5 Pediatric Neuroanesthesia

Huy Do and David L. McDonagh

Introduction

Pediatric anesthesiologists involved in the care of children undergoing neurosurgical procedures require a thorough knowledge of the age-dependent anatomic and physiologic development of children, the impact of anesthetics on the developing nervous system, and the consequences of these surgical procedures to children. As the specialties of pediatric neurosurgery and neurointerventional radiology evolve with newer innovations and techniques, so must the pediatric neuroanesthesia team evolve to meet new challenges.

Developmental Changes

The newborn cranial vault is dynamic. Unlike adults, neonates and infants have open fontanelles and expandable cranial sutures, which allow for a compliant intracranial space. Slow increases in intracranial volumes can be accommodated and present with an increase in head circumference in young children [1, 2]. However, acute increases in intracranial volume or pressure commonly result in detrimental

H. Do, MD (✉)
Departments of Anesthesiology & Pain Management, University of Texas Southwestern, Dallas, TX 75390, USA
e-mail: huy.do@childrens.com

D.L. McDonagh, MD
Departments of Anesthesiology & Pain Management, University of Texas Southwestern, Dallas, TX 75390, USA

Departments of Neurology, University of Texas Southwestern, Dallas, TX 75390, USA

Departments of Neurosurgery, University of Texas Southwestern, Dallas, TX 75390, USA
e-mail: david.mcdonagh@utsouthwestern.edu

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intracranial hypertension despite open fontanelles [3, 4]. These fontanelles close at different stages with the last fontanelle closing by 2 years in healthy children [5].

Cerebral blood flow (CBF) varies with age, reflecting changes in neural development. It is lower in premature infants and term neonates (40–50 ml/100 g/min) [6–8] and higher in infants and older children from 6 months to 7 years (70–110 ml/100 g/min) [9–11] of age as compared to adults (50 ml/100 g/min) [12]. CBF is coupled tightly with cerebral metabolism and cerebral metabolic rate of oxygen consumption ($CMRO_2$). $CRMO_2$ mirrors age-related changes in CBF. In children, $CRMO_2$ is higher (5.5 ml/100 g/min) than in adults (3.5 ml/100 g/min) [13]. Neonates have lower $CRMO_2$ (2.3–3.5 ml/100 g/min).

Unlike adults where the cerebral autoregulation is thought to be preserved in a mean arterial pressure (MAP) between 60 and 160 mmHg [14, 15], the autoregulatory limits are unclear in infants and children. Data from animal [16, 17] and preterm infants [18] postulate the lower limit for autoregulation to be a MAP of 30–40 mmHg. The lower limit of autoregulation for children aged 6 months and older may be similar to adults at 60 mmHg [19]. The autoregulatory range is poorly defined but is suspected to be lower and narrower than adults [2, 20].

Management of Anesthesia

Preoperative Evaluation and Preparation

Neonates and infants have a higher risk for perioperative morbidity and mortality than any other age group [21, 22]; therefore, a thorough history and physical examination should be performed in preparation for surgery. The preoperative evaluation requires a focused approach depending upon the indication for the surgical procedure. Particular considerations in the neurologic exam should include assessing for increased intracranial pressure (ICP), depressed level of consciousness, and focal neurological deficits. In infants and young children signs of intracranial hypertension can be subtle, such as irritability, lethargy, and failure to feed [23]. More obvious symptoms include full fontanelle, cranial enlargement, and cranial nerve palsies. Older children may present similarly to adults with headaches, vomiting, diplopia, and abnormal gait or coordination [23].

Preoperative laboratory testing may be indicated in pediatric patients for neurosurgical cases, such as craniotomies, where the risk of significant blood loss may occur. Hemoglobin or hematocrit levels, coagulation profile and typed and crossmatched blood should be ordered for these cases. Other preoperative labs may be tailored depending upon coexisting diseases (i.e. electrocardiogram or echocardiogram for congenital heart disease) or concurrent symptoms (i.e. electrolytes for diabetes insipidus or protracted vomiting). Identifying coexisting and concurrent diseases may prompt more extensive evaluations, which may require optimization prior to elective surgery. This may not be feasible for urgent and emergent cases.

