22 Avoidance of Complications in Neurosurgery

Travis R. Ladner, Nirit Weiss, Ronit Gilad, and Kalmon D. Post

This chapter includes an accompanying lecture presentation that has been prepared by the authors: Video 22.1.

In all neurosurgical procedures, avoidance of complications is as important as treatment of disease. Complication avoidance requires making the correct diagnosis, choosing the appropriate surgical procedure, and correctly selecting patients. This chapter reviews how to prevent complications of neurosurgical procedures in general, with additional emphasis on specific complications in particular cranial and spinal operations.

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Complications Related to Patient Positioning

SUPINE

Angle of Head

Obstruction of venous outflow
Spinal hyperflexion injury

Elevation of Head

Excessive bleeding
Air embolism

Pressure Injury

Heels, gluteus, shoulder, elbow

PRONE

Pressure Injury

Nerve palsy: ulnar, brachial plexus

Intra-abdominal Pressure

Excessive bleeding

Visual Loss

Orbital compartment syndrome
Retinal vascular occlusion
Ischemic optic neuropathy
Posterior reversible encephalopathy

LATERAL

Nerve Palsy

Brachial plexus
Nerve roots
Horner syndrome
Common peroneal nerve

Cranial Fixation Complications

- Use fixation when indicated
  - Consider use in operation cranial to the midthoracic spine
- Should be centered just below center of gravity
- Avoid insertion into face or weak points
  - Coronal suture
  - Temporal squamosal
- Pin pressure guidelines
  - 60–80 pounds in adults
  - 40–60 pounds in children younger than 15 years
  - Generally avoided when possible in children younger than 2 years
- Overtightening leads to fracture
- Undertightening leads to lacerations and lack of fixation

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KEY CONCEPTS

- Avoidance of complications in neurosurgery is as important as treatment of disease.
- Complications in neurosurgery can arise from the unique disease processes, delicate anatomy, and challenging surgical approaches encountered in neurosurgery.
- Complications can be minimized by selection of appropriate patients, surgical treatments, surgical approaches, surgical positioning, and postoperative care.
- Anticipating possible complications encountered at each step of treatment allows the neurosurgeon to minimize the risks to the patient.
- Attention to immediate preservation of neurological function, as well as to long-term overall patient functionality, leads to the best outcomes.
- New technical advances, such as intraoperative imaging, navigation, robotics, augmented reality, and artificial intelligence, are designed to help reduce the risk of complications.

In all neurosurgical procedures, avoidance of complications is as important as treatment of disease. Complication avoidance requires making the correct diagnosis, choosing the appropriate procedure, and correctly selecting patients. This chapter reviews how to prevent complications of neurosurgical procedures in general, with additional emphasis on specific complications in particular cranial and spinal operations.

Avoidance of neurosurgical complications begins with the correct selection of patients who are likely to benefit from the surgical intervention planned. When possible, a patient with nonmedical issues that have a known association with poor outcomes, such as workers' compensation claims or pending lawsuits, should be investigated further to determine the patient's motivation for recovery.[1-4] Taking the time to explain the probable risks and benefits allows the patient to make an informed decision and protects the surgeon in the event of an adverse outcome from claims of inadequate consent. It is also paramount to ensure that the patient is medically optimized, with appropriate consultations as needed, to undergo anesthesia and the operation itself along with postoperative recovery. The remainder of this chapter focuses on prevention of complications once the patient has arrived in the operating room. Intraoperative complications may be related to anesthetic issues, positioning of the patient, or technical or anatomic aspects of the specific operation selected.

Before induction of anesthesia, the surgeon and anesthesiologist must discuss the case in detail and review what is likely to happen and the possible risks. Ideally, an experienced neuroanesthesiologist should be available. Adequate venous access, placement of an arterial line for continuous blood pressure monitoring, and insertion of an intracardiac central venous pressure line to potentially remove air emboli must be planned in advance. The presence of blood products in proximity to the operating room should be ensured, and the blood bank should be notified that more might be required, depending on the scope of the surgical procedure. Antibiotics should be administered within 1 hour before incisions to ensure therapeutic blood levels.[5] In addition, during long cases, these should be readministered at regular intervals.[6,7]

COMPLICATIONS RELATED TO PATIENT POSITIONING

After the anesthesiologist has determined that the airway has been adequately secured and that all lines and monitoring equipment are in place, the patient is ready to be positioned. Several common positioning errors can lead to complications,[8-20] but most can be prevented with meticulous positioning protocols (Box 22.1).

Supine Positioning

Exposure, bleeding, and complications such as air embolism depend on the angle of the head relative to the operative site and the patient's heart. Overflexing the neck may lead to kinking of the endotracheal tube in the pharynx or obstruction of the jugular vein, which may increase venous pressure in the head and cause increased bleeding or decreased perfusion. The heels, gluteal area, shoulders, and head need to be sufficiently padded. Preferably, rolls are placed under both knees so that they are slightly flexed, and the feet should be suspended by padding

BOX 22.1 Complications Related to Patient Positioning

SUPINE

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under the calves. This position prevents heel pressure ulcers and compression on the Achilles tendon. If the arms are to be secured at the patient's side, adequate padding of the elbow and wrist and any points of contact with monitoring devices need to be verified before the procedure starts.

Prone Positioning

Nerve palsies and compression injuries are the most frequent complications seen and the most easily preventable. Radial and ulnar neuropathies can occur as a result of positioning the patient in the prone position with the arms extended if padding is inadequate or an inappropriate position is used. Keeping the arms in a mildly flexed position prevents excessive traction in either direction. Padding may be in the form of sheets or blankets placed under the elbows and forearms, or egg-crate foam padding can be used. Brachial plexus injuries can occur with rostral or caudal traction on the shoulders[21] and is frequently seen in the prone position when the arms are extended in the cruciate position or too far above the head. Downward traction, such as when the shoulders need to be pulled down for x-ray localization in the low cervical or cervicothoracic junction, can also cause brachial plexus injury. If possible, any tension placed on the patient's shoulders during radiography should be removed after the x-ray film has been obtained. There are newer traction devices available that can be fastened to the patient during positioning and apply traction only during fluoroscopy use.[22] Neurophysiologic monitoring of the ulnar nerve with somatosensory evoked potentials during spinal procedures has been shown to be effective in correcting and preventing position-related stretch injuries to the brachial plexus.[23,24] Another common peripheral neuropathy associated with the prone position is inadequate padding of the anterior superior iliac crest, which can lead to pain or numbness in the distribution of the lateral femoral cutaneous nerve.[12] A rare complication is obstruction of the external iliac artery or femoral artery from prolonged compression in the inguinal region.[25,26]

Starting at the top, the face and head should be gently suspended without any compression on any one area (discussed later in the chapter in further detail). If the patient is being placed on chest rolls or chest bolsters, the ideal position is to have the shoulders slightly overhanging the chest rolls. Breasts should be tucked between the two rolls to prevent excessive pressure. Prone positioning on a spinal table (e.g., Jackson table [Orthopedic Systems]) requires placement of the hip pads (of a size appropriate for the patient) so that the top of the pads is at the anterior superior iliac crest. The thigh pads are placed just below the hip pads. The ankles should be allowed to dangle off the edge of the leg supports, if possible. Inadequate padding of the anterior superior iliac crest can cause pressure necrosis of the overlying skin. Male genitalia should be examined to verify that they are not being compressed between the thighs or gluteal folds and that a Foley catheter, if present, is not causing undue traction on the penis. The knees need to be padded, and a padded roll should be placed underneath the ankles so that the feet hang suspended.

The abdomen should be hanging suspended to prevent venous compression and improve venous return to the heart. This point is critical because excessive venous compression can lead to significant intraoperative bleeding secondary to epidural venous hypertension. If the abdomen cannot be adequately suspended, the three-quarter prone position can be used instead (discussed later), particularly in morbidly obese patients, who may not fit on any chest bolstering system, such as the Kamden frame, the four-post Relton frame, or chest rolls. This position allows the abdomen to remain free while the surgeon works from behind, but the position also makes intraoperative radiography very difficult.

Another difficulty with positioning for spine surgery is the difference between the ideal position for a decompressive procedure, with the spine and hips flexed, and that for spinal fusion, with the spine in a more lordotic position and the hips and spine in neutral positions. Many patients have been subjected to iatrogenic flat-back syndrome because of improper position during a fusion procedure.[27]

Surgeons must be aware of the potential for unilateral or bilateral blindness after prolonged prone surgery. Causes have been hypothesized to be occlusion of the retinal artery or vein, direct trauma, orbital compartment syndrome, posterior reversible encephalopathy, and ischemic optic neuropathy. Although rare, devastating complications have been described even when no direct trauma occurred, and therefore patients' eyes should be checked frequently during the procedure. Minimizing blood loss and hypotensive episodes and maintaining a slightly elevated head of the bed may reduce the chance for this complication. If orbital compartment syndrome is suspected, emergency orbital decompression offers the best chance for recovery.[28-32]

Lateral Positioning

The lateral or three-quarters lateral decubitus position carries with it specific risks for peripheral nerve injuries. Stretch on the brachial plexus can be prevented by placement of an axillary roll slightly thicker than the diameter of the upper part of the arm. This roll should be placed approximately four fingerbreadths below the armpit to prevent compression of the long thoracic nerve. Failure to place an adequately sized roll may lead to excessive stretch of the brachial plexus, with the greatest effects on the C5 and C6 nerve roots. The upper extremities need to be supported in relatively neutral positions to prevent ulnar neuropathies. Horner syndrome can occur when the head is inadequately padded and allowed to hang laterally in such a manner that excessive tension is placed on the superior cervical ganglion.[33] Excessive traction on the lateral femoral cutaneous nerve can be caused by undue extension of the upper part of the leg at the hip while bending the dependent leg. Compression of the common peroneal nerve can occur as a result of inadequate padding laterally under the knee.

Intraoperative Monitoring

Various electrophysiologic modalities can be used to detect subtle signs of neurological compromise before they become fixed deficits. The use of intraoperative monitoring can reduce the likelihood of significant neurological deficits in the appropriate circumstances. Some positioning complications can be avoided with the concomitant use of intraoperative monitoring.[8,34-38] At our institution we use motor evoked potentials or somatosensory evoked potentials before and after positioning that may result in injury to the cervical cord. We have found excellent correlation between the lack of changes in evoked potentials and patient outcome. Monitoring is not necessary or indicated in all cases because it is time-consuming, can cause inappropriate movement of the patient, results in bleeding, and has the potential for needlestick injury to the operating room staff. However, in procedures with a potential for significant risk to the cord or neural structures, neurological monitoring is a helpful adjunct to the surgeon.

Electrophysiologic neurological monitoring can consist of somatosensory evoked potentials, motor evoked potentials, intraoperative electromyographic responses, nerve action potential monitoring, direct spinal cord stimulation, and other methods.[35,36,38-42] The information gleaned from these modalities can be used to determine whether manipulation of the neural elements is compromising conduction. Numerous authors have published series in which the surgeon has changed some portion of the procedure as a reaction to changes in electrophysiologic monitoring.[8,34,37,40,42-45] Changes in ulnar nerve somatosensory evoked potentials can also indicate traction injury to the brachial plexus and is increasingly being used to monitor positioning, even with lumbar and thoracic procedures.[23,24,44]

BOX 22.2 Cranial Fixation Complications

Use fixation when indicated
- Consider use in operation cranial to the midthoracic spine

Should be centered just below center of gravity
Avoid insertion into face or weak points
- Coronal suture
- Temporal squamosal

Pin pressure guidelines
- 60–80 pounds in adults
- 40–60 pounds in children younger than 15 years
- Generally avoided when possible in children younger than 2 years

Overtightening leads to fracture
Undertightening leads to lacerations and lack of fixation

Although not appropriate to monitor for positioning-related changes, direct epidural electrode motor evoked potential monitoring (D-wave monitoring) enables real-time evaluation of the spinal motor tracts and allows quantification of the measured output. This technique may be used during intramedullary spinal cord tumor resection and has been suggested to be helpful in minimizing injury during intramedullary resection.[46]

Cranial Fixation Complications

Positioning of the head for cranial fixation is a frequent source of complications (Box 22.2). In sacral, lumbar, and midthoracic surgery performed with the patient in the prone position, the head does not need to remain immobile, nor does the cervical spine need to be kept straight. In these circumstances, the head is positioned on loose foam padding (with a cutout for the airway and no compression on the eyes), or the head is turned to the side on loose padding. The objective is to prevent compression on the eyes, face, and forehead. However, for many types of cranial, craniocervical, cervical, or cervicothoracic surgery, it is necessary to firmly immobilize the head and prevent unwanted motion of the neck. Several devices can be used to immobilize the head, the most effective of which is the Mayfield head clamp. This clamp involves three-point pin fixation into the skull so that the skull and neck are rigid relative to the table and, assuming that the body is adequately secured to the table, rigid relative to the body. Because it is more difficult to correct spine deformities after the head is secured in this manner, if part of the goal is to reconstitute cervical lordosis, this issue needs to be considered when positioning. Placing the patient in traction with Gardner-Wells tongs, for example, may be more appropriate for this situation.

