CHAPTER 13
The Pediatric Spine

JOSEPH D. TOBIAS/DANIEL G. HOERNSCHEMEYER

INTRODUCTION

Spinal surgery is one of the most common of the major orthopaedic operations in children. Spinal deformities that require surgery may be caused by congenital, acquired, or traumatic conditions. They may be due to primary defects of the vertebral column (hemivertebrae), neuromuscular disease (muscular dystrophy, cerebral palsy), or related to cancer, infections, or therapy. In spinal surgery, irrespective of the cause of the deformity that is being corrected, there are several surgical factors that may result in morbidity or death, including underlying disease, positioning of the patient, blood loss, and neurologic damage. To limit such problems, these patients should be approached in a standardized manner. This includes (1) a preoperative evaluation to identify comorbid features; (2) the anesthetic plan with attention to monitoring, patient positioning, maintenance of normothermia, techniques to limit the need for homologous transfusion, and control of coagulation function during large-volume transfusions; and (3) the postoperative regimen to maintain hemodynamic and respiratory parameters and to provide analgesia.

Spinal surgery in children may involve any level of the vertebral column through an anterior approach or a posterior approach or, in the case of thoracic and lumbar spine procedures, a combined anteroposterior (AP) procedure. However, the vast majority of the operations performed in pediatric patients involve long-segment surgery on the thoracic and lumbar spine. This chapter reviews the developmental and gross anatomy of the spine and gives an outline of the specific surgical procedures; preoperative assessment; anesthetic care, including methods to limit the need for homologous blood transfusion and spinal cord monitoring; and postoperative care, including pain management.

DEVELOPMENTAL AND GROSS ANATOMY OF THE SPINE

Overview

The spine can be divided into four regions corresponding to four natural spinal curves: cervical, thoracic, lumbar, and sacral. The “normal” spine shows thoracic and sacral kyphosis and cervical and lumbar lordosis. The lordosis curvature of the cervical neck and of the lumbar spine develops in a response to weight bearing. As the posterior neck muscles of an infant gain strength, the spine develops lordotically to support the heavy head. At about 12 months of age, the lumbar spine develops a lordotic curve as a result of walking. Cervical and lumbar lordoses are considered secondary curves due to weight bearing. Their purpose is to keep the spine balanced and reduce the workload on the posterior spinal musculature. Thoracic and sacral kyphoses are considered to be primary curves. Normal cervical lordosis typically ranges from 20 to 40 degrees, while lumbar lordosis ranges between 30 and 50 degrees. An acceptable thoracic kyphosis curvature is 20 to 50 degrees. Medically, there is a broad range of acceptable sacral curvature, since S1–S5 are fused in a kyphotic angle.

Abnormal curvatures of the spine are scoliosis and kyphosis. Scoliosis is a complex three-dimensional deformity that involves changes in the coronal, sagittal, and axial alignment of the spine. The structural changes include wedging of the vertebral body, rotation of the vertebral body to the convex side of the curve, and deformities
of the posterior elements. These changes are greatest at the apex of the curve. At this point, one will find the pedicle shortened and thickened, the lamina heavier, and the spinous process deviated toward the concave aspect of the curve. The vertebral body becomes wedge-shaped and thicker on the concave aspect of the curve owing to compression during spinal growth, while the vertebral body becomes thinner on the convex side, since it is expanded. The transverse processes approach the sagittal plane on the convex side and are positioned more toward the concave side in the frontal plane. Additionally, rib prominence is often noticed on the convex side of the curve owing to the rotation of the thoracic vertebrae. These structural abnormalities cause an asymmetrical thoracic cavity that may compromise respiratory function.

Scoliosis can have many causes. Congenital scoliosis represents a failure of formation or failure of segmentation of the vertebrae. Neuromuscular scoliosis may be caused by cerebral palsy, muscular dystrophy, myelomeningocele, poliomyelitis, or other diseases that affect the muscles or nervous system. Syndromes associated with a scoliotic spine include Marfan’s syndrome, neurofibromatosis, and bone dysplasia. Idiopathic scoliosis is by far the most common of all scolioses and is classified according to age of development.

Abnormal kyphosis is usually classified as postural kyphosis, congenital kyphosis, or Scheuermann’s kyphosis. Postural kyphosis, often referred to as round-back deformity, is a flexible spinal deformity that responds well to nonoperative treatments. Less common but more serious is congenital kyphosis. Surgery is usually recommended for this condition because of its rapid rate of progression, at 5 to 7 degrees per year, and the potential for neurologic damage. Congenital kyphosis, like congenital scoliosis, is known to be caused by a failure of part or all of the vertebral body to form or a failure of segmentation of part or all of the vertebral body.

Scheuermann’s kyphosis presents in the thoracic, thoracolumbar, and/or lumbar spine. The etiology of both thoracic and thoracolumbar disease is unknown, although many researchers have suggested hormonal, nutritional, traumatic, vascular, and genetic factors as possible causes. Trauma is medically accepted to be the cause of lumbar Scheuermann’s kyphosis. Clinically, all three varieties of Scheuermann’s kyphosis show rigidity in the affected area. Radiographically, more than 5 degrees of wedging of at least three adjacent vertebrae in a lateral view is necessary for the diagnosis. Radiographs will also show that the vertebral endplates are irregular and the disk plates narrowed. Schmorl nodes, thought to be the result of a herniated disk protruding through the weakened endplate, are often visible on x-ray films. Treatment includes nonoperative methods and surgery, depending on the symptoms and the degree of curvature. A curve of more than 75 to 80 degrees warrants surgery.

The Spinal Cord and Spinal Nerves

There are 31 pairs of spinal nerves: 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal. The first cervical root exits between the skull and C1, while the root of the eighth cervical nerve exits between C7 and T1. Thereafter, all nerve roots exit at the same level as their corresponding vertebrae. However, one should realize that the nerve roots branch off the spinal cord at a higher level than their actual exit through the intervertebral foramen. Specifically, the spinal nerve usually travels caudal adjacent to the spinal cord before exiting through the vertebral foramen. The development of these nerves is complex. The neural tube, which is crucial in embryonic development, becomes the central nervous system, and the neural crest forms the majority of the peripheral nervous system. As the neural tube closes, the neural crest cells migrate between the neural tube and the somite to form the peripheral nervous system, Schwann cells, and melanocytes. The neural tube becomes the spinal cord, the brain, and the peripheral afferent nerves and preganglionic fibers of the autonomic nervous system. When the neural tube closes, the dorsal region separates into two halves, the alar and basal laminae, referred to as the roof and floor plates. The alar plate becomes the sensory pathways, or dorsal columns, while the basal plates develop into the motor pathways. The motor pathways or the ventral horn neurons develop axons that form the ventral roots. The axons of the ganglion cells form central processes, which become the dorsal roots and peripheral processes that end in sensory ganglia. Motor neurons become functional before sensory nerves. Autonomic nerve function is established last.

Dissection shows that the motor fibers are located on the anterior side of the spinal cord and the sensory fibers on the posterior side. A group of motor fibers is referred to as a ventral root (anterior root), while a collection of sensory fibers form a dorsal root (posterior root). The sensory nerves have groups of cell bodies outside of the spinal cord known as the dorsal root ganglia, which contain the nuclei of the sensory nerves. Directly lateral to the ganglia, the anterior and posterior (ventral and dorsal) nerve roots join to form a common spinal nerve surrounded by a dural sheath. This is the point where the peripheral nerve begins. Immediately after formation, the peripheral nerve divides into a small dorsal (posterior) ramus and a much larger ventral (anterior) primary ramus. The posterior primary rami innervate the paraspinal muscles on either side of the vertebral column and a narrow strip of overlying skin. All of the other muscles and skin are innervated by the anterior primary rami, which form the cervical, brachial, lumbar, and sacral nerve plexuses and the intercostal nerves.

Further dissection reveals the layers (meninges) that protect the spinal cord: the dura mater, arachnoid layer, and pia mater. The dura mater, the most external layer, is composed of connective tissue, is gray in color, and is easily identified. A narrow subdural space separates the
dura mater from the next layer, the arachnoid. This middle layer provides much of the vascular supply. Between the arachnoid layer and the deepest layer, the pia mater, lies the subarachnoid space, which contains the cerebrospinal fluid; it protects the nerve pathways by acting as a shock absorber. The pia mater is closely adherent to the spinal cord and the individual nerve roots. It is highly vascularized to provide the blood supply to the underlying neural structures.

The spinal cord extends from the foramen magnum to L1–L4, depending on the age of the patient. The caudal end of the cord moves from its initial position of L3–L4 in infancy to its adult position at L1. The spinal cord terminates as the conus medullaris. Below this, the thick flexible dural sac contains the spinal nerves collectively known as the cauda equina. Within the cauda equina, is the filum terminale, which extends from the conus medullaris to the coccyx and acts as an anchor to keep the lower spinal cord in its normal shape.

