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Pediatric neuroanesthesia

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Recent advances in pediatric neurosurgery have dramatically improved the outcome in infants and children afflicted with surgical lesions of the central nervous system (CNS). Although most of these techniques were first applied to adults, the physiologic and developmental differences that are inherent in pediatric patients present challenges to neurosurgeons and anesthesiologists alike. The aim of this paper is to highlight these age-dependent approaches to the pediatric neurosurgical patient.

Developmental considerations

Age-dependent differences in cerebrovascular physiology and cranial bone development influence the approach to the pediatric neurosurgical patient. Cerebral blood flow is coupled tightly to metabolic demand, and both increase proportionally immediately after birth. Estimates from animal studies place the autoregulatory range of blood pressure in a normal newborn between 20 and 60 mmHg [1]. This range is consistent with relatively low cerebral metabolic requirements and low blood pressure during the perinatal period. More importantly, the slope of the autoregulatory slope drops and rises significantly at the lower and upper limits of the curve, respectively. This narrow range, with sudden hypotension and hypertension at either end of the autoregulatory curve, places the neonate at risk for cerebral ischemia and intraventricular hemorrhage, respectively. Another developmental difference between adults and pediatric patients is the larger percentage of cardiac output that is directed to the brain, because the head of the infant and child accounts for a large percentage of the body surface area and blood volume. These factors place the infant at risk for significant hemodynamic instability during neurosurgical procedures.

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The infant cranial vault is also in a state of flux. Open fontanels and cranial sutures lead to a compliant intracranial space. The mass effect of a tumor or hemorrhage are often masked by a compensatory increase in the intracranial volume through the fontanels and sutures. As a result, infants presenting with signs and symptoms of intracranial hypertension have fairly advanced pathology.

Preoperative evaluation and preparation

Closed-claim studies have revealed that neonates and infants are at higher risk for morbidity and mortality than any other age group [2,3]. Respiratory and cardiac-related events account for a majority of these complications. However, a major pitfall in the management of infants and children for neurosurgery is the presence of coexisting diseases. Given the urgent nature of most pediatric neurosurgical procedures, a thorough preoperative evaluation may be difficult. However, a complete airway examination is essential, because some craniofacial anomalies may require specialized techniques to secure the airway [4]. Most cardiac morbidity due to congenital heart disease occurs during the first year of life [5]. Congenital heart disease may not be apparent immediately after birth, and the hemodynamic alterations caused by anesthetic agents, mechanical ventilation, and blood loss during surgery can unmask these cardiac defects. Echocardiography can be helpful in the assessment of the heart, and a pediatric cardiologist should evaluate patients with suspected problems to help optimize cardiac function prior to surgery. Other coexisting diseases that can alter the conduct of anesthesia are list in Table 1.

Table 1
Perioperative concerns for infants and children with neurological disease

Condition	Anesthetic implications
Congenital heart disease	Hypoxia and cardiovascular collapse
Prematurity	Postoperative apnea
Upper respiratory tract infection	Laryngospasm and postoperative hypoxia/pneumonia
Craniofacial abnormality	Difficulty with airway management
Denervation injuries	Hyperkalemia after succinycholine
	Resistance to nondepolarizing muscle relaxants
Chronic anticonvulsant therapy for epilepsy	Hepatic and hematological abnormalities
	Increased metabolism of anesthetic agents
Arteriovenous malformation	Potential congestive heart failure
Neuromuscular disease	Malignant hyperthermia
	Respiratory failure
	Sudden cardiac death
Chiari malformation	Apnea
	Aspiration pneumonitis
Hypothalamic/pituitary lesions	Diabetes insipidus
	Hypothyroidism
	Adrenal insufficiency

Preoperative sedatives given prior to induction of anesthesia can ease the transition from the preoperative holding area to the operating room [6]. Midazolam given orally is particularly effective in relieving anxiety and producing amnesia. If an indwelling intravenous (i.v.) catheter is in place, midazolam can be slowly administered to achieve sedation. Alternatively, sedatives such as barbiturates can be given rectally to induce sleep in preschool children who are uncooperative, and this avoids the use of intramuscular injections. However, methohexital administered rectally has been shown to induce seizures in patients with epilepsy [7].

