CHAPTER 1

PERIOPERATIVE MANAGEMENT
OF THE NEONATAL PATIENT

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INTRODUCTION

Over the past several decades, advances in prenatal evaluation, neonatal care, diagnostic techniques, anesthesia, and clinical management have enhanced care of pediatric surgical patients. Neonates have their own physiologic characteristics that must govern their care. The most distinctive and rapidly changing functions occur during the neonatal period. This is due to the newborn infant’s adaptation from complete placental support to the extrauterine environment, differences in physiologic maturity of individual neonates, small size of these patients, and demands of growth and development.1 Advances in neonatal care have resulted in survival of increasing numbers of extremely low birth weight infants. However, pediatric surgeons and neonatologists are now faced with more complex diseases due to extreme prematurity. Derangements in temperature regulation, fluid and electrolyte homeostasis, glucose metabolism, hematologic indices, and immune function are magnified in this setting. Preterm infants are more vulnerable to specific problems such as intraventricular hemorrhage, hyaline membrane

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disease, and hyperbilirubinemia. This chapter will focus on principle considerations that distinguish the perioperative care of neonates.

GENERAL CONSIDERATIONS

Fetal Circulation and Implications of the Ductus Arteriosus

Fetal growth and development occur in a “hypoxic” environment and the placenta, rather than the lung, is the source of oxygen. Oxygen saturation of blood that flows through the umbilical vein is only 65%, corresponding to a partial pressure of oxygen of 35 mmHg. In the fetal right atrium, this blood mixes with even lower oxygen saturated blood that comes from the fetal liver, inferior and superior vena cava, and coronary sinus. This hypoxic environment is compensated by different mechanisms that help provide adequate oxygen to fetal tissues. First, in contrast to adult hemoglobin, fetal hemoglobin has a lower p50 which allows more efficient oxygen extraction from the placenta. Second, there are three physiologic shunts that allow preferential circulation of more saturated umbilical vein blood into the systemic circulation. These include the ductus venosus, which helps bypass unsaturated portal flow, foramen ovale, which allows flow into the left heart avoiding mixture with the superior vena cava and coronary sinus, and ductus arteriosus, which shunts blood from the pulmonary artery into the aorta for systemic oxygen delivery. Finally, fetal cardiac output is about three times greater than that of adults. This, coupled with low systemic resistance, allows better oxygen delivery. The two umbilical arteries that originate from the internal iliac arteries return blood with lower oxygen content from the systemic circulation back to the placenta.

Pulmonary vascular resistance in fetal life is suprasystemic and therefore the right ventricle performs twice the work as the left ventricle. Ninety-percent of right ventricular output goes into the aorta via the ductus arteriosus. Within hours to days after birth, there is physiologic closure of the ductus arteriosus as pulmonary vascular resistance decreases and systemic vascular resistance increases. These hemodynamic changes, together with an increase in arterial oxygen saturation, cause constriction of the ductus’ vascular smooth muscle, which shortens and narrows its lumen. This functional closure is followed by an anatomic closure several weeks later, resulting in the fibrotic ligamentum arteriosus.² Postnatal failure of the ductus to close can result in a left-to-right shunt into the pulmonary artery with resultant pulmonary hypertension and high output congestive heart failure. If this problem persists, pulmonary hypertension can get so severe that the shunt reverses, resulting in systemic hypoxemia.
In preterm infants, clinical evidence of a patent ductus include a continuous murmur, bounding pulses with widened pulse pressure (greater than 20 mmHg), and respiratory failure. Diagnosis is confirmed by echocardiography. Initial treatment consists of relative fluid restriction and indomethacin, which inhibits cyclooxygenase activity and reduces local ductal tissue synthesis of prostaglandin E₂, the most potent dilator of the ductus arteriosus. Side effects of indomethacin include inhibition of platelet function and reduction of renal and splanchnic blood flow. Treatment of asymptomatic patent ductus arteriosus remains controversial due to these side effects. Surgical occlusion is reserved for patients who are refractory to medical treatment, have a contraindication to indomethacin therapy (e.g. intraventricular hemorrhage, established necrotizing enterocolitis), or have developed a complication of indomethacin treatment (e.g. ileal perforation).

**Low Birth Weight Infants**

Neonates may be classified (Tables 1 and 2) according to their level of maturation (gestational age) and development (weight). This classification is important because the physiology of neonates may vary significantly depending on these parameters.

Under this classification system, a term, appropriate for gestational age infant is born between 37- and 42-week gestation with a birth weight greater than

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Newborn classification by maturation (gestational age).</th>
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<tbody>
<tr>
<td>Classification</td>
<td>Age at birth</td>
</tr>
<tr>
<td>Preterm</td>
<td>Birth before 37-week gestation period</td>
</tr>
<tr>
<td>Term</td>
<td>Birth between 37- and 42-week gestation period</td>
</tr>
<tr>
<td>Post-term</td>
<td>Birth after 42-week gestation period</td>
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<table>
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<th>Table 2.</th>
<th>Newborn classification by development (weight).</th>
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<tr>
<td>Classification</td>
<td>Birth weight</td>
</tr>
<tr>
<td>Small for gestational age</td>
<td>Birth weight below 10th percentile</td>
</tr>
<tr>
<td>Appropriate for gestational age</td>
<td>Birth weight between 10th and 98th percentile</td>
</tr>
<tr>
<td>Large for gestational age</td>
<td>Birth weight greater than 98th percentile</td>
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In the United States, approximately 7% of all babies do not meet these criteria. This may be due to prematurity or intrauterine growth retardation. From a clinical standpoint, neonates born under 2500 g are broadly classified as low birthweight (LBW) infants. Further subclassification into moderately low birth weight, very low birth weight, and extremely low birth weight infants have been used for epidemiologic and prognostic purposes (Table 3). Using this terminology, low birth weight infants may be preterm and appropriate for gestational age, term but small for gestational age, or both preterm and small for gestational age. This distinction is important in that overall prognosis and potential risks may be significantly different for the different populations.

**Preterm infant**

By definition, preterm infants are born before 37 weeks of gestation. They generally have body weights appropriate for their age, though they may also be small for gestational age. The rate of premature birth is the major contributor to infant mortality and has not changed significantly. The United States ranks between 20th and 30th among countries around the world in infant mortality and premature delivery rates.\(^3\) If gestational age is not accurately known, the prematurity of an infant can be estimated by physical examination. Principle features of preterm infants are head circumference below 50th percentile, thin, semi-transparent skin with absence of plantar creases, soft and malleable ears with poorly developed cartilage, absence of breast tissue, undescended testes (testicular descent from the inguinal canal towards the scrotum begins in the 26th week of gestation) with a flat scrotum in boys, and relatively enlarged labia minora and small labia majora in girls.

In addition to these physical characteristics, several physiologic abnormalities exist in preterm infants. These abnormalities are often a result of unfinished

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**Table 3.** Alternative newborn classification by weight.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Birth weight</th>
<th>% of preterm births</th>
<th>Mortality rate vs. term infants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderately low birth weight</td>
<td>Birth weight between 2500 g and 1501 g</td>
<td>82%</td>
<td>40 times higher</td>
</tr>
<tr>
<td>Very low birth weight</td>
<td>Birth weight between 1500 g and 1001 g</td>
<td>12%</td>
<td>200 times higher</td>
</tr>
<tr>
<td>Extremely low birth weight</td>
<td>Birth weight &lt; 1000 g</td>
<td>6%</td>
<td>600 times higher</td>
</tr>
</tbody>
</table>
fetal developmental tasks that normally enable an infant to successfully transition from intrauterine to extraterine life. These tasks, which include renal, skin, pulmonary, and vascular maturation, are usually completed during final weeks of gestation. The more premature the infant, the more fetal tasks are left unfinished and the more vulnerable the infant.

