Paediatric neuroanaesthesia

Catherine Furay MRCP FRCA
Tanya Howell FRCA

Revalidation
FOR ANAESTHETISTS
RCA Revalidation matrix
Matrix reference 3E01

Key points

Differences in neurophysiology and cranial development influence the approach to the paediatric neurosurgical patient.

There are age-related differences in the spectrum of neurosurgical disease.

The anaesthetist should look for age-specific symptoms and signs of raised intracranial pressure in all preoperative paediatric neurosurgical cases.

The most practical monitor for venous air embolism is capnography.

Blood loss due to intracranial haemorrhage or surgery constitutes a greater proportion of circulating volume in the paediatric population.

This article will consider cerebral physiology and the differences between adults and children before reviewing the anaesthetic management of specific neurosurgical procedures in the paediatric population.

Neurophysiology

In children and infants, accurate data regarding normal neurophysiological values are limited and often extrapolated from human adult and animal data.

Cerebral blood flow

In the paediatric population, cerebral blood flow (CBF) varies with age.[1] In newborns and premature infants, values are lower than adults at 40–42 ml 100 g^{-1} min^{-1}. In infants and older children, values are thought to be higher than in adults. From 6 months to 3 yr, CBF is thought to be 90 ml 100 g^{-1} min^{-1} and from 3 to 12 yr at 100 ml 100 g^{-1} min^{-1}.[2]

Cerebral metabolic rate for oxygen

As in adults, cerebral metabolic rate for oxygen ($CMRO_2$) is closely linked to CBF in children (cerebral metabolic coupling). In children, $CMRO_2$ is higher at 5.2 ml 100 g^{-1} min^{-1} compared with 3.5 ml 100 g^{-1} min^{-1} in adults.[3] Their higher CBF and increased glucose usage is appropriate to this increased $CMRO_2$. Neonates have a lower $CMRO_2$ (2.3 ml 100 g^{-1} min^{-1}) and a lower CBF, with a relative tolerance of hypoxaemia.

Arterial carbon dioxide/oxygen tension (Pa_{CO_2}/Pa_{O_2})

Arterial Pa_{CO_2} has a potent vasodilatory effect on cerebral blood vessels, leading to an increase in CBF, which is linear between a Pa_{CO_2} of 3.5 and 8 kPa. At birth, the cerebrovascular response to changes in Pa_{CO_2} is incompletely developed. Moderate hypocapnia has less effect on the newborn brain than in adults and CBF changes relatively little until severe hypocapnia ensues. In adults, the cerebral vasculature is less sensitive to changes in Pa_{O_2}; CBF does not increase until Pa_{O_2} decreases below 50 mm Hg, and then it increases exponentially. In neonates, the CBF increases in response to smaller decreases in Pa_{O_2}.[4]

Autoregulation

CBF is autoregulated in response to changes in mean arterial pressure (MAP). Accurate values for autoregulatory ranges in infants and children are currently unavailable, but are probably related to their normal MAP. Data from animal and high-risk human neonate studies postulate the lower limit for autoregulation to be an MAP of 20–40 mm Hg.[4] Studies of extremely low birth weight infants show that autoregulation is functional in normotensive but not hypotensive infants.[5] Respiratory distress in infants also leads to impaired autoregulation;[2] increases in CBF outside of autoregulation may contribute to their susceptibility to intraventricular haemorrhage (IVH).

Intracranial pressure

The Monro-Kellie doctrine states that the skull is a closed box containing the brain, blood, and cerebrospinal fluid (CSF). An increase in volume of one of these components, with an increase in intracranial pressure (ICP), will result in a compensatory reduction in the other components to counteract the change. In the infant, before cranial suture fusion, decompression can occur through an increase in skull size. The posterior fontanelle closes at about 6 months of age, the anterior fontanelle at around 1 yr–18 months, and final cranial suture closure may be as late as 10 yr old. Increases in intracranial volume can only be accommodated if the change is gradual. Acute increases, such as after traumatic brain injury, will still result in raised ICP as in adults.

Catherine Furay MRCP FRCA
Salford Royal Hospital
Stott Lane
Salford M6 8HD
UK

Tanya Howell FRCA
Royal Manchester Children's Hospital
Oxford Road
Manchester M13 9WL
UK
Tel: +44 161 701 1263
Fax: +44 161 701 4875
E-mail: tanya.howell@cmft.nhs.uk
(for correspondence)

doi:10.1093/bjaceaccp/mkq036 Advance Access publication 9 September, 2010

Anaesthesia for neurosurgery

Preoperative assessment

A child with major or acute onset cranial pathology is likely to present with raised ICP (Table 1). These signs and symptoms should be sought together with other neurology such as bulbar symptoms and also sleep disturbances. The characteristic morning headaches and nausea seen in adults and older children may only be demonstrable as irritability and poor feeding in infants. The conscious level using an age-specific Glasgow Coma Scale should be ascertained. Cardiovascular system examination (including an echocardiogram of any murmurs detected clinically) is important in order to identify cardiac septal defects; intracardiac shunting of an inadvertent venous air embolism (VAE) may be fatal. Other considerations include preoperative anticonvulsant therapy and its effect on neuromuscular block,[4] hypovolaemia, and deranged serum electrolytes due to ICP-related vomiting and a peri-natal history which may reveal IVH and pre-existing disabilities associated with prematurity. Radiological images provide details of the size and site of any lesion, the presence of hydrocephalus, and any cerebral pressure effects.