Judicious use of oral or intravenous sedative premedications may be beneficial for small children to ease transition to the operating room [24]. Over-sedation may decrease ventilation, resulting in hypercapnia and further worsening ICP. These medications should best be avoided in all children with symptomatic intracranial hypertension. For children who do not have an IV catheter yet demonstrate symptomatic intracranial hypertension, an IV catheter may need to be started in the preoperative area.

Induction

The fundamental goal of anesthetic induction is to maintain cerebral perfusion pressure (CPP) by preventing increases in ICP and decreases in MAP. During induction, ICP can increase secondary to tracheal intubation, hypoxia, or hypercapnia; furthermore, certain anesthetic agents can influence MAP. For the patient with an IV catheter, induction with intravenous anesthetic and a paralytic agent is ideal. Pediatric patients that are at risk for aspiration (e.g. due to recent oral ingestion) require a rapid-acting paralytic agent such as rocuronium or succinylcholine. Succinylcholine is contraindicated for neurosurgical patients with spinal cord injuries, paretic extremities/denervating diseases, or suspected muscular dystrophy because of concerns for life-threatening hyperkalemia [25, 26] with its use.

For scheduled or elective surgical procedures in a neurologically stable patient who comes from home, commonly such a patient does not have an IV catheter. In children without (or having difficult) IV access, a smooth inhalational induction by facemask with sevoflurane and nitrous oxide with oxygen is preferred. This technique facilitates obtaining an IV in children and allows for a smooth tracheal intubation.

Airway Considerations

Because of the relatively short trachea in the pediatric population, the endotracheal tube can easily migrate with positional changes of the head. Neck flexion may result in endobronchial intubation or intraoral kinking of the tube. Conversely, excessive extension may result in extubation of the endotracheal tube especially in neonates and infants. Minimal movements may result in significant changes of the respiratory dynamics affecting oxygenation and/or ventilation, which may worsen during surgery. Reevaluation of the airway parameters is crucial after final positioning of all children.

Vascular Access

For neurosurgical procedures where the risk for significant blood loss may occur, attaining appropriate intravenous access is paramount. In most of these cases, two relatively large-bore IVs are sufficient. Due to the size of infants and neonates, the option may be limited to two 24-gauge venous cannulae. Placement of central venous access is reserved for pediatric patients with difficult/inadequate IV access or an increased risk of air embolism (e.g. sitting position). When surgeries involve risk for sudden hemodynamic swings due to hemorrhage, venous air embolism, and cranial nerve manipulation, an arterial line is also required for continuous blood pressure monitoring and blood chemistry sampling. In common neurosurgical cases that involve minimal blood loss (e.g. ventriculoperitoneal shunting, angiography), a single IV catheter alone is usually suitable.

Positioning

Neurosurgical procedures are performed in various positions to facilitate surgical access. Children with supratentorial lesions are often placed in supine or modified lateral positions. Surgeries for posterior fossa or spinal cord lesions commonly require the prone position. The placement of supportive rolls under the chest and pelvis is needed in this position to minimize abdominal and thoracic pressure, thereby, aiding in ventilation and venous drainage. The sitting position is seldom utilized in the pediatric population because of increased likelihood of venous air embolism (VAE) with risk for hemodynamic collapse and/or paradoxical systemic arterial embolization in the setting of a right to left cardiopulmonary shunt [27, 28]. The increased risk of VAE also occurs with any position where the head is slightly elevated above the heart (i.e. reverse trendelenberg). Similar to adults, head pinning is usually reserved for older infants and children when the skull is denser. Head pinning is avoided in neonates and infants because of an increased risk of skull fracture, dural tear, and hematoma. Due to the prolonged duration of many neurosurgical procedures, general considerations for all positions include proper padding, and prevention of pressure or traction on nerves.

Maintenance Anesthesia

The primary goal during maintenance anesthesia during neurosurgery is to optimize cerebral perfusion and minimize brain bulk (and/or ICP). This can be achieved with volatile agents, intravenous anesthesia (TIVA), or a combination of these agents along with opioids and controlled ventilation. There is no evidence to suggest that any particular anesthetic agents lead to better neurologic outcomes [29]. The technique of low dose volatile agent and opioid is commonly used for pediatrics patients of all ages. Nitrous oxide should be avoided in endovascular neurosurgical procedures as well as in procedures with risk for VAE due to nitrous oxide's rapid diffusion into and enlargement of intravascular air bubbles.

