduced in neonates compared with older children. The combination of midazolam and fentanyl can cause hypotension in patients of all ages.

Muscle Relaxants

For a wide variety of reasons (including pharmacology, convenience, case mix, and convenience), muscle relaxants are less commonly used during induction of anesthesia in pediatric than in adult patients. Many children will have a laryngeal mask airway (LMA) or endotracheal tube placed after receiving a sevoflurane inhalation induction, placement of an intravenous catheter, and administration of various combinations of propofol, opioids, or lidocaine.

All muscle relaxants generally have a faster onset (up to 50% less delay) in pediatric patients because of shorter circulation times than adults. In both children and adults, intravenous succinylcholine (1–1.5 mg/kg) has the fastest onset (see Chapter 11). Infants require significantly larger doses of succinylcholine (2–3 mg/kg) than older children and adults because of the relatively larger volume of distribution. This discrepancy disappears

TABLE 42–5 Approximate ED_{95} for muscle relaxants in infants and children.[1]

Agents	Infants ED_{95} (mg/kg)	Children ED_{95} (mg/kg)
Succinylcholine	0.7	0.4
Atracurium	0.25	0.35
Cisatracurium	0.05	0.06
Rocuronium	0.25	0.4
Vecuronium	0.05	0.08
Pancuronium	0.07	0.09

[1]Average values during nitrous oxide/oxygen anesthesia.

if dosage is based on body surface area. Table 42–5 lists commonly used muscle relaxants and their ED_{95} (the dose that produces 95% depression of evoked twitches). With the notable exclusion of succinylcholine and possibly cisatracurium, infants require significantly smaller muscle relaxant doses than older children. Moreover, based on weight, older children require larger doses than adults for some neuromuscular blocking agents (eg, atracurium, see Chapter 11). As with adults, a more rapid intubation can be achieved with a muscle relaxant dose that is twice the ED_{95} dose at the expense of prolonging the duration of action.

The response of neonates to nondepolarizing muscle relaxants is variable. Popular (and unproven) explanations for this include "immaturity of the neuromuscular junction" (in premature neonates), tending to increase sensitivity (unproven), counterbalanced by a disproportionately larger extracellular compartment, reducing drug concentrations (proven). The relative immaturity of neonatal hepatic function prolongs the duration of action for drugs that depend primarily on hepatic metabolism (eg, pancuronium, vecuronium, and rocuronium). Atracurium and cisatracurium do not depend on hepatic biotransformation and reliably behave as intermediate-acting muscle relaxants.

7 Children are more susceptible than adults to cardiac arrhythmias, hyperkalemia, rhabdomyolysis, myoglobinemia, masseter spasm, and malignant hyperthermia (see Chapter 52) associated with succinylcholine. When a child experiences cardiac arrest following administration of succinylcholine, immediate treatment for hyperkalemia should be instituted. Prolonged, heroic (eg, potentially including cardiopulmonary bypass) resuscitative efforts may be required. For this reason, succinylcholine is avoided for routine, elective paralysis for intubation in children and adolescents. Unlike adults, children may have profound bradycardia and sinus node arrest following the first dose of succinylcholine without atropine pretreatment. Atropine (0.1 mg minimum) must therefore always be administered prior to succinylcholine in children. Generally accepted indications for intravenous succinylcholine in children include rapid sequence induction with a "full" stomach and laryngospasm that does not respond to positive-pressure ventilation. When rapid muscle relaxation is required prior to intravenous access (eg, with inhaled inductions in patients with full stomachs), intramuscular succinylcholine (4–6 mg/kg) can be used. Intramuscular atropine (0.02 mg/kg) should be administered with intramuscular succinylcholine to reduce the likelihood of bradycardia. Some clinicians advocate intralingual administration (2 mg/kg in the midline to avoid hematoma formation) as an alternate emergency route for intramuscular succinylcholine.

8

Many clinicians consider rocuronium (0.6 mg/kg intravenously) to be the drug of choice (when a relaxant will be used) during routine intubation in pediatric patients with intravenous access because it has the fastest onset of nondepolarizing neuromuscular blocking agents (see Chapter 11). Larger doses of rocuronium (0.9–1.2 mg/kg) may be used for rapid sequence induction but a prolonged duration (up to 90 min) will likely follow. Rocuronium is the only nondepolarizing neuromuscular blocker that has been adequately studied for intramuscular administration (1.0–1.5 mg/kg), but this approach requires 3–4 min for onset.

Atracurium or cisatracurium may be preferred in young infants, particularly for short procedures, because these drugs consistently display short to intermediate duration.

As with adults, the effect of incremental doses of muscle relaxants (usually 25–30% of the initial dose) should be monitored with a peripheral nerve

stimulator. Sensitivity can vary significantly between patients. Nondepolarizing blockade can be reversed with neostigmine (0.03–0.07 mg/kg) or edrophonium (0.5–1 mg/kg) along with an anticholinergic agent (glycopyrrolate, 0.01 mg/kg, or atropine, 0.01–0.02 mg/kg). Sugammadex, a specific antagonist for rocuronium and vecuronium, has yet to be released in the United States.

PEDIATRIC ANESTHETIC RISK

The Pediatric Perioperative Cardiac Arrest (POCA) Registry provides a useful database for assessing pediatric anesthetic risk. This registry includes reports derived from approximately one million pediatric anesthetics administered since 1994. Case records of children experiencing cardiac arrests or death during the administration of or recovery from anesthesia were investigated regarding any possible relationship with anesthesia. Nearly all patients received general anesthesia alone or combined with regional anesthesia. In a preliminary analysis that included 289 cases of cardiac arrest, anesthesia was judged to have contributed to 150 arrests. Thus the risk of cardiac arrest in pediatric anesthetic cases would appear to be approximately 1.4 in 10,000. Moreover, an overall mortality of 26% was reported following cardiac arrest. Approximately 6% suffered permanent injury, but the majority (68%) had either no or only temporary injury. Mortality was 4% in American Society of Anesthesiologists (ASA) physical status 1 and 2 patients compared with 37% in ASA physical status 3–5 patients. It is important to note that 33% of patients who suffered a cardiac arrest were ASA physical status 1–2. Infants accounted for 55% of all anesthesia-related arrests, with those younger than 1 month of age (ie, neonates) having the greatest risk. As with adults, two major predictors of mortality were ASA physical status 3–5 and emergency surgery.

Most (82%) arrests occurred during induction of anesthesia; bradycardia, hypotension, and a low Spo_2 frequently preceded arrest. The most common mechanism of cardiac arrest was judged to be medication related (**Figure 42–2**). Cardiovascular depression from halothane, alone or in combination with other drugs, was believed to be responsible in

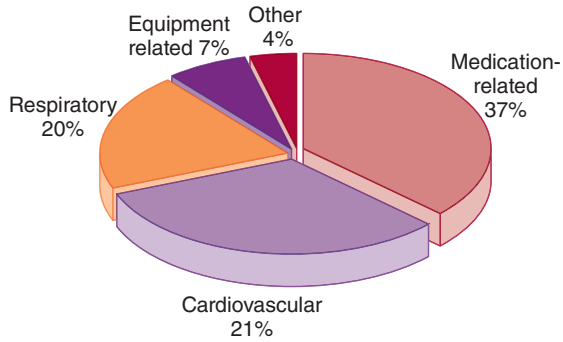

FIGURE 42–2 Mechanisms of cardiac arrest in pediatric patients, based on POCA Registry data.

66% of all medication-related arrests. Another 9% was due to intravascular injection of a local anesthetic, most often following a negative aspiration test during attempted caudal injection. Presumed cardiovascular mechanisms most often had no clear etiology; in more than 50% of those cases the patient had congenital heart disease. Where a cardiovascular mechanism could be identified, it was most often related to hemorrhage, transfusion, or inadequate or inappropriate fluid therapy.

Respiratory mechanisms included laryngospasm, airway obstruction, and difficult intubation (in decreasing order). In most cases the laryngospasm occurred during induction. Nearly all patients who had airway obstruction or were difficult to intubate had at least one other significant underlying disease.

The most common equipment-related mechanisms that led to a cardiac arrest were complications related to attempted central venous catheterization (eg, pneumothorax, hemothorax, or cardiac tamponade).

In recent years there has been increased concern and scientific interest in the possibility that general anesthesia and general anesthetic agents are toxic to the brains of small children. The experimental data in animals are consistently worrisome, but the clinical data are (currently) inconclusive as to the extent of the risk and whether one technique is safer than another. Progress in this area can be followed on the SmartTots web site (http://www.smarttots.org), maintained by the International Anesthesia Research Society.

Children are at greater risk than adults of developing malignant hyperthermia. This complex and important topic is covered in depth in Chapter 52.