This physiologic and anatomic vulnerability sets the preterm infant up for several specific and clinically significant problems:

1. Central nervous system immaturity leading to episodes of apnea and bradycardia, and a weak suck reflex;
2. Pulmonary immaturity leading to surfactant deficiency which can result in hyaline membrane disease and respiratory distress at birth;
3. Cerebrovascular immaturity leading to fragile cerebral vessels which lack the ability to autoregulate. This predisposes preterm infants to intraventricular hemorrhage, the most common acute brain injury of neonates;
4. Skin immaturity leading to underdeveloped stratum corneum with significant transepithelial water loss. This complicates thermal regulation and fluid status management of infants;
5. Gastrointestinal underdevelopment causing inadequate absorption and risk of necrotizing enterocolitis;
6. Impaired bilirubin metabolism causing predominantly indirect hyperbilirubinemia;
7. Cardiovascular immaturity leading to patent ductus arteriosus or patent foramen ovale. These retained elements of fetal circulation can cause persistent left-to-right shunting and cardiac failure;
8. Fragile retinal vessels leading to retinopathy of prematurity.

From a practical standpoint, care of preterm infants must therefore be directed at preventing and/or treating these specific problems. Episodes of apnea and bradycardia are common and may occur spontaneously or as nonspecific signs of problems such as sepsis or hypothermia. Prolonged apnea with significant hypoxemia leads to bradycardia and ultimately to cardiac arrest. All preterm infants should therefore undergo apnea monitoring and electrocardiographic pulse monitoring, with the alarm set at a minimum pulse rate of 90 beats per minute. In neonates with respiratory difficulties, chest radiography will help detect hyaline membrane disease and cardiac failure. The lungs and retinas of preterm infants are very susceptible to high oxygen levels, and even relatively brief exposures may result in various degrees of pulmonary insult and retinopathy of prematurity. Infants receiving supplemental oxygen therefore require continuous
pulse oximetry monitoring, with the alarm set to trigger below 85% and above 92%. Preterm infants may also be unable to tolerate oral feeding because they have a weak suck reflex, necessitating intragastric tube feeding or total parenteral nutrition. Finally, impaired bilirubin metabolism may necessitate serum bilirubin monitoring for rising levels of unconjugated bilirubin; this may require phototherapy or exchange transfusion in order to prevent brain damage (i.e. kernicterus).

**Small for gestational age infant**

Infants whose birth weight is below the 10th percentile are considered to be small for gestational age (SGA). SGA newborns are thought to be a product of restricted intrauterine growth due to placental, maternal, and fetal abnormalities. Table 4 lists several conditions which may lead to intrauterine growth retardation. It should be noted that not all infants in this group are truly growth retarded. Some infants are simply born small as a result of a variety of factors including race, ethnicity, sex, and geography. It is important to differentiate these infants from those whose relatively low birth weight is a result of genetic or intrauterine abnormality.

SGA infants can be divided into two broad categories; symmetric SGA infants and asymmetric SGA infants. This distinction is primarily based on when in the gestational period fetal growth was actually restricted. If fetal growth is restricted during the first half of pregnancy, when cellular hyperplasia and differentiation lead to tissue and organ formation, the neonate is generally a symmetric SGA

| Table 4. Common conditions associated with intrauterine growth retardation. |
|---|---|
| Age at delivery | Condition |
| Preterm | Placental insufficiency |
| | Discordant twin |
| | Chronic maternal hypertension |
| | Intrauterine infection |
| | Toxemia |
| Term | Congenital anomaly |
| | Microcephaly |
| Post-term | Placental insufficiency |
infant. Fetal factors such as genetic dwarfism, chromosomal and congenital abnormalities, inborn errors of metabolism, and fetal infection, as well as maternal factors such as genetics, toxin ingestion, and substance abuse, are all causative etiologies. While only 30% of SGA infants fall into this group, they have the highest morbidity and mortality rate.

In contrast, asymmetric SGA infants experience intrauterine growth restriction during the last half of gestation, often during the third trimester. This is usually due to inadequate nutrient supply. An example of this is twin gestations. Though both infants may be full term at birth, they generally have low birth weight because placental mass/function is inadequate to meet growth demands of both fetuses. Other causes of asymmetric growth retardation include maternal conditions that reduce uteroplacental blood flow such as hypertension, toxemia, and cardiac and renovascular disorders.

In general, SGA infants have low body weight for their gestational age, though their body length and head circumference are appropriate. SGA infants are older and developmentally more mature than preterm infants of equivalent weight. They therefore face significantly different physiologic problems. The metabolic rate of SGA infants is much higher in proportion to body weight than preterm infants of similar weight because of the longer gestational period and resultant well-developed organ systems. Therefore, fluid and caloric requirements are increased. Intrauterine malnutrition results in a relative lack of body fat and decreased glycogen stores. In fact, body fat levels in SGA infants are often below 1% of their total body weight. This, coupled with their relatively large surface area, greatly predisposes these infants to hypothermia and hypoglycemia. Close monitoring of blood sugar level, therefore, is essential. In addition, polycythemia is common in SGA infants due to increased red blood cell volumes, occurring in 15–40% of asymmetric SGA babies. Polycythemia may lead to hyperviscosity syndrome characterized by respiratory distress, tachycardia, pleural effusions, and risk of venous thrombosis. This requires frequent monitoring of the infant’s hematocrit level and possibly plasma exchange transfusions. Lastly, fetal asphyxia and distress due to inadequate placental support may lead to passage of meconium in utero, resulting in increased risk of meconium aspiration syndrome in SGA infants if the material is aspirated during labor and delivery. Perioperative management of these conditions will be detailed in following sections. While SGA infants are at significant risk for morbidity and mortality associated with these syndromes, their longer length of gestation reduces their risk for many conditions that affect preterm infants, such as retinopathy of prematurity, intraventricular hemorrhage, and hyaline membrane disease.
Physiologic Considerations in Perioperative Care of Neonates

Glucose homeostasis

The fetus receives glucose from its mother by facilitated placental diffusion; very little is derived from fetal gluconeogenesis. Limited liver glycogen stores accumulated during the later stages of gestation are rapidly depleted within 2 to 3 hours after birth. The neonate’s blood glucose level then depends on its capacity for gluconeogenesis, adequacy of substrate stores, and total energy requirements. Of note, the neonate’s ability to synthesize glucose from fat or protein substrates is severely limited, necessitating intake of exogenous carbohydrates to maintain adequate blood glucose levels.

The risk of developing hypoglycemia is high in low birth weight infants (especially SGA infants), those born to toxemic or diabetic mothers, and those requiring surgery that are unable to take oral nutrition and have additional metabolic stresses from their disease and surgical procedure. Clinical features of hypoglycemia are nonspecific and include a weak or high-pitched cry, cyanosis, apnea, jitteriness or trembling, and seizures. Differential diagnosis includes other metabolic disturbances or sepsis. Over 50% of infants with symptomatic hypoglycemia suffer significant neurologic damage. Neonatal hypoglycemia is defined as serum glucose level less than 30 mg/dl in full-term infants and less than 20 mg/dl in low birth weight infants. However, neurologic abnormalities have been reported with higher blood glucose levels.

Hyperglycemia is commonly a problem of very low birth weight infants on parenteral nutritional support since they have a lower insulin response to glucose. Hyperglycemia may lead to intraventricular hemorrhage and renal water and electrolyte loss from glycosuria. Prevention of hyperglycemia is by small and gradual incremental changes in glucose concentration and infusion rate.