Intraoperative management

Induction of anesthesia

The patient's neurological status and coexisting abnormalities will dictate the appropriate technique and drugs for induction of anesthesia. General anesthesia can be established by inhalation of sevoflurane and nitrous oxide with oxygen. A nondepolarizing muscle relaxant such as pancuronium is then administered to facilitate intubation of the trachea. Alternatively, if the patient has i.v. access, anesthesia can be rapidly induced with sedative/hypnotic drugs such thiopental (5–8 mg/kg) or propofol (3–5 mg/kg). Patients at risk for aspiration pneumonitis should have a rapid-sequence induction of anesthesia performed with thiopental or propofol, immediately followed by a rapid-acting muscle relaxant such as succinylcholine or rocuronium.

Airway management

Developmental differences in the cricoidthyroid and tracheobrochial tree have a significant impact on management of the pediatric airway. The infant's larynx is funnel shaped, and narrowest at the level of the cricoid, making this the smallest cross-sectional area in the infant airway. This feature places the infant at risk for subglotic obstruction secondary to mucosal swelling after prolonged endotracheal intubation with a tight-fitting endotracheal tube. Because the trachea is relatively short, an endotracheal tube can migrate into a mainstem bronchus if the infant's head is flexed, as is the case for a suboccipital approach to the posterior fossa or the cervical spine. Therefore, the anesthesiologist should auscultate both lung fields to rule out inadvertent intubation of a mainstem bronchus after positioning the patient. Nasotracheal tubes are best suited for situations when the patient will be prone and when postoperative mechanical ventilation is anticipated. Furthermore, the endotracheal tube can kink at the base of the tongue when the head is a flexed and also lead to pressure necrosis of the oral mucosa.

Maintenance of anesthesia

The choice of anesthetic agents for maintenance of anesthesia has been shown not to affect the outcome of neurosurgical procedures [8]. The most

frequently utilized technique for neurosurgery consists of the opioid fentanyl administered at a rate of 2–5 μg/kg/h intravenously along with inhaled nitrous oxide (70%) and low-dose isoflurane (0.2–0.5%). Deep neuromuscular blockade is maintained during most neurosurgical procedures to avoid patient movement. Patients on chronic anticonvulsant therapy will require larger doses of muscle relaxants and narcotics because of induced enzymatic metabolism of these agents (Fig. 1) [9,10] .Muscle relaxation should be withheld, or should not be maintained when assessment of motor function during seizure and spinal cord surgery is planned.

Fluid restriction and diuretic therapy may lead to hemodynamic instability and even cardiovascular collapse if sudden blood loss occurs during surgery. Therefore, normovolemia should be maintained through the procedure. Normal saline is commonly used as the maintenance fluid during neurosurgery because it is mildly hyperosmolar (308 mOsm/kg), and it theoretically attenuates brain edema. However, rapid infusion of normal saline (30 mL/kg/h) is associated with hyperchloremic acidosis [11]. Hyperventilation and maximization of venous