Neuromuscular blockade is maintained during most neurosurgical procedures to prevent spontaneous movements. Neuromuscular blockade is avoided during motor testing or cortical mapping. Potent titratable opioids, such as remifentanil, can be very useful in cases where neuromuscular blockade is contraindicated.

Intraoperative Fluid and Temperature Management

Crystalloid solutions such as normal saline or lactated ringers are recommended for maintenance fluids. Excessive amount of the former results in hyperchloremic acidosis [30]. Colloids (5 % albumin) are acceptable intravenous fluids but the available data has not shown improvement in outcomes when compared to crystalloids [31]. In the setting of cerebral ischemia, hyperglycemia is injurious and normoglycemia should be maintained; however, neonates and young infants are at risk for hypoglycemia due to their limited glycogen reserve and hepatic glucose production. Dextrose-containing solution may be judiciously used and the serum glucose should be periodically checked throughout the case. Similarly, hyperthermia exacerbates acute brain injury and should be avoided. There is no proven benefit to therapeutic hypothermia outside of the setting of anoxic brain injury. Therefore, the goal in most neurosurgical procedures should be controlled normothermia.

Brain Bulk Reduction

The multifaceted stepwise approach to reducing brain bulk (in order to avoid retraction injury or tissue herniation through the craniotomy) during pediatric neurosurgery includes:

1. CSF drainage via external ventricular or lumbar drains (if present).
2. Mild head elevation and avoidance of jugular compression to facilitate venous outflow.
3. Mild hyperventilation to reduce cerebral blood volume ($PaCO_2$ target ~30 mmHg)
4. Hyperosmotic therapy with mannitol or hypertonic saline (generally titrated to an serum osmolality limit of ≤320 mOsm/L).
5. Corticosteroids for vasogenic edema due to tumor
6. Metabolic suppression with propofol, etomidate, or barbiturates, ideally guided by EEG.
7. Therapeutic hypothermia in select cases.

Adequate cerebral perfusion pressure (as a surrogate for cerebral blood flow) must be maintained throughout, in addition to any of the above measures.

Neurophysiologic Monitoring

The increased use of intraoperative neurophysiological monitoring for the pediatric population has allowed for more aggressive neurosurgical resection of brain and spinal cord lesions while assessing and maintaining the functional integrity of sensorimotor pathways during surgery. Common monitoring modalities include somatosensory evoked potentials (SSEPs), motor evoked potentials (MEPs), electromyography (EMG), auditory brainstem evoked responses (ABR), and electroencephalography (EEG). Certain anesthetic agents can affect these modalities. In general, volatile agents have the most impact and are often used in lower amounts while intravenous agents (e.g. propofol) have lesser effects. Muscle relaxants should be avoided when monitoring MEPs or EMG. Open communication with the neurophysiologic technician is important in order to provide optimal anesthetic care without ablating the monitoring signals.

Anesthetic Neurotoxicity in the Developing Brain

No one topic has garnered more current interest in pediatric anesthesia than the effects of general anesthesia on developing brains. In animal models, prolonged anesthesia with gamma-aminobutyric acid (GABA) agonists (e.g. volatile anesthetics, midazolam, propofol) as well as N-methyl-D-aspartate (NMDA) antagonists (e.g. ketamine and nitrous oxide) produce accelerated neuronal apoptosis and altered synaptic plasticity [32–34]. Extrapolating these data to the human model is dubious. Ongoing human observational studies [35–37] are investigating the association between general anesthesia and neurocognitive development in children. Presently there is inadequate evidence to change the approach in anesthetizing children for neurosurgical procedures based on concerns over anesthetic induced neurotoxicity. What is clear is that insufficient anesthesia and analgesia during surgery are associated with poor neurologic outcome [38–42].

Pediatric Vascular Neurosurgery

There are unique aspects to the anesthetic management of the vascular neurosurgical patient.