Practical considerations

All pediatric surgical patients, particularly neonates, are monitored for hypoglycemia. To avoid delay, blood glucose levels can be rapidly determined in the neonatal unit using blood glucose reagent strips activated by blood from a heel stick. This may be correlated at intervals with serum glucose determinations, the frequency depending on patient stability. Any intravenous fluids administered should contain at least 10% dextrose. If non-dextrose–containing solutions such as blood or plasma are being administered, close monitoring of blood glucose levels is essential. Hypoglycemia should be treated urgently with intravenous
50% dextrose, 1–2 mL/kg, and maintenance intravenous 10% to 15% dextrose, 80–100 mL/kg every 24 hours.

**Hematologic regulation**

Total blood, plasma, and red cell volumes are higher during the first few hours after birth than any other time in an individual’s life. Levels may be further increased if significant placental transfusion takes place at delivery (e.g. delayed cord clamping). Several hours after birth, plasma shifts out of circulation and total blood and plasma volumes decrease. High red blood cell volume persists, decreasing slowly to reach adult levels by the third postnatal month. The estimated blood volume in infants ranges between 85 and 100 mL/kg.

Neonatal polycythemia may occur in SGA infants, infants of diabetic mothers, and of mothers with toxemia of pregnancy. In neonates, polycythemia is defined as central venous hematocrit greater than 65% or hemoglobin level greater than 22 g/dL. Values at or above this threshold may be associated with high blood viscosity which is further increased by a fall in body temperature. Partial exchange transfusion may be indicated since hyperviscosity is associated with central nervous system and gastrointestinal tract disorders.

**Anemia**

In neonates, anemia is generally due to hemolysis, blood loss, or decreased erythrocyte production. Hemolytic anemia in the newborn is most often caused by placental transfer of maternal antibodies that destroy the infant’s erythrocytes. Significant hemolytic anemia is most commonly due to Rh incompatibility, producing jaundice, palor, hepatosplenomegaly, and in severe cases, hydrops fetalis. In addition, congenital infections, inherited hemoglobinopathies, and thalassemias may all manifest as hemolytic anemia in the newborn period. In severe cases, these conditions may require exchange transfusions. Severe anemia in neonates also may occur secondary to acute hemorrhage as a result of placental abruption or in utero internal bleeding into the intraventricular, intraabdominal, subgaleal, or mediastinal spaces. Twin–twin transfusion syndrome may produce severe anemia in the “donor” twin. Lastly, “anemia of prematurity” can occur in preterm infants born before 30 to 34 weeks gestational age due to decreased red blood cell production, resulting from a lack of erythropoietin synthesis in the neonate’s kidneys.

Given an infant with normal blood volume, blood loss less than 10% of blood volume does not require transfusion. Transfusion of packed red blood cells at a
volume of 3 mL/kg or whole blood 6 mL/kg usually raises the hematocrit levels by 3–4%. Only warmed, fresh (<3 days old) whole blood or packed red cells should be transfused.

**Hemoglobin**

Erythropoiesis does not occur during the first 2 or 3 months of life. Until that time, fetal hemoglobin represents the vast majority of circulating hemoglobin in neonates. This is significant in that the high proportion of fetal to adult hemoglobin in neonates shifts the hemoglobin dissociation curve to the left. Since fetal hemoglobin has a higher affinity for retaining oxygen, lower peripheral oxygen levels are needed to release and deliver oxygen from fetal blood to the receiving tissues.

**Coagulopathy**

Levels of several clotting factors (II, VII, IX, X, XI, and XII) are significantly decreased in the neonatal period, mostly as a result of immature liver function. Levels in preterm infants are typically more severely decreased than in full term infants, and normal adult levels are only achieved by 6 months of age. This factor deficiency combined with rapid vitamin K depletion may produce hemorrhagic disease of the newborn, with localized (e.g. cephalohematoma) or diffuse bleeding classically developing in the first week of life. Routine administration of vitamin K to all neonates, therefore, is an established practice to prevent hemorrhagic disease. This may be overlooked during the activities attendant on major congenital anomalies or conditions requiring urgent surgical evaluation. When in doubt, 1.0 mg of vitamin K should be administered by intramuscular or subcutaneous injection. PT and especially PTT are typically elevated in the first months of life. This does not correlate with clinical bleeding and so these tests, that require a relatively large volume of blood, should not be done routinely in neonates.

**Jaundice**

Bilirubin is produced by catabolism of heme pigments, most notably hemoglobin, in the liver and spleen. Lipid-soluble, unconjugated (indirect) bilirubin in fetal circulation is bound to albumin and either is cleared across the placenta or taken up by the liver. Uridine diphosphate glucuronoyl transferase in the liver conjugates bilirubin with glucuronic acid, forming a water-soluble substance excreted via the biliary system into the intestine. In the fetal intestine β-glucoronidase hydrolyzes
conjugated (direct) bilirubin back to its unconjugated state, which is then reabsorbed for enterohepatic circulation or transplacental clearance.

The neonate’s capacity for conjugating bilirubin is not fully developed and may be exceeded by the bilirubin load. This imbalance results in transient physiologic jaundice which peaks at 4 days of age but typically resolves by the sixth day. Usually, the maximum bilirubin level does not exceed 10 mg/dL. Physiologic jaundice is particularly common in SGA and preterm infants in whom a higher and more prolonged hyperbilirubinemia may occur.

When serum levels are high, unconjugated bilirubin may cross the immature blood–brain barrier in the neonate and act as a neural poison leading to kernicterus. In its most severe form, kernicterus is characterized by athetoid cerebral palsy and sensorineural hearing loss. Predisposing factors are hypoalbuminemia, acidosis, cold stress, hypoglycemia, caloric deprivation, hypoxemia, and competition for bilirubin binding sites by drugs (e.g. furosemide, digoxin, and gentamicin) or free acids.

**Practical considerations**

Clinical jaundice is apparent at serum bilirubin levels of 7–8 mg/dL. A rapid bilirubin rise early in the neonatal period suggests hemolysis, either secondary to inherited enzyme defects or maternal–neonatal blood group incompatibilities. In otherwise healthy infants, jaundice associated with breast feeding commonly appears between 1 and 8 weeks of age and resolves rapidly with cessation of breast feeding. Prolonged hyperbilirubinemia associated with increased conjugated bilirubin often indicates biliary obstruction (e.g. biliary atresia) or hepatocellular dysfunction (e.g. hepatitis). Indirect hyperbilirubinemia may occur with pyloric stenosis and quickly disappears after pyloromyotomy. Intestinal obstruction can intensify jaundice by increasing enterohepatic circulation of bilirubin. Finally, jaundice is an early and important sign of septicemia. If hemolysis is suspected, serial hematocrit estimations, reticulocyte counts, peripheral blood smears, and a Coomb’s test are appropriate. Evaluation of neonatal sepsis includes hematocrit, white blood cell count and differential, platelet count, chest radiography and cultures of blood, urine, and cerebrospinal fluid.

Phototherapy is widely used prophylactically in high-risk neonates. This therapy decreases serum bilirubin levels by photodegradation of bilirubin in skin into water-soluble products. It is continued until total serum bilirubin level is less than 10 mg/dL and falling. Timing of phototherapy is based on the level of indirect bilirubin and patient weight. Exchange transfusion is indicated if the indirect bilirubin level exceeds 20 mg/dL, but precise indications vary according to the
individual patient. In very low birth weight infants, exchange transfusion is indicated at lower serum bilirubin levels. Factors increasing the risk of kernicterus also influence the indications for exchange transfusion.

**Immune function**

Neonates are particularly vulnerable to bacterial infections. This may be due to maternal factors as well as intrinsic deficiencies in their host defense system. Maternal factors independently associated with a higher incidence of neonatal sepsis include premature onset of labor, prolonged rupture of membranes (greater than 24 hours), chorioamnionitis, genital tract colonization with pathogenic bacteria such as group B streptococci, and urinary tract infection. In general, these factors increase the risk of neonatal infection by exposing the neonate to bacterial pathogens during gestation as well as delivery. The neonatal immune system is immature, characterized by a diminished neutrophil storage pool, abnormal neutrophil and monocyte chemotaxis, decreased cytokine and complement production, and diminished levels of type-specific immunoglobulins including IgG, secretory IgA, and IgM. Overall, these factors lead to a significantly impaired host defense mechanism in the neonate with compromised anatomical barriers. Furthermore, these deficiencies appear to be more severe in low birth weight infants.