Induction and maintenance of anaesthesia

Anaesthetic induction should aim to avoid increases in ICP such as those associated with hypercapnia, hypoxia, and variations in MAP and volatile agent induced increases in CBF. An i.v. induction with propofol or thiopental and neuromuscular block is therefore ideal. Ketamine causes an increase in ICP and is not recommended.

However, if the child is distressed or has difficult i.v. access, a smooth gas induction may be better than the raised ICP associated with crying or struggling. Sevoflurane confers benefits over other volatile agents, in that its odour is well tolerated and the likelihood of airway irritation, laryngospasm, and breath holding is reduced.

If a rapid sequence induction is necessary, the small increase in ICP associated with the use of succinylcholine can be attenuated by the use of opioids or preceding defasciculating doses of non-depolarizing neuromuscular blocking agents. Opioids such as remifentanil or alfentanil should be used to attenuate the hypertensive responses to laryngoscopy, intubation, and surgery.

Table 1 Signs of intracranial hypertension in infants and children.[4] Reproduced with permission from Elsevier Publishing

Infants	Children	Infants and children
Irritability	Headache	Decreased consciousness
Full fontanelle	Diplopia	Cranial nerve (III and VI) palsies
Widely separated cranial sutures	Papilloedema	Loss of upward gaze (setting sun sign)
Cranial enlargement	Vomiting	Signs of herniation, Cushing's triad, pupillary changes

Maintenance of anaesthesia utilizes volatile agents or total i.v. anaesthesia (TIVA) in combination with a short-acting opioid and controlled ventilation. A remifentanil infusion commenced at the induction of anaesthesia can readily be titrated to response and avoids the hypotension and bradycardia associated with boluses of remifentanil in children. Remifentanil usually obviates the need for repeated doses of neuromuscular blocking agents. TIVA may be used in older children, but its widespread use in younger children has been limited due to the original weight restrictions on target controlled infusion devices. Studies suggest that if volatile agents are used in concentrations of <1 minimum alveolar concentration (MAC), there will be no associated increase in CBF.[4] Halothane is a cerebral vasodilator and causes a dose-dependent increase in CBF. Isoflurane affects CBF less than halothane at equivalent MAC. Sevoflurane and desflurane appear to have similar effects on cerebral physiology to isoflurane, but confer the benefits of greater haemodynamic stability and rapid emergence after prolonged surgery.

Nitrous oxide should be avoided since its use leads to significant increases in CBF and $CMRO_2$. It also increases the volume of gas-filled spaces, increasing the potential for raised ICP in pneumocephalus after operation.

Intraoperatively, mannitol may be administered in doses of $0.25-1$ g kg^{-1} to attenuate acute increases in ICP.

Positioning

General principles relate to maintaining adequate ventilation and the avoidance of venous congestion and morbidity secondary to poor positioning. Excessive rotation of the head should be avoided as this can cause occlusion of the internal jugular veins. Postoperative airway problems may result from macroglossia, where neck flexion has compromised venous and lymphatic drainage. Head-up tilt will increase venous drainage, but also increases the risk of VAE. Eyes should be lubricated and protected from surgical cleaning solutions and external pressure that could cause postoperative visual impairment. Ease of access to i.v. lines and ability to visualize the child under the surgical drapes should be ensured. Care must be taken to protect all vulnerable pressure areas. Fixation in the Mayfield head frame with pins presents a risk of skull fracture, dural tear, and intracranial haematoma in small children.

Prone

Additional considerations include the use of appropriately sized positioning blocks to support a child, with attention paid to the abdomen and genital area. Neck flexion can result in tracheal tube displacement and endobronchial intubation especially in infants.

Sitting

Use remains controversial; however, a small percentage of neurosurgeons still routinely use this position for posterior fossa surgery. The advantages are surgical access and improved venous drainage.