**Vascular Components**

The blood supply to the spinal cord involves several arteries and arteriolar branches. The anterior arterial trunk and the two posterior lateral trunks, which arise from the vertebral arteries, are important aspects of the blood supply to the cervical, thoracic, and lumbar cord. To assist these longitudinal arterial pathways, there are up to 17 radicular arteries anteriorly and as many as 25 posteriorly. The thoracic and lumbar radicular arteries are supplied by the aorta, while the vertebral arteries supply the majority of the radicular arteries in the cervical spine. In addition, the artery of Adamkiewicz, which is usually located on the left at T9–T11, feeds the lumbar section. It is the largest of the radicular arteries supplying the spinal cord by anastomosing with the anterior (longitudinal) spinal artery. Injury to the artery of Adamkiewicz can cause devastating ischemia of the lower spinal cord and paraplegia. Additionally, the blood supply of the thoracic spine is more tenuous than that of the cervical or lumbar spine, especially at the T4–T9 watershed area, which is more prone to ischemic injury.

A pair of segmental arteries, arising from the aorta, is present at every vertebral level to provide blood to the extra- and intraspinal structures. The segmental arteries divide into many branches at the intervertebral foramen. A second network of segmental arteries lies within the spinal canal in the loose connective tissue of the extradural space. This second network provides an alternative pathway of blood flow that ensures adequate spinal cord circulation after ligation of the segmental arteries during surgery.

**Body Components**

The outer layer of the vertebrae consists of dense, solid cortical bone made of compact Haversian systems. On the inside is cancellous or trabecular bone; a porous, loosely connected bone. This bone is weaker and more susceptible to disease and loss of density than cortical bone. The outer cortical bone extends above and below the superior and inferior ends of the vertebrae to form rims. The pedicles, consisting of dense cortical bone surrounding the medullary canal, are two short, rounded processes that extend posteriorly from the lateral margin of the dorsal surface of the vertebral body. The anterior third of the pedicle and the vertebral body together are referred to as an anterior arch.

The posterior arch, which attaches laterally to the anterior arch, includes the laminae, processes (spinous process, transverse process, superior particular process), and posterior two-thirds of the pedicles. The laminae are two flat plates of bone extending mediially from the pedicles to form the posterior wall of the vertebral foramen. The part of the lamina located between the superior and inferior articular processes is called the pars interarticularis. Spondylolysis is a defect in the pars interarticularis, most commonly at the L5 level.

There are three spinal processes or projections of bony tissue that are attachment sites for tendons and ligaments. Two inferior and two superior articular processes extend from the junction of the pedicles and laminae. The inferior and superior articular processes meet to form facet joints. The facet joints are surrounded by a capsular membrane containing synovial fluid that, together with the intervertebral disk, provide mobility of the spine. Two transverse processes (one on each side of the pedicles) extend laterally and provide an attachment point for ligaments and tendons. A single spinous process, which rises posteriorly from the junction of the two laminae, also provides an attachment point for ligaments and tendons and serves as a lever for motion of the vertebrae.

Other bony components include the endplate and apophyseal ring. Endplates are located superiorly and inferiorly within the rim of each vertebral body. Each endplate consists of a cartilaginous external layer and a bony internal layer and provides vascular nutrition to the avascular intervertebral disk. These endplates also serve as growth rings, predominately in height, for the vertebral bodies. The endplates are closed by 17 to 18 years of age. The apophyseal ring of cortical bone surrounds the vertebral body below portions of the endplate. During surgical procedures, it is important to leave as much as possible of this bony endplate intact so as to prevent an implanted device from penetrating into the soft cancellous bone. The endplate is well vascularized, offering an excellent site for a fusion graft. The apophyseal ring is an ideal site for interbody fusion devices.

**Surgical Procedures on the Pediatric Spine**

Scoliosis is a lateral and rotational deformity of the vertebral column and it is most commonly idiopathic (60 to 70 percent), although it may also result from neuromuscular or
congenital bony deformities. It is three to four times more common in females than males. Surgery is indicated when the Cobb angle is greater than 40 degrees in the lumbar spine or 50 degrees in the thoracic spine. The goals of surgery are to stop further progression of the deformity and in many cases to partially correct it. Progressive curvature invariably leads to restrictive lung disease, respiratory insufficiency, chronic hypoxemia and hypercarbia, and death from cor pulmonale in the third to fifth decades of life.

The surgical treatment of pediatric spinal deformity can be divided into anterior and posterior procedures. The surgeon’s decision to use one or both of these approaches depends on the age of the patient, the underlying cause of the spinal deformity, and the severity of the curve. A patient with neuromuscular scoliosis can usually be treated surgically by using a posterior procedure but may require an anterior spinal release and fusion to aid correction, depending on the severity of the deformity. Procedures for the treatment of idiopathic scoliosis include anterior spinal release and fusion when a posterior procedure is involved, anterior spinal fusion with instrumentation for certain thoracic and thoracolumbar curves, and more recently thoracoscopic procedures to minimize dissection and decrease the morbidity of anterior spinal surgery.

Posterior procedures are effective in treating a wide variety of spinal deformities in children. Again, the underlying cause, degree of curvature, and patient’s age will determine the type of procedure. For the juvenile patient with idiopathic scoliosis, nonsegmental posterior spinal instrumentation without fusion is used. This is also known as a growing rod. Posterior spinal fusion with segmental instrumentation is the “gold standard” for treating the adolescent patient with idiopathic scoliosis. Patients with neuromuscular scoliosis will often require fixation to the pelvis in addition to the posterior spinal fusion to control their pelvic obliquity, which can affect their sitting balance. Posterior procedures for the treatment of congenital scoliosis are often performed in combination with anterior procedures. This includes a convex hemiepiphyseodesis or an in situ fusion to stop further progression of the curve. Posterior spinal fusion alone with instrumentation can be used to treat the older adolescent with congenital scoliosis.

Anterior Surgery for Scoliosis

Anterior approaches typically result in successful correction of the curvature while limiting the extent of the fusion. For all anterior approaches, the patient is placed in the lateral decubitus position and the operating table in a flexed position. For right thoracic curves, the patient is placed in a left lateral decubitus position. The opposite is true for a left lumbar curve. The upper arm is moved forward and rotated away from the posterior portion of the spine. To minimize pressure on the brachial plexus, an axillary roll should be placed between the table and the patient’s shoulder. Keeping all areas well padded is important to preventing nerve damage.

The surgeon will access the spine through the bed of the convex fifth rib for visualization of T5–T12 or via the bed of the tenth rib for access to the thoracolumbar spine. The initial incision extends anteriorly to the lateral border of the rectus sheath. The length of the incision will depend on the exposure required. As a general rule, the rib to be excised corresponds to the most superior vertebral body requiring exposure. For example, with a T6–T12 anterior fusion, the fifth rib would be excised. The rib below the level of incision is removed. The surgeon will split the costal cartilage anteriorly, which can later serve as a landmark for closure. When access to vertebral levels below T12 is necessary, the diaphragm must be divided. With fine dissection and gentle retraction, the peritoneum is separated off the diaphragm and the psoas muscle. Once the spine is exposed, retractors are positioned to protect the lung tissue and peritoneum. The surgeon can now access the vertebral disk or vertebral body, remembering that segmental vessels will be encountered at each level. Vascular compromise of the spinal cord after ligation of many segmental vessels is uncommon.

Video-Assisted Thoracoscopic Surgery

Video-assisted thoracoscopic technique is a new method for the surgical treatment of scoliosis. Specialized monitoring equipment is necessary for these surgical procedures, including the scope, light sources, cameras, flexible portals, monitors, and specific instrumentation. The anesthesiologist should be familiar with the use of double-lumen tubes with one-lung ventilation (see below). Contraindications to this method include a patient’s inability to tolerate single-lung ventilation, severe respiratory insufficiency, or high airway pressures with positive-pressure ventilation and previous thoracotomy. After general anesthesia is induced, the patient is turned into the lateral decubitus position, as previously mentioned for the anterior approach, and one-lung ventilation instituted. The upper arm is placed on a stand with the shoulder abducted and flexed. An axillary roll is positioned between the patient’s shoulder and the operating table. The surgeon identifies and outlines the scapular borders, 12th rib, and iliac crest. The first portal is usually placed at or near the T6–T7 interspace in the posterior axillary line. The surgeon makes an incision, continues with electrocautery through the intercostal muscle to enter the chest cavity, and ensures that the lung is deflated. Flexible portals are inserted in the intercostal spaces with a trocar. Using a blunt-tipped needle, a roentgenogram is completed to confirm the disk spaces.
The parietal pleura is completely resected with care not to ligate any segmental vessels. The surgeon then removes the disks and endplates. After the necessary diskectomies are completed, rib grafts are harvested through the portal sites. Before closure, a chest tube is placed through the most posterior inferior portal. The pleura may be closed or left open. The chest tube is connected to water seal and the anesthesiologist tests for an air leak in the reinflated lung.

Perioperative problems include bleeding, damage to the lung tissue, dural tears, lymphatic injury, and sympathetic nerve changes on the operative side. If hemostasis cannot be obtained and visualization remains poor, conversion to an open anterior approach may be required. Postoperatively, pulmonary problems can occur within the deflated lung. Often, mucous plugs form in this lung, requiring consistent, thorough suction, breathing treatments, and breathing exercises.