1. Aneurysm Surgery: Attention to blood pressure control during periods of noxious stimuli (endotracheal intubation, Mayfield head frame placement) is paramount, especially in the setting of aneurysmal subarachnoid hemorrhage. The use of adenosine arrest or rapid ventricular pacing to produce controlled hypotension and facilitate aneurysm clip placement has only occasionally been described in the pediatric neuroanesthesia literature, but remain options in select cases [43].
2. Moyamoya disease: These patients have very tenuous cerebral perfusion and are at risk for ischemia with hypotension, and at risk for cerebral hemorrhage with hypertensive surges. Tight hemodynamic control is essential, targeting preoperative blood pressure levels. Blood pressure goals should be established after communication with the neurosurgeon regarding patient specific factors [44]. There is theoretical concern for cerebral steal (also called the 'reverse Robinhood

syndrome') with the use of inhalational anesthetic agents due to nonspecific cerebral arterial dilation. However, there is no evidence to suggest that propofol TIVA is preferred/superior and either inhalational or intravenous anesthetics remain acceptable [45].

3. Endovascular Neurosurgery: As with other neurovascular interventions, open communication with the surgical team is essential to determine the predicted susceptibility for injury from hypo- or hypertension in the individual patient. Nitrous oxide should be avoided due to its potential to exacerbate any intra-arterial air emboli (which are a known risk in endovascular surgery) [46].

Conclusions

A pediatric anesthesiologist who specializes in neuroanesthesia best meets the unique and evolving needs of children undergoing neurosurgical procedures. Such specialization will facilitate thorough attention to the preoperative assessment, perioperative management, and interdisciplinary communication that will minimize morbidities and maximize outcomes.

Pearls

- The cerebral autoregulatory range in neonates and young infants is unclear but suspected to be lower and narrower than adults.
- A detailed history and physical, addressing any neurologic pathology and coexisting conditions or concurrent illnesses, reduce perioperative patient risk and morbidity.
- The clinical presentation of the child guides the need for preoperative anxiolytic medication.
- Airway reassessment is important with all position changes, especially when involving the head and neck.
- Neurosurgical procedures with the potential risk of significant blood loss require appropriate intravenous, arterial, and possible central access.
- Neonates and young infants may require dextrose-containing solution during surgery. Close monitoring of blood glucose prevents hypoglycemia and hyperglycemia.
- There is no evidence that any particular anesthetic agents provider better neurologic outcomes in pediatric patients.
- Preoperative and intraoperative communication with the neurophysiologic technician allows for optimal anesthetic tailoring.
- The long-term effects of various anesthetic agents on developing brains are unknown. At this present time, there is a lack of evidence to change the approach to anesthetizing children for neurosurgical procedures.