Complications relating to this position include cardiovascular instability and VAE. Recent studies have suggested that it is a safe technique, provided surgical and anaesthetic care is thorough.[6]

Monitoring

Intracranial surgery may be associated with sudden cardiovascular changes and the potential for rapid blood loss. Routine monitoring includes capnography, pulse oximetry, electrocardiography, temperature, and invasive arterial pressure. Urethral catheterization and the measurement of urine output are necessary for prolonged procedures and especially those associated with diabetes insipidus or the requirement for mannitol. A central venous catheter (CVC) provides large-bore access and allows for central administration of vasoactive drugs and potentially treatment of VAE. Readings can be unreliable in small children in the prone position but trends may be useful. Some centres use precordial Doppler ultrasonography to detect VAE.[7] Most UK centres use end-tidal CO_2 analysis as Doppler analysis can be oversensitive and there is troublesome interference by diathermy.[8]

Neurophysiological monitoring may be utilized with the aim to improve outcome and reduce morbidity by early detection of neurological injury at a point when damage can be limited or reversed. In brief, the modalities for monitoring include EEG, somatosensory-evoked potentials, motor-evoked potentials, and transcranial Doppler.

Venous air embolism

In infants and small children, the head lies above the heart even when supine and constitutes a greater proportion of body surface area,[9] thus rendering them more susceptible to VAE. In addition, the dural sinuses and diploic veins bridging the scalp and dura are held open by bony connections. Patients with cardiac shunts are at risk of paradoxical air emboli and even small amounts of air are significant. End-tidal CO_2 analysis and arterial catheterization ($\pm$ precordial Doppler) detect VAE. Both traces will demonstrate an instantaneous decrease in their waveforms, as a result of the sudden decrease in cardiac output. If a VAE is diagnosed, the surgeon should immediately occlude entry points and flood the surgical field with saline. Other manoeuvres include applying jugular venous compression, head-down tilt, and aspiration of air from the CVC. The mainstay of treatment is to provide cardiorespiratory support.

Intraoperative fluid management

It is widely agreed that glucose-containing and hypotonic solutions should not be used. Hyperglycaemia worsens reperfusion injury, and hypotonic infusions increase cerebral oedema. However, the dangers of hypoglycaemia particularly in the neonate or ex-premature infant should equally be borne in mind and blood glucose monitored closely in these patients.

In the goal to maintain normovolaemia, and thus haemodynamic stability, there is debate as to whether colloid confers any advantages over isotonic crystalloid in routine neurosurgery. The commonly used isotonic crystalloids are Ringer's lactate or 0.9% sodium chloride. Excessive quantities of the former can result in elevated intracellular glucose and the latter in hypernatraemia and hyperchloraemic metabolic acidosis.

Blood loss can be difficult to assess during craniotomies due to constant oozing onto the surgical drapes and irrigation with saline fluid. There is a potential for sudden and drastic losses, so cross-matched blood should always be available.

Temperature regulation

Mild hypothermia (34–35°C) encourages a decrease in $CMRO_2$ and may help to attenuate raised ICP. However, it is essential to appreciate the complications of hypothermia (e.g. disordered coagulation), the importance of normothermia for adequate emergence from anaesthesia, and the time required to rewarm even a mildly hypothermic child, especially an infant. Fluid warmers, warm air devices, and heated mattresses are required.

Postoperative care

The most appropriate setting will vary with the particulars of the child and the procedure, but all should have regular neurological observations. Post-craniotomy/craniectomy children are managed on a high dependency unit. Historically, many clinicians avoided morphine analgesia due to the side-effects of vomiting, sedation, and its potential effect on pupil size. However, in appropriate dose ranges, with antiemetics such as ondansetron, simple analgesics, and regular observations, a morphine infusion has been shown to provide safe and effective analgesia.[10] Acetaminophen is usually commenced intraoperatively and continued regularly after operation. Debate still exists around the potential contribution of non-steroidal anti-inflammatory drugs to postoperative bleeding, but most centres will commence these by 24 h after operation.

The presence of co-morbidities and procedures for craniofacial anomaly involving the airway are more likely to require postoperative care on the paediatric intensive care unit.

Specific neurosurgical cases

Hydrocephalus and shunt procedures

The term hydrocephalus (literally 'water on the brain') refers to an increased CSF volume due to either over production or reduced drainage. It may be associated with other neurosurgical conditions such as myelodysplasia or Chiari malformations. The urgency of treatment is related to the degree of raised ICP. Children commonly present for shunt procedures diverting CSF from the ventricles to another body cavity; peritoneal, pleural, or right atrium. Venticuloperitineal shunts are the commonest and are associated with less morbidity. Alternatively, internal CSF drainage can be provided with an endoscopic third ventriculostomy. Shunts may require revision due to natural growth of the child, blockage,

infection, or malfunction. Blockage commonly occurs distally, beyond the cranial valve; thus, symptoms can be temporarily alleviated by aspirating CSF from the cranial reservoir.

Shunt procedures require skin exposure and preparation from the head to the abdomen. Heat conservation strategies should be instituted in young children. Although intraoperative tunnelling of the shunt is particularly stimulating, after operation, these children only require simple analgesics.