PEDIATRIC ANESTHETIC TECHNIQUES

Preoperative Considerations

A. Preoperative Interview

Depending on age, past experiences, and maturity, children present with varying degrees of fright (even terror) when faced with the prospect of surgery. In contrast to adults, who are usually most concerned about the possibility of death, children are principally worried about pain and separation from their parents. Presurgical preparation programs—such as brochures, videos, or tours—can be very helpful in preparing many children and parents. Unfortunately, outpatient and morning-of-admission surgery together with a busy operating room schedule often make it nearly impossible for an anesthesiologist to break through the barriers presented by pediatric patients. For this reason, premedication (below) can be helpful. When time permits, one can demystify the process of anesthesia and surgery by explaining in age-appropriate terms what lies ahead. For example, the anesthesiologist might bring an anesthesia mask for the child to play with during the interview and describe it as like something the astronauts use. Alternatively, in some centers, someone the child trusts (eg, a parent, nurse, another physician) may be allowed to be in attendance during preanesthetic preparations and induction of anesthesia. This can have a particularly calming influence on children undergoing repeated procedures (eg, examination under anesthesia following glaucoma surgery). Some pediatric hospitals have induction rooms adjacent to their operating rooms to permit parental attendance and a quieter, less startling environment for anesthetic inductions.

B. Recent Upper Respiratory Tract Infection

Children frequently present for surgery with evidence—a runny nose with fever, cough, or sore throat—of a coincidental viral upper respiratory tract infection (URI). Attempts should be made to differentiate between an infectious cause of rhinorrhea and an allergic or vasomotor cause. A viral infection within 2–4 weeks before general anesthesia and endotracheal intubation appears to place the child at an increased risk for perioperative pulmonary complications, such as wheezing (10-fold), laryngospasm (5-fold), hypoxemia, and atelectasis. This is particularly likely if the child has a severe cough, high fever, or a family history of reactive airway disease. The decision to anesthetize children with URIs remains controversial and depends on the presence of other coexisting illnesses, the severity of URI symptoms, and the urgency of the surgery. When surgery will be performed in a child with a URI, one should consider giving anticholinergic premedication, avoiding intubation (if feasible), and humidifying inspired gases. In this circumstance one should anticipate that a longer-than-usual stay in the recovery room may be required.

C. Laboratory Tests

Few, if any, preoperative laboratory tests are cost effective. Some pediatric centers require *no* preoperative laboratory tests in *healthy* children undergoing *minor* procedures. Obviously, this places responsibility on the anesthesiologist, surgeon, and pediatrician to correctly identify those patients who should have preoperative testing for specific surgical procedures.

Most asymptomatic patients with cardiac murmurs do not have significant cardiac pathology. Innocent murmurs may occur in more than 30% of normal children. These are typically soft, short systolic ejection murmurs that are best heard along the left upper or left lower sternal border and that do not radiate. Innocent murmurs at the left upper sternal border typically are due to flow across the pulmonic valve (pulmonic ejection) whereas those at the lower left border typically are due to flow from the left ventricle to the aorta (Still's vibratory murmur). The pediatrician should carefully evaluate patients with a newly diagnosed murmur, particularly in infancy. Consultation with a pediatric cardiologist, echocardiography, or both, should be obtained if the patient is symptomatic (eg, poor feeding, failure to thrive, or easy fatigability); the murmur is harsh, loud, holosystolic, diastolic, or radiates widely; or pulses are either bounding or markedly diminished.

D. Preoperative Fasting

Because children are more prone to dehydration than adults, their preoperative fluid restriction has always been more lenient. Several studies, however, have documented low gastric pH (<2.5) and relatively high residual volumes in pediatric patients scheduled for surgery, suggesting that children may be at a greater risk for aspiration than was previously thought. The incidence of aspiration is reported to be approximately 1:1000. There is no convincing evidence that prolonged fasting decreases this risk. In fact, several studies have demonstrated lower residual volumes and higher gastric pH in pediatric patients who received clear fluids a few hours before induction (see Chapter 53). More specifically, infants are fed breast milk up to 4 h before induction, whereas formula or liquids and a "light" meal may be given up to 6 h before induction. Clear fluids are offered until 2–3 h before induction. These recommendations are for healthy neonates, infants, and children without risk factors for decreased gastric emptying or aspiration.

E. Premedication

There is great variation in the recommendations for premedication of pediatric patients. Sedative premedication is generally omitted for neonates and sick infants. Children who appear likely to exhibit uncontrollable separation anxiety should be given a sedative, such as midazolam (0.3–0.5 mg/kg, 15 mg maximum). The oral route is generally preferred because it is less traumatic than intramuscular injection, but it requires 20–45 min for effect. Smaller doses of midazolam have been used in combination with oral ketamine (4–6 mg/kg) for inpatients. For uncooperative patients, intramuscular midazolam (0.1–0.15 mg/kg, 10 mg maximum) or ketamine (2–3 mg/kg) with atropine (0.02 mg/kg) may be helpful. Rectal midazolam (0.5–1 mg/kg, 20 mg maximum) or rectal methohexital (25–30 mg/kg of 10% solution) may also be administered in such cases while the child is in the parent's arms. The nasal route can be used with some drugs but is unpleasant, and some concerns exist over potential neurotoxicity of nasal midazolam. Nasal dexmedetomidine has also been used by some clinicians. Fentanyl can also be administered as a lollipop (Actiq, 5–15 mcg/kg); fentanyl levels continue to rise intraoperatively and can contribute to postoperative analgesia.

In the past anesthesiologists routinely premedicated young children with anticholinergic drugs (eg, atropine, 0.02 mg/kg intramuscularly) in hope of reducing the likelihood of bradycardia during induction. Atropine reduces the incidence of hypotension during induction in neonates and in infants younger than 3 months. Atropine can also prevent accumulation of secretions that can block small airways and endotracheal tubes. Secretions can be particularly problematic for patients with URIs or those who have been given ketamine. Atropine may be administered orally (0.05 mg/kg), intramuscularly, or occasionally rectally. In current practice, most anesthesiologists prefer to administer atropine intravenously at or shortly after induction.

Monitoring

Monitoring requirements for infants and children are generally similar to those for adults with some minor modifications. Alarm limits should be appropriately adjusted. Smaller electrocardiographic electrode pads may be necessary so that they do not encroach on sterile surgical areas. Blood pressure cuffs must be properly fitted. Noninvasive blood pressure monitors have proved to be reliable in infants and children. A precordial stethoscope provides an inexpensive means of monitoring heart rate, quality of heart sounds, and airway patency. Finally, monitors may sometimes need to be first attached (or reattached) following induction of anesthesia in less cooperative patients.

Small pediatric patients have a reduced margin for error. Pulse oximetry and capnography assume an even more important role in infants and small children because hypoxia from inadequate ventilation remains a common cause of perioperative morbidity and mortality. In neonates, the pulse oximeter probe should preferably be placed on the right hand or earlobe to measure preductal oxygen saturation. As in adult patients, end-tidal CO_2 analysis allows assessment of the adequacy of ventilation, confirmation of endotracheal tube placement, and early warning of malignant hyperthermia. Flow-through (mainstream) analyzers are usually less accurate in patients weighing less than 10 kg. Even with

aspiration (sidestream) capnographs, the inspired (baseline) CO_2 can appear falsely elevated and the expired (peak) CO_2 can be falsely low. The degree of error depends on many factors but can be minimized by placing the sampling site as close as possible to the tip of the endotracheal tube, using a short length of sampling line, and lowering gas-sampling flow rates (100–150 mL/min). Furthermore, the size of some flow-through sensors may lead to kinking of the endotracheal tube or hypercapnia as a result of increased equipment dead space.

10 Temperature must be closely monitored in pediatric patients because of the greater risk for malignant hyperthermia and greater potential for intraoperative hypothermia or hyperthermia. The risk of hypothermia can be reduced by maintaining a warm operating room environment (26°C or warmer), by warming and humidifying inspired gases, by using a warming blanket and warming lights, and by warming all intravenous and irrigation fluids. The room temperature required for a neutral thermal environment varies with age; it is greatest in premature newborns. Note that care must be taken to prevent accidental burns and hyperthermia from overzealous warming efforts.

Invasive monitoring (eg, arterial cannulation, central venous catheterization) demands expertise and judgment. Air bubbles should be removed from pressure tubing and small volume flushes should be used to prevent air embolism, unintended heparinization, or fluid overload. The right radial artery is often chosen for cannulation in the neonate because its preductal location mirrors the oxygen content of the carotid and retinal arteries. A femoral artery catheter may be a suitable alternative in very small neonates, and left radial or right or left dorsalis pedis arteries are alternatives in infants. Critically ill neonates may retain an umbilical artery catheter. Internal jugular and subclavian approaches are often used for central lines. Ultrasonography should be used during placement of internal jugular catheters and provides useful information for arterial cannulation as well. Urinary output is an important (but neither sensitive nor specific) indicator of the adequacy of intravascular volume and cardiac output. Noninvasive monitors of stroke volume have only recently been tested in infants and young children.

Premature or small-for-gestational age neonates, and neonates who have received total parenteral nutrition or whose mothers are diabetic, are prone to hypoglycemia. These infants should have frequent blood glucose measurements: levels below 30 mg/dL in the neonate, below 40 mg/dL in infants, and below 60 mg/dL in children and adults indicate hypoglycemia requiring immediate treatment. Blood sampling for arterial blood gases, hemoglobin, potassium, and ionized calcium concentration can be invaluable in critically ill patients, particularly in those undergoing major surgery or who may be receiving transfusions.