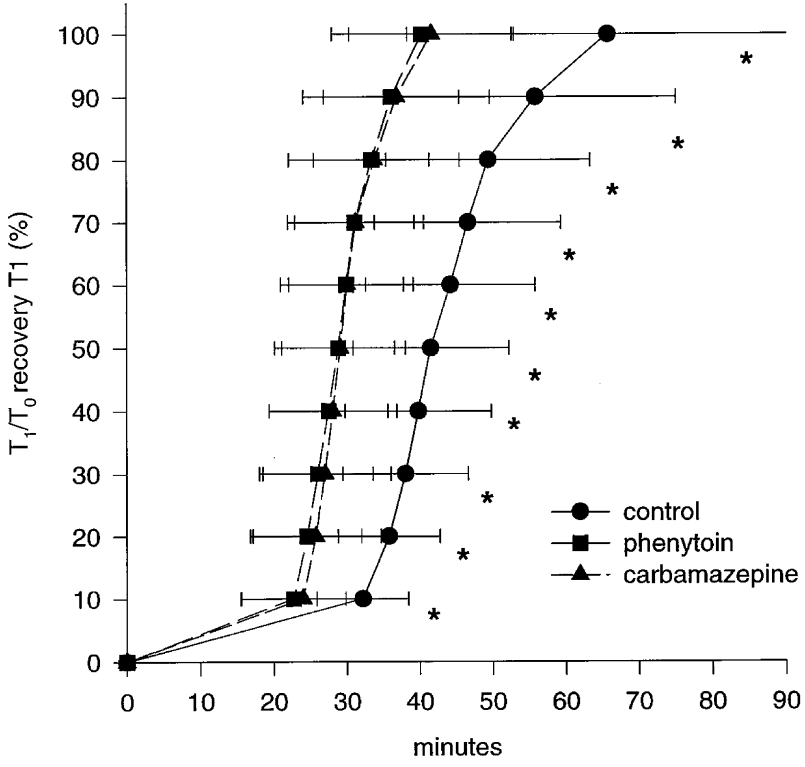

Fig. 1. Patients on chronic anticonvulsant therapy have increased requirements for nondepolarizing muscle relaxants. The recovery times for return of muscle function in the anticonvulsant was significantly faster than the control group ($*p < 0.05$, mean ± SD) [10].

drainage of the brain by elevating the head can minimize brain swelling. Should these maneuvers fail, mannitol can be given at a dose of 0.25 to 1.0 g/kg intravenously. This will transiently alter cerebral hemodynamics and raise serum osmolality by 10–20 mOsm/kg [12]. However, repeated dosing can lead to extreme hyperosmolality, renal failure, and further brain edema. Furosemide is a useful adjunct to mannitol in decreasing acute cerebral edema, and has been shown in vitro to prevent rebound swelling due to mannitol [13]. All diuretics will interfere with the ability to utilize urine output as a guide to intravascular volume status.

Vascular access

Due to limited access to the child during neurosurgical procedures, optimal intravenous access is mandatory prior to the start of surgery. Typically, two large-bore venous cannulae are sufficient for most craniotomies. Should initial attempts fail, central vein cannulation may be necessary. Cannulation of femoral vein avoids the risk of pneumothorax associated with subclavian catheters, and does not interfere with cerebral venous return.

Monitoring

Given the potential for sudden hemodynamic instability due to venous air emboli (VAE), hemorrhage, herniation syndromes, and manipulation of cranial nerves, the placement of an intra-arterial cannula for continuous blood pressure monitoring is mandatory for most neurosurgical procedures. An arterial catheter will also provide access for sampling serial blood gases, electrolytes, and hematocrit. The issue of central venous catheterization is controversial. Large-bore catheters are too large for infants and most children, and central venous pressures may not accurately reflect vascular volume, especially in a child in the prone position. Therefore, the risks may outweigh the benefits of a central venous catheter.

Standard neurosurgical technique may elevate the head of the table to improve venous drainage, and is conducive to air entrainment into the venous system through open venous channels in bone and sinuses (Fig. 2) [14]. Patients with cardiac defects, such as patent foramen ovale or ductus arteriosus, are at risk for arterial air emboli through these defects, and should be monitored carefully. A precordial Doppler ultrasound can detect minute VAE, and should be routinely used in conjunction with an end-tidal carbon dioxide analyzer and arterial catheter in all craniotomies to detect VAE. Doppler probe is best positioned on the anterior chest usually just to the right of the sternum at the fourth intercostal space. An alternate site on the posterior thorax can be used in infants weighing approximately 6 kg or less [15].

Recent advances in neurophysiologic monitoring have enhanced the ability to safely perform more definitive neurosurgical resections in functional areas of the brain and spinal cord. However, the CNS depressant effects of most anesthetic agents limit the utility of these monitors. A major part of preoperative planning