Cranial fixation pin site complications include lacerations,[47] skull fractures, associated intracranial hemorrhage (i.e., epidural, subdural, or subarachnoid hemorrhages), and infections that can lead to osteomyelitis.[48-53] Lacerations can be prevented by making sure that the two-pin arm swivels freely so that the force is evenly distributed between the two pins without one pin being shielded from tension, which can potentially result in pivoting on the other pin. If the pins are placed into muscle, it is wise to recheck tension on the single pin to make sure that the muscle has not settled and reduced the pressure. The three pins should be centered slightly below the center of gravity of the head when it is in final position to prevent gravity or personnel from pulling the head down and out of the pins. Ideally, the pins should not be placed directly into the coronal suture or temporal squamosal bone because these bones are most prone to fracture.[54-56] Pins should be tightened to 60 to 80 pounds in adults and 40 to 60 pounds in children younger than 15 years. Pins are generally avoided in children younger than 2 years; however, some skull clamp systems do exist for these patients for procedures in which they are required.[57] Pivoting within the pins by one of these methods or by inadequately locking the clamp before positioning the patient can result in changes in neck position (which can cause cervical spinal cord injury), lacerations, or compression on the eyes and subsequent blindness. These complications can also occur with Gardner-Wells–type tong traction.

Other forms of head support include the horseshoe headrest and the four-cup headrest. Because the horseshoe headrest is not a rigid form of fixation, the head may shift during the procedure, and thus it is imperative that the anesthesiologist continuously observe for any signs of movement. The four-cup headrest is an excellent alternative to the horseshoe, although blindness, skin and scalp compression, and abnormal cervical motion are possible with either support. Alopecia has been reported as a result of scalp compression.[58-64]

Dependent Edema

One complication associated with the prone position is the development of orofacial edema when the head is dependent. This complication occurs more frequently with longer procedures and when the spine is more flexed for facilitation of the surgical approach. Such edema can be prevented by minimizing the amount of fluid given by the anesthesiologist and by placing the patient slightly more in a reverse-Trendelenburg position to elevate the head relative to the heart. Facial edema can result in lingual or laryngeal edema and resultant airway obstruction. If obstruction occurs, the patient should be kept intubated until the edema has improved or resolved. Premature attempts at extubation can result in hypoxia and may necessitate emergency tracheotomy.

CATASTROPHIC MEDICAL COMPLICATIONS

Intraoperative Venous Air Embolism

In positioning patients for neurosurgical procedures, the anesthesia team and the surgeons must be aware of the gradient between the patient's head and the right atrium. Venous air embolism (VAE) is most often encountered with the patient in the seated position for posterior fossa surgery or cervical spine surgery.[65-70] It has also been described in patients who have undergone procedures in the prone, supine, and lateral positions.[65,68-74] Dehydration or blood loss leading to decreased central venous pressure may potentiate the risk for VAE. Patients with a patent foramen ovale or a known right-to-left shunt should be given special consideration before the seated position is used because the risk for paradoxical air embolism after VAE appears to be higher.

Most VAEs are thought to be caused by air entering noncollapsible veins, dural sinuses, or diploic veins. They also have arisen from central venous lines and pulmonary artery catheters. Air travels from the head down the venous system to the heart and eventually to the lungs, where pulmonary constriction and pulmonary hypertension ensue, or in patients with a right-left heart shunt, paradoxical air embolism may occur. Peripheral resistance decreases, and cardiac output initially increases to compensate and maintain blood pressure. Later, as the volume of air infused increases, cardiac output drops, as does blood pressure. Without intervention, cardiac arrest may occur.

Given the dangers of VAE, early detection of the embolus is paramount in reducing the severity of this complication. Monitors used to detect emboli include precordial Doppler ultrasonography, capnography or mass spectrometry, transesophageal echocardiography, transcutaneous oxygen, esophageal stethoscope, and right-side heart catheter.[65,66,69,71,74] The most sensitive are transesophageal echocardiography and Doppler imaging, followed by expired nitrogen and end-tidal carbon dioxide. Electrocardiographic changes, hypotension, and heart murmurs are late signs. Because no single monitor is completely reliable, two or more should be used simultaneously. In awake patients, the presence of a cough may be the earliest sign of VAE, and it can be treated before the VAE becomes hemodynamically significant.[75] Detection of VAE has increased over the past several decades, but serious morbidity and mortality have decreased. Its incidence varies from 1.2% to 60%, with morbidity and mortality rates of less than 3% in most series.

Treatment of VAE includes aspiration of air through a right atrial catheter, discontinuation of nitrous oxide because it may enlarge the air bubble, and administration of pure oxygen. Surgeons should immediately seal the portals of entry with bone wax, electrocautery, and full-field irrigation. Arrhythmias, hypotension, and hypoxemia should be corrected quickly. Repositioning the patient in the left lateral decubitus position may facilitate removal of air from the right atrium. Stabilization of the patient's hemodynamic status becomes the first priority, and the procedure may have to be prematurely terminated if hemodynamic stabilization cannot be achieved easily.

Deep Venous Thrombosis and Pulmonary Embolism

Deep venous thrombosis (DVT) and pulmonary embolism (PE) are major contributors to morbidity and mortality in postoperative neurosurgical patients. The incidence of DVT, as measured by the labeled fibrinogen technique, ranges from 29% to 43%. It can be as high as 60% in patients with malignant intracranial neoplasms.[76-86] Most DVTs are asymptomatic and never come to medical attention. PE, however, is thought to subsequently occur in 15% of such patients.[77,79,83] Significant thrombi are thought to arise from the popliteal and iliofemoral veins. Risk factors include prolonged surgery and immobilization, previous DVT, malignancy, direct lower extremity trauma, limb weakness, use of oral contraceptives, gram-negative sepsis, advanced age, hypercoagulability, pregnancy, and congestive heart failure.[76,78-80,82,83,87-92]

A diagnosis of DVT made by clinical examination is generally unreliable. Ankle swelling, calf pain, calf tightness, and a positive Homan sign may all be absent, even in the presence of significant DVT. Doppler ultrasonography and impedance plethysmography are useful in detecting proximal venous thrombosis and are the mainstay of diagnosis, with sensitivities exceeding 90%. When Doppler results are equivocal, extremity venography can be used to diagnose distal and proximal DVTs.

Because of the often-fatal result of PE, prophylaxis against DVT is of major importance in neurosurgery. This is especially true for malignancies, and prophylaxis should be considered even earlier for this population. Many studies have confirmed the usefulness of sequential pneumatic leg compression devices in preventing DVT.[77-79,83,84,87,93] These devices are placed on the patient preoperatively and should be continued until the patient is ambulatory. Early mobilization of postoperative patients is important in preventing thrombus formation. The prophylactic use of low-dose (minidose) subcutaneous heparin (e.g., 5000 IU twice daily) has been well studied over the past 25 years and has been demonstrated to be efficacious in preventing DVT.[92-98] However, some studies have shown an increase in the rate of postoperative intracranial bleeding with minidose administration of heparin.[93,95]

Low-molecular-weight heparin (LMWH) has more recently been used for DVT prophylaxis in surgical patients. Several meta-analyses have been conducted, but it remains unclear whether unfractionated heparin or LMWH is superior for DVT prophylaxis in neurosurgical patients or whether increased efficacy correlates with increased hemorrhagic complications.[99-102] A prospective study of early LMWH prophylaxis in the spinal cord injury population has revealed a low rate of DVT and PE and no hemorrhagic complications even in patients who had undergone surgery.[103] In the modern literature, a meta-analysis of 1200 neurosurgical patients showed no significant difference in bleeding complications with chemical DVT prophylaxis compared with placebo, but a sizeable reduction in thromboembolic complications.[104]

In patients with brain neoplasms, there are no clear guidelines as to when pharmacologic prophylaxis should be started. In general, those with hemorrhagic tumors as well as multiple metastasis from known hemorrhagic primary tumors (thyroid, renal cell, choriocarcinoma, and melanoma) should not receive pharmacologic prophylaxis. After surgery, safe prophylaxis has been reported as early as 12 hours. In addition, enoxaparin and heparin have been shown to be equally safe and effective.[86] For intracranial hemorrhages and subarachnoid hemorrhages, American Stroke Association (ASA) guidelines recommend mechanical prophylaxis and consideration of pharmacologic prophylaxis with heparin after documentation of cessation of growth of the hemorrhage. In subarachnoid hemorrhage patients, aneurysms should be secured prior to initiation of pharmacologic prophylaxis. LMWH may be used safely after elective neurosurgical procedures as early as postoperative day 1.[86,99]

Despite prophylaxis, thrombi inevitably develop in one or both lower extremities in some patients. Management options include full-dose heparinization or inferior vena cava filter placement. In the immediate and early postoperative period, many neurosurgeons believe that neurosurgical patients with documented DVT should undergo transvenous Greenfield filter placement.[a] There appears to be a general consensus that full anticoagulation is acceptable 1 to 3 weeks after surgery; our institution uses the 1-week rule. Treatment with intravenous heparin (without a bolus injection, target partial thromboplastin time of 45–60 seconds) is followed by oral warfarin sulfate (target international normalized ratio of 2) when not contraindicated. Anticoagulation should be continued for 6 weeks to 3 months in uncomplicated cases. Gastrointestinal bleeding is the most common serious complication encountered.

Patients experiencing PE complain of pleuritic chest pain, hemoptysis, and dyspnea. Jugular venous distention, fever, rales, tachypnea, hypotension, and altered mental status may be found on physical examination. Arterial blood gas determination reveals a PO_2 of less than 80 mm Hg in 85% of patients, accompanied by a widened alveolar-arterial gradient. The level of fibrin degradation products is elevated in most cases. In patients with massive embolism, right axis deviation, right ventricular strain, or right bundle branch block may be identified on electrocardiography. Chest radiography demonstrates an effusion or infiltrate in 90% of cases. A nuclear medicine ventilation-perfusion scan is sensitive in detecting PE but is not specific. The entire clinical scenario, including patient examination, laboratory results, and radiographic evaluation, leads to the diagnosis.[79,83,87,88,106-110] Spiral CT angiography has become the preferred diagnostic study for PE.[111,112] However, pulmonary angiography is the "gold standard" and may be necessary to confirm the diagnosis.

Guidelines similar to those discussed for treatment of DVT should be used for the treatment of PE. Patients with a massive, life-threatening embolus, however, should be fully anticoagulated despite the risk for intracranial hemorrhage. This subset of patients usually requires ventilatory support and vasopressor therapy to ensure adequate oxygenation and blood pressure. Because thrombolytic therapy has a higher risk for complications than does treatment with heparin, with no significant improvement in outcome, these modes of therapy have largely been abandoned.

[a] References 77–79, 82, 83, 87, 93, 105.

When all else fails, pulmonary embolectomy may be performed as a lifesaving measure.

Hemorrhagic and Transfusion-Related Issues

Two significant and somewhat similar complications related to bleeding are diffuse intravascular coagulation and transfusion reactions. Both are a consequence of excessive bleeding and transfusions. The first results in a consumptive coagulopathy and further paradoxical bleeding. The other is a reaction to incompatible blood and can result in fever, rash, or shock. Both can be prevented by meticulous hemostasis. When bone is bleeding in an area where the need for fusion precludes the use of bone wax, thrombin-soaked Gelfoam can be rubbed on the bleeding bone surfaces and acts in much the same way as bone wax. When hemostasis alone is not enough to minimize transfusion requirements, as with some long spinal procedures, autologous blood salvage (e.g., Cell Saver) can be used to recycle the patient's own blood. Other modalities to minimize allogeneic transfusions include autologous blood donation (with or without the use of preoperative erythropoietin), hemodilution, or induced hypotension. Patients about to undergo neurosurgery should, when medically suitable, avoid the use of antiplatelet products in the week before surgery and other nonsteroidal antiinflammatory agents on the day before surgery.

Wound Complications

Because of the vascularity of the scalp, most cranial wounds heal well, with wound complications reported in <1%.[113] Postoperative pseudomeningocele formation from persistent leakage of cerebrospinal fluid (CSF) is more common when the normal CSF reabsorption pathways are impaired, as with hydrocephalus, subarachnoid hemorrhage, and meningitis. CSF finds the path of exit of least resistance from the head. Harvesting and onlaying a vascularized pericranial flap prior to closure may minimize this risk.

Several potential problems related to the wound area and wound closure can be anticipated and prevented. The first category is postoperative blood collections, or hematomas. Ideally, postoperative hematomas can be prevented by meticulous hemostasis during the procedure, but such is not always the case. The use of postoperative drainage devices (e.g., Hemovac, Jackson-Pratt drain) in wounds for which hemostasis was difficult to achieve before closure can reduce the incidence of postoperative hematoma. Postoperative drainage may also be advantageous in patients in whom postoperative anticoagulation may be required, because some of these patients have slightly delayed hematoma formation.[114] An obese patient undergoing spine surgery may have significant serous exudation that can continue for up to 5 days or longer postoperatively. It is best to keep a drain in the submuscular space during this time to prevent a postoperative seroma that can become infected. Current guidelines for infection prevention recommend prophylactic antibiotics 1 hour prior to incision and 24 hours postoperatively. However, there is no consensus as to whether antibiotics should be continued until a wound drain is removed. For ventriculostomy drains, antibiotic-coated catheters have been shown to be more effective than prophylactic antibiotic use in preventing infection.[7,115,116]

Several factors can predispose to loss of wound integrity. Prolonged steroid use, irradiation or chemotherapy, reoperations, and malnutrition can predispose patients to poor wound healing. With the increasing use of bevacizumab, a vascular endothelial growth factor (VEGF) inhibitor, for malignant brain tumors, one may consider using a plastics closure for the scalp.[117-119] Patients who are likely to lie on their incisions because of an inability to move or the location of an incision are also likely to experience wound breakdown because of pressure-related ischemia and failure to heal adequately. Known or unknown intraoperative violations of sterility may lead to subcutaneous infection and resultant loss of wound integrity. Failure to use perioperative antibiotics can also lead to local infection and failure of the incision line. Maintenance of a dry, sterile wound area results in better wound healing, and if a dressing becomes significantly stained or wet, it must be changed immediately.