Induction

General anesthesia is usually induced by an intravenous or inhalational technique. Induction with intramuscular ketamine (5–10 mg/kg) is reserved for specific situations, such as those involving combative, particularly mentally challenged, children and adults. Intravenous induction is usually preferred when the patient comes to the operating room with a functional intravenous catheter or will allow awake venous cannulation. Prior application of EMLA (eutectic mixture of local anesthetic) cream (see Chapter 16) may render intravenous cannulation less painful for the patient, and less stressful for the parent and anesthesiologist. EMLA cream is not a perfect solution. Some children become anxious at the sight of a needle, particularly those who have had multiple needle punctures in the past, with or without EMLA. Furthermore, it can be difficult to anticipate in which extremity intravenous cannulation will prove to be successful. Finally, to be effective, EMLA cream must remain in contact with the skin for at least 30–60 min. Awake or sedated-awake intubation with topical anesthesia should be considered for emergency procedures in neonates and small infants when they are critically ill or a potential difficult airway is present.

Intravenous Induction

The same induction sequence can be used as in adults: propofol (2–3 mg/kg) followed by a nondepolarizing muscle relaxant (eg, rocuronium, cisatracurium, atracurium) or succinylcholine. We recommend that atropine be given routinely prior to

succinylcholine. The advantages of an intravenous technique include availability of intravenous access if emergency drugs need to be administered and rapidity of induction in the child at risk for aspiration. Alternatively (and very commonly in pediatric practice), intubation can be accomplished with the combination of propofol, lidocaine, and an opiate, with or without an inhaled agent, avoiding the need for a paralytic agent. Finally, paralytic agents are not needed for placement of LMAs, which are commonly used in pediatric anesthesia.

Inhalational Induction

Many children do not arrive in the operating room with an intravenous line in place and nearly all dread the prospect of being stuck with a needle. Fortunately, sevoflurane can render small children unconscious within minutes. We find this easier in children who have been sedated (most often with oral midazolam) prior to entering the operating room and who are sleepy enough to be anesthetized without ever knowing what has happened ("steal" induction). One can also insufflate the anesthetic gases over the face, place a drop of food flavoring on the inside of the mask (eg, oil of orange), and allow the child to sit during the early stages of induction. Specially contoured masks minimize dead space (see Figure 19–8).

There are many differences between adult and pediatric anatomy that influence mask ventilation and intubation. Equipment appropriate for age and size should be selected (Table 42–6). Neonates and most young infants are obligate nasal breathers and obstruct easily. Oral airways will help displace an oversized tongue; nasal airways, so useful in adults, can traumatize small nares or prominent adenoids in small children. Compression of submandibular soft tissues should be avoided during mask ventilation to prevent upper airway obstruction.

Typically, the child can be coaxed into breathing an odorless mixture of nitrous oxide (70%) and oxygen (30%). Sevoflurane (or halothane) can be added to the gas mixture in 0.5% increments every few breaths. As previously discussed, we favor sevoflurane in most situations. Desflurane and isoflurane are avoided for inhalation induction because they are pungent and associated with more coughing, breath-holding, and laryngospasm. We use a single (sometimes two) breath induction technique with sevoflurane (7–8% sevoflurane in 60% nitrous oxide) to speed the induction. After an adequate depth of anesthesia has been achieved, an intravenous line can be started and propofol and an opioid (or a muscle relaxant) administered to facilitate intubation. Patients typically pass through an excitement stage during which any stimulation can induce

TABLE 42–6 Sizing of airway equipment in children.

	Premature	Neonate	Infant	Toddler	Small Child	Large Child
Age	0–1 month	0–1 month	1–12 months	1–3 years	3–8 years	8–12 years
Weight (kg)	0.5–3	3–5	4–10	8–16	14–30	25–50
Tracheal (ET)[1] tube (mm i.d.)	2.5–3	3–3.5	3.5–4	4–4.5	4.5–5.5	5.5–6 (cuffed)
ET depth (cm at lips)	6–9	9–10	10–12	12–14	14–16	16–18
Suction catheter (F)	6	6	8	8	10	12
Laryngoscope blade	00	0	1	1.5	2	3
Mask size	00	0	0	1	2	3
Oral airway	000–00	00	0 (40 mm)	1 (50 mm)	2 (70 mm)	3 (80 mm)
Laryngeal mask airway (LMA#)	—	1	1	2	2.5	3

[1]ET, endotracheal tube.

laryngospasm. Breath-holding must be distinguished from laryngospasm. Steady application of 10 cm of positive end-expiratory pressure will usually overcome laryngospasm.

Alternatively, the anesthesiologist can deepen the level of anesthesia by increasing the concentration of volatile anesthetic, and place an LMA or intubate the patient under "deep" sevoflurane anesthesia. Because of the greater anesthetic depth required for tracheal intubation with the latter technique, the risk of cardiac depression, bradycardia, or laryngospasm occurring without intravenous access detracts from this technique. Intramuscular succinylcholine (4–6 mg/kg, not to exceed 150 mg) and atropine (0.02 mg/kg, not to exceed 0.4 mg) should be available if laryngospasm or bradycardia occurs before an intravenous line is established; intralingual succinylcholine may be an alterative route (see above).

Positive-pressure ventilation during mask induction and prior to intubation sometimes causes gastric distention, resulting in impairment of lung expansion. Suctioning with an orogastric or nasogastric tube will decompress the stomach, but it must be done without traumatizing fragile mucous membranes.

Intravenous Access

Intravenous cannulation in infants can be a vexing ordeal. This is particularly true for infants who have spent weeks in a neonatal intensive care unit and have few unpunctured veins left. Even healthy 1-year-old children can prove a challenge because of extensive subcutaneous fat. Venous cannulation usually becomes easier after 2 years of age. The saphenous vein has a consistent location at the ankle and an experienced practitioner can usually cannulate it even if it is not visible or palpable. Transillumination of the hands or ultrasonography will often reveal previously hidden cannulation sites. Twenty-four-gauge over-the-needle catheters are adequate in neonates and infants when blood transfusions are not anticipated. All air bubbles should be removed from the intravenous line, to reduce the risk of paradoxical air embolism from occult patent foramen ovale. In emergency situations where intravenous access is impossible, fluids can be effectively infused through an 18-gauge needle inserted into the medullary sinusoids within the tibial bone. This intraosseous infusion can be used for all medications normally given intravenously, with almost as rapid results (see Chapter 55), and is considered part of the standard trauma resuscitation (ACLS) protocol when large-bore intravenous access cannot be obtained.

Tracheal Intubation

One hundred percent oxygen should be administered prior to intubation to increase patient safety during the obligatory period of apnea prior to and during intubation. The choice of muscle relaxant has been discussed earlier in the chapter. For awake intubations in neonates or infants, adequate preoxygenation and continued oxygen insufflation during laryngoscopy (eg, Oxyscope) may help prevent hypoxemia.

The infant's prominent occiput tends to place the head in a flexed position prior to intubation. This is easily corrected by slightly elevating the shoulders with towels and placing the head on a doughnut-shaped pillow. In older children, prominent tonsillar tissue can obstruct visualization of the larynx. Straight laryngoscope blades aid intubation of the anterior larynx in neonates, infants, and young children (Table 42–6). Endotracheal tubes that pass through the glottis may still impinge upon the cricoid cartilage, which is the narrowest point of the airway in children younger than 5 years of age. Mucosal trauma from trying to force a tube through the cricoid cartilage can cause postoperative edema, stridor, croup, and airway obstruction.

The appropriate diameter inside the endotracheal tube can be estimated by a formula based on age:

$$4 + \text{Age}/4 = \text{Tube diameter (in mm)}$$

For example, a 4-year-old child would be predicted to require a 5-mm tube. This formula provides only a rough guideline, however. Exceptions include premature neonates (2.5–3 mm tube) and full-term neonates (3–3.5 mm tube). Alternatively, the practitioner can remember that a newborn takes a 2.5- or 3-mm tube, and a 5-year-old takes a 5-mm tube. It should not be that difficult to identify which of the three sizes of tube between 3 and 5 mm is required in small children. In larger children, small (5–6 mm)

cuffed tubes can be used either with or without the cuff inflated to minimize the need for precise sizing. Endotracheal tubes 0.5 mm larger and smaller than predicted should be readily available in or on the anesthetic cart. Uncuffed endotracheal tubes traditionally have been selected for children aged 5 years or younger to decrease the risk of postintubation croup, but many anesthesiologists no longer use size 4.0 or larger uncuffed tubes. The leak test will minimize the likelihood that an excessively large tube has been inserted. Correct tube size is confirmed by easy passage into the larynx and the development of a gas leak at 15–20 cm H_2O pressure for an uncuffed tube. No leak indicates an oversized tube that should be replaced to prevent postoperative edema, whereas an excessive leak may preclude adequate ventilation and contaminate the operating room with anesthetic gases. As noted above, many clinicians use a downsized cuffed tube with the cuff completely deflated in younger patients at high risk for aspiration; minimal inflation of the cuff can stop any air leak. There is also a formula to estimate endotracheal length:

$$12 + \text{Age}/2 = \text{Length of tube (in cm)}$$

Again, this formula provides only a guideline, and the result must be confirmed by auscultation and clinical judgment. To avoid endobronchial intubation, the tip of the endotracheal tube should pass only 1–2 cm beyond an infant's glottis. We favor an alternative approach: to intentionally place the tip of the endotracheal tube into the right mainstem bronchus and then withdraw it until breath sounds are equal over both lung fields.