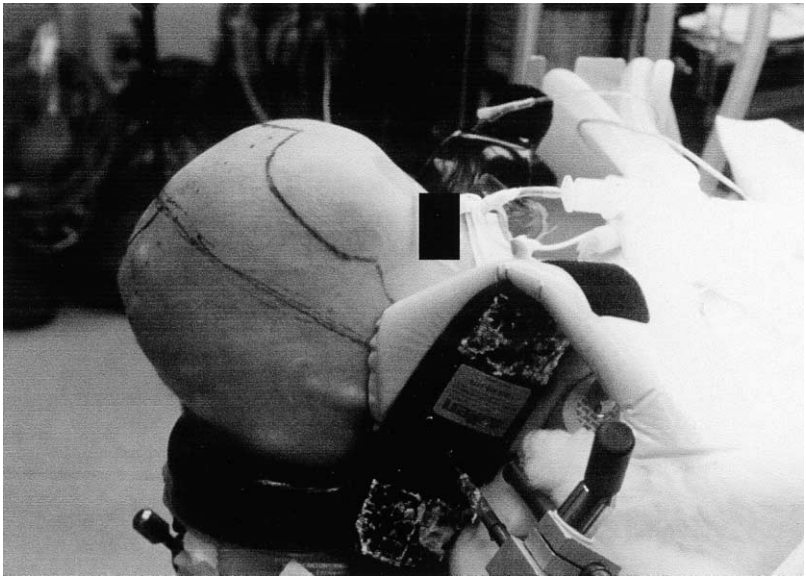

Fig. 2. Supine infant. Note that the infant's head lies at a higher plane than the rest of his body. This increases the likelihood for venous air embolism during craniotomies.

should include a thorough discussion of the modality and type of neurophysiologic monitoring to be used during any surgical procedure. In general, electrocorticography (ECoG) and electroencephalography (EEG) require low levels of volatile anesthetics and barbiturates. Somatosensory-evoked potentials used during spinal and brainstem surgery can be depressed by volatile agents and to a lesser extent, nitrous oxide. An opioid-based anesthetic is the most appropriate agent for this type of monitoring. Spinal cord and peripheral nerve surgery may require electromyography (EMG) and detection of muscle movement as an end point. Therefore, muscle relaxation should be avoided or not maintained during the monitoring period.

Positioning

Patient positioning for surgery requires careful preoperative planning to allow adequate access to the patient for both the neurosurgeon and anesthesiologist. Table 2 describes various surgical positions and their physiologic sequelae. The prone position is commonly used for posterior fossa and spinal cord surgery, although the sitting position may be more appropriate for obese patients who may be difficult to ventilate in the prone position (Fig. 3). In addition to the physiologic sequelae of this position, a whole spectrum of compression and stretch injuries has been reported. Padding under the chest and pelvis can support the torso. It is important to ensure free abdominal wall motion because increased intra-abdominal pressure can impair ventilation, cause venocaval

Table 2
Physiologic effects of patient positioning

Position	Physiological effect
Head-elevated	Enhanced cerebral venous drainage
	Decreased cerebral blood flow
	Increased venous pooling in lower extremities
	Postural hypotension
Head-down	Increased cerebral venous and intracranial pressure
	Decreased functional residual capacity (lung function)
	Decreased lung compliance
Prone	Venous congestion of face, tongue, and neck
	Decreased lung compliance
	Increased abdominal pressure can lead to venocaval compression
Lateral decubitus	Decreased compliance of down-side lung

compression, and increase epidural venous pressure and bleeding. Fig. 4 illustrates proper positioning for these patients. Soft rolls are used to elevate and support the lateral chest wall and hips to minimize increase abdominal and thoracic pressure. In addition, this should allow a Doppler probe to be on the chest without pressure. Many neurosurgical procedures are performed with the head slightly elevated to facilitate venous and cerebral spinal fluid (CSF) drainage from the surgical site. However, superior sagittal pressures decreases with increasing head elevation, and this increases the likelihood of VAE [14].

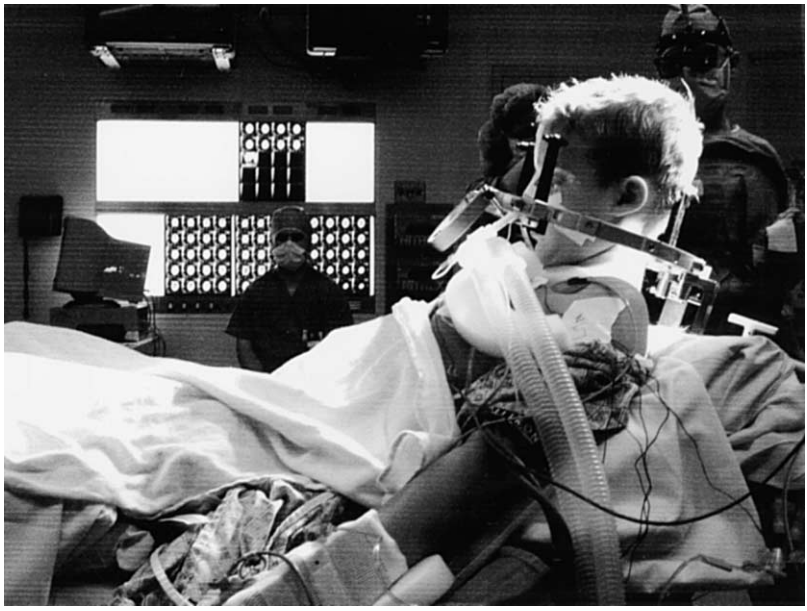

Fig. 3. Sitting position. The sitting position affords optimal chest wall compliance in children with respiratory disease and obesity.