One way to prevent wound breakdown in a compromised host is the use of an incision that avoids the impaired area. Craniotomies may require a larger incision, such as a bicoronal or larger curvilinear incision that avoids a focused previously irradiated area. In spine surgery, this may mean use of a paramedian incision, in the case of prior irradiation. Through removal of the incision from the avascular midline plane and creation of a vascularized myocutaneous flap, patients with cancer or severe malnutrition can have the same or better wound-healing rates as healthy patients. By making the incision off the midline, the pressure is also not directly on the wound and the instrumentation.

Other modalities being investigated include the use of cultured keratinocytes or fibroblasts injected back into the wound area, supplemental or hyperbaric oxygen therapy for several days after surgery, and injection of various growth factors into the wounds.

RISK FACTORS RELATED TO ANATOMY OR TECHNIQUE IN SPECIFIC SURGICAL PROCEDURES

Cranial Surgery

Postoperative Seizures

The risk for postoperative seizures within the first week after supratentorial procedures has been well described in the literature.[120-130] The underlying cause of these seizures may be metabolic derangements, cerebral hypoxia, preoperative structural defects, stroke and vascular abnormalities, or congenital seizure disorder. Manipulation of brain tissue, postoperative edema, and hematoma formation are common causes of surgically induced seizures. The overall incidence of immediate and early seizures after craniotomy is 4% to 19%. It is important to identify any risk factors that may contribute to the development of seizures postoperatively. Lesions of the supratentorial intracranial compartment are responsible for seizures after craniotomy in most situations; seizures after infratentorial procedures are attributed to the resultant retraction or movement of supratentorial structures.[b] Brain abscesses, hematomas, intra-axial and extra-axial tumors, aneurysms, arteriovenous malformations, and shunts have been reported to be epileptogenic.[126,133-141] Patients with a preoperative history of epilepsy are at a higher risk for seizures postoperatively. Patients with subtherapeutic levels of prophylactic agents are also at a higher risk for immediate and early postoperative seizures.[125,127,142-144]

All types of seizures can occur after neurosurgery. The diagnosis of a postoperative epileptic event is usually obvious. Multiple episodes are more common than single episodes, but status epilepticus is relatively uncommon. Seizures can occur in unconscious, comatose patients and may manifest as nonconvulsive status epilepticus. An electroencephalogram may

[b] References 120, 121, 124–127, 129, 131, 132.

be useful in these situations. The consequences of seizures are neurological and systemic and include neuronal damage, increased cerebral blood flow, and increased intracranial pressure (ICP). Metabolic acidosis, hyperazotemia, hyperkalemia, hypoglycemia, hyperthermia, and hypoxia may develop and exacerbate the situation, thereby leading to further seizure activity.

Preventing a seizure is preferable to treating one that has already begun. Adequate preoperative loading of parenteral or oral phenytoin has definitively been shown to decrease the incidence of postoperative seizures.[145,146] However, reports have called into question the routine practice of phenytoin prophylaxis in patients without a history of seizures.[125,147,148] Meta-analyses have shown no significant difference in levetiracetam (Keppra) and phenytoin in seizure prophylaxis.[146]

In patients unable to tolerate phenytoin, levetiracetam, phenobarbital, or carbamazepine may be substituted. It follows that therapeutic preoperative levels should be measured in patients undergoing supratentorial procedures whenever possible. Administration of the anticonvulsant should continue through the acute and early postoperative period. Electrolyte abnormalities should be corrected immediately in the postoperative period to further reduce the chance for a seizure.[145,146] Most seizures in neurosurgical patients are self-limited and last between 2 and 4 minutes. A chemistry profile should be obtained and any abnormalities corrected. Blood levels of antiseizure medications should also be verified and brought into the therapeutic range. Multiple seizures or any seizure lasting longer than 5 minutes should be aggressively treated rather than waiting 30 minutes to fulfill the criteria for status epilepticus. Treatment may entail the administration of lorazepam, diazepam, or midazolam, followed by fosphenytoin. Cardiorespiratory support measures may need to be initiated as well. For refractory cases, reintubation followed by phenobarbital coma or general anesthesia may be necessary. In most cases it is probably best to image the patient postoperatively after the seizure episode has been managed. The possibility of intracranial hemorrhage, edema, infarction, or pneumocephalus must be entertained and the appropriate surgical or medical management initiated as soon as possible.

Electrocorticography has recently been studied in patients preoperatively as a way to predict whether a patient is at risk of seizures following supratentorial procedures.[145,146,149] However, in our institution, all patients undergo seizure prophylaxis for 1 week after supratentorial procedures. In patients who have a history of seizures preoperatively, antiepileptics are continued for 3 to 6 months after surgery.

Postoperative Edema and Increased Intracranial Pressure

Neurosurgical procedures involving direct manipulation of brain tissue may lead to postoperative swelling. The amount of edema is related to many factors. The duration and force of tissue retraction on CNS tissue are directly related to the amount of postoperative swelling in the supratentorial and infratentorial compartments. Bipolar coagulation can further contribute to this edema when cortical bleeding is caused by retraction. The edema may be worsened if venous drainage is impaired and results in local congestion. Sustained venous hypertension may cause infarction and petechial hemorrhage, often with disastrous consequences. Noncompliance of the cranium then leads to increased ICP. Cerebral perfusion is limited, and neurological dysfunction ensues. In severe cases, herniation follows.

For lengthy procedures or when significant brain retraction is necessary, the use of a rigid, self-retaining retractor system combined with rigid head fixation can help limit the damage caused by tissue manipulation. Preservation of the cerebral vasculature during surgery, with limited coagulation and careful tissue handling, can reduce the occurrence of severe edema postoperatively.

The neurological deficits caused by brain swelling may be permanent or transient, and the severity of the deficit depends on the patient. Edema usually begins within 5 hours after the procedure and reaches its maximum approximately 48 to 72 hours later.[150-154] Altered mental status, cranial nerve deficits, and motor or sensory dysfunction can all occur. The diagnosis may be confirmed with non–contrast-enhanced CT, and hemorrhage, hydrocephalus, and pneumocephalus may be ruled out. Cerebral hypodensity, sulcal effacement, midline shift, loss of the gray-white matter interface, and small lateral ventricles are the hallmarks of postoperative edema. If impaired venous drainage secondary to the incompetence of venous sinuses is suspected, conventional venous-phase angiography or MR venography may be helpful in diagnosing the location and severity of the occlusion. Appropriate surgical and medical measures may then be instituted.

The goal of treatment of increased ICP is to maintain cerebral perfusion pressure (CPP) at greater than 55 to 60 mm Hg while reducing the amount of cerebral edema.[155-160] This entails measuring arterial blood pressure and ICP continuously. Induction of arterial hypertension with vasopressors may be necessary to achieve the desired CPP. Short-term hyperventilation to a P_{CO_2} of 30 mm Hg can reduce ICP effectively. High-dose dexamethasone should be given to patients with vasogenic edema to alleviate tumor-related swelling. Increasing the head of the bed to 30 to 45 degrees can assist in venous return, and maintaining a neutral midline head position and administering diuretics such as furosemide and mannitol can further reduce ICP. When using diuretics, it is important that serum chemistries and osmolalities be monitored to ensure that the patient does not become severely dehydrated. Hypertonic saline solutions are now increasingly being used with success for the treatment of vasogenic edema.[161,162] In refractory cases, sedation may be used to suppress cerebral metabolism and paralysis induced to reduce ICP by limiting agitation and muscle exertion. As a final resort, barbiturate coma with mild hypothermia or temporal lobectomy may be used to control ICP and maintain CPP.

Specific Cranial Approaches

Supratentorial Craniotomy. Numerous lesions may be approached via supratentorial craniotomy. In low-grade gliomas, long-term control and cure are possible. Because high-grade gliomas are not curable by surgery, surgery represents a palliative treatment aimed at reducing tumor bulk and maximizing quality of life. However, there is general agreement that maximum safe resection improves overall survival in this population.[163,164] Patients with metastatic brain lesions can have a significant improvement in their survival by removal of brain metastases. It is therefore incumbent on neurosurgeons to minimize complications when patients are in the early stages of their disease and their clinical condition is best. The decision about whether surgery is warranted involves carefully weighing the possible surgical complications against the potential benefits. Studies have shown that craniotomies for intraparenchymal lesions typically result in mortality rates of 2.2% and morbidity rates of 15% (Table 22.1).[113,165-167]

Tumors located in eloquent or deep brain areas are more difficult to surgically debulk and carry a higher risk for neurological morbidity. Navigable tubular retractor systems have been developed that might make these deep lesions easier to access.[168,169] Laser interstitial thermal therapy (LITT) is also a newer option using MRI to target and ablate deep tumors or seizure foci less amenable to a conventional open resection, or as a palliative option for recurrent high-grade glioma (Table 22.2).[170-172] Surgery on gliomas typically results in more morbidity and mortality than does surgery on brain metastases.[113] Surgical outcome is closely tied to the patient's age and preoperative

TABLE 22.1 Morbidity and Mortality Rates for Cranial Parenchymal Tumors

Study	No. of Patients	Medical Morbidity (%)	Neurological Morbidity (%)	Mortality (%)
Fadul et al.,[165] 1988	104	12	19.7	3.3
Cabantog and Bernstein,[166] 1994	207	8.2	17	2.4
Sawaya et al.,[113] 1998	327	5	8.5	1.7
Taylor and Bernstein,[167] 1999	200	3.5	13	1

TABLE 22.2 Complications in Laser Interstitial Thermal Therapy for Recurrent High-Grade Gliomas

Complication	Rate (%)
Edema requiring hemicraniectomy	1.6
Seizure	1.6
Transient neurological deficit	11.1
Permanent neurological deficit	11.1
Wound complication	1.6
Medical complication	6.3

From Lee I, Kalkanis S, Hadjipanayis CG. Stereotactic laser interstitial thermal therapy for recurrent high-grade gliomas. Neurosurgery. 2016;79(suppl 1):S24–34.

TABLE 22.3 Neurological Complications in Intraparenchymal Tumor Surgery

Complication	Rate (%)
Motor or sensory deficit	7.5
Aphasia	0.5
Visual field deficit	0.5

From Sawaya R, Hammoud M, Schoppa D. Neurosurgical outcomes in a modern series of 400 craniotomies for treatment of parenchymal tumors. Neurosurgery. 1998;42:1044–1055.

neurological status as measured with the Karnofsky performance scale.[113,165,166] Patients are at risk for general complications of craniotomies, including complications related to positioning, anesthesia, infection, seizures, hemorrhage, and neurological compromise. Neurological compromise may result from resection or retraction of normal functional brain tissue or compromise of the vascular supply. Neurological morbidities usually consist of motor or sensory deficits or aphasias (Table 22.3). Occasionally, visual field deficits can occur.

Gliomas lack a well-defined boundary between abnormal and normal tissue. Pathologic analysis demonstrates tumor cells in grossly normal-appearing tissue. The result is a tradeoff between radical tumor resection and risk for resection of functional brain tissue and subsequent neurological deterioration. Avoidance of vascular compromise involves meticulous attention to detail and preservation of all significant vasculature seen to supply normal brain tissue. If significant vessels are taken during surgery, postoperative CT or MRI can reveal the evolution of an infarction in the vessel's vascular distribution.