Maintenance

Ventilation is almost always controlled during anesthesia of neonates and infants with a conventional semiclosed circle system. During spontaneous ventilation, even the low resistance of a circle system can become a significant obstacle for a sick neonate to overcome. Unidirectional valves, breathing tubes, and carbon dioxide absorbers account for most of this resistance. For patients weighing less than 10 kg, some anesthesiologists prefer the Mapleson D circuit or the Bain system because of their low resistance and light weight (see Chapter 3). Nonetheless, because breathing-circuit resistance is easily overcome by positive-pressure ventilation, the circle system can be safely used in patients of all ages if ventilation is controlled. Monitoring of airway pressure may provide early evidence of obstruction from a kinked endotracheal tube or accidental advancement of the tube into a mainstem bronchus.

Many anesthesia ventilators on older machines are designed for adult patients and cannot reliably provide the reduced tidal volumes and rapid rates required by neonates and infants. Unintentional delivery of large tidal volumes to a small child can generate excessive peak airway pressures and cause barotrauma. The pressure-limited mode, which is found on nearly all newer anesthesia ventilators, should be used for neonates, infants, and toddlers. Small tidal volumes can also be manually delivered with greater ease with a 1-L breathing bag than with a 3-L adult bag. For children less than 10 kg, adequate tidal volumes are achieved with peak inspiratory pressures of 15–18 cm H_2O. For larger children the volume control ventilation may be used and tidal volumes may be set at 6–8 mL/kg. Many spirometers are less accurate at lower tidal volumes. In addition, the gas lost in long, compliant adult breathing circuits becomes large relative to a child's small tidal volume. For this reason, pediatric tubing is usually shorter, lighter, and stiffer (less compliant). Nevertheless, one should recall that the dead space contributed by the tube and circle system consists only of the volume of the distal limb of the Y-connector and that portion of the endotracheal tube that extends beyond the airway. In other words, the dead space is unchanged by switching from adult to pediatric tubing. Condenser humidifiers or heat and moisture exchangers (HMEs) can add considerable dead space; depending on the size of the patient, they either should not be used or an appropriately sized, pediatric HME should be employed.

Anesthesia can be maintained in pediatric patients with the same agents as in adults. Some clinicians switch to isoflurane following a sevoflurane induction in the hope of reducing the likelihood of emergence agitation or postoperative delirium (see above). If sevoflurane is continued for maintenance, administration of an opioid (eg, fentanyl, 1–1.5 mcg/kg) 15–20 min before the end of the

procedure can reduce the incidence of emergence delirium and agitation if the surgical procedure is likely to produce postoperative pain. Although the MAC is greater in children than in adults (see Table 42–4), neonates may be particularly susceptible to the cardiodepressant effects of general anesthetics. Neonates and sick children may not tolerate increased concentrations of volatile agents required when the volatile agent alone is used to maintain good surgical operating conditions.

Perioperative Fluid Requirements

11 One must pay particular attention to fluid management in younger pediatric patients because these patients have limited margins for error. A programmable infusion pump or a buret with a microdrip chamber is useful for accurate measurements. Drugs can be flushed through low dead-space tubing to minimize unnecessary fluid administration. Fluid overload is diagnosed by prominent veins, flushed skin, increased blood pressure, decreased serum sodium, and a loss of the folds in the upper eyelids.

Fluid therapy can be divided into maintenance, deficit, and replacement requirements.

A. Maintenance Fluid Requirements

Maintenance requirements for pediatric patients can be determined by the "4:2:1 rule": 4 mL/kg/h for the first 10 kg of weight, 2 mL/kg/h for the second 10 kg, and 1 mL/kg/h for each remaining kilogram. The choice of maintenance fluid remains controversial. A solution such as D_5½ NS with 20 mEq/L of potassium chloride provides adequate dextrose and electrolytes at these maintenance infusion rates. D_5¼ NS may be a better choice in neonates because of their limited ability to handle sodium loads. Children up to the age of 8 years require 6 mg/kg/min of glucose to maintain euglycemia (40–125 mg/dL); premature neonates require 6–8 mg/kg/min. Older children and adults require only 2 mg/kg/min and in these patients euglycemia is normally well maintained by hepatic glycogenolysis and gluconeogenesis. Both hypoglycemia and hyperglycemia should be avoided; however, the amount of hepatic glucose production is widely variable during major surgery and critical illness. Thus glucose infusion rates during longer surgeries, particularly in neonates and infants, should be adjusted based on blood glucose measurements.

B. Deficits

In addition to a maintenance infusion, any preoperative fluid deficits must be replaced. For example, if a 5-kg infant has not received oral or intravenous fluids for 4 h prior to surgery, a deficit of 80 mL has accrued (5 kg × 4 mL/kg/h × 4 h). In contrast to adults, infants respond to dehydration with decreased blood pressure and without increased heart rate. Preoperative fluid deficits are often administered with hourly maintenance requirements in aliquots of 50% in the first hour and 25% in the second and third hours. In the example above, a total of 60 mL would be given in the first hour (80/2 + 20) and 40 mL in the second and third hours (80/4 + 20). Bolus administration of dextrose-containing solutions is avoided to prevent hyperglycemia. Preoperative fluid deficits are usually replaced with a balanced salt solution (eg, lactated Ringer's injection) or ½NS. In both cases, glucose is omitted to prevent hyperglycemia. Compared with lactated Ringer's injection, normal saline has the disadvantage of promoting hyperchloremic acidosis.

C. Replacement Requirements

Replacement can be subdivided into blood loss and third-space loss.

1. Blood loss—The blood volume of premature neonates (100 mL/kg), full-term neonates (85–90 mL/kg), and infants (80 mL/kg) is proportionately larger than that of adults (65–75 mL/kg). An initial hematocrit of 55% in the healthy full-term neonate gradually falls to as low as 30% in the 3-month-old infant before rising to 35% by 6 months. Hemoglobin (Hb) type is also changing during this period: from a 75% concentration of HbF (greater oxygen affinity, reduced Pao_2, poor tissue unloading) at birth to almost 100% HbA (reduced oxygen affinity, high Pao_2, good tissue unloading) by 6 months.

Blood loss has been typically replaced with non–glucose-containing crystalloid (eg, 3 mL of lactated Ringer's injection for each milliliter of blood lost) or colloid solutions (eg, 1 mL of 5% albumin for each milliliter of blood lost) until the patient's hematocrit reaches a predetermined lower limit. In recent years there has been increased

emphasis on avoiding excessive fluid administration; thus blood loss is now commonly replaced by either colloid (eg, albumin) or packed red cells. In premature and sick neonates, the target hematocrit (for transfusion) may be as great as 40%, whereas in healthy older children a hematocrit of 20–26% is generally well tolerated. Because of their small intravascular volume, neonates and infants are at an increased risk for electrolyte disturbances (eg, hyperglycemia, hyperkalemia, and hypocalcemia) that can accompany rapid blood transfusion. Dosing of packed red blood cell transfusions is discussed in Chapter 51. Platelets and fresh frozen plasma, 10–15 mL/kg, should be given when blood loss exceeds 1–2 blood volumes. Recent practice, particularly with blood loss from trauma, favors "earlier" administration of plasma and platelets. One unit of platelets per 10 kg weight raises the platelet count by about 50,000/μL. The pediatric dose of cryoprecipitate is 1 unit/10 kg weight.

2. "Third-space" loss—These losses are impossible to measure and must be estimated by the extent of the surgical procedure. In recent years the third space has even been attributed to overzealous fluid administration during resuscitation.

One popular fluid administration guideline is 0–2 mL/kg/h for relatively atraumatic surgery (eg, strabismus correction where there should be *no* third-space loss) and up to 6–10 mL/kg/h for traumatic procedures (eg, abdominal abscess). Third-space loss is usually replaced with lactated Ringer's injection (see Chapter 49). It is safe to say that all issues relating to the third space have never been more controversial.

Regional Anesthesia and Analgesia

The primary uses of regional techniques in pediatric anesthesia have been to supplement and reduce general anesthetic requirements and to provide better postoperative pain relief. Blocks range in complexity from the relatively simple peripheral nerve blocks (eg, penile block, ilioinguinal block); to brachial plexus, sciatic nerve, and femoral nerve blocks; to major conduction blocks (eg, spinal or epidural techniques). Regional blocks in children (as in adults) are often facilitated by ultrasound guidance, sometimes with nerve stimulation.

Caudal blocks have proved useful following a variety of surgeries, including circumcision, inguinal herniorrhaphy, hypospadias repair, anal surgery, clubfoot repair, and other subumbilical procedures. Contraindications include infection around the sacral hiatus, coagulopathy, or anatomic abnormalities. The patient is usually lightly anesthetized or sedated and placed in the lateral position.

For pediatric caudal anesthesia, a short-bevel 22-gauge needle can be used. If the loss-of-resistance technique is used, the glass syringe should be filled with saline, not air, because of the latter's possible association with air embolism. After the characteristic pop that signals penetration of the sacrococcygeal membrane, the needle angle of approach is reduced and the needle is advanced only a few more millimeters to avoid entering the dural sac or the anterior body of the sacrum. Aspiration is used to check for blood or cerebrospinal fluid; local anesthetic can then be slowly injected; failure of a 2-mL test dose of local anesthetic with epinephrine (1:200,000) to produce tachycardia helps exclude intravascular placement.