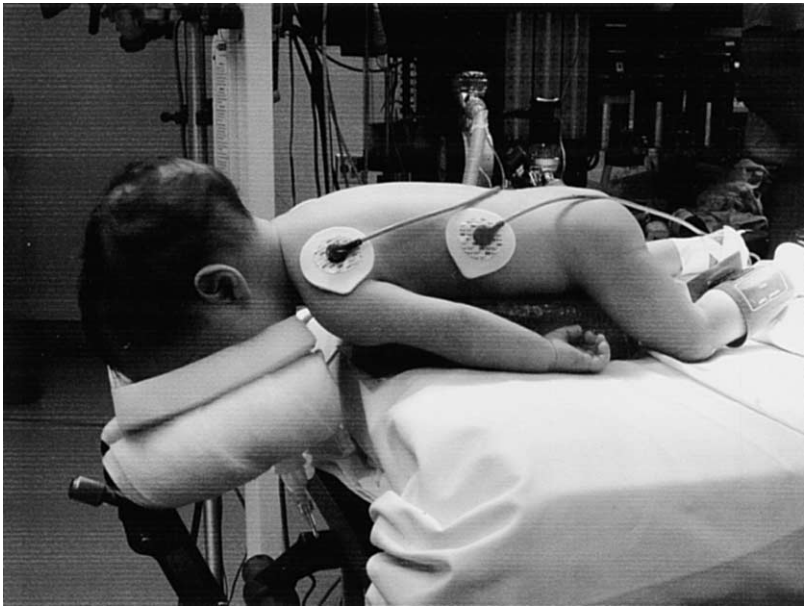

Fig. 4. Prone infant. Lateral rolls are used to elevate the infant and minimize thoracic and abdominal pressure.

Extreme head flexion can cause brainstem compression in patients with posterior fossa pathology, such as mass lesions or an Arnold-Chiari malformation. Extreme rotation of the head can impede venous return through the jugular veins and lead to impaired cerebral perfusion, increased intracranial pressure, and cerebral venous bleeding.

Postoperative management

Close observation in an intensive care unit with serial neurologic examinations and invasive hemodynamic monitoring is helpful for the prevention and early detection of postoperative problems. Respiratory dysfunction is the leading complication after posterior fossa craniotomies [16]. Airway edema is usually self-limited, and may require endotracheal intubation as a stent. Occasionally, ischemia or edema of the respiratory centers in the brainstem will interfere with respiratory control and lead to postoperative apnea. Children with Chiari malformations may be more prone to the respiratory depression [17]. Diabetes insipidus can occur after surgery in the region of the hypothalamus and pituitary gland, and can be managed acutely with an intravenous vasopressin infusion. Postoperative nausea and vomiting can cause sudden rises in intracranial pressure, and should be treated with a nonsedating antiemetic. However, prophylactic administration of ondansteron during surgery is not effective in decreasing the incidence of vomiting following craniotomies in children [18].

Clinical approaches

Neonatal emergencies

Most neonatal surgery is performed on an emergent basis [19], and there is more than a 10-fold increase in perioperative morbidity and mortality in neonates when compared with other pediatric age groups [2]. In addition to existing congenital heart defects, congestive heart failure can occur in neonates with large cerebral arteriovenous malformations, and this condition requires aggressive hemodynamic support. Management of the neonatal respiratory system may be difficult because of the diminutive size of the airway, craniofacial anomalies, laryngotracheal lesions, and acute (hyaline membrane disease, retained amniotic fluid) or chronic (bronchopulmonary dysplasia) disease. Because these conditions are in a state of flux, they should be addressed preoperatively to minimize morbidity.