**Posterior Surgery for Scoliosis**

Because of recent advancements with segmental posterior spinal instrumentation, correction of both sagittal and coronal plane spinal deformities is felt to be superior to older systems such as the Harrington rods (Fig. 13-1). For this reason, the posterior approach to the spine has become increasingly popular. The posterior instrumentation method takes advantage of the spinous processes, pedicles, facets, and laminae to control the alignment of the vertebral bodies with the use of laminar hooks, pedicle hooks, pedicle screws, facet screws, and wires. The patient is placed prone on an appropriate spinal frame so that the inferior vena cava is less compressed and the abdomen hangs free. Traditionally a Hall frame or more recently a Jackson table is used to support the patient without increasing intraabdominal pressure. The patient's face should be well padded to avoid any pressure on the eyes. The patient's back is completely draped, with the entire spine and the iliac crest (for graft harvest) exposed.

The surgeon makes a midline incision over the spinous processes, splitting the apophysis and using subperiosteal dissection to expose the transverse processes laterally. The appropriate vertebrae are then identified using fluoroscopy or a plain radiograph. After a facetectomy and wide posterior release at each level, instrumentation is performed. Pedicle hooks, pedicle screws, laminar hooks, and sublaminar wires are inserted at the appropriate levels to obtain adequate correction. The first rod is placed on the concave side of the curve and subsequently rotated to correct the spinal deformity. Changes in spinal cord function, seen with neuromonitoring, usually occur during this phase of the surgery. While correction is maintained with the first rod, the second rod is placed. Cross-links are added to increase the torsional stiffness of the rod.

Figure 13-1. Harrington rods.
Decortication of the posterior elements prepares the spine for fusion. Bone grafts and layered closure complete the operation.

**Preoperative and Intraoperative Care**

**Preoperative Evaluation**

The first step in the anesthetic care of these patients is a thorough preoperative evaluation to identify comorbid features that may affect their perioperative care. The effect of the disease on airway management is of primary importance. Patients presenting for surgery of the cervical spine should be assumed to have an unstable cervical spine or the potential for subluxation during neck movement, which can endanger the spinal cord. Problems of the cervical spine may be due to trauma or a congenital syndrome (Trisomy 21, achondroplasia, or rare craniofacial syndromes such as Pfeiffer’s, Apert’s, or Crouzon’s syndromes). Subluxation and upper cervical intervertebral fusions have been reported in 30 percent of patients with Pfeiffer’s syndrome, while odontoid hypoplasia and the risk of C1–C2 subluxation have been reported in patients with Crouzon’s syndrome and the mucopolysaccharidoses (see Chap. 6). Even in the absence of such problems, scoliosis or kyphosis may limit normal movement of the cervical spine and make endotracheal intubation difficult. Preoperative evaluation of spinal abnormalities, including a physical examination with an evaluation of neck movement, should be supplemented as needed with radiographic examination (flexion/extension films) or computed tomography (CT) scanning. An additional abnormality that may affect airway management is foramen magnum stenosis, which has been reported in patients with achondroplastic dwarfism. It results from hypertrophy of the bony margins of the foramen magnum, which can cause narrowing of the cervical spinal canal and compression of the cervical spinal cord or medulla. In children with achondroplasia who show neurologic or respiratory symptoms related to foramen magnum stenosis, the diameter of the foramen magnum has been shown to be three standard deviations below the mean for age-matched controls with normal stature.

Patients with craniofacial syndromes may also have midface abnormalities that affect airway management, including difficult bag-valve-mask ventilation and endotracheal intubation. Common abnormalities of the craniofacial syndromes include micrognathia, microstoma, midface hypoplasia, and lip/palatal abnormalities. Glossal hypertrophy may be present in neuromuscular conditions (see Chap. 6). If fiberoptic endotracheal intubation is anticipated, the patency of the nares should be assessed because choanal atresia is a feature of these syndromes. The equipment required for management of a difficult airway, as outlined by Vener and Lerman, should be readily available, including fiberoptic bronchoscopes and various sizes of laryngeal mask airways. During airway manipulation, excessive cervical spinal movement is prevented by manual in-line stabilization. In older, cooperative children and adolescents, awake intubation techniques commonly used in adults (intravenous sedation with glossopharyngeal nerve and superior laryngeal nerve blockade) followed by direct laryngoscopy or fiberoptic bronchoscopy may be feasible for endotracheal intubation.

After the airway examination, organ systems should be examined in sequence. Nervous system problems may be frequent comorbid features in children presenting for spinal surgery. Children with scoliosis presenting for posterior spinal fusion may have cerebral palsy and static encephalopathy, which may sometimes be complicated by mental retardation and seizure disorders. The preoperative evaluation should document therapeutic anticonvulsant concentrations in the serum. Anticonvulsant medication should be administered preoperatively to maintain therapeutic levels and should be started again during the postoperative period. The induction of hepatic enzymes by certain anticonvulsants may increase the metabolism of several drugs, including neuromuscular blocking agents (NMBAs) and some anesthetic induction agents. Increased intraoperative doses of these drugs may therefore be necessary for children treated with anticonvulsants. Mental retardation and visual and hearing disturbances may obviously make assessment of the patient difficult. Some degree of intellectual impairment is noted in 30 to 50 percent of patients with Duchenne’s muscular dystrophy. These effects may also complicate the postoperative course by making pain assessment difficult.

Depending on the degree of scoliosis and the associated conditions, respiratory function may be compromised due to restrictive lung disease. Patients with scoliosis have decreased vital capacity, total lung capacity, and forced expiratory volume, while the residual volume remains normal. The decrease is greater in patients with congenital or infantile scoliosis than in those with adolescent scoliosis. The severity of the impairment is related to the angle of the scoliosis, the number of vertebral levels involved, the cephalad level of the scoliosis, and the loss of normal thoracic kyphosis. Muirhead and Conner found that 14 of 41 children with either infantile or congenital scoliosis had a moderate or severe ventilation defect (40 to 59 percent predicted for age) compared to only 4 of the 51 children with adolescent scoliosis. They also found that no child whose vital capacity was greater than 40 percent of that predicted for age required postoperative respiratory support. The effect of surgery on lung function depends on the surgical approach and the type of surgery. Surgical procedures that involve the thorax (anterior spinal fusion) reduce lung function for 3 months, with a return to preoperative values by 2 years. However, a pure posterior approach improves respiratory function at both 3 months and 2 years.
Controversy also exists about the degree of respiratory compromise that may contraindicate scoliosis surgery. In adults it has been suggested that a reduction of the forced vital capacity (FVC) or the forced expiratory volume in 1 s (FEV₁) to less than 40 to 60 percent of the predicted value may indicate a higher risk of postoperative complications and the need for postoperative mechanical ventilation. However, the criteria used to predict postoperative respiratory function in adults cannot necessarily be applied to children, because there are fewer comorbid features such as cardiac disease in children. The fact that preoperative tests of pulmonary function in children have little predictive value has been demonstrated by Tobias et al. Although the authors noted a consistent decrement in predicted-for-age values after 32 thoracotomies in 19 pediatric oncology patients, with a decrease in the FVC (percent predicted for age) from 68 ± 3.6 to 60 ± 2.4 percent (p < 0.01) and the FEV₁ from 69 ± 4.2 to 60 ± 3.8 percent (p < 0.01), no permanent morbidity was noted in the small cohort of patients with severe restrictive lung disease. Five of the patients had severe preoperative decreases in pulmonary function (less than 40 percent predicted for age). In this group the incidence of morbidity, defined as a postoperative need for ventilation and supplemental oxygen for more than 12 h or persistent air leak, was 3 of 5 versus 3 of 20 in patients with mild or moderate lung disease (60 to 80 percent predicted for age). There was, however, no postoperative mortality and no need for prolonged mechanical ventilation. Respiratory function may be further threatened by conditions that predispose to chronic upper respiratory tract infections or recurrent bouts of aspiration due to chronic gastroesophageal reflux. Any of the neuromuscular disorders (e.g., Duchenne’s muscular dystrophy) may significantly affect respiratory function by adding chronic lung disease to the restricted function associated with the scoliosis. In all patients with severe restrictive lung disease, the decision to operate must therefore be based on an assessment of the potential for long-term postoperative ventilation versus the potential of benefits of surgery.

Cardiovascular abnormalities in patients with scoliosis may be due to the primary disease process or less commonly due to cor pulmonale and chronic hypoxemia from restrictive lung disease. The latter is uncommon because scoliosis is frequently treated before cardiovascular effects develop. Various neuromuscular conditions, such as the muscular dystrophies or myotonic dystrophies, may lead to changes in myocardial contractile function or conduction abnormalities. Of these conditions, Duchenne’s muscular dystrophy is the most common disorder, with an incidence of 1 in 3300 male births. It is inherited as an X-linked disorder, which presents as weakness during the fourth to eighth years of life. The diagnosis is confirmed by muscle biopsy. The genetic defect results in a deficiency of the protein dystrophin in skeletal, cardiac, and smooth muscle. As these patients enter their second decade of life and definitely by the third decade, the myocardium is progressively affected by depressed contractility, conduction disturbances, and arrhythmias. Several reports in the literature have described a significantly increased risk of morbidity and even mortality during anesthetic care in patients with Duchenne’s muscular dystrophy. Sethna et al. reported intraoperative cardiac arrest and death in 2 of 25 patients. In patients with associated myopathic conditions, the preoperative evaluation should include echocardiography and a 12-lead electrocardiogram (ECG).