Many anesthetic agents have been used for caudal anesthesia in pediatric patients, with 0.125–0.25% bupivacaine (up to 2.5 mg/kg) or 0.2% ropivacaine being most common. Ropivacaine, 0.2%, can provide analgesia similar to bupivacaine but with less motor blockade. Ropivacaine appears to have less cardiac toxicity than bupivacaine when compared milligram to milligram. Addition of epinephrine to caudal solutions tends to increase the degree of motor block. Clonidine, either by itself or combined with local anesthetics, has also been widely used. Morphine sulfate (25 mcg/kg) or hydromorphone (6 mcg/kg) may be added to the local anesthetic solution to prolong postoperative analgesia for inpatients, but it increases the risk of delayed postoperative respiratory depression. The volume of local anesthetic required depends on the level of blockade desired, ranging from 0.5 mL/kg for a sacral block to 1.25 mL/kg for a midthoracic block. Single-shot injections generally last 4–12 h. Placement of 20-gauge caudal catheters with continuous infusion of local anesthetic (eg, 0.125% bupivacaine or 0.1% ropivacaine at 0.2–0.4 mg/kg/h) or an opioid (eg, fentanyl, 2 mcg/mL at 0.6 mcg/kg/h)

allows prolonged anesthesia and postoperative analgesia. Complications are rare but include local anesthetic toxicity from increased blood concentrations (eg, seizures, hypotension, arrhythmias), spinal blockade, and respiratory depression. Postoperative urinary retention does not appear to be a problem following single-dose caudal anesthesia.

Lumbar and thoracic epidural catheters can be placed in anesthetized children using the standard loss-of-resistance technique and either a midline or paramedian approach. In small children, caudal epidural catheters have been passed into a thoracic position with the tip localized radiographically.

Unilateral transversus abdominis plane (TAP) blocks are commonly used to provide analgesia after hernia repair. Bilateral TAP blocks can be used to provide effective postoperative analgesia after abdominal surgery with a lower midline incision. Rectus sheath blocks can be used for midline incision in the upper abdomen.

Spinal anesthesia has been used in some centers for infraumbilical procedures in neonates and infants. Infants and children typically have minimal hypotension from sympathectomy. Intravenous access can be established (conveniently in the foot) after the spinal anesthetic has been administered. This technique has become more widely used for neonates and infants as the potential neurotoxicity risks of general anesthesia in these patients have received greater attention.

Most children will not tolerate placement of nerve blocks or nerve block catheters while awake; however, most peripheral block techniques can be performed safely in anesthetized children. When the area of operation is the upper extremity we recommend those brachial plexus procedures that can most readily be performed using ultrasound guidance, specifically axillary, supraclavicular, and infraclavicular blocks. We suggest that interscalene block be performed only by those having experience and skill with ultrasound guidance and only for procedures where other block techniques would be inferior (eg, upper shoulder procedures) due to the reported rare occurrence of accidental intramedullary injections when interscalene blocks were performed in anesthetized adults. Single-shot and continuous femoral and sciatic blocks are easily performed using ultrasound guidance. The latter can be performed using either a gluteal or a popliteal approach.

A wide variety of other terminal nerve blocks (eg, digital nerve, median nerve, occipital nerve, etc) are easily performed to reduce postoperative pain in children.

Sedation for Procedures in and out of the Operating Room

Sedation is often requested for pediatric patients inside and outside the operating room for nonsurgical procedures. Cooperation and motionlessness may be required for imaging studies, bronchoscopy, gastrointestinal endoscopy, cardiac catheterization, dressing changes, and minor procedures (eg, casting and bone marrow aspiration). Requirements vary depending on the patient and the procedure, ranging from anxiolysis (minimal sedation), to conscious sedation (moderate sedation and analgesia), to deep sedation/analgesia, and finally to general anesthesia. Anesthesiologists are usually held to the same standards when they provide moderate or deep sedation as when they provide general anesthesia. This includes preoperative preparation (eg, fasting), assessment, monitoring, and postoperative care. Airway obstruction and hypoventilation are the most commonly encountered problems associated with moderate or deep sedation. With deep sedation and general anesthesia cardiovascular depression can also be a problem.

Table 42–3 includes doses of sedative-hypnotic drugs. One of the sedatives commonly used by nonanesthesia personnel in the past was chloral hydrate, 25–100 mg/kg orally or rectally. It has a slow onset of up to 60 min and a long half-life (8–11 h) that results in prolonged somnolence. Although it generally has little effect on ventilation, it can cause fatal airway obstruction in patients with sleep apnea. Overall, chloral hydrate is a poor choice given its propensity for producing cardiac arrhythmias when it is used in the larger doses needed for moderate sedation. Midazolam, 0.5 mg/kg orally or 0.1–0.15 mg/kg intravenously, is particularly useful because its effects can be readily reversed with flumazenil. Doses should be reduced whenever more than one agent is used because of the potential for synergistic respiratory and cardiovascular depression.

Propofol is by far the most useful sedative-hypnotic drug. Although the drug is not approved for sedation of pediatric ICU patients and is not approved for administration by anyone other than those trained in the administration of general anesthesia, it can be dosed safely for most procedures at infusion rates up to 200 mcg/kg/min. In countries other than the United States, propofol is often administered using the Diprifusor, a computer-controlled infusion pump that maintains a constant target site concentration. Supplemental oxygen and close monitoring of the airway, ventilation, and other vital signs are mandatory (as with other agents). An LMA is usually well tolerated at higher doses.

Emergence & Recovery

Pediatric patients are particularly vulnerable to two postanesthetic complications: laryngospasm and postintubation croup. As with adult patients, postoperative pain requires close, careful attention. Pediatric anesthesia practice varies widely, particularly in regard to extubation following a general anesthetic. In some pediatric hospitals, all children who will be extubated after a general anesthetic arrive in the postanesthesia care unit (PACU) with the tube still in place. They are subsequently extubated by the PACU nurse when defined criteria are reached. In other centers, nearly all children are extubated in the operating room before arriving in the PACU. High quality and safety are reported at centers following either protocol.

A. Laryngospasm

Laryngospasm is a forceful, involuntary spasm of the laryngeal musculature caused by stimulation of the superior laryngeal nerve (see Chapter 19). It may occur at induction, emergence, or any time in between without an endotracheal tube. Presumably it can also occur when a tube is in place, but its occurrence will not be recognized. Laryngospasm is more common in young pediatric patients (almost 1 in 50 anesthetics) than in adults, and is most common in infants 1–3 months old. Laryngospasm at the end of a procedure can usually be avoided by extubating the patient either while awake (opening the eyes) or while deeply anesthetized (spontaneously breathing but not swallowing or coughing); both techniques have advocates and despite strong opinions, evidence is lacking as to which is the better approach. Extubation during the interval between these extremes, however, is generally recognized as more hazardous. Recent URI or exposure to secondhand tobacco smoke predisposes children to laryngospasm on emergence. Treatment of laryngospasm includes gentle positive-pressure ventilation, forward jaw thrust, intravenous lidocaine (1–1.5 mg/kg), or paralysis with intravenous succinylcholine (0.5–1 mg/kg), or rocuronium (0.4 mg/kg) and controlled ventilation. Intramuscular succinylcholine (4–6 mg/kg) remains an acceptable alternative in patients without intravenous access and in whom conservative measures have failed. Laryngospasm is usually an immediate postoperative event but may occur in the recovery room as the patient wakes up and chokes on pharyngeal secretions. For this reason, recovering pediatric patients should be positioned in the lateral position so that oral secretions pool and drain away from the vocal cords. When the child begins to regain consciousness, having the parents at the bedside may reduce his or her anxiety.

B. Postintubation Croup

Croup is due to glottic or tracheal edema. Because the narrowest part of the pediatric airway is the cricoid cartilage, this is the most susceptible area. Croup is less common with endotracheal tubes that are small enough to allow a slight gas leak at 10–25 cm H_2O. Postintubation croup is associated with early childhood (age 1–4 years), repeated intubation attempts, overly large endotracheal tubes, prolonged surgery, head and neck procedures, and excessive movement of the tube (eg, coughing with the tube in place, moving the patient's head). Intravenous dexamethasone (0.25–0.5 mg/kg) may prevent formation of edema, and inhalation of nebulized racemic epinephrine (0.25–0.5 mL of a 2.25% solution in 2.5 mL normal saline) is an often effective treatment. Although postintubation croup is a complication that occurs later than laryngospasm, it will almost always appear within 3 h after extubation.

C. Postoperative Pain Management

Pain in pediatric patients has received considerable attention in recent years, and over that time the use

of regional anesthetic and analgesic techniques (as described above) has greatly increased. Commonly used parenteral opioids include fentanyl (1–2 mcg/kg), morphine (0.05–0.1 mg/kg), hydromorphone (15 mcg/kg), and meperidine (0.5 mg/kg). A multimodal technique incorporating ketorolac (0.5–0.75 mg/kg) will reduce opioid requirements. Oral, rectal, or intravenous acetaminophen may also be a helpful substitute for ketorolac.