**Practical considerations**

Impaired immune function and compromised anatomical barriers may contribute to postoperative infection rates in newborn surgical patients. Specifically, wound infections, as well as indwelling catheter-related sepsis, may complicate the perioperative course. For this reason, many surgeons advocate utilization of prophylactic, broad-spectrum antimicrobials in neonatal surgical patients. While this practice may be common, it should be noted that the specific antibiotics used as well as duration of therapy are very site- and surgeon-specific parameters. At this time, there are no conclusive studies supporting the use of any particular regimen. Therefore, use of prophylactic antibiotics in these patients is determined on a case-by-case and surgeon-by-surgeon basis.

**Fluid and electrolyte homeostasis**

**Total body water**

In the fetus, total body water (TBW) constitutes 94% of the body weight during early gestation. As the fetus grows, this percentage progressively diminishes to a
value of approximately 78% at term. During the first 5 days of life, TBW decreases by another 3–5%, and eventually reaches adult levels by 9 months to 1 year of age. Extracellular water (ECW) in the term infant is often 40% of birth weight at 5 days. Similar to TBW, ECW decreases over time and by 3 months of age is only 33%. ECW stabilizes at adult values of 20–25% by 1–3 years of age. Conversely, fetal intracellular water (ICW) slowly increases during gestation and the neonatal period. At the 20th week of gestation, ICW is around 25% and increases to 33% by birth. ICW finally reaches adult levels of approximately 44% by 3 months of age.

Under normal conditions, changes in fetal body water progress in an orderly fashion in utero and after birth. The neonate must complete these water redistribution tasks to effectively transition from the intrauterine to extraterrestrial environment. Premature birth or intrauterine growth retardation may interrupt this process leaving specific tasks unfinished and predisposing the infant to increased risk of serious complications such as necrotizing enterocolitis, patent ductus arteriosus, and congestive heart failure.

Renal function

Renal function is significantly limited in neonates. Compared to adults, the newborn has a relatively low renal blood flow and plasma flow and a high renovascular resistance. In fact, only 6% of the newborn’s cardiac output is directed towards the kidneys. This is in contrast to 25% of cardiac output in adults. Overall, these factors lead to a relatively decreased glomerular filtration rate (GFR) in neonates. In term infants, the GFR rises rapidly during the first 3 months of life, nearing adult levels by 12 to 24 months of age. In premature infants, this process is delayed and GFR may lag behind that of the term infant. One should aim to achieve a urine output which will maintain urine osmolality of approximately 280 mOsm/kg. In neonates, this usually results in a urine output of 2 mL/kg/h. For infants and older children, hydration is adequate if the urine output is 1–2 mL/kg/h with an osmolality of 280–300 mOsm/kg.

In addition to GFR, concentrating capacity of the neonatal kidney is significantly lower than that of the adult kidney. Specifically, while the adult kidney can concentrate urine up to 1200 mOsm/kg, the neonatal kidney is only able to achieve 500–600 mOsm/kg. Furthermore, newborn renal tubules are particularly insensitive to effects of antidiuretic hormone. Similarly, newborn tubules respond to a lesser degree to aldosterone. This blunted response is magnified in preterm infants. In addition, preterm infants are at significant risk for salt wasting. The fractional excretion of sodium, which is normally about 2%, can be as high as 5%
in normal preterm infants. This may lead to further growth retardation as sodium appears to be a permissive growth factor.

A rising blood urea nitrogen level and falling urine output may be due to acute renal failure or prerenal oliguria with azotemia resulting from hypovolemia. The distinction between these two states is important for appropriate treatment. Initially, response to a fluid challenge of 20 mL/kg of 5% dextrose and sodium chloride administered over 1 hour is monitored. If oliguria persists, blood and urine sodium, creatinine and osmolality levels are measured. Fractional excretion of sodium (FeNa) is calculated using the formula:

\[
FeNa = \left( \frac{\text{Urine creatinine}}{\text{Serum creatinine}} \right) \times \left( \frac{\text{Urine Na}}{\text{Serum Na}} \right) \times 100.
\]

A normal FeNa is 2–3%. In neonates, a value below 2% implies prerenal azotemia and a value above 3% implies renal failure.

**Calculating maintenance needs**

The neonate’s basic maintenance requirement for water is the volume required to support growth and replace losses from renal excretion (renal water), skin, lungs, and stool. Stool water loss has been estimated at 5–10 mL per 420 Joules expended, the lower figure applying to those patients not being fed. In the surgical patient with postoperative ileus, stool water loss is usually insignificant. Growth is inhibited during periods of severe stress and is also not a major factor under these conditions. The basal fluid maintenance requirement is therefore renal water plus insensible loss. Requirements during the first day of life are unique because of the greatly expanded extracellular fluid volume in the neonate, which decreases after 24 hours. In addition, neonates with intestinal obstruction are not hypovolemic at birth because of intrauterine adjustments across the placenta. During these first 24 hours, basic maintenance fluid should not exceed 90 mL/kg in preterm infants weighing less than 1000 g or less than 32 weeks of gestation. In larger infants, maintenance fluid rates should not exceed 75 mL/kg.

Basic electrolyte and energy requirements are provided by NaCl (2–5 mEq/kg/day) in 5% or 10% dextrose with addition of potassium (2–3 mEq/kg/day) once urine production has been established. Calcium gluconate (1–2 g/L fluid) may be added, especially in preterm infants.

**Insensible losses**

Invisible continuing water loss occurs from the lungs (respiratory water loss) and skin (transepithelial water loss) and constitutes insensible water loss (IWL).
Respiratory water loss (RWL) accounts for approximately one-third of IWL in infants older than 32 weeks’ gestation and is approximately 5 mL/kg body weight per 24 hours at a relative humidity of 50%. Transepithelial water loss (TEWL) for a full-term infant in a thermoneutral environment is approximately 7 mL/kg body weight. The insensible water loss for a full-term infant in a thermoneutral environment at 50% humidity is therefore 12 mL/kg per 24 hours.

The main factors that affect IWL are the gestational age of the infant and the relative humidity of the environment. For infants 25–27 weeks’ gestation, TEWL has been estimated at 128 mL/kg per 24 hours at 50% relative humidity. Relative humidity has a marked inverse effect on TEWL, which decreases to almost zero as relative humidity approaches 100%. Plastic sheets may be used to increase the relative humidity around the infant and reduce TEWL by 50–70%. Conversely, radiant warmers and phototherapy increase IWL. This loss is magnified in preterm infants.

Management Program

The most commonly used method of calculating fluid requirements is based on body weight. After the first 24 to 48 hours of life, full-term appropriate-weight infants typically require approximately 100 mL/kg/day, but preterm or SGA infants typically need up to 180 mL/kg/day depending upon gestational age and total fluid losses (Table 5). However, because of many factors affecting maintenance requirements, there is no close or constant relationship between body weight and fluid and electrolyte needs. Thus, many surgeons advocate use of a dynamic approach to fluid management. Such approaches generally begin with administration of a safe fluid volume for the patient’s status. This initial volume is essentially a “best guess” volume. The effects of this volume on the patient’s physiology are then monitored and appropriate changes are made.