The preoperative evaluation and preparation of the patient are essential to limit the use of allogeneic blood products. This may include arrangements for preoperative autologous donation with or without the use of erythropoietin (see below for a discussion of intraoperative techniques to limit the need for homologous transfusion). Patients presenting for major orthopaedic surgery may have chronic medical or nutritional conditions that affect blood coagulation. Chronic treatment with anticonvulsants, including phenytoin and carbamazepine, may adversely affect coagulation function. Poor nutritional status and poor intake of vitamin K may predispose to chronically low levels of vitamin K-dependent coagulation factors, resulting in preoperative coagulation dysfunction. Preoperative screening of coagulation function and simple measures such as the administration of vitamin K (oral or intramuscular) may prevent these problems. Patients with chronic orthopaedic problems and pain frequently use NSAIDs. Although acetylsalicylic acid irreversibly inhibits cyclooxygenase and platelet function for the life of the platelet, NSAIDs cause reversible inhibition of platelet function, which depends on the plasma concentration and half-life of the NSAID. Discontinuation of most NSAIDs for 2 to 5 days before surgery will result in the return of normal platelet function.

Premedication, Anesthetic Induction, Monitoring and Positioning

Premedication may include (1) high-flow nebulization of albuterol and an anticholinergic agent such as ipratropium in patients with airway reactivity; (2) gastrointestinal prophylaxis with H₂ antagonists (e.g., ranitidine), oral nonparticulate antacids and motility agents for patients at risk for aspiration; (3) dexamethasone for patients with airway reactivity as well as to decrease postoperative nausea and vomiting; (4) an anticholinergic agent such as glycopyrrolate or atropine to dry secretions, especially if fiberoptic intubation technique is planned, to blunt airway reactivity and to prevent bradycardia during laryngoscopy and endotracheal intubation; and (5) an anxiolytic. Premedication for anxiolysis follows the standard practice in pediatric anesthesia, including oral midazolam in patients without intravenous access or intravenous midazolam in those with such access.
After premedication, the patient is transported to the operating room and routine American Society of Anesthesiology (ASA) monitors are attached. In the operating room, normothermia should be maintained. This is particularly important in patients with little body fat. Normothermia is generally easily maintained by (1) keeping the operating room warmed until the patient is positioned and covered; (2) warming intravenous fluids, blood and blood products; and (3) the use of forced-air warming devices. Normothermia affects coagulation and makes its maintenance one of many essential steps to control blood loss.

The technique of anesthetic induction is guided by the patient’s medical conditions, an assessment of the ease of intubation, and the patient’s preference when appropriate. For anterior or posterior spine surgery, a reinforced endotracheal tube may be used to prevent inadvertent airway occlusion during surgical dissection and neck flexion. When neck flexion is prolonged, a nonreinforced endotracheal tube may become bent and occluded. In the patients with stable cardiovascular function, there are several options for the induction and maintenance of anesthesia. These include either inhalation techniques that utilize sevoflurane or halothane in oxygen or intravenous anesthesia. In patients with existing intravenous lines, several of the commonly used intravenous induction agents are suitable. If it is intended to perform endotracheal extubation in the operating room or immediately postoperatively, propofol may provide a more rapid awakening and a better recovery profile during the immediate postoperative period than barbiturates, while etomidate is an appropriate choice in patients with diminished myocardial function.

When adequate bag-mask ventilation has been achieved, inhalation or intravenous induction can be followed by the administration of a nondepolarizing neuromuscular blocking agent (NMBA). Succinylcholine is contraindicated in patients with various neurologic and myopathic conditions, given the potential for rhabdomyolysis, hyperkalemia, and cardiac arrest. Similar problems with succinylcholine may occur in patients after a spinal cord injury. Therefore our practice includes the use of intermediate-acting (vecuronium, rocuronium, cis-atracurium, atracurium) or short-acting (mivacurium) nondepolarizing NMBA. The doses of these agents should be adjusted by using train-of-four (TOF) monitoring, especially in patients with myopathies, in whom the response to these agents can vary. In patients with underlying neuromuscular disease, a single dose of an intermediate-acting agent may cause prolonged neuromuscular blockade. We have found similar variability even when using mivacurium in these patients. We have also noted that the response to neuromuscular blocking (onset and duration of action) did not correlate with the patient’s preoperative muscle strength.

After the airway is secured, adequate intravenous access and invasive cardiovascular monitoring are obtained. Several factors may cause hemodynamic changes during spinal surgery in children, including the patient’s associated medical conditions, positioning on the operating table, blood loss, and the administration of vasoactive agents to induce controlled hypotension. Arterial monitoring is routine in the majority of cases of pediatric spinal surgery. Adequate vascular access for the administration of blood, intravenous fluids, and medications is mandatory. This generally includes two large-bore (16- or 14-gauge) peripheral intravenous cannulas. The need for more invasive hemodynamic measurements remains controversial. Our practice has been to monitor central venous pressure (CVP) in patients with underlying conditions that may affect their myocardial function or in those in whom a protracted postoperative course is expected and prolonged venous access may be needed, such as patients with severe cerebral palsy and mental retardation. However, the correlation of CVP with myocardial function becomes less reliable in the prone position. Supkis et al. demonstrated that CVP increased from 8.7 ± 1.3 to 17.7 ± 2.5 mmHg when patients were turned from the supine to the prone position. At the same time the left ventricular end-diastolic pressure measured by transesophageal echocardiography decreased from 37.1 ± 2.9 to 33.2 ± 3.0 mmHg, thereby demonstrating a decrease in ventricular filling despite the increased CVP. The accuracy and utility of CVP measurements in the prone position are therefore questionable in such patients. Other monitoring procedures follow the routine recommended by the ASA, including electrocardiography, precordial or esophageal stethoscopy, observation of end-tidal carbon dioxide and temperature plus placement of a urinary catheter.

When appropriate vascular access and monitoring have been established, the patient is positioned on the operating table. The position will depend on the specific type of surgery but is generally prone or lateral. For cervical spinal and upper thoracic surgery, the head may have to be in a neutral position, supported in a ring device with the face directed toward the floor. Alternatively, for posterior spinal fusion that does not involve the lower cervical or high thoracic area or isolated lumbar surgery, the patient can be positioned prone and the head turned 90 degrees, thereby limiting the potential for pressure points on the eyes and face. Regardless of the positioning, careful padding of pressure points is necessary, since these surgical procedures may last up to 8 to 12 h.

The patient is positioned to minimize venous pressure at the surgical site in order to reduce bleeding. This is done by placing rolls under the chest and pelvis to keep the abdomen free and by reverse Trendelenburg positioning. The latter also helps to limit the development of dependent edema in the face, tongue, and upper airway and may also limit the increase in intraocular pressure (IOP), which may occur with prone positioning. Increased IOP due to prone positioning has been proposed...
as a possible cause of the rare but devastating complication of blindness following these surgical procedures. Keeping the abdomen free also facilitates mechanical ventilation by preventing restriction of diaphragmatic movement. Alternatively, specialized frames (e.g., the Wilson frame) can be used to position the patient so that venous pressure and surgical bleeding are decreased. For anterior procedures, the patient is positioned in the lateral position and a thoracotomy is performed to gain access to the vertebral column. There is also increasing experience with thorascopic approaches for such procedures. Regardless of whether open thoracotomy or thoracoscopy is performed, one-lung ventilation (OLV), as described below, will be required.

**One-Lung Ventilation for Anterior Approaches**

There are three basic options for OLV: (1) a double-lumen endotracheal tube (DLT), (2) a bronchial blocker, and (3) selective mainstem intubation. The smallest commercially available double-lumen endotracheal tube is 26 Fr, which precludes its use in patients less than 8 to 10 years of age. When the patient’s size permits, a DLT may be preferable because it provides several advantages over other techniques of lung separation, including (1) rapid and easy separation of the lungs, (2) access for suctioning of both lungs, (3) a rapid switch to two-lung ventilation if needed, and (4) the feasibility of providing continuous positive airway pressure (CPAP) or oxygen insufflation to the operative lung should it become necessary.

In patients in whom a DLT cannot be used, the bronchus on the operative side can be occluded with a balloon-tipped catheter placed under fiberoptic bronchoscopic guidance. Several different devices can be used as bronchial blockers, including a Fogarty embolectomy catheter, atrioseptostomy catheter, pulmonary artery catheter, the Arndt endobronchial blocker (Gook Critical Care, Birmingham, IN), and the Univent endotracheal tube (Fuji Systems, Tokyo, Japan). Devices with a small central channel allow some suctioning, but not enough to clear the lung of secretions. Instead, it is used to deflate the operative lung and improve surgical visualization or for the insufflation of oxygen and the application of CPAP. Without the central channel, air or gas cannot escape from the lung once the balloon is inflated. The lung may therefore not deflate completely and may obscure surgical visualization. If there is no separate central channel, the lung can be manually compressed by the surgeon during a brief period of apnea and the balloon then inflated prior to the provision of positive-pressure ventilation.