Patient-controlled analgesia (see Chapter 48) can also be successfully used in patients as young as 6–7 years old, depending on their maturity and on preoperative preparation. Commonly used opioids include morphine and hydromorphone. With a 10-min lockout interval, the recommended interval dose is either morphine, 20 mcg/kg, or hydromorphone, 5 mcg/kg. As with adults, continuous infusions increase the risk of respiratory depression; typical continuous infusion doses are morphine, 0–12 mcg/kg/h, or hydromorphone, 0–3 mcg/kg/h. The subcutaneous route may be used with morphine. Nurse-controlled and parent-controlled analgesia remain controversial but widely used techniques for pain control in children.

As with adults, epidural infusions for postoperative analgesia often consist of a local anesthetic combined with an opioid. Bupivacaine, 0.1–0.125%, or ropivacaine, 0.1–0.2%, are often combined with fentanyl, 2–2.5 mcg/mL (or equivalent concentrations of morphine or hydromorphone). Recommended infusion rates depend on the size of the patient, the final drug concentration, and the location of the epidural catheter, and range from 0.1 to 0.4 mL/kg/h. Local anesthetic infusions can also be used with continuous nerve block techniques, but this is less common than in adults.

Anesthetic Considerations in Specific Pediatric Conditions

PREMATURITY

Pathophysiology

Prematurity is defined as birth before 37 weeks of gestation. This is in contrast to *small for gestational age*, which describes an infant (full-term or premature) whose age-adjusted weight is less than the fifth percentile. The multiple medical problems of premature neonates are usually due to immaturity of major organ systems or to intrauterine asphyxia. Pulmonary complications include hyaline membrane disease, apneic spells, and bronchopulmonary dysplasia. Exogenous pulmonary surfactant has proved to be an effective treatment for respiratory distress syndrome in premature infants. A patent ductus arteriosus leads to shunting, and may possibly lead to pulmonary edema and congestive heart failure. Persistent hypoxia or shock may result in ischemic gut and necrotizing enterocolitis. Prematurity increases susceptibility to infection, hypothermia, intracranial hemorrhage, and kernicterus. Premature neonates also have an increased incidence of congenital anomalies.

Anesthetic Considerations

The small size (often <1000 g) and fragile medical condition of premature neonates demand that special attention be paid to airway control, fluid management, and temperature regulation. The problem of retinopathy of prematurity, a fibrovascular proliferation overlying the retina that may lead to progressive visual loss, deserves special consideration. While hyperoxia is associated with this blinding disease, the presence of fetal hemoglobin and treatment with vitamin E may be protective. Recent evidence suggests that fluctuating oxygen levels may be more damaging than increased oxygen tensions. Moreover, other major risk factors, such as respiratory distress, apnea, mechanical ventilation, hypoxia, hypercarbia, acidosis, heart disease, bradycardia, infection, parenteral nutrition, anemia, and multiple blood transfusions, must be present. Nonetheless, oxygenation should be continuously monitored with pulse oximetry or transcutaneous oxygen analysis, with particular attention given to infants younger than 44 weeks postconception. Normal Pao_2 is 60–80 mm Hg in neonates. Excessive inspired oxygen concentrations are avoided by blending oxygen with air. Excessive inspired oxygen tensions can also predispose to chronic lung disease.

Anesthetic requirements of premature neonates are reduced. Opioid-based anesthetics are often favored over pure volatile anesthetic-based

techniques because of the perceived tendency of the latter to cause myocardial depression.

Premature infants whose age is less than 50 (some authorities would say 60) weeks postconception at the time of surgery are prone to postoperative episodes of obstructive and central apnea for up to 24 h. In fact, even term infants can experience rare apneic spells following general anesthesia. **Risk factors for postanesthetic apnea include a low gestational age at birth, anemia (<30%), hypothermia, sepsis, and neurological abnormalities**. The risk of postanesthetic apnea may be decreased by intravenous administration of caffeine (10 mg/kg) or aminophylline.

Thus, elective (particularly outpatient) procedures should be deferred until the preterm infant reaches the age of at least 50 weeks postconception. A 6-month symptom-free interval has been suggested for infants with a history of apneic episodes or bronchopulmonary dysplasia. If surgery must be performed earlier, monitoring with pulse oximetry for 12–24 h postoperatively is mandatory for infants less than 50 weeks postconception; infants between 50 and 60 weeks postconception should be closely observed in the postanesthesia recovery unit for at least 2 h.

Sick, premature neonates often receive multiple transfusions of blood during their stay in the intensive care nursery. Their immunocompromised status predisposes them to cytomegalovirus infection following transfusion. Signs of infection include generalized lymphadenopathy, fever, pneumonia, hepatitis, hemolytic anemia, and thrombocytopenia. Preventive measures include using cytomegalovirus-seronegative donor blood or, more commonly, leukocyte-reduced blood cells.

INTESTINAL MALROTATION & VOLVULUS

Pathophysiology

Malrotation of the intestines is a developmental abnormality that permits spontaneous abnormal rotation of the midgut around the mesentery (superior mesenteric artery). The incidence of malrotation is estimated to be about 1:500 live births. Most patients with malrotation of the midgut present during infancy with symptoms of bowel obstruction. Coiling of the duodenum with the ascending colon can produce complete or partial duodenal obstruction. The most serious complication of malrotation, a midgut volvulus, can rapidly compromise intestinal blood supply causing infarction. Midgut volvulus is a true surgical emergency that most commonly occurs in infancy, with up to one third occurring in the first week of life. The mortality rate is high (up to 25%). Typical symptoms are bilious vomiting, progressive abdominal distention and tenderness, metabolic acidosis, and hemodynamic instability. Bloody diarrhea may be indicative of bowel infarction. Abdominal ultrasonography or upper gastrointestinal imaging confirms the diagnosis.

Anesthetic Considerations

Surgery provides the only definitive treatment of malrotation and midgut volvulus. If obstruction is present but obvious volvulus has not yet occurred, preoperative preparation may include stabilization of any coexisting conditions, insertion of a nasogastric (or orogastric tube) to decompress the stomach, broad-spectrum antibiotics, fluid and electrolyte replacement, and prompt transport to the operating room.

These patients are at increased risk for pulmonary aspiration. Depending on the size of the patient, rapid sequence induction (or awake intubation) should be employed. Patients with volvulus are usually hypovolemic and acidotic, and may tolerate anesthesia poorly. Ketamine may be the preferred anesthetic induction agent. An opioid-based anesthetic can also be used as postoperative ventilation will often be necessary. Fluid resuscitation, likely including blood products, and sodium bicarbonate therapy are usually necessary. Arterial and central venous lines are helpful. Surgical treatment includes reducing the volvulus, freeing the obstruction, widening the base of mesenteric attachments, and resecting any obviously necrotic bowel. Bowel edema can complicate abdominal closure and has the potential to produce an abdominal compartment syndrome. The latter can impair ventilation, hinder venous return, and produce renal compromise; delayed

fascial closure or temporary closure with a Silastic "silo" may be necessary. A second-look laparotomy may be required 24–48 h later to ensure viability of the remaining bowel.

CONGENITAL DIAPHRAGMATIC HERNIA

Pathophysiology

During fetal development, the gut can herniate into the thorax through one of three possible diaphragmatic defects: the left or right posterolateral foramen of Bochdalek or the anterior foramen of Morgagni. The reported incidence of diaphragmatic hernia is 1 in 3000–5000 live births. Left-sided herniation is the most common type (90%). Hallmarks of **diaphragmatic herniation** include hypoxia, a scaphoid abdomen, and evidence of bowel in the thorax by auscultation or radiography. Congenital diaphragmatic hernia is often diagnosed antenatally during a routine obstetric ultrasound examination. A reduction in alveoli and bronchioli (pulmonary hypoplasia) and malrotation of the intestines are almost always present. The ipsilateral lung is particularly impaired and the herniated gut can compress and retard the maturation of both lungs. Diaphragmatic hernia is often accompanied by marked pulmonary hypertension and is associated with 40–50% mortality. Cardiopulmonary compromise is primarily due to pulmonary hypoplasia and pulmonary hypertension rather than to the mass effect of the herniated viscera.

Treatment is aimed at immediate stabilization with sedation, paralysis, and moderate hyperventilation. Pressure-limited ventilation is used. Some centers employ permissive hypercapnia (postductal $Paco_2$ < 65 mm Hg) and accept mild hypoxemia (preductal Spo_2 > 85%) in an effort to reduce pulmonary barotrauma. High-frequency oscillatory ventilation (HFOV) can improve ventilation and oxygenation with less barotrauma. Inhaled nitric oxide may be used to lower pulmonary artery pressures but does not appear to improve survival. If the pulmonary hypertension stabilizes and there is little right-to-left shunting, early surgical repair may be undertaken. If the patient fails to stabilize, extracorporeal membrane oxygenation (ECMO) may be undertaken. When initiated in the critical care unit in a neonate, venoarterial ECMO usually involves pumping blood from the jugular vein through a membrane oxygenator and countercurrent heat exchanger before returning it to ipsilateral carotid artery. Timing of the repair following ECMO is controversial. Treatment with prenatal intrauterine surgery has not been shown to improve outcomes.