Computer-assisted stereotactic systems enhance the ability of the surgeon to delineate between normal brain and tumor. Stereotactic systems also facilitate targeting of tumors that cannot be visualized at the brain's surface, and plan safe corridors for resection.[173-175] Intraoperative ultrasonography is also a low-cost adjunct to distinguish normal and pathologic tissue, and quickly assess extent of resection.[176] Intraoperative functional mapping helps identify and avoid injury to eloquent cortex.[177,178] Craniotomy performed while the patient is awake is particularly helpful in resecting lesions surrounding the speech or motor centers.[167,179] Increasingly, functional imaging is being applied intraoperatively, with evidence suggesting that it allows more complete resection while minimizing the risk for deficits. Functional MRI and diffusion-weighted imaging can be integrated with most neuronavigation systems to allow identification and protection of motor tracts.[180-183] Intraoperative MRI is another modality to identify residual tumor that might be resectable prior to completion of the case, and appears to improve gross total resection rates and survival.[184] Increasingly, Raman spectroscopy is seeing more use in distinguishing pathologic versus normal tissue intraoperatively, and may have a role for in situ delineation of tumor during resections.[185]

Another in situ tool for distinguishing glioma is use of fluorescence-guided surgery with 5-aminolevulinic acid (5-ALA). One group found a 15% increase in extent of resections when combined with navigation and intraoperative MRI.[186] Meta-analysis has shown a higher rate of gross total resection with 5-ALA compared with conventional neuronavigation.[187] 5-ALA was approved by the US Food and Drug Administration (FDA) in 2017 for use in high-grade gliomas, and is being investigated for use in other brain neoplasms.[188,189]

Hemorrhage into the postoperative tumor bed represents a serious complication that may require reoperation for evacuation of hematoma. Prevention begins with checking preoperative coagulation studies and ensuring that the patient has not been taking blood thinners. This is especially true given the increase in prescriptions of novel oral anticoagulants and other conventional anticoagulants in the aging population. Intraoperatively, meticulous hemostasis must be achieved with a variety of hemostatic agents and bipolar electrocautery. The tumor cavity may be lined with hemostatic agents such as Surgicel. Tight blood pressure control during extubation and in the postoperative period is important. Rarely, distal intracerebral or intracerebellar hemorrhages can occur, although their cause is unexplained.[190]

Surgery for gliomas is rarely curative, and many patients with recurrences are subject to reoperation. However, studies have demonstrated that reoperation does not necessarily predispose patients to a greater complication rate.[113,165,191] More important, carmustine (BCNU) wafer implantation, adjuvant chemotherapeutic agents, and radiation increase the rates of wound complications significantly. Preparations for such complications should be made in advance if the patient is anticipated to receive these treatments.[118,119]

Meningiomas differ from parenchymal tumors in that they are often associated with venous sinuses, and thus venous infarction or injury to the sinuses is an additional risk. These tumors can invade the wall of sinuses and eventually narrow and obliterate the sinus lumen. When meningiomas are located in proximity to a sinus, preoperative venous angiography, MR angiography, or MR venography is essential to avoid complications. Entering a patent sinus can result in difficult bleeding that may require surgical reconstruction or bypass of the sinus. Sacrifice of a major venous sinus should be avoided. Complications associated with sacrificing a major venous sinus include increased ICP as a result of brain edema and venous hemorrhagic infarction. Obtundation and seizures can develop in such patients (Table 22.4). Aggressive ICP management is essential in controlling this complication. Prudent surgical management may necessitate leaving a portion of the tumor adherent to the sinus and using adjuvant therapy or observation with surveillance MRI.[192] Postoperative seizures are seen with convexity and parasagittal meningiomas.[193] Sacrifice of a significant vein can result in venous infarction and an increased

TABLE 22.4 Meningiomas and Seizure Frequency

Study	Preoperative Seizure Frequency (%)	Postoperative Seizure Frequency (%)	First Seizure Occurring Postoperatively (%)
Chan and Thompson,[193] 1984	—	36	19
Chozick et al.,[120] 1996	40	20	9
Fang et al.,[149] 2013	100	32	0

risk for seizures. The mortality rate for craniotomies performed for convexity and parasagittal meningiomas is 3.7% to 13%.[193-198]

Posterior Fossa Craniotomy. Infratentorial craniotomies carry many of the same risks as do supratentorial craniotomies. However, some risks are more pronounced when operating in the posterior fossa. Positioning-related risks have been described earlier (e.g., air embolism) and are particularly commonly encountered when performing surgery with the patient in the sitting position. Most surgeons choose to operate with the patient in a lateral, park bench, or prone position instead.

Leakage of CSF is seen frequently after a posterior fossa craniotomy and occurs in 3% to 15% of patients.[199-201] Leakage can occur from the wound or may manifest as rhinorrhea or otorrhea. Openings into the mastoid air cells and air cells in the vicinity of the meatus can lead to otorrhea. Fluid can drain into the nasopharynx through the eustachian tube. Packing the mastoid air cells with bone wax can prevent CSF leakage. Aggressive drilling of the porus acusticus and larger tumor size have been associated with an increasing risk for CSF leaks.[202] To minimize the risk for postoperative rhinorrhea, we apply bone wax aggressively to all mastoid air cells exposed during the craniectomy, as well as fibrin glue before closure. However, unroofing of air cells within the internal auditory canal can lead to persistent leakage, and we routinely apply a muscle plug, Gelfoam, and fibrin glue in this region to minimize the risk for leakage. In addition, routine prophylactic high-volume lumbar puncture may be performed daily for 3 days postoperatively to minimize the risk for leakage. When leakage occurs, management typically involves placement of a spinal drain. Operative repair may be necessary in patients in whom a trial of spinal drainage fails. Early recognition plus treatment of CSF leaks is imperative because CSF leakage places patients at risk for meningitis.[201] Meningitis occurs in about 1% of patients, and early treatment with appropriate antibiotics is essential. Aseptic meningitis also occurs infrequently after surgery. Patients may have some elements of ataxia postoperatively, but these symptoms are usually limited and resolve within a few days. Significant headaches occur in half of patients postoperatively, and 25% complain of headaches persisting for more than a year after surgery.[203]

Mortality from infratentorial surgery is generally higher than that seen with supratentorial procedures. Compromise of the anterior inferior cerebellar artery and the resultant lateral pontine infarction are implicated in a third of postoperative deaths.[204] The second biggest contributor to postoperative mortality is aspiration pneumonia resulting from lower cranial nerve deficits. Patients may require placement of a feeding tube and a tracheostomy to prevent aspiration pneumonia. Cerebellar contusions or hematomas can occur as a result of overaggressive retraction. Distant supratentorial hemorrhages occasionally occur for unclear reasons.[205] Surgeons must be prepared to place an occipital ventricular catheter intraoperatively on an emergency basis if acute hydrocephalus results.

Transsphenoidal Surgery. Transsphenoidal surgery is commonly used to reach tumors in the sellar region. This procedure can be performed with extremely low mortality and low morbidity. Deaths have occurred in 0% to 1.75% of patients

TABLE 22.5 Common Complication Rates in Transsphenoidal Surgery

Complication	Rate (%)
Mortality	0–1.75
Nasal septum perforation	1–3
Sinusitis	1–4
Epistaxis	2–4
Visual disturbances	0.6–1.6
Transient diabetes insipidus	10–60
Permanent diabetes insipidus	0.5–5
Anterior pituitary insufficiency	1–10
Cerebrospinal fluid leakage	1–4
Meningitis	0–1.75

(Table 22.5). Laws[206] reported seven deaths in 786 procedures (0.9%), and Wilson[207] reported two deaths (0.2%) in a series of 1000 patients. At our institution, two deaths occurred in 1800 procedures. Morbidities associated with the transsphenoidal approach are distinct from general neurosurgical complications because the approach is quite different from most transcranial approaches.

Avoidance of complications begins with appropriate patient selection. Patients with sphenoid sinus infections should not undergo transsphenoidal surgery because of the risk for meningitis. Tumor morphology may also dictate the operative approach. Tumors located eccentrically may not be accessible transsphenoidally and instead might require a transcranial approach. In tumors with dumbbell morphology, a constrictive diaphragma sellae may limit adequate tumor decompression. Tumor consistency also influences the surgical outcome. Most adenomas have a soft consistency and are easily and safely removed with curettes and suction. Firm tumors, seen in 5% of patients, can be difficult to remove transsphenoidally. Adequate preoperative radiologic evaluation is essential because of the wide range of pathologies that are found in the sella. For example, misdiagnosis of an aneurysm as an adenoma can result in a potentially fatal complication. Any vascular anomalies in the sellar region may be a contraindication to the transsphenoidal approach.

Anesthetic complications in transsphenoidal surgery are rare. Acromegalic patients exhibit cardiomyopathy and macroglossia, which may complicate airway management. Patients with pituitary lesions are often deficient in one or more pituitary hormones. A comprehensive preoperative endocrine analysis is essential, and adequate stress doses of steroids should be administered. Postoperatively, the patient's endocrine status should be carefully monitored. Other medical complications are relatively rare and are commensurate with complications in other elective procedures.

Several complications can arise as a consequence of the transsphenoidal approach. If a sublabial incision is used, anesthesia of the upper lip and anterior maxillary teeth can occur, although this condition is usually transient.[208] Removal of the superior cartilaginous septum may result in a saddle nose deformity.[209] Perforation of the nasal septum occurs in 1% to 3% of patients and is more likely with reoperations.[206] Postoperative sinusitis can occur in 1% to 4% of patients and may be reduced by postoperative antibiotics.[210] Opening the speculum can result in diastasis of the maxilla or fracture of the medial orbital wall.[206,211] Damage to the optic nerve or the carotid arteries can occur if the speculum is advanced too far. Inadequate removal of mucosa in the sphenoid sinus can lead to the postoperative formation of a mucocele.[212]

Vascular injuries represent serious morbidities and can lead to death. Intraoperative mucosal bleeding and delayed postoperative bleeding from the mucosal branch of the sphenopalatine artery can occur. If postoperative epistaxis persists, embolization of the internal maxillary artery may be necessary.[213] Damage to the carotid arteries can occur in the sphenoid sinus or in the sella. Maintaining a midline trajectory is vital to avoid the carotid artery, and preoperative radiologic studies are essential in localizing the carotids. There are significant variations in the carotid's parasellar course, and the distance between the two arteries may be as little as 4 mm.[208] Frameless stereotaxis can be used to maintain a midline approach and may be especially useful in reoperations.[214] Neuronavigation can also help visualize the location of the carotid arteries, and in planning the size of sellar and dural opening for tumor resection. Here also, intraoperative micro-Doppler imaging is helpful to confirm the course of the carotid.

In the transsphenoidal approach, excessive arterial bleeding signals intraoperative injury to the carotid artery, and the only treatment involves packing the operative field.[213] Other maneuvers are limited by the exposure, although if packing fails, ligation of the carotid may be required. Carotid artery injury can result in subarachnoid hemorrhage, vasospasm, pseudoaneurysms, and carotid cavernous fistulas. A postoperative cerebral angiogram is essential to identify any of these complications.[215] About 25% of deaths occurring during transsphenoidal operations are attributable to vascular injuries.[213]

Visual disturbances are also possible because of the close association of the chiasm, optic nerve, and pituitary. Damage can occur as a result of direct trauma, traction injury, or vascular compromise. Visual disturbances are more likely after reoperations because of adhesion formation between the chiasm and sella. Adhesions predispose the chiasm, optic nerve, and hypothalamus to traction injuries. In general, visual disturbances occur in 0.6% to 1.6% of patients.[216]

Postoperative visual loss can also signal the formation of a hematoma in the tumor bed. Such hematomas can be prevented by meticulous hemostasis. They can occur in 0.3% to 1.2% of cases.[206,210,212] Injuries to the hypothalamus can also take place and potentially result in death.[213] These patients are comatose and exhibit hyperthermia. Hypothalamic injury is the most common cause of death in patients undergoing transsphenoidal operations.[213]

In recent years, nasal endoscopy is increasingly being used to minimize tissue trauma and to obtain more expansive views than those provided by microscopic visualization alone.[217,218] Endoscopic endonasal techniques may be used to access and visualize the more difficult-to-reach regions of the anterior skull base, which might minimize the brain retraction needed for craniotomy-based approaches.[219-221] Endoscopic techniques have also led to the development of a vascularized nasoseptal flap, which appears effective in minimizing postoperative CSF leak, with an incidence as low as 3.2%.[222,223] Tensor fasciae latae might also be harvested and laid into the sella endoscopically for large skull base reconstructions.

Several complications can be anticipated in the postoperative period, and early recognition and appropriate treatment can circumvent catastrophic results. Patients should be closely monitored for diabetes insipidus (DI) with frequent serum sodium evaluations and careful accounting of patients' fluid intake and urine output. An elevated serum sodium level or urine output may indicate DI. Temporary postoperative DI can occur in 10% to 60% of patients.[210,224] Permanent DI is much less common and occurs in just 0.5% to 5% of patients.[210] Delayed onset of the syndrome of inappropriate antidiuretic hormone secretion can also occur about a week postoperatively.[213]

Postoperative anterior pituitary insufficiency is one of the most commonly seen postoperative complications. Its incidence varies from 1% to 10%.[206,207] Postoperative steroid therapy should be used in all postoperative patients until a thorough endocrine evaluation is complete. Adrenal insufficiency is a potentially serious complication if adequate steroid replacement therapy is not initiated.

CSF rhinorrhea is another commonly encountered complication of the transsphenoidal approach and occurs in 1% to 4% of patients.[206,213] Intraoperatively, penetration of the arachnoid membrane can result in a gush of CSF into the operative field and the potential for postoperative CSF rhinorrhea. Packing the sella intraoperatively with an autologous fat graft and bone from the removed vomer can help prevent CSF leakage. Care must be taken to not overpack the sella, which could lead to compression of the chiasm.[212]

Patients in whom CSF rhinorrhea develops are first treated with spinal drainage for several days. Failure to close a CSF fistula with spinal drainage may indicate the need for reoperation and repacking of the sella. Early recognition and treatment of CSF rhinorrhea are important because a CSF leak can lead to meningitis. The incidence of meningitis in patients undergoing transsphenoidal surgery has been reported to be 0% to 1.75%.[210,212,225] Patients with diabetes mellitus are at greater risk for the development of meningitis.

Cranial Base Surgery. Cranial base lesions represent a heterogeneous group of pathologies associated with the cranial base bony structures.[201,226-228] Complications are generally related to the lesion's location and the surgical approach necessary for exposure. Approaches often call for brain retraction to adequately expose the lesion. Overly aggressive retraction can lead to tissue damage and infarction, with postoperative swelling resulting in increased ICP. Several maneuvers, including adequate bone removal, CSF drainage, and diuretics, can aid in achieving adequate exposure without excessive brain retraction. Resection of noneloquent brain tissue may be required to prevent contusions and possible postoperative herniation occurring from retraction injuries. Retraction can also compromise or injure venous outflow and result in venous stasis and hemorrhagic infarctions. This is especially important with regard to the vein of Labbé. Excessive retraction of the posterior temporal lobe can lead to tearing of the vein of Labbé and severe hemorrhagic temporal lobe edema.[226]

Postoperative hematomas can also develop. Prevention involves meticulous hemostasis, tight blood pressure control in the postoperative period, and prompt correction of any coagulopathy. Early recognition involves having a high index of suspicion and performing early postoperative CT. Treatment usually involves operative evacuation of the hematoma.