Regardless of which catheter and technique of placement are chosen, there is a risk that the bronchial blocker may be displaced during the surgical procedure or repositioning of the patient. If this occurs, the bronchial blocker may occlude the tracheal lumen just beyond the ETT, resulting in inadequate ventilation. Continuous auscultation of breath sounds on the nonoperative side and monitoring of inflating pressures and respiratory compliance should help to identify this problem rapidly. Clinical experience indicates that inflating the balloon of the bronchial blocker with saline instead of air may limit its movement and dislodgment. With any change in the patient’s position, the correct position of the bronchial blocker should be confirmed with fiberoptic bronchoscopy or auscultation.

The third method of OLV is selective endobronchial intubation. The major disadvantage of mainstem intubation is that it is not possible to change quickly to two-lung ventilation or vice versa. Furthermore movement of the ETT may cause extubation, which can be particularly troublesome when the patient is in the lateral decubitus position. Intubation of the right mainstem bronchus can generally be performed blindly, but intubation of the left bronchus requires bronchoscopic guidance because of anatomic differences in orientation of the bronchi.

When OLV is being utilized, general anesthesia is maintained with a combination of intravenous and inhalational agents. Because hypoxic pulmonary vasoconstriction (HPV) restricts blood flow to the nonventilated lung to limit hypoxemia, any nonspecific vasodilator (terbutaline, albuterol, isoproterenol, dobutamine, nicardipine, nitroglycerin, sodium nitroprusside, or an inhalational anesthetic agent) can impair oxygenation. Isoflurane has been shown to affect hypoxic vasoconstriction less than halothane or enflurane. However, no difference in oxygenation has been noted with isoflurane, sevoflurane, or desflurane at concentrations of 1 MAC. Anesthesia is supplemented as needed with intravenous agents including opioids, ketamine, benzodiazepines, propofol, and barbiturates, which have no clinically significant effect on vasoconstriction. Ventilation is maintained with tidal volumes of 8 to 10 mL/kg, the rate being adjusted as needed to maintain normocarbia. Hypocarbia is avoided because it may interfere with hypoxic pulmonary vasoconstriction (HPV). If adequate oxygenation cannot be maintained with 100% oxygen to the nonoperative side, CPAP of 4 to 5 cmH₂O can be applied to the operative lung provided that a DLT, Univent, or bronchial blocker with a central channel is used. Although this will improve oxygenation, it may also distort the operative lung to some degree and impair surgical visualization. Another option to improve oxygenation is to apply positive end-expiratory pressure (PEEP) to the nonoperative side. Applying excessive PEEP to the down or nonoperative side may impair oxygenation by increasing HPV in the nonoperative lung and shunting blood to the nonventilated, operative side. If the above measures fail, it may be necessary to ventilate both lungs intermittently.
Techniques to Limit Homologous Transfusion

There is increasing recognition of the potential adverse effects associated with the administration of allogeneic blood products, including the transmission of infectious diseases, immunosuppression, acute lung injury, transfusion reactions, and graft-versus-host disease. Techniques to limit the need for homologous blood products include (1) general methods such as preoperative optimization of coagulation function, anesthetic technique, proper patient positioning, and maintenance of normothermia (see above); (2) autologous donation, including preoperative donation with the use of erythropoietin and intraoperative collection using acute normovolemic hemodilution (ANH); (3) intraoperative and postoperative blood salvage; (4) pharmacologic manipulation of the coagulation cascade with epsilon-aminocaproic acid (EACA), tranexamic acid, aprotinin, desmopressin (DDAVP), and recombinant factor VIIa (rFVIIa); and (5) controlled hypotension (see Chap. 14). Surgery without the use of allogeneic blood products is best accomplished by combining several of these techniques.

The choice of intraoperative fluid administration may affect coagulation function and blood loss. During ANH (see below), blood is removed and replaced with crystalloids and/or colloids. Due to the dilution of anti-coagulatory factors such as antithrombin III, hemodilution increases coagulation function. Albumin and gelatins have been found to have no effect or may actually improve coagulation function. Medium- or high-molecular-weight hydroxyethyl starches, because of their effects on von Willebrand factor (vWF), adversely affect coagulation function, particularly platelet function when used in doses exceeding 10 to 15 mL/kg.

Preoperative Donation

Although preoperative donation of autologous blood was first suggested by Fantus in 1937, when he founded the first blood bank in the United States, the technique did not become popular until the 1980s. Advantages of the technique include reduced exposure to allogeneic blood, the availability of blood for patients with rare phenotypes, reduction of blood shortages, avoidance of transfusion-induced immunosuppression, and the availability of blood to some patients who refuse transfusions based on religious beliefs. There are no limitations in regard to a patient’s weight or age. Patients who weigh 50 kg or more donate a standard unit of blood (450 mL), while those who weigh less than 50 kg donate proportionately smaller volumes. The hematocrit should be 245 percent prior to each donation. Red blood cell production can be augmented by iron supplementation and the administration of erythropoietin (see below). Donations may be made every 3 days, but the usual practice is to donate one unit per week. The last unit should be donated at least 5 to 7 days before surgery to allow plasma proteins to normalize and to restore intravascular volume.

Acute Normovolemic Hemodilution

Acute normovolemic hemodilution (ANH) involves the removal of blood on the day of surgery (generally after the induction of anesthesia) and its replacement with crystalloid or colloid solution. Blood is removed by means of a large-bore intravenous cannula or a central line and is replaced with an equal volume of colloid or crystalloid in a ratio of 1 to 3. The blood is collected in standard CPD-A blood-bank bags and weighed to ensure that the appropriate amount is removed. The blood is kept in the operating room at room temperature for up to 4 h. A significant advantage of ANH over stored autologous blood is that the coagulation factors and platelets are still active. Intraoperatively, the blood is then infused in the opposite order to that in which it was withdrawn so that the units with the highest hematocrit value are saved until the end of the procedure, when bleeding is the least. The amount to be removed, is determined by the following formula:

Estimated blood volume × (initial hematocrit – target hematocrit)/starting hematocrit

Mechanisms that maintain oxygen delivery despite decreased hematocrit values include a decrease in blood viscosity (which increases venous return), peripheral vasodilation, increased cardiac output, and rightward shift of the oxyhemoglobin dissociation curve. Additionally, as oxygen delivery declines, oxygen extraction at the tissue level can increase to maintain adequate oxygenation. Fontana et al. evaluated the effects of ANH in 8 adolescents undergoing posterior spinal fusion for idiopathic scoliosis. Hemodilution decreased the hemoglobin from 10.0 ± 1.6 gm/dL to 3.0 ± 0.8 gm/dL. Oxygen delivery decreased from 532.1 ± 138.1 to 262 ± 57.1 mL/min/M2, oxygen extraction ratio increased from 17.3 ± 6.2 to 44.4 ± 5.9 percent, and cardiac output increased without a change in the heart rate. Mixed venous oxygen saturation decreased from a baseline level of 90.8 ± 5.4 to 72.3 ± 7.8 percent after ANH.

Intraoperative Blood Salvage

There are three techniques to salvage blood intraoperatively. Semicontinuous flow devices were the first to be introduced and, although they are the most complex, are still the type used most commonly. The disposable equipment consists of an aspiration and anticoagulation assembly, a reservoir (various sizes are available), a centrifuge bowl, a waste bag, and tubing. A double-line aspiration set includes an anticoagulation line that permits heparin or citrate to combine with the aspirated blood at a controlled rate. The anticoagulated blood is
collected in a disposable reservoir containing a filter. The filtered blood is then pumped into a bowl, centrifuged, washed with saline, and pumped into a reinfusion bag. Most of the white blood cells, platelets, clotting factors, free plasma hemoglobin, and anticoagulant are removed in the washing process and disposed of in the waste bag. The process takes approximately 5 to 10 min and yields a blood cell suspension with a hematocrit value of 45 to 60 percent.

The second type of intraoperative salvage, otherwise known as the canister collection technique, uses a rigid canister with a sterile, disposable liner. Blood is aspirated from the wound and anticoagulant added in a manner similar to that of semicontinuous flow devices. The blood can be washed before infusion or reinfused without washing. Functioning platelets and coagulation factors are present in the unwashed blood, but it poses an increased risk of adverse effects due to cellular debris, free hemoglobin, and fragmented blood components. This type is rarely used in the perioperative setting.

The third type of collection uses a single-use, self-contained rigid plastic reservoir with an anticoagulant (citrate) placed in it before use. This apparatus is most commonly used for postoperative blood collection and reinfusion. The surgical drains are connected to the canister, which is replaced and the blood reinfused every 4 h. Coagulation factors and platelets are present in this blood, but adverse effects may occur as a result of cell fragmentation and the release of free hemoglobin.

Suggested indications for intraoperative blood salvage include an anticipated blood loss exceeding 20 percent of the patient’s blood volume or a procedure during which more than 10 percent of patients require transfusion. Contraindications include situations in which there may be contamination of the collected blood with infectious or noninfectious agents (infected wounds, amniotic fluid, hemostatic agents, or protamine). Potential complications include air and fat embolism, hemolysis, pulmonary dysfunction, renal dysfunction, coagulopathy, hypocalcemia, and sepsis. Coagulopathy may be related to the initiation of disseminated intravascular coagulation (DIC) by improper technique and the infusion of blood cell fragments or the infusion of residual anticoagulant after washing. Hemolysis may occur if the suction level is too high or if the aspiration method causes excessive mixing of air with blood. Free hemoglobin may be released during salvage and washing because of erythrocyte damage. Free hemoglobin levels exceeding 100 to 150 mg/dL may lead to hemoglobinuria and acute renal failure, as the binding capacity of haptoglobin is saturated and free hemoglobin is filtered in the renal tubules. Metabolic consequences of cell salvage may also be seen, including a metabolic acidosis and alterations in electrolytes such as magnesium, calcium, and potassium. These alterations may be lessened by using a balanced electrolyte solution instead of saline for washing the cells before reinfusion. Regardless of the technique, periodic measurement of electrolytes and acid-base status is suggested during blood salvage.