Anesthetic Considerations

Gastric distention must be minimized by placement of a nasogastric tube and avoidance of high levels of positive-pressure ventilation. The neonate is preoxygenated and intubated awake, or without the aid of muscle relaxants. Anesthesia is maintained with low concentrations of volatile agents or opioids, muscle relaxants, and air as tolerated. Hypoxia and expansion of air in the bowel contraindicate the use of nitrous oxide. If possible, peak inspiratory airway pressures should be less than 30 cm H_2O. **A sudden fall in lung compliance, blood pressure, or oxygenation may signal a contralateral (usually right-sided) pneumothorax and necessitate placement of a chest tube**. Arterial blood gases are preferably monitored by sampling a preductal artery if an umbilical artery catheter is not already in place. Surgical repair is performed via a subcostal incision of the affected side; the bowel is reduced into the abdomen and the diaphragm is closed. Aggressive attempts at expansion of the ipsilateral lung following surgical decompression are detrimental. Postoperative prognosis parallels the extent of pulmonary hypoplasia and the presence of other congenital defects.

TRACHEOESOPHAGEAL FISTULA

Pathophysiology

There are several types of tracheoesophageal fistula (Figure 42–3). The most common (type IIIB) is the combination of an upper esophagus that ends in a blind pouch and a lower esophagus that connects to

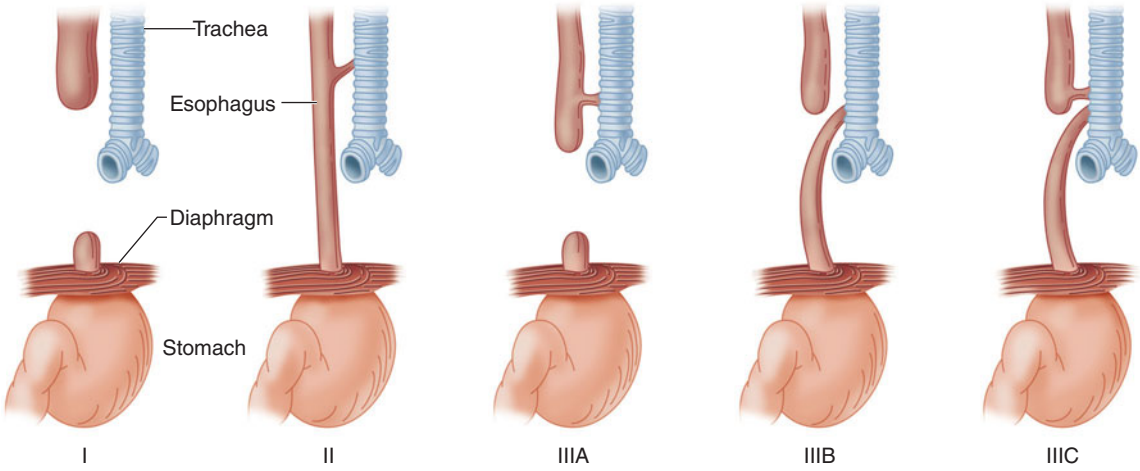

FIGURE 42–3 Of the five types of tracheoesophageal fistula, type IIIB represents 90% of cases.

the trachea. Breathing results in gastric distention, whereas feeding leads to choking, coughing, and cyanosis (three Cs). The diagnosis is suspected by failure to pass a catheter into the stomach and confirmed by visualization of the catheter coiled in a blind, upper esophageal pouch. Aspiration pneumonia and the coexistence of other congenital anomalies (eg, cardiac) are common. These may include the association of *v*ertebral defects, *a*nal atresia, *t*racheoesophageal fistula with *e*sophageal atresia, and *r*adial dysplasia, known as the VATER syndrome. The VACTERL variant also includes *c*ardiac and *l*imb anomalies. Preoperative management is directed at identifying all congenital anomalies and preventing aspiration pneumonia. This may include maintaining the patient in a head-up position, using an oral-esophageal tube, and avoiding feedings. In some instances gastrostomy may be performed under local anesthesia. Definitive surgical treatment is usually postponed until any pneumonia clears or improves with antibiotic therapy.

Anesthetic Considerations

These neonates tend to have copious pharyngeal secretions that require frequent suctioning before and during surgery. Positive-pressure ventilation is avoided prior to intubation, as the resulting gastric distention may interfere with lung expansion. Intubation is often performed awake and without muscle relaxants. These neonates are often dehydrated and malnourished due to poor oral intake.

The key to successful management is correct endotracheal tube position. Ideally, the tip of the tube lies distal to the fistula and proximal to the carina, so that anesthetic gases pass into the lungs instead of the stomach. This is impossible if the fistula connects to the carina or a mainstem bronchus. In these situations, intermittent venting of a gastrostomy tube may permit positive-pressure ventilation without excessive gastric distention. Suctioning of the gastrostomy tube and upper esophageal pouch tube helps prevent aspiration pneumonia. Surgical division of the fistula and esophageal anastomosis is performed via a right extrapleural thoracotomy with the patient in the left lateral position. A precordial stethoscope should be placed in the dependent (left) axilla, since obstruction of the mainstem bronchus during surgical retraction is not uncommon. A drop in oxygen saturation indicates that the retracted lung needs to be reexpanded. Surgical retraction can also compress the great vessels, trachea, heart, and vagus nerve. Blood pressure should be continuously monitored with an arterial line. These infants often require ventilation with 100% oxygen. Blood should be immediately available for transfusion. Postoperative complications include gastroesophageal reflux, aspiration pneumonia, tracheal compression, and anastomotic leakage. Most patients

must remain intubated and receive positive-pressure ventilation in the immediate postoperative period. Neck extension and instrumentation (eg, suctioning) of the esophagus may disrupt the surgical repair and should be avoided.

GASTROSCHISIS & OMPHALOCELE

Pathophysiology

Gastroschisis and omphalocele are congenital disorders characterized by defects in the abdominal wall that allow external herniation of viscera. Omphaloceles occur at the base of the umbilicus, have a hernia sac, and are often associated with other congenital anomalies such as trisomy 21, diaphragmatic hernia, and cardiac and bladder malformations. In contrast, the gastroschisis defect is usually lateral to the umbilicus, does not have a hernia sac, and is often an isolated finding. Antenatal diagnosis by ultrasound can be followed by elective cesarean section at 38 weeks and immediate surgical repair. Perioperative management centers around preventing hypothermia, infection, and dehydration. These problems are usually more serious in gastroschisis, as the protective hernial sac is absent.

Anesthetic Considerations

The stomach is decompressed with a nasogastric tube before induction. Intubation can be accomplished with the patient awake or asleep and with or without muscle relaxation. Nitrous oxide should be avoided to prevent further bowel distention. Muscle relaxation is required for replacing the bowel into the abdominal cavity. A one-stage closure (primary repair) is often not advisable, as it can cause an abdominal compartment syndrome. A staged closure with a temporary Silastic "silo" may be necessary, followed by a second procedure a few days later for complete closure. Suggested criteria for a staged closure include intragastric or intravesical pressure greater than 20 cm H_2O, peak inspiratory pressure greater than 35 cm H_2O, or an end-tidal CO_2 greater than 50 mm Hg. **Third-space fluid losses are replaced with a balanced salt solution and 5% albumin**. The neonate remains intubated after the procedure and is weaned from the ventilator over the next 1–2 days in the ICU.

HYPERTROPHIC PYLORIC STENOSIS

Pathophysiology

Hypertrophic pyloric stenosis impedes emptying of gastric contents. **Persistent vomiting depletes potassium, chloride, hydrogen, and sodium ions, causing hypochloremic metabolic alkalosis**. Initially, the kidney tries to compensate for the alkalosis by excreting sodium bicarbonate in the urine. Later, as hyponatremia and dehydration worsen, the kidneys must conserve sodium even at the expense of hydrogen ion excretion (paradoxic aciduria). Correction of the volume and ion deficits and metabolic alkalosis requires hydration with a sodium chloride (rather than lactated Ringer's) solution supplemented with potassium chloride.

Anesthetic Considerations

Surgery should be delayed until fluid and electrolyte abnormalities have been corrected. Operation for correction of pyloric stenosis is never an emergency. The stomach should be emptied with a nasogastric or orogastric tube; the tube should be suctioned with the patient in the supine, lateral, and prone positions. Diagnosis often requires contrast radiography, and all contrast media will need to be suctioned from the stomach before induction. Techniques for intubation and induction vary, but in all cases the patient's increased risk of aspiration must be considered. Experienced clinicians have variously advocated awake intubation, rapid sequence intravenous induction, and even careful inhalation induction in selected patients. Pyloromyotomy is a short procedure that requires muscle relaxation. These neonates may be at increased risk for respiratory depression and hypoventilation in the recovery room because of persistent metabolic (measurable in arterial blood) or cerebrospinal fluid alkalosis (despite neutral arterial pH).