CSF leakage is one of the most common postoperative complications in cranial base surgery. The operation often creates a communication between the CSF space and the facial sinuses. The sphenoid sinus is most commonly involved because of its association with the clivus and cavernous sinus.[226] CSF leaks occur in about 8% of patients undergoing cranial base operations. A persistent CSF fistula may develop. Leaks generally occur in the immediate postoperative period, or they rarely develop months after surgery.[226] CSF leaks manifest clinically as clear spinal fluid draining from the nose, ear, or wound. The fluid can be collected on a pledget, and the presence of β2-transferrin confirms the discharge as CSF. Confirmatory radiographic examinations can be performed. Radioisotopic cisternography with cotton pledgets in the nasal cavity can corroborate the presence of a

CSF leak. CT cisternography with intrathecal metrizamide or MR cisternography can be used to localize the leak.[229] At our institution we have been using a noncontrast protocol that fuses thin-slice bone window CT with a T2-weighted MRI sequence to visualize possible sites of leakage.[230]

A watertight dural closure can prevent CSF leaks, and a patch graft should be sewn in if primary repair of the native dura cannot be achieved; however, invasion of the dura by tumor or anatomic considerations often make closing the dura impossible. If watertight closure cannot be achieved, the cranial base should be reconstructed with muscle, fat, and fascia packing. Spinal fluid drainage can divert CSF and allow the dura or reconstruction to seal. Initial treatment of a postoperative CSF leak is a trial period of lumbar spinal drainage. CSF leaks that fail to resolve or CT demonstrating progressive increases in intracranial air requires surgical repair. A leak that recurs after spinal drainage is stopped necessitates reexploration with repacking and reconstruction of the cranial base. Early recognition of hydrocephalus is important because increased ICP can predispose a patient to a CSF leak, and correction of hydrocephalus may prevent a CSF leak.

Pneumocephalus is another postoperative complication frequently encountered in cranial base surgery. Air may be found in the extradural or intradural spaces. Intracranial air can produce alterations in a patient's mental status that result in lethargy or agitation. Some degree of pneumocephalus is commonly found on postoperative CT, and the air is usually reabsorbed quickly. Patients operated on in the sitting position have a higher incidence of pneumocephalus.[231] Increasing amounts of intracranial air signal the presence of a communication between the subarachnoid space and air sinuses and imply an undetected CSF leak. Having patients lie flat in bed and discontinuing external spinal drainage can facilitate the absorption of intracranial air. Passing a spinal needle through the bur-hole site into the air pocket can decompress the subdural air in the event of a tension pneumocephalus.[226]

Infection-related complications are relatively rare in cranial base neurosurgery, but they are of concern because of the communication established by surgery between the paranasal sinuses and the brain. Prevention involves standard sterile techniques and the administration of broad-spectrum antibiotics in the operating room and in the immediate postoperative period. Meningitis can occur, and early diagnosis, isolation of the causative agent, and appropriate antibiotic treatment are essential. CSF leaks predispose patients to meningitis, so repair of the CSF leak must be performed promptly. Epidural and parenchymal brain abscesses can also occur and are treated by operative drainage and appropriate antibiotics.

Skull base lesions often involve the cranial blood vessels. Tumors can encase or displace these vessels, and adequate tumor removal may require sacrifice of vessels. The neurosurgeon must know the consequences of sacrificing cranial base blood vessels to minimize morbidity. Sacrifice of vessels can result in ischemic neurological deficits and infarctions in a vascular territory or watershed distribution. Preoperatively, balloon occlusion testing and xenon-enhanced CT cerebral blood flow testing can determine whether patients can tolerate sacrificing a blood vessel. Patients in whom neurological deficits develop with the balloon occlusion test or who have cerebral blood flow of less than 35 mL/100 g per minute cannot tolerate vessel sacrifice and may require a bypass graft.[232]

Cranial nerve morbidity is commonly encountered with cranial base surgery, and the dysfunction may be temporary or permanent. Accurate preoperative cranial nerve examination is important because postoperative dysfunction is more likely in patients with preoperative deficits. Neurophysiologic monitoring is an important adjuvant for localizing cranial nerves and preventing injury. Cranial nerve VII may be monitored via continuous facial electromyographic responses. A nerve stimulator can help locate the facial nerve. Cranial nerve VIII can be monitored using brainstem auditory evoked potentials. New devices that attach to the cuff of the endotracheal tube can be placed such that they make contact with the posterior pharyngeal wall. These devices are useful in monitoring cranial nerves IX and X, and continuous monitoring of these nerves has been shown to help reduce swallowing difficulties postoperatively.[233] Cranial nerve XI can be localized with a nerve stimulator and observation of shoulder twitching.[234]

Cranial nerve injury can occur as a result of nerve retraction or direct injury during tumor dissection. Cranial nerves may also be injured by compromise of the nerves' blood supply during surgical dissection distant from the nerves. Damage to the cranial nerves is especially significant during surgery in the cavernous sinus. Optic nerve damage occurs in 0% to 6% of patients.[235,236] Permanent damage involving extraocular nerve function (i.e., cranial nerves III, IV, and VI) occurs in 20% to 30% of patients.[235,237] The incidence of V_1 neuropathy is 8% to 20%.[235-237]

Certain cranial nerves are more susceptible to injury than others. Cranial nerves I, II, and VIII are very sensitive to injury. Minimal manipulation can result in profound deficits, and the loss of function is often irreversible. Cranial nerves III, IV, and VI are less sensitive to manipulation, and some recovery typically occurs postoperatively if the nerve's continuity is maintained. Injury to these nerves results in diplopia. Loss of cranial nerve IV function can be corrected by tilting the head or the use of prism glasses. Oculoplastic procedures may be necessary to correct persistent diplopia caused by injury to cranial nerve III or VI. Cranial nerve V damage is generally well tolerated, with the exception of damage to the V1 segments, which mediate the corneal reflex. Damage to the V_1 division results in corneal sensory dysfunction, and patients must have meticulous eye care to prevent corneal abrasions and loss of vision in the desensitized eye.[226]

Damage to cranial nerve VII results in significant cosmetic morbidity as a consequence of facial paralysis, and functional loss because of an inability to close the eye effectively. Damage can occur from direct injury to the nerve, injury to the geniculate ganglion, or nerve traction. Traction can occur during retraction of the greater superficial petrosal nerve or caudal retraction of the mandible after dislocating the temporomandibular joint (TMJ). Maintaining nerve continuity offers the best chance of functional recovery. Direct end-to-end anastomosis can be performed, or a cable graft using a sural nerve graft may be necessary. Other options include XII–VII or XI–VII anastomoses. Tarsorrhaphy or insertion of a gold weight implant in the upper eyelid may be necessary if eye closure is not adequate. In the immediate postoperative period, eye care with artificial tears and eye lubricants is essential to prevent keratitis.

Cranial nerves IX and X are usually injured together. Unilateral, slowly developing lesions are usually well tolerated because of the patient's compensatory mechanisms. Acute lesions result in difficulty swallowing, inability to protect the airway, and unilateral vocal cord paralysis. Long-term dysfunction requires treatment with a tracheostomy and placement of a gastrostomy tube. Tracheostomies and feeding tubes may be removed if patients recover function sufficiently or compensatory mechanisms develop. Failure to initiate such measures can lead to malnutrition and aspiration pneumonia.

Unilateral injury to cranial nerve XII is generally well tolerated. When combined with other cranial nerve injuries, such as injury to cranial nerves VII, IX, or X, significant dysarthria can occur. Bilateral cranial nerve XII injury results in severe functional limitation and ultimately requires a tracheostomy and placement of a feeding tube.[226]

Cranial base surgery, especially orbitozygomatic approaches, can cause morbidity from TMJ manipulation, and special care should be taken to avoid injury to this joint. Dislocation of the TMJ can result in postoperative trismus. Resection of the mandibular condyle may be preferred if needed because it avoids retraction of the mandible and associated postoperative trismus. Resection of the condyle leads to a contralateral jaw deviation but no functional loss.[226]

Complications of Stereotactic Brain Surgery

Advances in medical technology have resulted in a host of neurosurgical procedures using three-dimensional (3D) stereotactic guidance systems. Many procedures involve the use of stereotactic guidance in performing conventional craniotomies or other operations. This section deals with complications related to stereotactic procedures performed through small bur holes or using focused radiation (i.e., Gamma Knife). Such procedures include brain biopsy, cyst aspiration, functional lesioning, deep brain stimulation, neuromodulation, and stereotactic radiosurgery.

A stereotactic frame is applied to the patient, and CT or MRI is performed. The most commonly used frames are the Leksell (Elektra Instruments) and the Brown-Roberts-Wells (Radionics) systems.[238,239] The fiducial markers on the frame are registered into the system and allow accurate 3D navigation and localization in reference to the neuroimaging. Proper application of the stereotactic frame and precise registration are essential to achieve accurate results. Frameless systems that use cutaneous or bone-driven fiducial markers are available, as well as some that use surface landmarks alone, commonly facial tracing, with no need to place cutaneous fiducial markers. In many instances, frameless stereotaxy has replaced the frame-based methods. It is not always necessary to have the head fixed in pins for frameless stereotaxy; this is advantageous, for example, in shunt placement, wherein ventricular catheter placement for shunts has been shown to be more accurate with use of stereotactic neuronavigation.[240]

One of the most commonly performed stereotactic procedures is brain biopsy. Brain biopsies are safe and effective procedures. The procedure can usually be performed under monitored anesthesia care and can avoid the complications associated with general anesthesia. CT or MRI is used to stereotactically guide biopsy of a lesion through a small bur hole. Possible complications include hemorrhage, neurological deficits, seizures, and infections.[239] The mortality rate in several large series has been less than 1%, and complication rates vary from 0% to 7% (Table 22.6).[239,241-244] Seizures and infections are rare during brain biopsy. The most serious complication usually involves postoperative hematoma formation. Properly performed brain biopsies are more than 90% effective in establishing a tissue diagnosis in patients with radiographic lesions.[239]

Studies have demonstrated no significant difference in the accuracy and the retrieval of diagnostic tissue between frame-based and frameless stereotactic biopsy. Most biopsies are now performed with frameless methods. The use of frozen section is critical in confirming the retrieval of diagnostic tissue, and if further samples might be needed to taken and/or the trajectory replanned.[245,246]

Preventing complications related to brain biopsy requires adequate preoperative planning. Only patients in whom the results of brain biopsy may change medical management should undergo biopsy. Because thrombocytopenia or coagulopathies predispose patients to intracranial hemorrhage, all candidates should have normal coagulation profiles and platelet counts. Preoperative radiographic imaging is essential to rule out vascular lesions that may result in serious hemorrhage when biopsied. The planned trajectory must avoid vessels and important structures. Intraoperative hypertension may predispose patients to hemorrhage.[239]

When bleeding is discovered during a brain biopsy, allowing the blood to drain out of the needle may prevent the formation of a hematoma. Craniotomy may be required to control persistent hemorrhage. Instillation of thrombin through the biopsy canula has been used to control hemorrhage.[247] Routine postoperative CT can be performed to rule out hematoma formation, and asymptomatic hematomas are often discovered postoperatively. Neurological deficits develop in about 10% of patients with asymptomatic postoperative hematomas.[248] Most postoperative hematomas are managed with observation and serial CT.

Brain biopsies are increasingly being performed on patients infected with human immunodeficiency virus (HIV), who may be subject to several CNS infections or neoplasms. Biopsies in patients with AIDS have higher complication rates. Skolasky and coworkers reviewed 435 HIV-positive patients undergoing biopsy and determined that the morbidity rate was 8.4% and the mortality rate was 2.9%.[249] Complications were associated with preoperative poor functional status and thrombocytopenia. It is not clear whether the presence of HIV infection predisposes to higher complication rates.

Stereotactic Radiosurgery

Stereotactic radiosurgery is a safe and effective treatment modality for vascular malformations, brain tumors, and in some cases, functional surgery. Stereotactically applied radiation provides precise delivery of high-dose radiation to a well-defined target. Complications in radiosurgery are related to the effects of radiation on the brain and structures in proximity to the lesion.

Significant early complications rarely occur but can include seizures or worsening neurological deficits. Approximately a third of patients experience mild transitory symptoms, including headaches, nausea, and dizziness.[250] This is thought to be secondary to transient swelling 12 to 48 hours after therapy. A course of steroids may help alleviate some of these symptoms.