Pharmacological Manipulation of the Coagulation Cascade

Various agents have been used prophylactically to decrease blood loss, even in patients with normal baseline coagulation function. Although these agents have been studied in well-designed, prospective trials, the results of the studies are conflicting. A theoretical issue with any of these agents is the potential to cause a prothrombotic state with venous or arterial thrombotic complications.

Desmopressin (DDAVP) is a synthetic analog of vasopressin initially used in the treatment of diabetes insipidus. It affects hemostasis by promoting the release of factor VIII and vWF from endothelial cells. Factor VIII, a glycoprotein, accelerates the activation of factor X by factor IX. The hemostatic functions of vWF include increasing platelet adherence to vascular subendothelium, formation of molecular bridges between platelets to increase aggregation, protection of factor VIII in plasma from proteolytic enzymes, and stimulation of factor VIII synthesis. Prospective trials have failed to show an effect of DDAVP on blood loss during spinal surgery in pediatric patients.

Epsilon-aminocaproic acid (EACA) and tranexamic acid (TA) are α-amino carboxylic acid analogs of lysine that inhibit fibrinolysis by preventing the conversion of plasminogen to plasmin. Plasminogen is activated by tissue plasminogen activator to form plasmin, which cleaves fibrin, thereby preventing the formation of the fibrin mesh. This fibrinolytic system is a basic defense mechanism that prevents the excessive deposition of fibrin following the activation of the coagulation cascade. Plasmin can also hydrolyze activated factors V and VIII. EACA and TA bind to the lysine group, which binds plasminogen and plasmin to fibrinogen, thus displacing these molecules from the fibrinogen surface and inhibiting fibrinolysis. EACA is administered at an intravenous loading dose of 100 to 150 mg/kg followed by an infusion of 10 to 15 mg/kg/h. Ninety percent is excreted in the urine within 4 to 6 h of administration. TA is 7 to 10 times as potent as EACA and may be used at lower doses (loading dose of 10 mg/kg followed by an infusion of 1 mg/kg/h). Ninety percent is present in the urine after approximately 24 h. Adverse effects of EACA or TA may be related to the effect on coagulation function and the route of excretion. Since these agents are cleared by the kidneys, thrombosis of the kidneys, ureters, or lower urinary tract may occur if urologic bleeding is present. Both EACA and TA may be associated with hypotension during rapid intravenous administration. Florentino-Pineda
et al. evaluated the efficacy of EACA (100 mg/kg followed by 10 mg/kg/h) in 28 adolescents undergoing posterior spinal fusion. Patients who received EACA had decreased intraoperative blood loss (988 ± 411 mL versus 1405 ± 670 mL, p = 0.024) and decreased transfusion requirements (1.2 ± 1.1 U versus 2.2 ± 1.3 U, p = 0.003).

Aprotinin is a naturally occurring serine protease inhibitor first isolated from bovine lung in 1930. Aprotinin’s effects on coagulation function are twofold: (1) inhibition of fibrinolysis through the inactivation of several serine proteases, including trypsin and plasma kallikrein, which convert plasminogen to plasmin, and (2) preservation of platelet adhesion by protecting membrane-bound glycoprotein receptors (vWF receptor) from degradation by plasmin. Aprotinin is administered intravenously and undergoes rapid redistribution into the extracellular fluid, followed by accumulation in renal tubular epithelium with subsequent lysosomal degradation. The dose is expressed as kallikrein-inhibitory units (KIU). To date, most of the experience with aprotinin has involved patients undergoing cardiovascular surgery, although its efficacy has also been demonstrated in adult patients undergoing orthopaedic surgery procedures. Potential adverse effects of aprotinin include allergic reactions and renal toxicity. Anaphylactic reactions have been reported and are more frequent in patients previously exposed to aprotinin. However, even in these cases, the incidence of anaphylaxis is less than 0.1 percent. Reports of aprotinin’s effect on renal function have been controversial. Renal toxicity is postulated to result from aprotinin’s strong affinity for renal tissue and subsequent accumulation in proximal tubular epithelial cells or its inhibition of serine proteases (kallikrein-kinin system). With high doses, obstructed proximal convoluted tubules and swollen tubular epithelial cells have been observed microscopically. These effects have been shown to be reversible in experiments on dogs. Additional adverse effects include decreases in renal plasma flow, glomerular filtration rate, and electrolyte excretion, which result from the inhibition of intrarenal kallikrein activation and decreased prostaglandin synthesis.

**Controlled Hypotension**

Controlled hypotension (also referred to as deliberate or induced hypotension) may be defined as a reduction of systolic blood pressure to 80 to 90 mmHg and a reduction of mean arterial pressure (MAP) to 50 to 65 mmHg, or a 30 percent reduction of baseline MAP (see Chap. 14). The latter is relevant for children whose baseline MAP may already be within the range of 50 to 65 mmHg. Although the main purpose of controlled hypotension is to limit intraoperative blood loss, an additional benefit may be improved visibility of the surgical field. As explained fully in Chap. 14, reduction of arterial blood pressure will not necessarily decrease bleeding which is mainly venous in origin. Depressing cardiac output with beta-adrenergic blocking agents may decrease cardiac output, increase venous pressure and increase bleeding. Drugs that decrease venous pressure, such as trinitroglycerin (TNG), are ideal.

Advances in drug therapy have provided several drugs for controlled hypotension in children. The available agents for controlled hypotension can be divided into those used alone (primary agents) and adjunctive or secondary agents used to limit the doses and adverse effects of primary agents. The primary agents include regional anesthetic techniques, the inhalational anesthetic agents (halothane, isoflurane, sevoflurane), the nitrovasodilators (sodium nitroprusside and nitroglycerin), trimethaphan, prostaglandin E₁ (PGE₁), and adenosine. The calcium channel blockers and beta-adrenergic antagonists have been used as primary agents and as adjuncts to other agents. The drugs primarily used as adjuncts include the angiotensin-converting enzyme inhibitors and alpha-adrenergic agonists such as clonidine. If neurologic monitoring is used (see below), the potential impact of the agent used for controlled hypotension must be considered.

Sodium nitroprusside (SNP) is one of the most commonly used agents for controlled hypotension. It is a direct-acting nonselective peripheral vasodilator that primarily dilates resistance vessels, leading to venous pooling and decreased systemic vascular resistance. It has a rapid onset of action (approximately 30 s), a peak hypotensive effect within 2 min, and a return of blood pressure to baseline values within 3 min of its discontinuation. Sodium nitroprusside releases nitric oxide (formerly termed endothelial-derived relaxant factor), which in turn activates guanylate cyclase, leading to an increase in the intracellular concentration of cyclic guanosine monophosphate (cGMP). Cyclic GMP decreases the availability of intracellular calcium through one of two mechanisms: decreased release from the sarcoplasmic reticulum or increased uptake by the sarcoplasmic reticulum. The net result is decreased free cytosolic calcium and vascular smooth muscle relaxation. Adverse effects include rebound hypertension, coronary steal, increased intracranial pressure, increased intrapulmonary shunt with ablation of HPV, platelet dysfunction, and cyanide/thiocyanate toxicity. Direct peripheral vasodilation also results in baroreceptor-mediated sympathetic responses with tachycardia and increased myocardial contractility in normovolemic patients. The renin-angiotensin system and sympathetic nervous system are also activated. The result is increased cardiac output, which may offset the initial drop in MAP. Plasma catecholamine and renin activity may remain elevated after discontinuation of SNP, resulting in rebound hypertension.

Nicardipine is a calcium channel blocker of the dihydropyridine class that dilates the systemic, cerebral, and coronary vasculature, with limited effects on myocardial contractility and stroke volume. Nicardipine does have some intrinsic negative chronotropic effects, which may limit the rebound tachycardia. Like other direct-acting vasodilators,
nicardipine and the other calcium channel antagonists may increase intracranial pressure. Studies comparing SNP with nicardipine have demonstrated several potential advantages of nicardipine, including fewer episodes of excessive hypotension, less rebound tachycardia, less activation of the renin-angiotensin and sympathetic nervous systems, and in some studies, decreased blood loss. One disadvantage of nicardipine is that its effect is somewhat prolonged (20 to 30 min) following discontinuation of the infusion. The references listed at the end of this chapter provide a more comprehensive review of the agents available for controlled hypotension.

Spinal Cord Monitoring

The incidence of neurologic deficits following surgical procedures on the vertebral column when spinal cord monitoring is not used has been estimated at 3.7 to 6.9 percent. This can be decreased to less than 1 percent with appropriate monitoring. The American Academy of Neurology in its guidelines on intraoperative monitoring concluded that “considerable evidence favors the use of monitoring as a safe and efficacious tool in clinical situations where this is a significant nervous system risk, provided its limitations are appreciated.” An important limitation, shown by animal studies, is that within less than 10 min of changes noted in monitoring, permanent damage is done.