The neonatal central nervous system is capable of sensing pain and mounting a stress response after a surgical stimulus [20]. However, neonatal myocardial function is particularly sensitive to both inhaled and intravenous anesthetics, and the use of these agents needs to be judicious to block surgical stress without causing myocardial depression. An opioid-based anesthetic is generally the most stable hemodynamic technique for neonates. The hepatic and renal systems are also not fully developed, and neonates anesthetized with a narcotic technique will often have delayed emergence and may require post-operative mechanical ventilation.

Closure of a myelomeningocele or encephalocele presents special problems. Positioning the patient for tracheal intubation may rupture the membranes covering the spinal cord or brain. Therefore, careful padding of the lesion (Fig. 5), and in some cases intubation of the neonate's trachea in the left lateral decubitus position, may be necessary. Most surgical closures of simple myelomeningoceles have relatively minimal blood loss. However, large lesions may requirement significant undermining of cutaneous tissue to cover the defect and pose larger risks for blood loss and hemodymanic instability. Recent advances in the management of myelomeningoceles have lead to early intervention into the intrauterine period [21]. The management of the fetus and mother during fetal surgery has been reviewed extensively elsewhere [22,23].

Hydrocephalus

The most common neurosurgical procedure performed in major pediatric centers is for the management of hydrocephalus. Regardless of the etiology, whether it be overproduction of CSF due to choroid plexus papillomas or obstruction of CSF flow secondary to a tumor or Chiari malformation, diagnosis and alleviation of life-threatening intracranial hypertension should proceed expeditiously. The mental status of the child should dictate the anesthetic management as noted above, and intracranial hypertension can be managed with hyperventilation and diuretics. Most neonates undergoing a closure of a

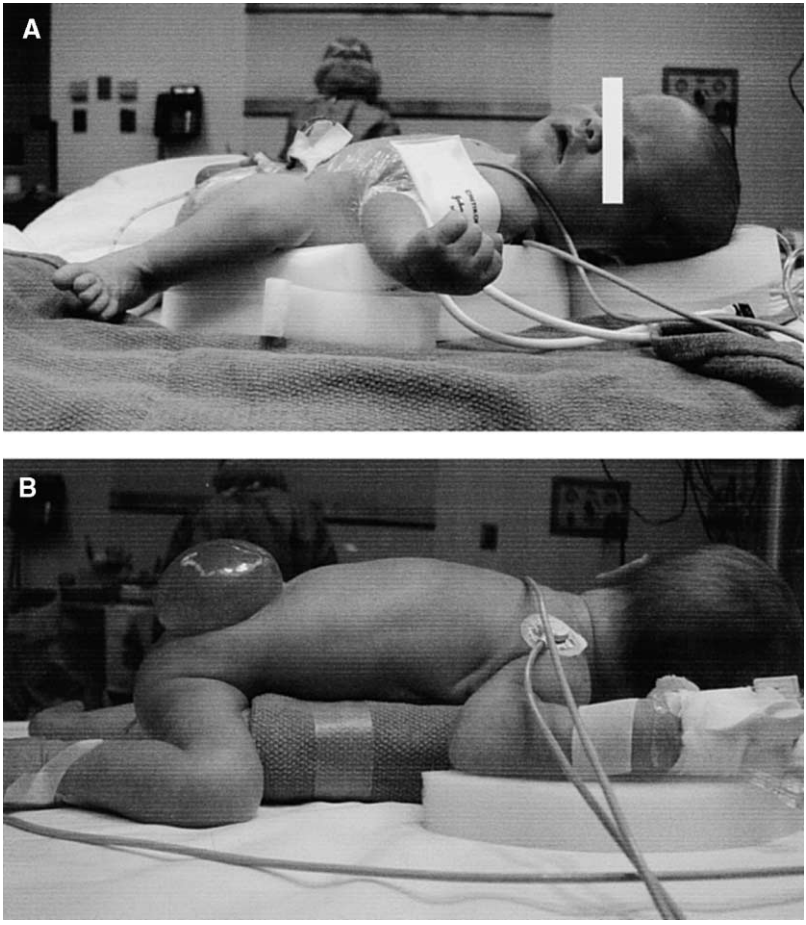

Fig. 5. Positioning of a neonate with a myelomeningocele. (A) Prior to induction of general anesthesia, the neonate is elevated on a soft padding with a center cutout to relieve pressure on the myelomeningocele. (B) Positioning of the neonate for closure of the myelomeningocele.

myelomeningocele are potential candidates for a ventriculo-peritoneal shunt (VPS), and may have both procedures performed in one sitting. The long-term management of hydrocephalus with VPS invariably increases the incidence of mechanical failure and shunt infections. Should the peritoneum be infected, alternate sites for the drainage limb of these extracranial shunts include the right atrium and pleural cavity.