References

1. Shapiro HM. Intracranial hypertension: therapeutic and anesthetic considerations. Anesthesiology. 1975;43(4):445–71.
2. Vavilala MS, Soriano SG. Chapter 22: Anesthesia for neurosurgery. In: Motoyama PJDPCK, editor. Smith's anesthesia for infants and children. 8th ed. Philadelphia: Mosby; 2011. p. 713–44.
3. Shapiro K, Marmarou A, Shulman K. Characterization of clinical CSF dynamics and neural axis compliance using the pressure-volume index: I. The normal pressure-volume index. Ann Neurol. 1980;7(6):508–14.
4. McClain CD, Soriano SG, Rockoff MA. Chapter 24: Pediatric neurosurgical anesthesia. In: Todres CJCLD, editor. Cote and Lerman's a practice of anesthesia for infants and children. 5th ed. Philadelphia: Elsevier/Saunders; 2013. p. 510–32.
5. Engelhardt T, Crawford MW, Lerman J. Chapter 33: Plastic and reconstructive surgery. In: Todres CJCLD, editor. Cote and Lerman's a practice of anesthesia for infants and children. 5th ed. Philadelphia: Elsevier/Saunders; 2013. p. 697–711.
6. Borch K, Greisen G. Blood flow distribution in the normal human preterm brain. Pediatr Res. 1998;43(1):28–33.
7. Cross KW, Dear PR, Hathorn MK, Hyams A, Kerslake DM, Milligan DW, et al. An estimation of intracranial blood flow in the new-born infant. J Physiol. 1979;289:329–45.
8. Younkin DP, Reivich M, Jaggi J, Obrist W, Delivoria-Papadopoulos M. Noninvasive method of estimating human newborn regional cerebral blood flow. J Cereb Blood Flow Metab. 1982;2(4):415–20.
9. Chiron C, Raynaud C, Maziere B, Zilbovicius M, Laflamme L, Masure MC, et al. Changes in regional cerebral blood flow during brain maturation in children and adolescents. J Nucl Med. 1992;33(5):696–703.
10. Kennedy C, Sokoloff L. An adaptation of the nitrous oxide method to the study of the cerebral circulation in children; normal values for cerebral blood flow and cerebral metabolic rate in childhood. J Clin Invest. 1957;36(7):1130–7.
11. Wintermark M, Lepori D, Cotting J, Roulet E, van Melle G, Meuli R, et al. Brain perfusion in children: evolution with age assessed by quantitative perfusion computed tomography. Pediatrics. 2004;113(6):1642–52.
12. Vavilala MS, Lee LA, Lam AM. Cerebral blood flow and vascular physiology. Anesthesiol Clin North America. 2002;20(2):247–64, v.
13. Takahashi T, Shirane R, Sato S, Yoshimoto T. Developmental changes of cerebral blood flow and oxygen metabolism in children. AJNR Am J Neuroradiol. 1999;20(5):917–22.
14. Lassen NA, Christensen MS. Physiology of cerebral blood flow. Br J Anaesth. 1976;48(8):719–34.
15. Paulson OB, Strandgaard S, Edvinsson L. Cerebral autoregulation. Cerebrovasc Brain Metab Rev. 1990;2(2):161–92.
16. Papile LA, Rudolph AM, Heymann MA. Autoregulation of cerebral blood flow in the preterm fetal lamb. Pediatr Res. 1985;19(2):159–61.
17. Purves MJ, James IM. Observations on the control of cerebral blood flow in the sheep fetus and newborn lamb. Circ Res. 1969;25(6):651–67.
18. Munro MJ, Walker AM, Barfield CP. Hypotensive extremely low birth weight infants have reduced cerebral blood flow. Pediatrics. 2004;114(6):1591–6.
19. Vavilala MS, Lee LA, Lam AM. The lower limit of cerebral autoregulation in children during sevoflurane anesthesia. J Neurosurg Anesthesiol. 2003;15(4):307–12.
20. Pryds A, Tonnesen J, Pryds O, Knudsen GM, Greisen G. Cerebral pressure autoregulation and vasoreactivity in the newborn rat. Pediatr Res. 2005;57(2):294–8.
21. Cohen MM, Cameron CB, Duncan PG. Pediatric anesthesia morbidity and mortality in the perioperative period. Anesth Analg. 1990;70(2):160–7.
22. Flick RP, Sprung J, Harrison TE, Gleich SJ, Schroeder DR, Hanson AC, et al. Perioperative cardiac arrests in children between 1988 and 2005 at a tertiary referral center: a study of 92,881 patients. Anesthesiology. 2007;106(2):226–37; quiz 413–4.