**Calcium and magnesium homeostasis**

In addition to fluid and sodium management, calcium and magnesium homeostasis are clinically significant challenges in the newborn surgical patient. The fetus receives calcium by active transport across the placenta, with 75% of the total requirement being transferred after the 18th week of gestation. Hypocalcemia, defined as a serum level of ionized calcium below 1 mg/100 mL, is most likely to occur 24 to 48 hours after birth. Causes include decreased calcium
stores, decreased renal phosphate excretion, and relative hypoparathyroidism secondary to suppression by high fetal calcium levels. Low birth weight infants are at great risk (particularly if preterm) as are those born of a complicated pregnancy or delivery (e.g. diabetic mother) or those receiving bicarbonate infusions. Exchange transfusions or rapid administration of citrated blood may also lead to hypocalcemia. The symptoms of hypocalcemia are nonspecific and include jitteriness, high-pitched crying, cyanosis, vomiting, twitching, and seizures. Diagnosis is confirmed by determining the serum calcium level. However, evaluation of serum ionized calcium level is often useful as clinical hypocalcemia may result from low serum ionized calcium without a great reduction in total serum calcium.

**Practical considerations**

Most seizures that occur in the neonatal period have a central nervous system etiology and are not secondary to hypoglycemia or hypocalcemia. However, hypocalcemia should be suspected in high-risk infants, particularly after surgery. Immediate serum glucose and calcium measurements, therefore, should be performed in a “jittery” neonate. Treatment should be prompt with intravenous glucose when hypoglycemia is suspected, followed by intravenous calcium if symptoms persist.

**PREOPERATIVE CARE**

Goals of appropriate preoperative care include\(^1\) identifying and optimizing potential coexisting diseases,\(^2\) preparing the patient for the specific operation, and\(^3\) preparing the family for the perioperative period.
Identifying and Managing Coexisting Diseases

Preoperative evaluations performed by the anesthesia team are extremely important in identifying potential perioperative complications. In a study including more than 90,000 pediatric noncardiac and cardiac anesthesia cases, the incidence of perioperative cardiac arrest attributable to anesthesia was 0.65 per 10,000 anesthetics, which represented 7.5% of all perioperative cardiac arrests, suggesting that the large majority of perioperative cardiac arrests in children are caused by factors not related to anesthetic management. However, neonates and infants continue to have the highest risk for perioperative cardiac arrest and death during procedures requiring general anesthesia.

A full review of systems is very valuable during perioperative risk assessment. History of seizures, head trauma, hydrocephalus, brain tumors, or neuromuscular disease may result in increased intracranial pressure, adverse medication interactions or malignant hyperthermia. Murmurs, cyanosis, or hypertension can be indicative of congestive heart failure or congenital heart disease. History of prematurity, bronchopulmonary dysplasia, croup, asthma or cystic fibrosis usually mandates postoperative monitoring for apnea or subglottic stenosis, as well as institution of appropriate pulmonary toilette. Electrolyte abnormalities and aspiration pneumonia should be suspected in patients with gastrointestinal abnormalities, including gastroesophageal reflux disease, diarrhea, or bowel obstruction.

Preparing the Patient for the Specific Procedure

Informed consent

Informed consent has become a fundamental doctrine of modern medicine based on ethical and legal principles of respect for individual autonomy, beneficence, and justice. Except in the rare case where surgical intervention is necessary to prevent imminent death, informed consent in infants requiring surgery mandates effective preoperative family education and counseling. Several critical elements must be included in the informed consent process: the physician provides adequate information with which to make a decision, a competent patient or legal representative who indicates full understanding of the intervention, including indications, risks, and possible alternatives, and voluntarily consents to the proposed intervention.

All legal jurisdictions, either by statutory law, case law, or both, currently require informed consent be obtained before any medical intervention, whether performed for diagnostic, therapeutic, or research purposes.
The American College of Surgeons has provided guidelines on the content of information provided to patients needed to meet informed consent requirements. Although adequate for most adult patients, existing guidelines may not always satisfy the needs of pediatric patients since by definition they lack decision making capacity. Parents may give informed “permission” for the procedure, but it is very difficult to assess whether the child’s best interest are being represented. Informed consent should disclose as a minimum information which includes:

(a) Surgeon’s understanding of the problem;
(b) Further measures to be taken to clarify the diagnosis, if indicated;
(c) Indication for emergency operation;
(d) Brief description of the procedure;
(e) Alternatives to treatment, including the option to do nothing;
(f) Surgeon’s recommendation as to the best alternative;
(g) Benefits and risks of the proposed operation, compared with alternatives;
(h) Anticipated outcome.

It is very important for the pediatric surgeon to spend quality time providing informed consent because it helps gain parents’ trust and promotes adequate communication and physician-to-patient relationships.

**Preoperative fasting guidelines**

Neonates and infants who are able to be fed enterally require a period of fasting before major surgery in an attempt to avoid regurgitation and possible aspiration of particulate matter or liquid from the child's stomach during anesthesia induction. Each institution has its own fasting guidelines. As an example, our institution’s guidelines are outlined below:

Minimum fasting intervals for neonates and infants over 3 kg in weight:

(A) >6 hours for milk, formula, solids, barium contrast, citrus juice etc.;
(B) >4 hours for breast milk;
(C) >2 hours for clear liquids.

Minimum fasting interval for neonates and infants under 3 kg in weight:

(A) Greater than usual duration between feedings for formula, breast milk, barium contrast etc.
Perioperative Management of Neonates

For example, if a former premature neonate weighing 2 kg is fed formula or breast milk every 3 hours, then the fasting period must be > 3 hours.

(B) Formula, breast milk and fluids administered to the jejunum continuously through a stoma may be continued until operation.

**Antimicrobial prophylaxis**

The immaturity of an immune system renders newborn infants vulnerable to major bacterial insults. Therefore, prophylactic antimicrobial therapy is advised for neonates undergoing major surgery, particularly of the gastrointestinal tract or genitourinary system. Adequate coverage is provided by combining a penicillin (e.g. ampicillin) or first-generation cephalosporin (e.g. cefazolin) with an aminoglycoside (e.g. gentamicin). Clindamycin or metronidazole is added when anaerobic coverage is deemed necessary. Alternatively, single-drug therapy using a broad-spectrum cephalosporin (e.g. cefoxitin) may be appropriate. Antibiotics are commenced prior to operation and may be discontinued postoperatively at the surgeon’s discretion.

**Preoperative bowel preparation**

Varied opinion exists whether mechanical bowel preparation is needed for elective intestinal procedures. There is also lack of consensus as to the best regimen to accomplish bowel preparation and whether administration at home or in hospital is superior. An example of a regimen is shown in Table 6.

**Diagnostic studies**

Most laboratory tests pose an additional burden to already stressed neonates. Therefore, diagnostic studies should be restricted to those essential for diagnosis and disease management. The volume of blood drawn for laboratory tests should be documented as these small volumes can cumulatively represent significant loss in a small infant.

When the patient is transferred to other departments for investigational procedures, monitoring and resuscitation equipment should be available. All studies should be performed with minimal disturbance, taking steps to prevent heat loss. Before using hyperosmolar radio-opaque contrast materials, intravenous fluids must be administered and fluid deficits corrected, regardless of route of administration. To counteract osmotic effects of contrast medium, intravenous infusion
of sodium chloride 34 mEq/L at twice the maintenance rate should be given during the radiographic study and for 2–4 hours afterwards. During this period, the patient should be carefully monitored.