Late complications develop 6 to 9 months after the procedure and can include facial palsy, trigeminal neuropathy, and visual symptoms.[239] Exposure of the optic nerve to more than 8 to 10 Gy of radiation leads to visual deterioration and optic neuropathy.[238,251] Patients may become symptomatic from radiation necrosis or local brain edema. The risk for carcinogenesis secondary to radiosurgery is estimated to be less than 1 in 1000.[252]

Gamma Knife radiosurgery has been applied effectively to the treatment of acoustic neuromas. The complications associated with acoustic neuroma radiosurgery are related to exposure of cranial nerves to radiation. The rate of facial nerve paresis after 5-year follow-up has been 21%, and the rate of trigeminal dysfunction has been 27%. Hearing was preserved in 51% of patients undergoing radiosurgery for acoustic

TABLE 22.6 Complications of Stereotactic Brain Biopsy

Series	No. of Cases	Hemorrhage (%)	Nonhemorrhage Deficit (%)	Seizure (%)	Infection (%)	Death (%)
Lunsford and Martinez,[241] 1984	102	2	0	1	1	0
Apuzzo et al.,[242] 1987	500	0.4	0.2	0.2	0.2	1
Kelly,[243] 1991	547	0.9	0.9	1.1	—	0.3
Bernstein and Parrent,[244] 1994	300	4.7	0	0	0	1.7
Kondziolka et al.,[239] 1998	367	0.3	0.3	0	0	0
Dammers et al.,[245] 2008	164	2.4	1.2	3	0	3.7

neuromas.[253,254] Peritumoral edema after radiosurgery has occasionally led to hydrocephalus.[255] There is a significant increase in mass effect and tumor size, approximately 43%, after high-dose Gamma Knife radiosurgery for vestibular schwannomas that correlates with deterioration of facial and trigeminal function. The effect is much smaller at lower doses.[256] Because tumor control is greater with larger doses of radiation, fractionated stereotactic radiosurgery is usually performed to allow increased control of growth while minimizing risk to the facial, cochlear, and trigeminal nerves.[257] Intracanalicular tumors may be associated with higher cranial nerve morbidity when treated with radiosurgery.[258] Improvements in target imaging and reduction in doses have led to lower cranial nerve morbidity.[253,255]

Radiosurgery has also been applied to cranial base meningiomas. The morbidity rate is about 5% to 8%.[251,252,259,260] Most complications involve transient cranial nerve palsies and occur 3 to 31 months after surgery. High radiation doses applied to the Meckel cave increase risk for the development of trigeminal neuropathy.[251] Radiosurgery is also used to treat gliomas and brain metastasis. Preliminary reports indicate a morbidity rate of about 10% and a mortality rate of 1%.[261] However, newer studies are reporting a morbidity of up to 40% for treatment of multiple metastatic lesions.[262] Early complications can involve increased ICP, which may lead to death.[263] Radiotherapy for brain parenchymal lesions can result in seizure complications. Patients with lesions in the motor cortex are especially susceptible to seizures after radiosurgery.[264] Gamma Knife radiosurgery for trigeminal neuralgia is generally well tolerated and associated with minimal morbidity. Loss of facial sensation has been reported infrequently.[265]

Robotics, Augmented Reality, and Artificial Intelligence

A number of applications for robotics are being developed, particularly using the ROSA device (Zimmer Biomet). It is an articulating robotic arm that can mount an instrument such as a drill, probe, or tube. It is registered to the skull as with other frameless stereotaxy platforms, and can navigate to preplanned trajectories. It has been used in stereotactic biopsy, implantation of depth electrodes, neuromodulation in epilepsy, and deep brain stimulation. Current reports suggest it is safe and accurate.[266-270] It is also being evaluated for planning and implanting spine instrumentation.[271] Other robotic applications for endoscopic endonasal approaches are also being developed.[272]

Augmented reality platforms in cerebrovascular and skull base surgery are an emerging adjunct to overlay 3D reconstructions of pathology and relevant nearby anatomy into the eyepieces of the operating microscope, and might make these operations safer.[273-275] They can be used to plan positioning, skin incisions, craniotomy, and dural opening. Although not a substitute for trusting one's eyes, the heads-up display can provide additional visual clues to reorient oneself, for example, when anatomy is distorted by tumor. It is routinely used in our hospital. Similar applications for endoscopic endonasal skull base surgery also exist.[276,277]

Artificial intelligence in neurosurgery is in its infancy. There are active efforts to use machine learning for many decision-support applications relevant to neurosurgery: automated segmentation of tumors on preoperative imaging, grading and diagnosis of tumors on histopathology, detecting epileptic zones, segmenting brainstem anatomy, and predicting survival in neuro-oncology and traumatic brain injury.[278] Use of Adaptive Hybrid Surgery Analysis (AHSA; Brainlab) is another application, wherein real-time radiation plans for residual tumor can be estimated in cases inwhich subtotal resection is planned, and further resection halted to minimize risk of intraoperative neurological injury.[279]

Spine Surgery

Cerebrospinal Fluid Leak or Pseudomeningocele Formation

Prevention of CSF leakage is critical for optimizing wound healing, for preventing neural elements from herniating through the defect in the dura and leading to pain syndromes or neurological deficits, and for eliminating positional headaches. It is generally accepted that reduction of intraspinal CSF pressure facilitates healing of a dural defect. This can be achieved by maintenance of strict bed rest or by placement of a CSF diversion drain, such as a lumbar drain. The use of spinal subarachnoid drains after a CSF leak is supported as an adjunct.[280-284] One treatment element that seems to be accepted almost uniformly as being beneficial is the use of fibrin glue sealants.[285-290] The sealant can be prepared autologously in the operating room, from cryoprecipitate obtained from the blood bank, or from commercial kits made from donated blood products. Regardless of the cause, fibrin glue sealants, when applied in the area of the dural repair, dramatically increase the rate of healing. The use of dural replacements is more controversial. Repair with fascia, AlloDerm, Duragen, or other techniques is more a matter of choice than evidence-based medicine.

Primary repair of a dural violation, when possible, is clearly indicated. Multiple surgeons have documented increased infection rates and decreased fusion rates associated with CSF leaks.[282,289-292] In addition to CSF leaking from the durotomy, nerve roots have been known to herniate into the durotomy and result in painful syndromes.[293]

A tight, multilayer closure is critical to prevent local CSF collections from leaking outward to the skin. If a CSF leak exists, organisms have a portal of entry and may cause meningitis. Any CSF leak should be treated immediately by oversewing of the wound and institution of some form of CSF pressure–reducing strategy. The decision to surgically revise a wound rather than treat conservatively depends on several factors, including the tightness of the dural and fascial closure, the presence of and size of the subfascial collection, and the patient's underlying ability to heal a wound spontaneously. A CSF pseudomeningocele, even in the absence of an external leak, can increase the likelihood of local infection.

Instrumentation-Related Risks

Instrumentation has increased the incidence of complications in all series that have compared the results of instrumented with noninstrumented fusions.[294-297] This finding is not surprising, in that instrumentation adds time, complexity, and an implanted foreign body to the operative procedure. Fusion rates are uniformly higher in instrumented cases, and most experienced spine surgeons believe that the risks are outweighed by the benefits of rigid segmental fixation. However, each surgeon must feel confident and comfortable with any technique because morbidity rates vary from surgeon to surgeon.[298-316]

Identification of the correct level is critical for most spine operations. Radiography or fluoroscopy to adequately identify the level is vital for medical and legal documentation. Surgical operations at the wrong level can be prevented by identifying landmarks with radiographs, but surface and deeper landmarks must be correlated. One common problem is failure to take into account the downward projection of the spinous process; for example, a needle placed on one spinous process but in front of the next lower body may lead to confusion about the level. This is especially problematic in the thoracic spine. Obvious bony landmarks (e.g., loss of a pedicle or a fracture seen on the localizing film) can facilitate identifying the surgical site. Subtle findings, such as the location of unique osteophytes or

BOX 22.3 Intraoperative Guidance

CRANIOTOMY

Ultrasonography
Cortical mapping
Intraoperative MRI
Computer-assisted stereotaxis
  Incorporating fMRI, DTI, spectroscopy
Fluorescence guidance with 5-ALA
Robotics, augmented reality, artificial intelligence

SPINE SURGERY

Ultrasonography
Intraoperative electrophysiologic monitoring
  Include direct epidural D-wave monitoring when appropriate
Intraoperative fluoroscopy, CT, CT reconstructions
Stereotactic navigation
Robotics

5-ALA, 5-Aminolevulinic acid; *DTI,* diffusion tensor imaging; *fMRI,* functional magnetic resonance imaging.

compression fractures, can assist in localization when obvious findings are absent. The use of a tangible marker, such as a bite from bone with a rongeur or placement of a stitch into a spinous process, reduces ambiguity later in the procedure.

The use of intraoperative imaging has grown dramatically. Ultrasonography as an intraoperative localizing device can help verify the correct level and locate hidden, deep lesions within the spinal cord (Box 22.3).[317-320] More medical centers are using portable and dedicated MRI and CT scanners for determination of the adequacy of procedures for resection of tumor or osteophytes, placement of instrumentation, or other needs of the surgeon. Stand-alone MRI scanners have been developed that function in an operating room or even as an operating room.[321] Some of these modalities require specialized equipment that is compatible with the modality (e.g., nonmagnetic instruments for intraoperative MRI). Each has its advantages and limitations, and the use of these devices depends on the needs of the surgeon and the institution. Intraoperative CT scanners are available, as are fluoroscopy-based systems that create 3D reconstructions resembling CT scans. These modalities can be useful in confirming the adequacy of decompression or screw placement before leaving the operating room.

Stereotactic navigational adjuncts have increasingly been used in spine surgery.[321-325] The accuracy of stereotaxis depends on the quality of the scan used, the position of the patient intraoperatively and in the scanner, performance of the stereotactic portion of the procedure before any resection or opening that would distort the landmarks used for calibration, and user-dependent variables. Currently, numerous intraoperative navigation techniques are available that rely on preoperative CT, intraoperative 3D reconstruction from fluoroscopy, or 3D reconstruction from intraoperative CT. Although each system has its pros and cons, there is no evidence that one system is clearly superior to another.[326] All appear to provide accuracy with respect to screw placement, and this may be especially helpful in thoracic instrumentation, where the pedicles are narrower and the spinal cord is at greater risk compared with the lumbar spine.[326-331] One center demonstrated a 96% versus 79% accuracy for thoracic pedicle screws placed via CT navigation versus conventional fluoroscopy.[332] Another study using the O-Arm intraoperative imaging system (Medtronic) showed 99% accuracy in thoracolumbar pedicle screw insertion.[333]

Robotic systems are also being developed to improve the accuracy of targeting and screw placement.[329,330] Navigational techniques are increasing being applied to spinal arthroplasty procedures, as well as fusion procedures.[331] Most recent analyses of the Renaissance Guidance System (Mazor Robotics/Medtronic) and ROSA device show an 85% to 100% accuracy rate in pedicle screw placement.[334] Current platforms enable speeds of approximately 4 minutes per screw.[335]

Complications of Bracing and Halo Use

No intervention is without risk for complications, and the use of external orthoses is no exception. Problems are related to improper placement, to proper placement but brace limitations, and to the brace itself. Improper placement of cervical collars can result in skin and spinal cord injuries. The skin can be abraded if the chin falls inside the jaw support. Use of a properly fitted collar and instruction to the patient that the chin is not supposed to slide under the chin support can significantly reduce this risk. Spinal cord injury can occur when an unstable spine is moved as a result of placement of a brace. A brace should be applied in such a way that the spine is not moved, and this includes not reducing a deformity. One common situation is a patient with ankylosing spondylitis and a fixed kyphotic deformity who sustains a transdiscal fracture.[336-341] A well-intentioned first responder may place this patient in neutral alignment and cause a spinal cord injury. It is critical to obtain a history from the patient or family before reduction, if possible, and to keep the patient in the baseline position, not just what "looks right." Many spinal cord injuries occur after the patient has been placed in a collar. Injury may also result because no external orthotic device limits movement completely.[342-344] The range of motion in a given device varies but is easily quantifiable. Wearing a brace of any kind can trap moisture and impede dressing changes, thereby leading to wound maceration and cellulitis. A brace that does not contour the patient's anatomy can cause pressure, pain, necrosis, and wound breakdown.

Use of a halo vest orthotic, which has less range of motion than nonfixed devices, is complicated by several factors, including local pin site complications, problems with the vest device, movement despite the halo, and issues related to the size, bulk, and location of the device.[48,50,52,53,345-350]

Local pin-related complications range from the mundane, such as cellulitis at the skin insertion site, to deeper complications related to the point at which the pin enters the skull.[49,50,53,351,352] Pin-related complications also include the development of epidural hematoma or epidural/subdural abscess at the placement site. These complications are insidious because they cannot be seen directly. Loosening of the pin in the outer table may result in a catastrophic loss of tension, which leads to loss of fixation, scalp laceration, and in rare instances, oculofacial trauma. Fracture of the outer table can also lead to fracture of the inner table and intracranial injury.[350,351] The halo is large, unwieldy, and for many frail or slender patients, heavy. It raises the center of gravity for the patient and challenges the coordination skills of many patients, especially those already neurologically impaired.

Anterior Cervical Approach

Anterior cervical approaches include the transoral, ventromedian, and ventrolateral approaches for vertebrectomy or odontoidectomy, discectomy, and instrumentation. Each has a particular complication pattern, and there are steps to minimize them.

The transoral approach, because of passage through the oral cavity, is associated with a significant incidence of wound infection and healing problems.[353-355] They can be diminished by judicious minimization of steroids, care on opening to not destroy tissue planes and the mucosa, and the perioperative use of antibiotics. Unfortunately, many patients requiring a transoral approach are metabolically or nutritionally challenged to begin with, and they may not heal well. Palate injury is also a significant potential problem. The palate (soft and hard) may need to be split for adequate exposure, and it does not always heal well afterward. The assistance of an ear, nose, and throat surgeon for the approach and closure can help a surgeon who is not familiar with the management of these tissues. The potential neurological morbidities related to the transoral approach to the dens and anterior rostral spinal cord are related to the approach, the use of rongeurs instead of drilling, and the adequacy of exposure. Endoscopic transoral routes might also be explored.