There are four techniques of intraoperative monitoring: (1) the ankle clonus test, (2) the wakeup test, (3) somatosensory evoked potentials (SSEPs), and (4) motor evoked potentials (MEPs).

The ankle clonus test was the first to be used to assess spinal cord integrity intraoperatively. During the normal awake state, descending inhibitory fibers prevent clonus in response to an ankle stretch. The reflex is also inhibited during deep levels of anesthesia. However, during emergence from anesthesia, inhibition of the central descending pathways allows ankle clonus to be elicited following dorsiflexion of the foot/ankle. If there has been damage to the spinal cord, flaccid paralysis will be present and therefore no spinal reflexes can be elicited. To elicit ankle clonus, neuromuscular blockade must be reversed or absent and the patient is allowed to emerge from general anesthesia as is done with a wakeup test (see below). In most circumstances, the ankle clonus test can be elicited before the patient regains consciousness and therefore is usable at a deeper level of anesthesia than a true wakeup test. The test is extremely sensitive and specific; however, it does not provide a continuous monitor of spinal cord function.

The wakeup test was originally reported in the 1970s as a means of monitoring spinal cord integrity. Use of the technique requires a preoperative explanation to the patient about the test, its purpose and timing during the procedure, and the fact that there may be some intraoperative recall of its performance. At the appropriate time, neuromuscular blockade is reversed and the plane of anesthesia decreased. The speed with which a patient will awaken and respond to verbal stimuli has been facilitated by the use of short-acting anesthetic agents (desflurane, propofol, and remifentanil). With the use of these agents, a successful wakeup test can generally be accomplished within 3 to 10 min of the surgeon’s request. Alternatively, reversal agents can be used to antagonize the effects of benzodiazepines and opioids. The depth of anesthesia and the patient’s awakening can also be judged by the use of neurophysiological monitors such as the BIS monitor (Aspect Medical, Newton, MA). When the patient reaches a light plane of anesthesia, a voluntary movement in the motor groups above the level of surgery (e.g., squeezing one’s hand) is requested initially followed by a request to move the lower extremities. Once a positive response is achieved in the lower extremities, anesthesia is deepened by the administration of propofol or thiopental. Although easy to perform, the test does entail certain risks, including having an awake patient in the prone position on the operating table. Inadvertent or sudden movements may injure the patient or cause dislodgement of venous cannulas, arterial cannulas, or the endotracheal tube or may lead to hypertension with increased bleeding. Like the ankle clonus test, it provides only a single assessment of spinal cord integrity. In most centers, the wakeup test is used only when there are questionable findings on electrophysiologic monitoring (see below).

Electrophysiologic monitoring includes somatosensory evoked potentials (SSEPs) and MEPs (see Chap. 14). The first are monitored by stimulation of a distal nerve, generally in the leg (posterior tibial) and measuring the response at the cervical level and the central nervous system via standard electroencephalographic electrodes. The pathways involved include the peripheral nerve, the dorsomedial columns (fasciculus gracilis and fasciculus cuneatus) of the spinal cord, and the cerebral cortex. SSEPs do not monitor anterior cord (motor) function. Given the close proximity of the motor and sensory tracts the spinal cord, damage to the motor tracts generally results in damage to the sensory tracts, making SSEPs a fairly reliable measure of motor function. However, since the dorsomedial tracts and the anterior aspect of the spinal cord do not share the same arterial supply, isolated damage to the motor tract has been reported while the SSEP was normal.

Since SSEPs can be affected by anesthetic agents, baseline recordings are performed after an appropriate level of anesthesia has been achieved. The variables measured include both the height of the response (amplitude) and the time it takes the response to travel from the periphery to the central nervous system (latency). Significant changes include a reduction in the amplitude of ≥50 percent or an increase in the latency of
210 percent. Both the inhalational anesthetic agents and nitrous oxide cause a decrease in the amplitude and an increase in the latency of SSEPs; however, acceptable monitoring can be achieved with 0.5 MAC of isoflurane or desflurane in 50 to 60 percent nitrous oxide. Intravenous anesthetic agents have been shown to have less of an effect on SSEPs, making total intravenous anesthesia with propofol or midazolam combined with an opioid an effective technique. Neuromuscular blocking agents have no effect on SSEPs.

More recently, owing to the concern that there can be isolated motor damage with normal SSEPs, many centers have started to monitor MEPs along with SSEPS. Like SSEPs, MEPs are affected by the type of anesthetic agent used. Various techniques have been recommended and there remains variation from center to center. With MEP monitoring, the level of neuromuscular blockade must be kept stable, with maintenance of one to two twitches of the train-of-four or elimination of the use of an NMB. We prefer to use neuromuscular blockade with a short-acting agent only for endotracheal intubation and no NMBAs during the operation. Anesthesia is provided by continuous infusion of a combination of intravenous agents (propofol and remifentanil). We have also found that these agents can be effectively titrated to provide controlled hypotension with a limited need for antihypertensive agents.

**Postoperative Care Including Pain Management**

One of the keys to the successful care of children after spinal surgery is to provide a smooth transition from the operating room to the intensive care unit (ICU). This process begins with the preoperative preparation and instruction of the patient preferably with a tour of the ICU. The patient should also be instructed regarding the correct use of incentive spirometry and patient-controlled analgesia if the use of these devices is planned. In some institutions and with specific patients (idiopathic scoliosis with no underlying medical conditions), direct postoperative admission to the ward and not the PICU may be feasible. In such instances, a 2- to 4-h stay in the postanesthesia care unit is used to ensure cardiorespiratory stability.

At the completion of the procedures, it may be desirable to have an appropriate level of responsiveness so that a neurologic examination can be performed to evaluate adequate upper and lower extremity function. The continuation of mechanical ventilation into the postoperative period is decided on an individual basis. When there is any possibility that postoperative mechanical ventilation may be needed, this should be discussed preoperatively with the parents and the patient. Mechanical ventilation may be needed owing to neuromuscular disorder, preoperative pulmonary dysfunction, or the surgical procedure (blood loss of more than one blood volume). In specific cases, the best option may be to provide 2 to 4 h of postoperative mechanical ventilation to ensure cardiorespiratory stability, normal coagulation function, and correction of metabolic variables. Once this is accomplished, the trachea can be extubated in the ICU.

Owing to the length of the surgical incision and extensive bony and soft tissue dissection in spinal surgery, there will be significant postoperative pain. Effective analgesia is therefore essential to provide a stable postoperative course. Effective analgesia is generally best provided by using analgesic agents, anxiolytic agents, and medications to control muscle spasms. Muscle spasms may be particularly troublesome in patients with underlying cerebral palsy. Options for the provision of analgesia include intravenous administration and/or regional anesthesia. For intravenous administration, we prefer the use of patient-controlled analgesia (PCA), or, when the patient may not be able to activate the device, we use nurse-controlled analgesia. By using the device in this manner, the bedside nurse has ready access to a supply of opioid to provide an immediate dose to a patient who is in pain. Before starting PCA, an appropriate level of analgesia must be achieved by the careful titration of opioid. This is generally done in the operating room at the completion of the surgical procedure. When the remifentanil infusion is discontinued, we titrate in additional doses of morphine (0.02 mg/kg) or hydromorphone (3 to 4 µg/kg) based on the patient’s respiratory rate and complaints of pain. Once adequate analgesia is achieved, the PCA device is started to maintain analgesia. Given the significant interpatient variability, it is necessary to use age-appropriate pain scores and adjust the PCA according to the patient’s response.

To limit the total dose of opioid, adjunctive agents can be used. The potential adverse effects of nonsteroidal anti-inflammatory drugs (NSAIDs) on bone formation is still controversial. Given these concerns, many centers do not use these agents after spinal surgery in children. We prefer to administer acetaminophen (10 mg/kg either by mouth or per rectum) every 4 to 6 hours around the clock. Because many of these patients tend to develop muscle spasms or require axionalysis, benzodiazepines such as diazepam may be added to the postoperative regimen as needed or at fixed intervals. Alternatively, *α*-adrenergic agonists may be used to relieve anxiety and muscle spasms. Dexmedetomidine is a novel *α*-adrenergic agonist which currently has FDA approval for the sedation of adult patients in the ICU for 24 h. Unlike clonidine, it has a half-life of 2 to 3 h, thereby allowing its titration by continuous infusion. Given its limited effects on respiratory function and its ability to potentiate opioid-induced analgesia, it may also help to provide anxiolysis following major surgical procedures.
procedures. In our experience a continuous infusion of dexmedetomidine (0.25 to 0.5 µg/kg/h) may be efficacious in these patients. Adverse effects of analgesia, including respiratory depression may occur especially in patients with comorbid features. Close monitoring of respiratory function with continuous pulse oximetry may therefore be necessary.