Craniosynostosis

Repairs of craniosynostosis are likely to have the best result if done early in life [24]. However, these procedures are associated with loss of a significant percentage of an infant's blood volume, with great losses occurring when more

sutures are involved [25]. Venous air embolism detected by echocardiography and precordial Doppler occurred in 66% to 83% of craniectomies in infants [25,26]. Fortunately, direct morbidity and mortality rarely occur. Venous air emboli can be minimized by early detection with continuous precordial Doppler ultrasound and maintaining euvolumia. When hemodynamic instability does occur, the operating table can be placed in the Trendelenburg position, flooding the surgical field with warm saline and sealing the sites of egress with bone wax and direct pressure. These maneuvers will augment the patient's blood pressure and prevent further entrainment of intravascular air.

Tumors

Because the majority of intracranial tumors in children occurs in the posterior fossa, CSF flow is often obstructed, and intracranial hypertension and hydrocephalus is often present. Most neurosurgeons approach this region with children in the prone position. The patient's head is often secured with a Mayfield head frame. Pins used in small children can cause skull fractures, dural tears, and intracranial hematomas. Elevation of the bone flap can tear the transverse and straight sinuses, and massive blood loss and/or VAE can occur. Surgical resection of tumors in the posterior fossa can also lead to brainstem and/or cranial nerve damage. Sudden changes in blood pressure and heart rate may be sentinel signs of encroachment on these structures. Damage to the respiratory centers and cranial nerves can lead to apnea and airway obstruction after extubation of the patient's trachea. Children requiring stereotactic-guided radiosurgery or craniotomies need general anesthesia to tolerate the procedures. Special head frames have been devised to allow airway manipulations, and should be used in these patients [27].

Epilepsy

Surgical treatment has become a viable option for many patients with medically intractable epilepsy. Two major considerations should be kept in mind. Chronic administration of anticonvulsant drugs, phenytoin and carbamazepine, induces rapid metabolism and clearance of several classes of anesthetic agents including neuromuscular blockers and opioids [9,28]. Therefore, the anesthetic requirements for these drugs are increased, and require close monitoring of their effect and frequent redosing. Intraoperative neurophysiologic monitors can be used to guide the actual resection of the epileptogenic focus, and general anesthetics can compromise the sensitivity of these devices [29].

Because some epileptogenic foci are in close proximity to cortical areas controlling speech, memory, and motor or sensory function, monitoring of patient and electrophysiologic responses are frequently utilized to minimize iatrogenic injury to these areas [30,31]. Cortical stimulation of the motor strip in a child under general anesthesia will require either EMG or direct visualization of muscle movement. Neuromuscular blockade should not be used in this situation. Neural

function is best assessed in an awake and cooperative patient. Awake craniotomies in children can be accomplished with local anesthesia and propofol and fentanyl for sedation and analgesia, respectively [32]. Positioning of the patient is critical for success of this technique. The patient should be in a semilateral position to allow both patient comfort as well as surgical and airway access to the patient. Propofol does not interfere with the ECoG if it is discontinued 20 minutes before monitoring. Highly motivated children older that 10 years of age were able to withstand the procedure without incident. However, it is imperative that candidates for an awake craniotomy be mature and psychologically prepared to participate in this procedure. Therefore, patients who are developmentally delayed or have a history of severe anxiety or psychiatric disorders should not be considered appropriate for an awake craniotomy. Very young patients cannot be expected to cooperate for these procedures, and usually require general anesthesia with extensive neurophysiologic monitoring to minimize inadvertent resection of the motor strip and eloquent cortex. Repeat craniotomies for removal of ECoG leads and depth electrodes used for chronic invasive EEG monitoring and subsequent resection of the seizure focus are at risk for expansion of residual pneumocephalus. It is important to avoid nitrous oxide until the dura is opened, because intracranial air can persist up to 3 weeks following a craniotomy [33].