Anterior ventromedian cervical approaches carry with them risks related to the structures nearby, including the esophagus, carotid and jugular branches, and nerves such as the vagus and recurrent laryngeal. Care in the approach includes remaining in an avascular plane and making sure that the prevertebral fascia is dissected inferiorly with a peanut to prevent direct injury to these structures.

Esophageal injury can result from the dissection or from manipulation during the procedure after the retractors are in place. Migration of the retractors may tear the esophagus directly, or the esophagus may creep into the surgical field and then be injured by a wayward instrument. Injury can be prevented by the surgeon remaining constantly aware of the position of the retractors and the esophagus. After the procedure but before closure, the entire length of the exposed esophagus should be inspected for tears because an unnoticed tear can allow spillage of contents into the surgical bed and lead to infection, pseudarthrosis, or osteomyelitis. The esophagus can be repaired directly with a muscle patch from the sternocleidomastoid (as a vascularized pedicle of the manubrial head or as a free segment) or with a direct external drain and an esophagostomy.[356-360] If the surgeon does not have experience with such a repair, an ear, nose, and throat surgeon should be called in to perform the restoration. Reoperations are frequently associated with problems related to scarring of the esophagus at the old surgical site, especially with instrumentation. If there is a question about difficult planes of dissection, an ear, nose, and throat surgeon should obtain exposure. The incidence of acute or subacute esophageal tears ranges from 0% to 1.9% and averages less than 1% in most series.[361] Delayed perforation has been described and may occur a decade after the surgery. Whether this represents an injury at the time of surgery or a delayed injury caused by erosion from the anterior plate or screws is unclear. Every attempt should be made to place the anterior plate as flush along the spine as possible.[362] Esophageal perforations appear to be occur most commonly at C5–6 because the wall of the esophagus is thinnest at this level.[362] Some surgeons prefer to place a nasogastric tube at the beginning of the procedure to serve as a palpable landmark for the esophagus in an effort to avoid injuring it.

Dysphagia without direct esophageal perforation is far more common in patients after anterior cervical spine surgery. Reports range from rates of 10% to 60%. When carefully studied, there appears to be a 13.6% rate of dysphagia in patients 2 years after surgery.[363] Dysphagia was more common in women, after revision surgery, and in patients undergoing multilevel surgeries. Minimizing retraction and retraction time and avoiding injury to the upper pharyngeal nerves are recommended. There are reports that placement of newer stand-alone devices, cages with inherent screws, have no profile from a plate and result in lower incidences of dysphagia.[364]

Recurrent laryngeal nerve (RLN) injury is a well-described risk with this anterior cervical approach. It leads to hoarseness and other changes in voice quality. The incidence is generally reported to be 2% to 3%.[365] RLN injury appears to be less likely when the spine is approached through a left-sided exposure because of anatomic differences in the right and left RLNs. There does not appear to be a clear benefit from endotracheal tube cuff deflation.[366] When considering the choice of approach for a revision anterior cervical procedure, preoperative laryngoscopy should be performed to look for evidence of existing unilateral RLN palsy.[367] If identified, the approach should be through the ipsilateral side to prevent bilateral RLN palsy and the need for emergency tracheostomy. Continuous RLN electromyographic monitoring during surgery is practiced by some surgeons in an attempt to minimize the risk for injury.[368,369]

The risk of graft movement (i.e., migration in toward the cord or ventrally out of the disk space) can be reduced with use of a plate to buttress the graft ventrally or by drilling an adequate ledge to prevent the graft from moving dorsally. Use of a graft slightly longer than the space available (requiring some distraction but maintenance of tension and compression on the graft) can maintain adequate tension such that the graft is unlikely to move. This force needs to be balanced against too much tension, which may lead to telescoping of the graft into the bodies above or below or to overdistraction, which may result in cord or root injury.

One of the most feared complications in the anterior cervical approach is injury to the vertebral artery. The incidence of this injury during anterior cervical approaches is less than 0.2%.[370,371] When such an injury occurs, packing of the vessel to obtain hemostasis should be followed by angiography and consideration of endovascular vessel occlusion. The risk for vertebral artery injury can be minimized by an understanding of the anatomy of the transverse foramen to the vertebral bodies and careful evaluation of preoperative CT and MRI studies.[372]

Postoperative formation of a hematoma in the operative field can have devastating consequences.[373-377] It may lead to a retropharyngeal hematoma or an epidural hematoma. It can initially manifest as dysphagia or pain but may result in stridor and airway obstruction. Immediate surgical evacuation and reestablishment of hemostasis must be instituted if there is any chance of significant size of the hematoma. It may be able to be prevented with the use of a drain leading from the vertebral surface (bone edges are often the source of the bleeding), although removal of the drain sometimes promotes bleeding.

Complications related specifically to corpectomies rather than discectomies include C5 traction injuries, collapse of the fusion segment, dislodgement of the implant, and a higher incidence of CSF leaks as a result of the more extensive involvement, especially in patients with ossification of the posterior longitudinal ligament.[378-386] The C5 nerve root is especially at risk because of the short length of the root and its tendency to be injured when overdistraction takes place.[380,385,387] By limiting the distraction and width of the decompression, this risk can be minimized.

The longer a fusion segment, the greater impact collapse or telescoping has on alignment of the spine. With graft settling, loss of lordosis and frank kyphosis can lead to pain, instability, and compromise of the canal. This problem can be prevented by not overdrilling the end plates above or below and by choosing a graft that is as wide as possible to decrease the pressure (i.e., force per unit area) of the graft into the adjacent bodies.

The approach for placing an odontoid screw is similar to that for anterior cervical discectomy and fusion. This method has all the risks of complication associated with the other anterior cervical approaches, with additional risks related to capture of the odontoid tip. Risks include failure to maintain the correct lateral angle and missing the tip of the dens and the potential for spinal cord injury from migration of the dens or a poorly placed drill or screw.[301,388-390] Risks can be minimized by means of wide exposure of the C2–3 interspace to demonstrate the uncovertebral joints bilaterally and determine the midline more accurately. Patients should be selected in whom the dens is aligned with the C2 body and not significantly displaced. Screw fracture, because of the long moment arm and high torque on the odontoid screw, can be prevented by using a tapered thread (i.e., the screw is thicker at the end), which strengthens the screw at the point where the force is greatest. Dens capture is easier with threaded lag screws because they reduce the likelihood of the screw pushing the fragment instead of threading into it.

Posterior Cervical Approach

Posterior cervical surgical procedures carry risks different from those of anterior procedures. The prototypical procedure is cervical laminectomy, which is performed for numerous indications, from Chiari decompression to cervical stenosis to intramedullary tumor exposure. The primary risks associated with cervical laminectomy are similar to those of laminectomy at other levels and include cord injury, dural injury, and nerve root injury. The simplest way to minimize injury to these elements is to judiciously and minimally use monopolar cautery when down to the lamina and dura, use cottonoids to retract the dura away from the ligamentum flavum and lamina, and take care in preventing overly aggressive use of rongeurs, which can result in fragments being twisted into the dura or nerve roots. Even with no evidence of direct trauma to the roots, transient C5 palsy can be seen in approximately 5% to 15% of patients undergoing posterior cervical decompression, with or without instrumentation.[391,392] This injury manifests as a deltoid muscle weakness. Although some authors recommend intraoperative monitoring with motor evoked potentials and deltoid electromyographic recording, C5 root injury may occur in the absence of intraoperative findings.[391,393]

The risk for injury to vascular elements is primarily limited to the vertebral artery, which runs laterally in the vertebral canal until its exit from the C2 body. At this point, the artery becomes most vulnerable to injury because the vessel turns from a lateral course and moves dorsally before entering the dura adjacent to the C1 lamina. Frequently, injury to the venous plexus is initially confused with injury to the vertebral artery, but the consequences are not nearly as significant. As with most venous bleeding, it can be controlled easily by tamponade with Gelfoam or Surgicel and a cottonoid. Injury to the vertebral artery may require opening the dura and ligating or performing a bypass or end-to-end anastomosis, depending on the nature of the injury and its location. Injury to the vertebral artery during posterior cervical procedures occurs more frequently than during anterior procedures, with a rate of up to 1.9%.[371]

Complications associated with posterior subaxial cervical spinal procedures are related to the degree of exposure, the neural elements exposed, and the use of instrumentation. Risks related to the decompression procedures laminotomy and laminectomy are similar, regardless of location, and consist primarily of injury to surrounding neural elements, injury to bony elements, and excessive bleeding. CSF leakage from an unintended durotomy may be minimized if care is taken to not leave any sharp bone spicules that may point downward into the thecal sac. Additional care should be taken with placement of a Kerrison rongeur to exclude dura within the teeth of the instrument. A small cottonoid can be gently passed underneath the bony edge and used to bluntly dissect the dura away while protecting it from the rongeur. Generous and temporary use of thrombin-soaked Gelfoam along the lateral aspects of the bony opening assists in obtaining hemostasis at the Batson plexus.

Lateral mass screws require precise localization of the entry point and angle with respect to the lateral and rostrocaudal planes. The orientation of the facet joints is an angle oblique to the coronal plane, and to avoid injury to the vertebral artery when anteromedial to the entry point, the screws need to be aimed significantly laterally. One rule of thumb is that if the drill guide is not leaning on the spinous process of the caudal vertebra, the surgeon is not aiming laterally or cranially enough. It is easier to understand the angle in the coronal plane if the dissection is taken widely enough that the lateral aspect of the facet joints' angle can be visualized directly. The angle should be parallel to the facet joints. Failure to angle upward sufficiently may result in the screw leaving the lateral mass and pinching the nerve root distal to the pedicle. As with the use of anterior plates, overtightening a screw results in fracture of the threads and loss of pullout integrity. If this complication occurs, a rescue screw should be used, or methyl methacrylate should be injected into the screw hole and the screw replaced. Use of a screw that is a little too long (1–2 mm), if in the correct orientation, is not likely to cause significant morbidity and can achieve bicortical purchase. Screws that are too long and in the inappropriate orientation are potentially dangerous.

Thoracic Spinal Procedures

Thoracic spinal procedures, because of the surrounding organs, carry risks different from those of cervical spine procedures. Anterior approaches, such as the transthoracic, endoscopic, and retropleural approaches, put major arteries, veins, and organs such as the heart, lungs, and diaphragm at risk for injury.[299,394-399] Posterior approaches, such as laminectomy, costotransversectomy, and transpedicular approaches, have fewer risks but can still injure the ventral organs and vessels if reaching too far forward.[77,299,400-402] All approaches can result in complications involving neural elements, CSF leakage, and infection. Some complications are related to the exposure, whereas others are related to the procedure being performed.

Thoracic laminectomy has long been performed for many procedures, including repair of intramedullary, intradural, and epidural lesions. Risks are similar to those for the subaxial cervical spine, and it is important to keep the lateral exposure to the minimum that can provide the necessary exposure. Too wide an exposure risks taking down the costotransverse ligaments and even risks pneumothorax. For tumor patients in whom the wound has been or will be irradiated, a curvilinear incision with a myocutaneous flap should be used to maintain vascular supply to the skin and reduce the risk for infection and tissue breakdown.[403,404]

Thoracic pedicle screw instrumentation can be performed safely by experienced surgeons using freehand techniques.[316,405-407] However, many of the intraoperative navigation systems previously discussed were designed specifically to increase safety in thoracic instrumentation.

Thoracoscopic procedures need smaller incisions to approach the spine and thus reduce the likelihood of significant wound breakdown and postoperative incisional pain, but because of the multiple ports used and the limited sight angles, the potential for injury to structures such as vessels and organs remains significant.[396,408-411] Conversion to open thoracotomy should be performed if there is a significant problem because trying to fix a large injury through a small opening will probably provide greater challenges.

Anterior Lumbar Procedures

Anterior lumbar procedures can be subdivided into three main categories: transperitoneal open, endoscopic transperitoneal, and retroperitoneal approaches. Potential morbidities are associated more with the approach than with the individual procedure, and when the spinal procedures differ, they are discussed separately. Anterior procedures are performed to augment spinal stability or correct deformity by bone fusion or instrumentation or to perform arthroplasty. The choice of approach depends on the exposure needs of the procedure, the type of instrumentation being used, and preferences of the surgeon and patient.

The transperitoneal open procedure is performed through a laparotomy, usually through a midline incision, although a Pfannenstiel bathing suit line incision can also be performed. The procedure calls for mobilization of the abdominal viscera with a midline anterior approach to the spine after mobilization of the various branches of the aorta, inferior vena cava, or iliac vessels. This approach has a higher risk than the retroperitoneal approach for postoperative complications such as injury to the major vessels, adhesions, and adynamic ileus.[412-417] Injury to other structures, including the ureter and pelvic contents, is rare but of significant consequence.

Anterior endoscopic procedures are performed through multiple small incisions and with the use of multiple ports.[418,419] The smaller incisions are thought to heal better than a single, large incision of the same total length. The approach is essentially the same as an anterior transperitoneal approach, although the port size and endoscopic techniques make mobilization of visceral structures more difficult. The assistance of a general surgeon with significant endoscopic experience in performing the exposures is recommended. Other possible complications include hypercapnia if carbon dioxide insufflation is used and delay in converting to an open procedure if bleeding or another major complication occurs. Lost time in gaining control of a difficult situation can lead to greater morbidity from blood loss.