INFECTIOUS CROUP, FOREIGN BODY ASPIRATION, & ACUTE EPIGLOTTITIS

Pathophysiology

Croup is obstruction of the airway characterized by a barking cough. One type of croup, postintubation croup, has already been discussed. Another type is due to viral infection. **Infectious croup** usually follows a viral URI in children aged 3 months to 3 years. The airway *below* the epiglottis is involved (laryngotracheobronchitis). Infectious croup progresses slowly and rarely requires intubation. Foreign body aspiration is typically encountered in children aged 6 months to 5 years. Commonly aspirated objects include peanuts, coins, screws, nails, tacks, and small pieces of toys. Onset is typically acute and the obstruction may be supraglottic, glottic, or subglottic. Stridor is prominent with the first two, whereas wheezing is more common with the latter. A clear history of an aspiration may be absent. **Acute epiglottitis** is a bacterial infection (most commonly *Haemophilus influenzae* type B) classically affecting 2- to 6-year-old children but also occasionally appearing in older children and adults. It rapidly progresses from a sore throat to dysphagia and complete airway obstruction. The term *supraglottitis* has been suggested because the inflammation typically involves all supraglottic structures. Endotracheal intubation and antibiotic therapy can be lifesaving. Epiglottitis has increasingly become a disease of adults because of the widespread use of *H influenza* vaccines in children.

Anesthetic Considerations

Patients with croup are managed conservatively with oxygen and mist therapy. Nebulized racemic epinephrine (0.5 mL of a 2.25% solution in 2.5 mL normal saline) and intravenous dexamethasone (0.25–0.5 mg/kg) are used. Indications for intubation include progressive intercostal retractions, obvious respiratory fatigue, and central cyanosis.

Anesthetic management of a foreign body aspiration is challenging, particularly with supraglottic and glottic obstruction. Minor manipulation of the airway can convert partial into complete obstruction. Experts recommend careful inhalational induction for a supraglottic object and gentle upper airway endoscopy to remove the object, secure the airway, or both. When the object is subglottic, a rapid-sequence or inhalational induction is usually followed by rigid bronchoscopy by the surgeon or endotracheal intubation and flexible bronchoscopy. Surgical preferences may vary according to the size of the patient and the nature and location of the foreign body. Close cooperation between the surgeon and anesthesiologist is essential.

Children with impending airway obstruction from epiglottitis present in the operating room for definitive diagnosis by laryngoscopy followed by intubation. A preoperative lateral neck radiograph may show a characteristic thumblike epiglottic shadow, which is very specific but often absent. The radiograph is also helpful in revealing other causes of obstruction, such as foreign bodies. Stridor, drooling, hoarseness, rapid onset and progression, tachypnea, chest retractions, and a preference for the upright position are predictive of airway obstruction. Total obstruction can occur at any moment, and adequate preparations for a possible tracheostomy must be made prior to induction of general anesthesia. Laryngoscopy should not be performed before induction of anesthesia because of the possibility of laryngospasm. In most cases, an inhalational induction is performed with the patient in the sitting position, using a volatile anesthetic and oxygen. Oral intubation with an endotracheal tube one half to one size smaller than usual is attempted as soon as an adequate depth of anesthesia is established. The oral tube may be replaced with a well-secured nasal endotracheal tube at the end of the procedure, as the latter is better tolerated in the postoperative period. If intubation is impossible, rigid bronchoscopy or emergency tracheostomy must be performed.

TONSILLECTOMY & ADENOIDECTOMY

Pathophysiology

Lymphoid hyperplasia can lead to upper airway obstruction, obligate mouth breathing, and even

pulmonary hypertension with cor pulmonale. Although these extremes of pathology are unusual, all children undergoing tonsillectomy or adenoidectomy should be considered to be at increased risk for perioperative airway problems.

Anesthetic Considerations

Surgery should be postponed if there is evidence of acute infection or suspicion of a clotting dysfunction (eg, recent aspirin ingestion). Administration of an anticholinergic agent will decrease pharyngeal secretions. A history of airway obstruction or apnea suggests an inhalational induction without paralysis until the ability to ventilate with positive pressure is established. A reinforced or preformed endotracheal tube (eg, RAE tube) may decrease the risk of kinking by the surgeon's self-retaining mouth gag. Blood transfusion is usually not necessary, but the anesthesiologist must be wary of occult blood loss. Gentle inspection and suctioning of the pharynx precede extubation. Although deep extubation decreases the chance of laryngospasm and may prevent blood clot dislodgment from coughing, most anesthesiologists prefer an awake extubation because of the risks of aspiration. Postoperative vomiting is common. The anesthesiologist must be alert in the recovery room for postoperative bleeding, which may be evidenced by restlessness, pallor, tachycardia, or hypotension. If reoperation is necessary to control bleeding, intravascular volume must first be restored. Evacuation of stomach contents with a nasogastric tube is followed by a rapid-sequence induction with cricoid pressure. Because of the possibility of bleeding and airway obstruction, children younger than 3 years old may be hospitalized for the first postoperative night. Sleep apnea and recent infection increase the risk of postoperative complications.

MYRINGOTOMY & INSERTION OF TYMPANOSTOMY TUBES

Pathophysiology

Children presenting for myringotomy and insertion of tympanostomy tubes have a long history of URIs that have spread through the eustachian tube, causing repeated episodes of otitis media. Causative organisms are usually bacterial and include *Pneumococcus, H influenza, Streptococcus*, and *Mycoplasma pneumoniae*. Myringotomy, a radial incision in the tympanic membrane, releases any fluid that has accumulated in the middle ear. Tympanostomy tubes provide long-term drainage. Because of the chronic and recurring nature of this illness, it is not surprising that these patients often have symptoms of a URI on the day of scheduled surgery.

Anesthetic Considerations

These are typically very short (10–15 min) outpatient procedures. Inhalational induction is a common technique. Unlike tympanoplasty surgery, nitrous oxide diffusion into the middle ear is not a problem during myringotomy because of the brief period of anesthetic exposure before the middle ear is vented. Because most of these patients are otherwise healthy and there is no blood loss, intravenous access is usually not necessary. Ventilation with a face mask or LMA minimizes the risk of perioperative respiratory complications (eg, laryngospasm) associated with intubation.

TRISOMY 21 SYNDROME (DOWN SYNDROME)

Pathophysiology

An additional chromosome 21—part or whole—results in the most common pattern of congenital human malformation: Down syndrome. Characteristic abnormalities of interest to the anesthesiologist include a short neck, irregular dentition, mental retardation, hypotonia, and a large tongue. Associated abnormalities include congenital heart disease in 40% of patients (particularly endocardial cushion defects and ventricular septal defect), subglottic stenosis, tracheoesophageal fistula, chronic pulmonary infections, and seizures. These neonates are often premature and small for their gestational age. Later in life many patients with Down syndrome undergo multiple procedures requiring general anesthesia.

Anesthetic Considerations

Because of anatomic differences, these patients often have difficult airways, particularly during infancy. The size of the endotracheal tube required is typically smaller than that predicted by age. Respiratory complications such as postoperative stridor and apnea are common. Neck flexion during laryngoscopy and intubation may result in atlantooccipital dislocation because of the congenital laxity of these ligaments. The possibility of associated congenital diseases must always be considered. As in all pediatric patients, care must be taken to avoid air bubbles in the intravenous line because of possible right-to-left shunts and paradoxical air emboli.

CYSTIC FIBROSIS

Pathophysiology

Cystic fibrosis is a genetic disease of the exocrine glands primarily affecting the pulmonary and gastrointestinal systems. Abnormally thick and viscous secretions coupled with decreased ciliary activity lead to pneumonia, wheezing, and bronchiectasis. Pulmonary function studies reveal increased residual volume and airway resistance with decreased vital capacity and expiratory flow rate. Malabsorption syndrome may lead to dehydration and electrolyte abnormalities.

Anesthetic Considerations

Premedication should not include respiratory depressants. Anticholinergic drugs have been used in large series without ill effects, and the choice either to use or not to use them appears to be inconsequential. Induction with inhalational anesthetics may be prolonged in patients with severe pulmonary disease. Intubation should not be performed until the patient is deeply anesthetized to avoid coughing and stimulation of mucus secretions. The patient's lungs should be suctioned during general anesthesia and before extubation to minimize the accumulation of secretions. Outcome is favorably influenced by preoperative and postoperative respiratory therapy that includes bronchodilators, incentive spirometry, postural drainage, and pathogen-specific antibiotic therapy.

SCOLIOSIS

Pathophysiology

Scoliosis is lateral rotation and curvature of the vertebrae and a deformity of the rib cage. It can have many etiologies, including idiopathic, congenital, neuromuscular, and traumatic. Scoliosis can affect cardiac and respiratory function. Elevated pulmonary vascular resistance from chronic hypoxia causes pulmonary hypertension and right ventricular hypertrophy. Respiratory abnormalities include reduced lung volumes and chest wall compliance. Pao_2 is reduced as a result of ventilation/perfusion mismatching, whereas an increased $Paco_2$ signals severe disease.

Anesthetic Considerations

Preoperative evaluation may include pulmonary function tests, arterial blood gases, and electrocardiography. Corrective surgery is complicated by the prone position, significant blood loss, and the possibility of paraplegia. Spinal cord function can be assessed by neurophysiological monitoring (somatosensory and motor evoked potentials, see Chapters 6 and 26) or by awakening the patient intraoperatively to test lower limb muscle strength. Patients with severe respiratory disease often remain intubated postoperatively. Patients with scoliosis due to muscular dystrophy are predisposed to malignant hyperthermia, cardiac arrhythmias, and untoward effects of succinylcholine (hyperkalemia, myoglobinuria, and sustained muscular contractures).

WEB SITE & GUIDELINES

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