Vascular

Vascular anomalies are rare in infants and children. Most of these conditions are congenital anomalies, and present early in life. Large arteriovenous malformations (AVM) in neonates may be associated with high output congestive heart failure and require vasoactive support. Initial treatment of large AVMs often consists of intravascular embolization in the radiologic suite [34]. Operative management is commonly associated with massive blood loss, and these patients require several i.v. access sites and invasive hemodynamic monitoring. Ligation of an AVM can lead to sudden hypertension with hyperemic cerebral edema [35]. Vasodilators such as labetalol or nitroprusside can be used to control a hypertensive crisis.

Moyamoya syndrome is a rare chronic vaso-occlusive disorder of the internal carotid arteries that presents as transient ischemic attacks and/or recurrent strokes in childhood. The etiology is unknown, but the syndrome can be associated with prior intracranial radiation, neurofibromatosis, Down's syndrome, and a variety of hematological disorders. The anesthetic management of these patients is directed at optimizing cerebral perfusion by maintaining euvolumia and the blood pressure within the patient's preoperative levels [36]. Maintenance of normocapnia is also essential in patients with Moyamoya syndrome because both hyper- and hypocapnia can lead to stealing phenomenon from the ischemic region and further aggravate cerebral ischemia [37]. A nitrous oxide and narcotic-based anesthetic provides a stable level of anesthesia for these patients, and are compatible with intraoperative EEG monitoring. Once the patient emerges from anesthesia, the same maneuvers that optimize cerebral perfusion should be

extended into the postoperative period. These patients should receive i.v. fluids to maintain adequate cerebral perfusion, and be given adequate narcotics to avoid hyperventilation induced by pain and crying.

Trauma

Pediatric head trauma requires a multiorgan approach to minimizing morbidity and mortality [38]. A small child's head is often the point of impact in injuries, but other organs can also be damaged. Basic life support algorithms should be immediately applied to assure a patent airway, spontaneous respiration, and adequate circulation. Immobilization of the cervical spine is essential to avoid secondary injury with manipulation of the patient's airway until radiologic clearance is confirmed. Blunt abdominal trauma and long bone fractures frequently occur with head injury, and can be major sources of blood loss. To assure tissue perfusion during the operative period, the patient's blood volume should be restored with crystalloid solutions and/or blood products. Ongoing blood loss can lead to coagulopathies, and should be treated with specific blood components.

Infants with "Shaken Baby Syndrome" often present with a myriad of chronic and acute subdural hematomas [39]. As with all traumatic events, the presence of other coexisting injuries, fractures, and abdominal trauma should be identified. Craniotomies for the evacuation of either epidural or subdural hematomas are at high risk for massive blood loss and VAE. Postoperative management of these victims is marked by the management of intracranial hypertension, and in the most severe cases, determination of brain death.

Spine surgery

Spinal dysraphism is the primary indication for laminectomies in pediatric patients. Many of these patients have a history of a meningomyelocele closure followed by several corrective surgeries. These patients have been exposed to latex products, and may develop hypersensitivity to latex. Latex allergy can manifest itself by a severe anaphylactic reaction heralded by hypotension and wheezing, and should be rapidly treated by removal of the source of latex, and administration of fluid and vasopressors [40]. Patients at risk for latex allergy should have a latex-free environment.

Tethered cord releases require EMG monitoring to help identify functional nerve roots. EMG of the anal sphincter and muscles of the lower extremities is performed intraoperatively to minimize inadvertent injury to nerves innervating these muscle groups [41]. Muscle relaxation should be discontinued or antagonized to allow accurate EMG monitoring.

Neuroradiology

Recent advances in imaging technology have provided less invasive procedures to diagnose and treat lesions in the CNS. Most neuroradiological studies

such as CT scans and magnetic resonance imaging can be accomplished with light sedation. Recommendations have been published by consensus groups of anesthesiologists and pediatricians, and can serve as guidelines for managing these patients [42,43]. General anesthesia is typically used for uncooperative patients, patients with coexisting medical problems, and potentially painful procedures such as intravascular embolization of vascular lesions [34].

Summary

The perioperative management of pediatric neurosurgical patients presents many challenges to neurosurgeons and anesthesiologists. Many conditions are unique to pediatrics. Thorough preoperative evaluation and open communication between members of the health care team are important. A basic understanding of age-dependent variables and the interaction of anesthetic and surgical procedures are essential in minimizing perioperative morbidity and mortality.

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