Given its success in other surgical procedures, there is much interest in the possible use of regional anesthesia to control pain after spinal surgery in children. Published reports on regional anesthesia after spinal surgery have included several variations: (1) the dose of the medications used; (2) the route of delivery (intrathecal or epidural); (3) the mode of delivery (single dose, intermittent bolus dosing, or continuous infusion); (4) the number of catheters used (one versus two); (5) the medications infused (opioids or local anesthetics or both); (6) the opioid used (morphine, fentanyl, hydromorphone); (7) analgesic regimen of the control group if present (intermittent “as needed” morphine or PCA); (8) the type of surgery (short-segment lumbar fusion, short-segment laminectomy for dorsal rhizotomy, posterior spinal fusion, and anterior spinal fusion); and (9) the surgical approach (open versus thoracoscopic). A review of the reports on regional anesthetic techniques after spinal surgery in children is outlined in Tables 13-1 through 13-4. The evaluation of regional anesthetic techniques is clouded by the variation in these techniques. Future trials are needed to determine the optimal postoperative analgesic regimens for these procedures.

### TABLE 13-1. INTRATHECAL MORPHINE FOLLOWING ANTERIOR OR POSTERIOR SPINAL FUSION

<table>
<thead>
<tr>
<th>Authors and References</th>
<th>Type of Surgery</th>
<th>Analgesic Technique</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalens B, Tanguy A. <em>Spine</em> 13:494–498, 1988.</td>
<td>Anterior spinal fusion (n = 5) Posterior spinal fusion (n = 12)</td>
<td>Open label trial with no comparison or control group. Lumbar intrathecal morphine: 0.02 mg/kg.</td>
<td>No patient required supplemental analgesia during the initial 36 postoperative h.</td>
</tr>
<tr>
<td>Blackman RG et al. <em>Orthopedics</em> 14:555–557, 1991.</td>
<td>Posterior spinal fusion (n = 33)</td>
<td>Open label trial, no control group. Lumbar intrathecal morphine mean dose: 0.01 mg/kg; range: 0.007–0.019 mg/kg in 10 mL of normal saline.</td>
<td>Duration of postoperative analgesia (mean: 18.8 h; range: 0–40 h). Early respiratory depression (n = 3), late respiratory depression (n = 4). Authors postulate this was related to large volume of fluid used for intrathecal injection.</td>
</tr>
<tr>
<td>Goodarzi M. <em>Paediatr Anaesth</em> 8:131–134, 1998.</td>
<td>Posterior spinal fusion (n = 80)</td>
<td>Prospective, randomized trial. Lumbar intrathecal morphine (0.02 mg/kg) plus intrathecal sufentanil (50 mcg) compared to inhalational agent plus intravenous sufentanil.</td>
<td>Decreased intraoperative blood loss in the intrathecal group and longer duration of analgesia. Mean duration of postoperative analgesia: 14.5 h, range 0–36 h with intrathecal morphine versus immediate need for analgesia in the intravenous sufentanil group.</td>
</tr>
<tr>
<td>Gall O et al. <em>Anesthesiology</em> 94:447–452, 2001.</td>
<td>Posterior spinal fusion (n = 30)</td>
<td>Prospective, randomized trial. Lumbar intrathecal morphine: 0.2 or 5 mcg/kg.</td>
<td>Decreased intraoperative blood loss with 5 mcg/kg. Decreased postoperative intravenous morphine use and lower pain scores at 2, 4, and 14 h in 2 and 5 mcg/kg group. No difference in adverse effect profile.</td>
</tr>
</tbody>
</table>
### TABLE 13-2. SINGLE EPIDURAL CATHETER WITH INTERMITTENT DOSING FOLLOWING POSTERIOR SPINAL FUSION OR DORSAL RHIZOTOMY

<table>
<thead>
<tr>
<th>Authors and References</th>
<th>Type of Surgery</th>
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<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adu-Gyamfi Y et al. J Internat Med Res 23:211–217, 1995.</td>
<td>Posterior spinal fusion (n = 22)</td>
<td>Open label trial with no control group. Epidural catheter at T₉₋₁₀ and dosed with 2 mg morphine plus 4 mL of 0.25% bupivacaine.</td>
<td>Complete analgesia in 18 of 22 patients. Mean pain score: 0.6 ± 0.1 in the other 4 patients. Epidural doses per day: 5.5 ± 1.9. Days catheters left in place: 4.1 ± 0.7 days.</td>
</tr>
<tr>
<td>Sparkes ML et al. Pediatr Neurosci 15:229–232, 1989.</td>
<td>Dorsal rhizotomy (n = 28)</td>
<td>Open label trial with no control group. Intermittent, epidural morphine (0.05 mg/kg). Sixteen of 28 patients also received bupivacaine.</td>
<td>Adequate analgesia in all patients without intravenous opioids. Days catheters left in place: 3. Duration of analgesia following epidural morphine: 11.44 ± 3.1 h; range: 6.5 to 18 h.</td>
</tr>
</tbody>
</table>

### TABLE 13-3. SINGLE EPIDURAL CATHETER WITH A CONTINUOUS INFUSION FOLLOWING POSTERIOR OR ANTERIOR SPINAL FUSION

<table>
<thead>
<tr>
<th>Authors and References</th>
<th>Type of Surgery</th>
<th>Analgesic Technique</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Arms DM et al. Orthopedics 21:539–544, 1998.</td>
<td>Posterior spinal fusion (n = 12)</td>
<td>Open label trial. Morphine (30–50 mcg/kg) plus 5–10 mL of 0.25% bupivacaine followed by 4–10 mL/h of 0.0625–0.125% bupivacaine plus morphine 5–10 mcg/kg.</td>
<td>Satisfactory postoperative analgesia in all patients.</td>
</tr>
<tr>
<td>Shaw BA et al. J Pediatr Ortho 16:374–377, 1996.</td>
<td>Posterior spinal fusion (n = 50), anterior spinal fusion (n = 5), anterior–posterior fusion (n = 16)</td>
<td>Retrospective (n = 30) and prospective, open label evaluation (n = 41). Continuous infusions of 0.0625–0.125% bupivacaine plus hydromorphone (n = 61) or morphine/fentanyl (n = 10).</td>
<td>Successful analgesia in 64 patients (arousable yet denying pain). Of the remaining 7, there were 5 failures and 2 that could not be assessed.</td>
</tr>
</tbody>
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(Continued)
### TABLE 13-3. SINGLE EPIDURAL CATHETER WITH A CONTINUOUS INFUSION FOLLOWING POSTERIOR OR ANTERIOR SPINAL FUSION (Continued)

<table>
<thead>
<tr>
<th>Authors and References</th>
<th>Type of Surgery</th>
<th>Analgesic technique</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turner et al. <em>Anaesthesia</em> 55:367–390, 2000.</td>
<td>Posterior spinal fusion (n = 14)</td>
<td>Open label trial with no control group. Epidural fentanyl + bupivacaine</td>
<td>Used dye injection to demonstrate location of catheter. No analgesia obtained if dye was not seen in epidural or paravertebral space.</td>
</tr>
</tbody>
</table>

### TABLE 13-4. DUAL EPIDURAL CATHETER WITH CONTINUOUS INFUSION FOLLOWING SPINAL FUSION

<table>
<thead>
<tr>
<th>Authors and References</th>
<th>Type of Surgery</th>
<th>Analgesic Technique</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobias JD et al. <em>Paediatr Anaesth</em> 11:199–203, 2001.</td>
<td>Posterior spinal fusion (n = 14)</td>
<td>Dual epidural catheter. Tip of upper catheter at T1–4 and lower L1–4. Bolus: hydromorphone (5 mcg/kg) + fentanyl (1 mcg/kg) diluted in 0.3 mL/kg of normal saline with 0.1 mL/kg into upper catheter and 0.2 mL/kg into lower catheter. Continuous infusion: 0.1% ropivacaine + hydromorphone (10 mcg/mL) at 0.2 mL/kg/h into lower catheter and 0.1 mL/kg/h into upper catheter.</td>
<td>Adequate analgesia as assessed using pain scores.</td>
</tr>
<tr>
<td>Ekatodramis G et al. <em>Reg Anesth Pain Med</em> 49:173–177, 2002.</td>
<td>Posterior spinal fusion (n = 23)</td>
<td>Dual epidural catheter technique. Tip of upper catheter at T1–4 and lower catheter at T12–L4. Initial bolus: 0.0625% bupivacaine after normal postoperative neurologic examination followed by a continuous infusion of 0.0625% bupivacaine + fentanyl 2 mcg/mL + clonidine 3 mcg/mL at 10 mL/h.</td>
<td>Complete analgesia at rest in all patients. Adequate analgesia with mobilization and respiratory physiotherapy in 19 of 23 patients. The other 4 required supplemental intravenous morphine for pain scores greater than 30 (maximum score = 100).</td>
</tr>
</tbody>
</table>
SUMMARY

Many challenges face the anesthesiologist during spinal surgery in children. As with any surgical procedure, the care of these patients begins with a thorough preoperative evaluation to identify comorbid features, which are present in many of these patients. Idiopathic scoliosis is a common disease, and many of these patients will have associated neurologic or myopathic conditions that affect anesthetic care. Intraoperative issues include techniques for airway management, vascular access, blood conservation, patient positioning, intraoperative neurologic monitoring, the administration of blood and blood products, and the maintenance of fluid and electrolyte homeostasis. There is also a need for a smooth transition to the postoperative period, with ongoing monitoring to ensure stable cardiorespiratory function and an aggressive approach for the provision of effective postoperative analgesia.

SUGGESTED FURTHER READING