**OPERATIVE CARE**

**Operative Checklist: “The Time Out”**

Even though there are scarce data in the pediatric literature, adult data suggest at least half of all surgical complications are avoidable. In 2008, the World Health Organization published guidelines identifying multiple recommended practices to ensure safety of surgical patients worldwide. Using these guidelines as reference, the Safe Surgery Saves Lives Study Group implemented a prospective 19-point checklist and showed the rate of any complication significantly decreased from 11% to 7%. Overall rates of surgical-site infection and unplanned reoperation also declined significantly, and overall surgical outcomes were improved. At our hospital, the checklist verifies the patient’s identity and surgical site mark, introduces all team members by name and role, reviews the need for preoperative antibiotics and/or blood products, highlights significant concerns or previous adverse reactions, reviews the need for any special equipment, and matches the operative procedure with the informed consent. Use of a preoperative checklist involves a radical change in behavior of surgical teams, since it introduces formal pauses in the usual flow as well as does implementation of briefings and postoperative debriefings. The idea of ensuring correct patient identity and surgical site through preoperative site marking, oral confirmation in the operating room, and postoperative debriefings sets a new bar in the care of surgical patients and has

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**Table 6.** Bowel preparation for elective pediatric surgery.

| Inpatient preparation | • Begin preparation at noon or sooner, the day before surgery.  
|                       | • Place a small nasogastric (NG) feeding tube.  
|                       | • Administer Reglan® 0.1–0.2 mg/kg/dose (maximum of 0.8 mg/kg over 24 hours) per NG every 4 hours (unless contraindicated).  
|                       | • Begin Golytely 25 mL/kg/hour per NG tube for 4 hours or until effluent is clear.  
|                       | • Clears or Pedialyte® by mouth ad lib until fasting period.  

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potential to prevent a large number of disabling complications and deaths in the perioperative period.

**Thermoregulation**

Neonates are susceptible to heat loss because of their large surface area, low body fat-to-body weight ratio, and limited heat sink capacity due to their small size. In addition, neonates have a relatively high thermoneutral temperature zone. Optimal thermal environment (thermoneutrality) is defined as a range of ambient temperatures in which an infant, at a minimal metabolic rate, can maintain a constant normal body temperature by vasomotor control. Environmental temperature must be maintained near the appropriate thermoneutral zone for each individual. In adults, this critical temperature range is 26°C–28°C while in term infants it is 32°C to 34°C. In low birth weight infants, this critical range is even higher at 34°C to 35°C.

**Mechanisms of heat loss**

In neonates, heat loss may occur by evaporation, conduction, convection, and radiation. Evaporative heat loss occurs as result of transepithelial water loss and depends on gestational age of the infant, relative humidity, and other environmental conditions. In addition, the presence of liquid (e.g. prep solution) in contact with an infant's skin contributes to evaporative heat loss. Conductive heat loss occurs when an infant’s skin is in contact with a solid object of lower temperature, causing heat to flow from the infant to the object at a rate dependent on the temperature difference between the two as well as the insulating properties of the baby and object. Similarly, convective heat loss occurs when ambient air temperature is less than the infant’s skin temperature. Convective heat loss depends on the temperature gradient between the infant’s skin and the air as well as the speed of the air current over the infant. Lastly, radiant heat loss occurs via passage of infrared rays from the infant’s skin to a cooler surface, such as the incubator or nursery wall. This type of heat loss is often most difficult to control. Table 7 details the types of heat loss affecting neonates.

**Thermogenesis in neonates**

Neonates generate heat by increasing metabolic activity. This can occur via shivering, as in adults, or non-shivering thermogenesis using brown fat. This has
practical consequences because pressors, anesthetic and neuromuscular blocking agents may render brown fat inactive. Brown fat stores may also be depleted due to poor nutritional intake, such as in an SGA infant. When an infant is exposed to the cold, metabolic work increases above basal levels and calories are consumed to maintain body temperature. If prolonged, this depletes the neonate’s limited energy reserves and predisposes them to hypothermia and increased mortality.

Practical considerations

The neonate’s environmental temperature is best controlled in an incubator where ambient temperature can be monitored and thermoneutrality maintained. Clothing the infant can increase insulation, reducing radiant and convective heat loss inside the incubator. In particular, covering the head with an insulated hat can reduce heat loss and total metabolic activity during cold stress by up to 15%. Similarly, conductive heat loss is minimized by the use of insulating padding. Incubators themselves are plastic-walled containers that warm the infant by convection. Air in the incubator is heated by a heating element and then circulated by a fan. A servo system regulates incubator temperature according to the patient’s skin temperature monitored by a skin probe. In this manner, the infant’s skin temperature is maintained at a relatively constant value. Double-walled incubators minimize radiant heat loss by maintaining the inner wall of the incubator at the same temperature as the air temperature inside the incubator. Finally, humidity can be provided to the incubator environment, thereby reducing evaporative heat loss.
Optimal air temperature for individual infants varies with gestational age and condition of the infant as well as specific environmental factors such as humidity and air-flow. Standard nomograms are available that aid in determining appropriate incubator temperature necessary to achieve thermoneutrality. Term infants usually require incubator air temperature to be 32°C to 34°C. Low birth weight infants may require temperatures at or above 35°C.

In contrast to fully enclosed incubators, radiant warmers provide open access to and visibility of infants. Their use has become common for ill neonates who require frequent manipulation. Radiant warmers generate heat by means of an overhead panel that produces infrared radiation. However, these warmers do not prevent heat loss by convection and often lead to higher evaporative water and heat losses. This evaporative heat loss may be reduced by plastic sheets.

Feedback mechanisms of both incubators and radiant warmers are used to maintain an infant’s skin temperature in the normal range. Normal skin temperature for term infants is 36.2°C and for low birth weight infants is 36.5°C. Increased metabolic activity can be detected by comparing skin and rectal temperatures which normally differ by 1.5°C. Decreasing skin temperature with constant rectal temperature suggests metabolic rate has increased to maintain core temperature.

In a cold environment, such as the operating room or radiology suite, heat loss may be reduced by wrapping the head, extremities, and as much of the trunk as possible in clothing, plastic sheets, or aluminum foil. A plastic sheet placed beneath the infant decreases humidity of the microenvironment between it and the sheet. Any exposed intestine (e.g. gastroschisis) should be wrapped in plastic. An overhead infrared heating lamp should be focused on the infant during induction of anesthesia, preparation for operation, and at the termination of the operation. Solutions used for skin cleansing as well as intracorporeal irrigation should be warmed.

A major advance in the intraoperative care of neonates has helped curtail episodes of hypothermia and made operating rooms much more pleasant since the room no longer has to approach the uncomfortable temperatures of the neonate’s thermal neutral environment. Forced air devices circulate warm air into disposable soft blankets in which the patient rests while on the operating table.

Gastrointestinal Decompression

The importance of gastric decompression in neonates undergoing surgery cannot be overemphasized. Gastric distension carries the risk of regurgitation, aspiration
and pneumonia, and it may impair diaphragmatic excursion, resulting in respiratory distress. With congenital diaphragmatic hernia, ventilation is progressively impaired as herniated intestine becomes distended with air and fluid. With gastroschisis, omphalocele and diaphragmatic hernia intestinal distension impedes reduction of herniated intestine into the abdominal cavity. This may be alleviated by adequate orogastric decompression. A double-lumen sump tube is preferred, utilizing low continuous suction. If a single-lumen tube is used, intermittent aspiration is required. Correct tube position in the stomach is confirmed by carefully measuring the tube before insertion, noting the nature of the aspirate, and radiography. The tube should be carefully taped to avoid displacement. Use of gastrostomy tubes for postoperative gastric decompression is decreasing in popularity but should be considered when prolonged postoperative gastric or intestinal stasis is anticipated.

**Invasive Monitoring**

The dynamic physiology of the neonatal period requires newborn surgical patients to be monitored continuously in the neonatal unit. As described above, transcutaneous pulse oximetry is useful to monitor for episodes of apnea and bradycardia which can be common in preterm infants. In addition, accurate monitoring of fluid status often requires an indwelling urinary catheter and frequent laboratory evaluations.

Invasive blood pressure monitoring and intravenous access in newborns can be achieved through the umbilical vessels as they are relatively accessible in this population. Umbilical venous catheters can provide central venous access.