The retroperitoneal approach can be used in two ways. It can be performed with a wide exposure to allow extensive instrumentation,[416,420,421] or it can be used with a short incision for placement of an interbody fusion construct (e.g., mini–anterior lumbar interbody fusion [mini-ALIF]). The main risks are vascular, although entry into the peritoneum or sigmoid colon is possible. Previous surgery in this area distorts the anatomy and leads to scarring. The primary risk with this approach is tearing segmental arteries and veins that may be under tension and difficult to visualize as retraction for the exposure proceeds. This exposure may be extended up to the diaphragm, with further mobilization of the kidney and, if necessary, the spleen and liver. The approach is usually done from the left side because of the smaller size of the liver on the left. Because of the retroperitoneal exposure, the ureter is less subject to injury in the lower levels than with a transperitoneal approach. The location of the ureter should be anticipated to reduce the chance for injury.

Anterior interbody fusions can be performed with various cages, or autograft fusion can be performed from a straight anterior transperitoneal or a lateral retroperitoneal approach, depending on the technique and device used. Whether an endoscopic or open procedure is used depends on the body habitus of the patient, the preference of the surgeon and patient, and the availability of equipment and assistance.

One significant risk related to the anterior approach is retrograde ejaculation in male patients undergoing L5–S1 fusion.[422] The incidence of this complication was initially reported to be about 5%, but the later literature has reported an incidence as high as 20%. There is a 10-fold higher incidence of retrograde ejaculation with a transperitoneal approach than with a retroperitoneal approach to L4–5 and L5–S1.[423] This is thought to be due to the fact that the superior hypogastric sympathetic plexus lies midline over the disk spaces at L4–5 and L5–S1. When approaching from a retroperitoneal trajectory, the plexus is mobilized off the disk spaces along with the posterior peritoneum to protect it from injury. When the approach is via a midline transperitoneal route, the plexus itself is directly injured. This may play a role in the choice of approach in men. Minimal use of electrocautery in this region is also recommended. If a transperitoneal approach is required, dissecting the plexus off the right-sided iliac vessels and mobilizing the fascia toward the left may protect the plexus and prevent this complication.[424]

Other major risks associated with anterior interbody procedures include the possibility of neurological injury or CSF leakage from the anterior discectomy, pushing of disk fragments dorsally as the cage is advanced, and misdirection or misplacement of the fusion construct. The best way to reduce the chance of neurological injury is to remove the disk under fluoroscopic guidance. If the surgeon can visualize just how deep each pass of the pituitary rongeur goes, there is less chance of going too deep, passing the anulus, and biting the dura or nerve roots. Continuous use of fluoroscopy allows evaluation of each step of the reaming and tapping, thereby allowing the surgeon to correct any misalignment before it becomes irreversible and leads to instability of the construct. One way to reduce the chance that the cage or bone graft will push disk fragments posteriorly is to ensure that the discectomy is adequately performed and that no residual disk remains in the path of the construct.

Vertebrectomies are best performed through the retroperitoneal approach because the screws can be placed along the long axis of the bodies and achieve better purchase. The exposure can be carried up or down multiple levels without significant risk to structures that cross the midline and only minimal risk to structures that cross the exposure (primarily the radicular arteries and veins). The chance of causing a significant injury to the artery of Adamkiewicz and resulting in ischemia of the lower cord can be reduced by avoiding sacrificing the radicular artery too far distal from the aorta. The location of the radicular vessels in the middle of the bodies makes it nearly impossible to save them at the level above or below if a plate or other instrumentation is applied. To prevent unnecessary blood loss, it is best to isolate the vessels, sacrifice them cleanly with ties or hemoclips, and then cut them under direct vision. This technique prevents avulsion and retraction of the vessels into surrounding soft tissue or, worse, avulsion at their insertion into the aorta or vena cava.

Posterior Lumbar Procedures

Dorsal lumbar procedures are primarily used for laminectomy, laminotomy, and fusions, with or without instrumentation, and they are the oldest and most commonly performed procedures for spine surgery.

Hemilaminotomies can be performed for small exposure of intraspinal epidural lesions such as disk herniations, synovial cyst herniations, and ligamentous or bony hypertrophy as a result of degenerative disk disease. Minimal exposure (i.e., unilateral muscle and bone dissection) results in reduced pain, decreased length of hospital stay, and reduced operative time for most patients. However, the reduced exposure carries several risks. Retraction of the muscles laterally is often performed with a Taylor retractor. If retraction is performed too aggressively or in the wrong location, a facet fracture can occur. This risk can be minimized with the use of a retractor that spreads the tissue without digging lateral to the facet joint. Use of such a retractor, however, carries with it the risk of spinous process fracture, so careful use of any retractor is recommended. Other options are use of tubular retractors or endoscopic approaches, which allow for smaller skin incision and less retraction and muscular dissection, especially for lateral disk herniations.[425,426] Fracture of the facet can also occur if the medial facetectomy is carried too far laterally. The usual landmark for completion of bone removal laterally is the medial border of the pedicle below, which is located right under the root of the ascending facet. Going beyond this point confers a greater chance of fracture of the ascending or descending facet and, consequently, pain on movement postoperatively. At least half the width of the pars interarticularis should be preserved to prevent postoperative pars fracture and spondylolisthesis.

Prevention of postoperative epidural scarring after dorsal procedures is a challenge that does not have a simple answer. Several techniques are available, such as placement of a fat graft, Gelfoam sponge, or artificial adhesion barrier.[427-430] None is without complications or is universally effective.[431-434]

Postoperative reherniation of disk fragments occurs in approximately 10% of cases.[435-442] Differentiating reherniation from scar requires a contrast-enhanced scan (unless it is in the first week or two after surgery); the scar enhances, and the disk usually enhances only in the periphery of a fragment.[281,428,443-446] Injury to the nerve root can occur in several ways. The nerve root can be unintentionally cut during opening of the anulus if the root has not been adequately identified and retracted. Frequently, overly aggressive retraction can result in transient weakness or sensory changes in a root that has not been cut. This injury tends to respond to steroids and physical therapy, although it is better avoided by careful dissection. Failure to recognize a redundant nerve root may lead to injury to the root, even after presumed protection of one of the branches.

Cauda equina syndrome as an immediate or delayed result of lumbar discectomy is a catastrophic neurological complication. It can occur as a result of injury to the nerve roots from epidural hematoma after closure, from infection of the arachnoid or epidural space, from retraction of neural elements against a calcified herniated fragment, or from extrusion of disk or end plate fragments postoperatively.[447-453] The mechanism usually determines the time frame for the onset of symptoms.

Catastrophic injury to the organs or vessels of the abdomen and pelvis can result from discectomy.[412,454-461] Injury can occur from placement of any sharp instrument into the disk space that passes through the anulus and anterior longitudinal ligament. Bleeding, which may or may not well up into the surgical field, is not responsive to attempts to arrest it. The patient may become tachycardic or hypotensive. The onset of symptoms may be more insidious and not appear until the patient is in recovery, or in the case of bowel injury, symptoms can develop after discharge. Management of life-threatening vascular injury requires termination of the neurosurgical procedure, turning the patient over, and performing an exploratory laparotomy and vascular repair of some kind. Ignoring the problem, failing to obtain a vascular surgical consultation, or simply transfusing the patient can result in catastrophic blood loss and perhaps death.

Minimally invasive techniques for the treatment of lumbar disease include chemonucleosis, thermal or laser coagulation, and automated percutaneous discectomy.[462-479] These procedures are performed with use of local anesthesia with fluoroscopic guidance, and their aim is internal decompression of the disk and the affected nerve roots. One benefit of the absence of regional or global anesthesia is that any irritation or compression of the nerve root can be felt, and the surgeon is able to change whatever it was that triggered the response. The entry point is from the side of the disk, and it may be difficult to enter the L5–S1 space directly because of the position of the iliac crest relative to the disk space. Up to 10% of patients are unable to have percutaneous instruments placed into this disk space. Causalgia, injury to the thecal sac or nerve roots, injury to the end plate, fracture of an instrument, injury to a hollow viscus, injury to a vessel, and hematoma of the psoas muscle are all acute complications of percutaneous discectomy.[463-467,470,477,480-482] Delayed complications include discitis and progression of the degenerative processes.[483,484] Success rates for percutaneous treatment are in the range of 60% to 80%,[462-467,480,484,485] much lower than those for microdiscectomy but without the attendant risks associated with general or regional anesthesia.

The risks related to posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF) are similar to those for posterior decompression but are amplified by the additional manipulation required to distract the two end plates, retract the neural elements, and implant the interbody graft. Posterior instrumentation further adds to these risks.[294,486-498] Overdistraction can lead to neurapraxia of one of the nerve roots and may tear adherent dura. Actions that can reduce the complications associated with PLIF include having the appropriate instruments for distraction and implantation. When performing PLIF for spondylolisthesis, the nerve roots exiting through the same foramen (e.g., the L5 root for L5–S1 PLIF) may be under significant compression and tension because of the anterolisthesis and pseudodisk. The path of the nerve root takes it directly over the desired entry point into the interspace, and the plane of the disk space causes distractors to go through the region of the axilla of this root. One way to avoid the problem is to use a drill or osteotome to remove the dorsal osteophyte lateral to the lower root and medial to the exiting root. This allows a flatter trajectory into the disk space and avoids unnecessary manipulation of an already tenuous root. The additional lateral recess and foraminal decompressions performed during the TLIF also offer direct decompression of the nerve, and the placement of the cage offers an indirect decompression by further widening the foraminal space.

Several types of bone or cage constructs, including titanium and carbon fiber cages, polyetheretherketone (PEEK) cages, femoral bone dowels, or impacted bone wedges, can be placed into the intervertebral space. Placement of cages and bone dowels from behind requires more extensive exposure than needed for PLIF with impacted bone grafts. Although the literature on this type of procedure may describe removal of only the medial facets, more surgeons find that the whole facet or most of the facet needs to be removed to provide adequate exposure and protection of the nerve root and thecal sac. Because this approach results in some posterior instability, it is almost always combined with some form of posterior instrumentation such as pedicle screws. The most common complications include tearing of the thecal sac or nerve root sleeve with subsequent CSF leakage, injury to the nerve root, and infection. Prevention of nerve root sleeve and dural tears requires adequate removal of the posterior elements (e.g., lamina, medial or full facets) and placement of some kind of protective retractor to prevent the threads from catching the dura. Excessive retraction of the nerve root can result in significant neurapraxia.

Pedicle Screw Fixation

The use of pedicle screw fixation has significantly increased fusion rates over those with noninstrumented fusions.[306,314,316,499-504] Use of the pedicle screw fixation technique, which has undergone significant medicolegal scrutiny, has been vindicated, and it is applied to lumbar, thoracic, and cervical spinal cases. A preoperative understanding of the patient's global spinal alignment, taking into account spinopelvic harmony on standing radiographs and using tools such as the Global Alignment and Proportion (GAP) score, may help the surgeon plan on the amount of correction needed (if any) and what instrumentation constructs to use in fusion cases. There is general agreement that correcting factors such as lumbar lordosis or pelvic incidence mismatch and vertical sagittal alignment in thoracolumbar fusion cases is highly correlated with biomechanical stability and patient quality of life (Box 22.4).[505-507] The major risks are related to misplacement of the screws, fracture of the neural elements being stabilized, injury to neural and vascular structures, and infection or poor wound healing.[c] Reduction of risk is undertaken on several fronts. Understanding the biomechanical parameters and indications can reduce the risk for surgical misadventure. Pedicle screws can be placed by relying only on anatomic parameters to determine the entry point and angulation, but for surgeons who wish to have confirmatory assistance, several imaging and image-guided techniques are available, as discussed previously.[325,511,513]

Facet Screw Fixation

Two types of facet screws can be used for segmental fixation: the Boucher technique of facet screw fixation[522,523] and the Magerl translaminar facet screw fixation.[524-531] The translaminar screw fixation technique is as stiff as pedicle screw

[c]References 294, 306–308, 315, 492, 500, 501, 508–521.

BOX 22.4 Considerations in Thoracolumbar Surgery

Decompression of neural elements
Fixation/stabilization/fusion of unstable levels
Balanced global alignment
 Lumbar lordosis
 Pelvic incidence
 Vertical sagittal alignment

fixation except in extension, in which it is less stiff than pedicle screws.[532] Fusion rates are reportedly comparable to those with pedicle screws, but the lower perioperative morbidity rates of translaminar screws make them an acceptable option for some surgeons and patients. The practice at our institution is to not place them at L5–S1 because of stress concentration or when significant spondylolisthesis is present (i.e., grade II or greater after reduction).

CONCLUSION

Spinal and cranial surgery can be made safer with a better understanding of the complications that are likely to arise. The use of various technologic advances, such as stereotactic navigation and neurophysiologic monitoring, can help improve accuracy. A thorough understanding of the types of problems encountered with a given procedure or approach makes the surgeon more wary and probably reduces the incidence of such complications. Newer techniques are being developed to improve exposure with lower morbidity, and over time it is likely that many of the procedures now commonly performed will be replaced by less invasive and more effective ones as our understanding of the underlying processes progresses.

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