23. Wilne S, Collier J, Kennedy C, Koller K, Grundy R, Walker D. Presentation of childhood CNS tumours: a systematic review and meta-analysis. Lancet Oncol. 2007;8(8):685–95.
24. McCann ME, Kain ZN. The management of preoperative anxiety in children: an update. Anesth Analg. 2001;93(1):98–105.
25. Gronert GA. Succinylcholine-induced hyperkalemia and beyond. 1975. Anesthesiology. 2009;111(6):1372–7.
26. Martyn JA, Richtsfeld M. Succinylcholine-induced hyperkalemia in acquired pathologic states: etiologic factors and molecular mechanisms. Anesthesiology. 2006;104(1):158–69.
27. Mammoto T, Hayashi Y, Ohnishi Y, Kuro M. Incidence of venous and paradoxical air embolism in neurosurgical patients in the sitting position: detection by transesophageal echocardiography. Acta Anaesthesiol Scand. 1998;42(6):643–7.
28. Papadopoulos G, Kuhly P, Brock M, Rudolph KH, Link J, Eyrich K. Venous and paradoxical air embolism in the sitting position. A prospective study with transoesophageal echocardiography. Acta Neurochir. 1994;126(2–4):140–3.
29. Todd MM, Warner DS, Sokoll MD, Maktabi MA, Hindman BJ, Scamman FL, et al. A prospective, comparative trial of three anesthetics for elective supratentorial craniotomy. Propofol/fentanyl, isoflurane/nitrous oxide, and fentanyl/nitrous oxide. Anesthesiology. 1993;78(6):1005–20.
30. Scheingraber S, Rehm M, Sehmisch C, Finsterer U. Rapid saline infusion produces hyperchloremic acidosis in patients undergoing gynecologic surgery. Anesthesiology. 1999;90(5):1265–70.
31. Finfer S, Bellomo R, Boyce N, French J, Myburgh J, Norton R, SAFE Study Investigators. A comparison of albumin and saline for fluid resuscitation in the intensive care unit. N Engl J Med. 2004;350(22):2247–56.
32. Jevtovic-Todorovic V, Absalom AR, Blomgren K, Brambrink A, Crosby G, Culley DJ, et al. Anaesthetic neurotoxicity and neuroplasticity: an expert group report and statement based on the BJA Salzburg Seminar. Br J Anaesth. 2013;111(2):143–51.
33. Jevtovic-Todorovic V, Hartman RE, Izumi Y, Benshoff ND, Dikranian K, Zorumski CF, et al. Early exposure to common anesthetic agents causes widespread neurodegeneration in the developing rat brain and persistent learning deficits. J Neurosci. 2003;23(3):876–82.
34. Loepke AW, Soriano SG. An assessment of the effects of general anesthetics on developing brain structure and neurocognitive function. Anesth Analg. 2008;106(6):1681–707.
35. Gleich SJ, Flick R, Hu D, Zaccariello MJ, Colligan RC, Katusic SK, et al. Neurodevelopment of children exposed to anesthesia: design of the Mayo Anesthesia Safety in Kids (MASK) study. Contemp Clin Trials. 2015;41:45–54.
36. Hansen TG. Anesthesia-related neurotoxicity and the developing animal brain is not a significant problem in children. Paediatr Anaesth. 2015;25(1):65–72.
37. Sun LS, Li G, DiMaggio CJ, Byrne MW, Ing C, Miller TL, et al. Feasibility and pilot study of the Pediatric Anesthesia NeuroDevelopment Assessment (PANDA) project. J Neurosurg Anesthesiol. 2012;24(4):382–8.
38. Anand KJ, Hickey PR. Pain and its effects in the human neonate and fetus. N Engl J Med. 1987;317(21):1321–9.
39. Anand KJ, Soriano SG. Anesthetic agents and the immature brain: are these toxic or therapeutic? Anesthesiology. 2004;101(2):527–30.
40. Anand KS. Relationships between stress responses and clinical outcome in newborns, infants, and children. Crit Care Med. 1993;21(9 Suppl):S358–9.
41. Bouwmeester NJ, Anand KJ, van Dijk M, Hop WC, Boomsma F, Tibboel D. Hormonal and metabolic stress responses after major surgery in children aged 0–3 years: a double-blind, randomized trial comparing the effects of continuous versus intermittent morphine. Br J Anaesth. 2001;87(3):390–9.
42. Chacko J, Ford WD, Haslam R. Growth and neurodevelopmental outcome in extremely-low-birth-weight infants after laparotomy. Pediatr Surg Int. 1999;15(7):496–9.

43. Nimjee SM, Smith TP, Kanter RJ, Ames W, Machovec KA, Grant GA, Zomorodi AR. Rapid ventricular pacing for a basilar artery pseudoaneurysm in a pediatric patient: case report. J Neurosurg Pediatr. 2015;15(6):625–9.
44. Lee JK, Williams M, Jennings JM, Jamrogowicz JL, Larson AC, Jordan LC, Heitmiller ES, Hogue CW, Ahn ES. Cerebrovascular autoregulation in pediatric moyamoya disease. Paediatr Anaesth. 2013;23(6):547–56.
45. Parray T, Martin TW, Siddiqui S. Moyamoya disease: a review of the disease and anesthetic management. J Neurosurg Anesthesiol. 2011;23(2):100–9.
46. Landrigan-Ossar M, McClain CD. Anesthesia for interventional radiology. Paediatr Anaesth. 2014;24(7):698–702.