**Umbilical artery catheter placement**

A 3.5 French catheter is required for infants less than 1500 g while 1500- to 3500-g infants can accommodate a 5 French catheter. Umbilical artery catheters may be indicated in infants with significant respiratory distress or who may require frequent blood sampling. These catheters usually enter the aorta through the internal iliac arteries. The umbilical cord base is tied with an umbilical tape tightly enough to prevent blood loss but loosely enough to allow passage of the catheter. The umbilical cord above the tie is divided sharply leaving a 1-cm stump. Usually two arteries and one vein are identified. The arteries are smaller and located at the 4 and 7 o’clock position. The artery is gently dilated with a hemostat and the catheter is advanced. A practical formula to calculate an appropriate catheter length in centimeters is:
(Weight kg × 3) + 9 + length of umbilical cord stump.

Appropriate positioning is either below L3 (where the renal artery orifices lie) or between T6 and T9 (below the ductus arteriosus orifice). The tip of the umbilical artery catheter is a site of thrombogenesis and should not be near the orifice of the major visceral vessels. Catheter position is confirmed by a post-insertion chest/abdomen radiograph ("babygram").

**Umbilical vein catheter placement**

The umbilical vein can usually accommodate a 5 French catheter. Placement technique is very similar to the umbilical artery catheter. Appropriate length is calculated by using the following formula:

\[
\frac{1}{2} \left( (\text{Weight kg} \times 3) + 9 \right) + 1.
\]

A babygram is obtained to confirm positioning, and the catheter tip should be about 1 cm above the diaphragm. If the catheter enters the portal vein, it should be repositioned by either flushing and advancing the catheter simultaneously or by placing a second smaller catheter into the umbilical vein so one passes through the ductus venosus while the other enters the portal vein. The catheter in the portal vein can then be removed.

**POSTOPERATIVE CARE**

**Nutrition**

In neonatal surgical patients, proper nutrition must be delivered to meet their relatively large energy requirements. Specifically, neonates require a large energy intake because of their high basal metabolic rate, requirements for growth and development, energy needs to maintain body heat, and limited energy reserves. On average, neonates require between 90 and 120 kcal/kg/day, with 30–35% of this total energy need expended for growth. SGA infants may use up to 50% of their total energy expenditure for growth. Hepatic glycogen stores make up most of the neonate’s major energy reserve and are usually consumed in the first 3 hours of life. These limited reserves are even more restricted in preterm and SGA infants. Young infants can tolerate up to 4 or 5 days without nutrition before signs of starvation develop. Premature infants, however, may develop signs of starvation in as little of 2 days without nutrition.
In older children and adults, energy requirements are significantly increased by cold stress, surgical procedures, infections, and injuries. On the contrary, a neonate’s energy requirements actually decrease significantly during periods of metabolic stress, including surgery and critical illness. Cessation of growth during catabolic stress likely accounts for much of this reduced energy need; however, close thermoregulation in the humidified environment of the incubator, mechanical ventilation, and chemical sedation and paralysis also contribute to reduced energy expenditure. In one study of critically ill infants undergoing major surgery, mean energy expenditure (MEE) was only 43 kcal/kg/day immediately following operation, approximately 54% of predicted values. In a follow-up study comparing infants with high and low levels of metabolic stress, MEE was increased significantly in high stress infants, but still both groups were expending less than 60 kcal/kg/day. Also, infants with high metabolic stress took longer to recover while those with low stress returned to near baseline in 8 days.

Energy needs of individual newborns, therefore, can be calculated according to the requirements for basal metabolism plus growth regardless of the degree of critical illness or metabolic stress. Using this approach more closely approximates actual MEE for most infants. Failing to appropriately adjust postoperative predicted energy needs for stressed infants may lead to complications from overfeeding. The goal of nutritional support should be to achieve a normal weight gain of 10–15 g/kg/24-hr. Typically, this can be accomplished by providing protein at a rate of 2–3 g/kg/24-hr. Thirty to forty percent of total nonprotein calories are often provided as fat, although lowering and/or altering the lipid content in the diet is a strategy to limit cholestasis in patients dependent on parenteral nutrition for prolonged periods, such as those with short gut syndrome.

**Enteral nutrition**

The best means of providing calories is via the gastrointestinal tract either by mouth, nasogastric or nasojejunal feeding tube, or through a surgically placed gastrostomy or jejunostomy tube. Enteral nutrition has a direct trophic effect on bowel integrity and development. Furthermore, early enteral nutrition has been demonstrated to have a beneficial effect on intestinal tract maturity in very low birth weight and sick infants. It should be started right after birth unless otherwise contraindicated. Average neonates should gain between 20 and 30 g per day or 1–2% of total body weight per day.
Intragastric feeding is preferable because it allows for normal digestive processes and hormonal responses, greater tolerance for large osmotic loads, and low incidence of dumping. Breast or bottle feeding is preferable for infants greater than 32 to 34 weeks’ gestation who have a coordinated suck and swallow mechanism. Gavage feeding is indicated for infants with an impaired suck and swallow mechanism, or for supplementing those infants with a high metabolic rate who cannot gain weight with oral feeding alone. This is performed by passing a number 5 French silastic or polyethylene feeding tube into the stomach. The use of nasoduodenal or nasojejunal tubes is reserved for infants who cannot tolerate intragastric feeding (e.g. delayed gastric emptying, gastroesophageal reflux, depressed gag reflex). A Silastic mercury-tipped feeding tube (length: tip of nose to knee) is passed through the nose into the stomach. Transpyloric tube placement can be accomplished by either placing a mercury-weighted tube into the stomach, positioning the patient right side down, and administering a prokinetic agent if gastric peristalsis does not propel the tube into the duodenum, or by fluoroscopic guidance. It is mandatory to confirm proper tube placement by aspirating bilious fluid and obtaining a radiograph.

Common contraindications for establishing enteral nutrition include hemodynamic instability, respiratory distress, sepsis, abdominal distention, and necrotizing enterocolitis or intestinal obstruction. Prolonged delay or inability to initiate oral feeding mandates placement of a gastrostomy or jejunostomy tube. These can be placed during open surgery, laparoscopic surgery, or by percutaneous approach aided by gastroscopy or fluoroscopy.

**Formula selection**

Mother’s breast milk

Every effort should be made before and after delivery to encourage maternal pumping. Breast milk contains an average of 20 kcal/oz and has several advantages compared to commercial formula feeds including:

(a) Lactoferrin, which limits availability of iron to pathogenic bacteria;
(b) Secretory IgA antibodies against specific pathogens;
(c) Numerous hormones and growth factors such as epidermal growth factor;
(d) Lysosome, a protective factor thought to influence flora in the intestinal tract through cell wall lysis;
(e) Ability to meet growth needs for preterm infants with addition of human milk fortifier.
Infant formulas

Iron-fortified formulas are an appropriate substitute for infants who are not breast fed. Standard infant formulas all contain a similar distribution of macronutrients with 40–45% of calories from carbohydrate, 8–12% of calories from protein, and 45–50% of calories from fat. These formulas usually contain 20 kcal/oz, but can be concentrated to 24 kcal/oz. Infant formulas are classified into the following categories based on source and/or type of protein: cow’s milk, soy, protein hydrolysate, and amino acid (Table 8).

(1) Cow’s milk-based formulas

Cow’s milk formulas are the most commonly used formulas in infants who are not breastfed and can meet nutritional needs during the first 6 months of life. Lactose is the carbohydrate source in standard cow’s milk-based formulas; however, there is a lactose-free version. Whey and casein are the main protein sources,

<table>
<thead>
<tr>
<th>Formula type</th>
<th>Product names</th>
<th>Protein source</th>
<th>Fat source</th>
<th>Carbohydrate source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow’s milk (term)</td>
<td>Enfamil, LIPIL, Similac</td>
<td>Casein, whey</td>
<td>Vegetable oils</td>
<td>Lactose</td>
</tr>
<tr>
<td></td>
<td>Advance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cow’s milk (preterm)</td>
<td>Premature Enfamil,</td>
<td>Casein, whey</td>
<td>MCT oil, soy, coconut or sunflower,</td>
<td>Corn syrup solids,</td>
</tr>
<tr>
<td></td>
<td>Similac Special Care</td>
<td></td>
<td>DHA, ARA</td>
<td>lactose</td>
</tr>
<tr>
<td>Soy</td>
<td>Prosobee, Isomil,</td>
<td>Soy protein</td>
<td>Soy and coconut oils</td>
<td>Glucose polymers,</td>
</tr>
<tr>
<td></td>
<td>Good Start Essential</td>
<td></td>
<td></td>
<td>sucrose, lactose</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>free</td>
</tr>
<tr>
<td>Hydrolyzed protein</td>
<td>Nutramigen, Pregestimil</td>
<td>Hydrolized casein, added amino</td>
<td>55% MCT, 45% vegetable oil</td>
<td>Glucose polymers,</td>
</tr>
<tr>
<td></td>
<td>Alimentum</td>
<td>acids</td>
<td></td>
<td>lactose free</td>
</tr>
<tr>
<td>Free amino acid</td>
<td>Neocate, Elecare</td>
<td>L-amino acids</td>
<td>Soy, safflower, coconut and MCT oils</td>
<td>Corn syrup solids</td>
</tr>
</tbody>
</table>

ARA: arachidonic acid, DHA: long-chain polyunsaturated fats docosahexaenoic acid, MCT: medium chain triglycerides.
and fat content comes from vegetable oil. Cow’s milk formulas can be used in both term and preterm infants.

(2) Soy-based formulas

Soy formulas contain soy protein and are lactose-free. They are indicated for infants with lactose intolerance and galactosemia, and are a safe alternative for term infants. However, studies in preterm infants show slower gains in weight and length, as well as decreased bone mineralization.21

(3) Hydrolyzed protein formulas

Hydrolyzed protein formulas contain casein and/or whey which have been enzymatically hydrolyzed into peptide chains and free amino acids. These formulas are recommended for infants intolerant to cow’s milk and soy proteins. They contain a higher concentration of medium chain triglycerides which can be absorbed by intestinal venules and bypass the lymphatic system, thus requiring less pancreatic and biliary secretions for absorption. Indications for a formula high in medium-chain triglycerides include liver disease, cystic fibrosis, lymphangiectasia, and chylothorax.

(4) Amino acid-based formulas

Amino acid formulas contain 100% free amino acids and are designed for infants with extreme protein hypersensitivity. These formulas are nutritionally complete but are the most expensive of all infant formulas. Amino acid-based formulas are often used in patients with short bowel syndrome.

Parenteral nutrition

Indications for parenteral nutrition include the following: extremely low birth weight infant, surgical gastrointestinal tract abnormalities with prolonged post-operative ileus (e.g. gastroschisis, necrotizing enterocolitis), short gut syndrome following extensive bowel resection, chronic diarrhea (e.g. malabsorption syndrome), chylothorax, and intestinal fistulae.22

Short-term or supplemental, relatively low calorie, parenteral nutrition may be administered via peripheral vein. However, the glucose concentration in peripheral parenteral nutrition is limited to 12.5% dextrose solution, because more concentrated solutions can thrombose peripheral veins. In contrast, central venous administration allows higher dextrose loads as greater blood flow immediately dilutes the
solution. Central venous access can be obtained percutaneously or via cutdown. Catheter tip position should be at the superior vena cava/right atrial junction as judged by fluoroscopy. A post-procedure chest radiograph is recommended to rule out pneumothorax following percutaneous central catheter placement through a subclavian vein. Daily total parenteral nutrition (TPN) component requirements for neonates with comparison values for older children are detailed in Table 9.

### Initiating total parenteral nutrition

1. **Carbohydrates**

Begin neonates at 4–6 mg/kg/min of dextrose and infants at 7–8 mg/kg/min. Increase by 2 mg/kg/min every day until the goal of 10–12 mg/kg/min is reached. Do not exceed 12.5% dextrose in peripheral veins. Central veins can tolerate up to 30% dextrose.

2. **Protein**

Begin neonates and infants at 0.5 gm/kg/day and advance by 0.5–1 gm/kg/day up to a maximum of 3 gm/kg/day. Do not exceed 10–12% of total daily caloric intake. Protein intake should be restricted in patients who cannot tolerate a large nitrogen load (e.g., patients with renal insufficiency).

### Table 9. Total parenteral nutrition requirements.

<table>
<thead>
<tr>
<th>Component</th>
<th>Neonate</th>
<th>6 m–10 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calories (kcal/kg/d)</td>
<td>90–120</td>
<td>60–105</td>
</tr>
<tr>
<td>Fluid (cc/kg/d)</td>
<td>120–180</td>
<td>120–150</td>
</tr>
<tr>
<td>Dextrose (mg/kg/min)</td>
<td>4–6</td>
<td>7–8</td>
</tr>
<tr>
<td>Protein (gm/kg/d)</td>
<td>2–3</td>
<td>1.5–2.5</td>
</tr>
<tr>
<td>Fat (gm/kg/d)</td>
<td>0.5–3</td>
<td>1–4</td>
</tr>
<tr>
<td>Sodium (mEq/kg/d)</td>
<td>3–4</td>
<td>3–4</td>
</tr>
<tr>
<td>Potassium (mEq/kg/d)</td>
<td>2–3</td>
<td>2–3</td>
</tr>
<tr>
<td>Calcium (mg/kg/d)</td>
<td>80–120</td>
<td>40–80</td>
</tr>
<tr>
<td>Phosphate (mg/kg/d)</td>
<td>25–40</td>
<td>25–40</td>
</tr>
<tr>
<td>Magnesium (mEq/kg/d)</td>
<td>0.25–1</td>
<td>0.5</td>
</tr>
<tr>
<td>Zinc (mcg/kg/d)</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Copper (mcg/kg/d)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Chromium (mcg/kg/d)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Manganese (mcg/kg/d)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Selenium (mcg/kg/d)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
(3) Fat

Begin neonates at 0.5 gm/kg/day, infants at 1.0 gm/kg/day and advance 0.5–1.0 gm/kg/day as a continuous infusion up to a goal of 3.0 gm/kg/day. Contraindications to lipid infusion include allergy to egg yolk phospholipids and fat metabolism abnormalities (e.g. hyperlipidemia, lipoid nephrosis). Thrombocytopenia is a relative contraindication to lipids as intralipid may interfere with platelet function. Do not exceed 1 gm/kg/day in premature infants with hyperbilirubinemia as free fatty acids can displace bilirubin from albumin. Intralipids must account for at least 2% of caloric requirements to prevent essential fatty acid deficiency. Omega 3 fatty acids are an alternative form of lipid that may help limit cholestasis.

**Pain Management**

Postoperative pain management in newborn surgical patients may be challenging. During the 1980s, the World Health Organization designed a three-step analgesic ladder using cancer pain as reference. Step 1 includes nonsteroidal analgesics such as acetaminophen, ketorolac, ibuprofen etc. Step 2 includes mild opioids like codeine, oxycodone, and tramadol. Step 3 is reserved for stronger opioids like morphine, fentanyl, and methadone. Use of opioid analgesics in neonates must be monitored carefully. As a group, neonates have a narrower therapeutic window for postoperative morphine analgesia than older age groups. In addition, neonates treated with opioids exhibit variable pharmacokinetics and are at high risk for respiratory depression. Despite these challenges, postoperative opiate analgesia can be effectively used to control pain in neonates.

**REFERENCES**