Children undergoing third ventriculostomy surgery will be positioned in a Mayfield headrest. Warmed Ringer's lactate fluid is used to irrigate the operating site; measuring the volume of fluid infused and drained is imperative to avoid rapid increases in ICP. Acute distension of the third ventricle can cause cardiac arrhythmias and cardiovascular instability due to the close proximity of the third ventricle to midbrain CVS centres.[11]

Tumours

Brain tumours are the most common solid tumour of childhood. Two-thirds arise infratentorially, compared with adults where two-thirds arise supratentorially.[4] The anaesthetic implications of posterior fossa pathology include an increased likelihood of raised ICP due to CSF outflow obstruction and a higher occurrence of postoperative airway problems due to perioperative compromise of brainstem respiratory centres and lower cranial nerve function. The pressor response to laryngoscopy and fixation of the head in pins may lead to a detrimental increase in ICP that should be attenuated by a potent opioid such as remifentanil.

A reinforced tracheal tube is recommended to aid positioning away from the surgical field and avoid kinking associated with positioning and surgery duration. A throat pack aids in stabilizing the tube position. The relatively 'dry' airway at the end of surgery also facilitates a smooth extubation.

Craniopharyngioma is the third most common intracranial tumour in children. Although benign, associated problems arise from a local effect on neighbouring structures—the pineal gland, hypothalamus, and optic chiasm. Disturbances of thyroid and adrenal function must be quantified before surgery. Diabetes insipidus frequently occurs perioperatively. If treated with desmopressin, it is important to identify prescribed dose, normal urine volumes, and serum electrolytes.

Epilepsy surgery

Where seizures are intractable to medical therapy, a number of surgical options exist, for example, insertion of a vagal nerve stimulator or craniotomy for resection of an epileptic focus or hemispherectomy. Anaesthetic considerations include those associated with developmental delay, perioperative seizures, and co-existing disease, and the effects of anticonvulsants. Awake craniotomy offers the advantage of allowing electrocorticographic mapping intraoperatively, minimizing unnecessary tissue resection, but this is not usually possible in children.

Acute head injury

Head trauma may give rise to an intracranial haematoma or, more commonly, result in diffuse axonal injury and oedema. Autoregulation and intracranial compliance may be impaired. The anaesthetic technique should aim to avoid further increases in ICP and minimize secondary brain injury. Emergency surgery for the evacuation of intracranial blood often involves transfer into specialist centres. In a child, an intracranial bleed may result in a significant proportion of circulating volume being lost; therefore, cross-matched blood should be available. Subsequent hypotension may be further exacerbated by mannitol. Additional problems include co-existing injuries, which may be life-threatening and concealed. Resuscitative measures must be ongoing while preparing for emergency evacuation of an intracranial haematoma.

Congenital spinal lesions

Failure of the neural tube to close during the first trimester results in a disease spectrum ranging from spina bifida occulta to anencephaly. The most common conditions presenting for neurosurgical correction are lumbosacral meningoceles; these result from herniation of the dural elements posteriorly. Where this includes neural tissues (myelomeningocele), distal neurological function is often severely impaired. These defects require correction within the first few days of life to minimize bacterial contamination and sepsis. The anaesthetic implications of surgery for neural tube defects are as follows:

(i) Neonates: general principles for anaesthesia in this population apply. If skin grafting is required, there may be a need for blood replacement.
(ii) Positioning: care must be taken to minimize pressure on the cystic structure, leading to further damage or rupture. Induction of anaesthesia may be carried out in the lateral decubitus position or more commonly supine, with a ring-shaped sponge to support and relieve pressure from the herniation. Surgery is conducted in the prone position and particular care is required to avoid abdominal compression and venous congestion of the operating site.
(iii) Latex: children with myelodysplasia have an increased risk of latex allergy.

The majority of meningomyelocele cases have an associated Arnold–Chiari malformation (Table 2).

Craniofacial abnormalities

Craniosynostosis is the premature fusion of one or more cranial sutures. Single-suture craniosynostosis usually occurs in otherwise healthy children. Multiple suture disease often occurs as part of a craniofacial syndrome such as Apert's, Crouzon's, or Pfeiffer's. Techniques for cranial remodelling are varied and involve removal of the skull vault by the neurosurgical team followed by careful refashioning by plastic or maxillofacial surgeons.

Table 2 The Chiari malformations.[4] Reproduced with permission from Elsevier Publishing

Chiari Type 1
Tonsillar herniation >5 mm below the plane of foramen magnum
No associated brainstem herniation or supratentorial anomalies
Low frequency of hydrocephalus
Chiari Type II
Caudal herniation of the vermis, brainstem and fourth ventricle
Associated with myelomeningocele and multiple brain anomalies
High frequency of hydrocephalus and syringohydromyelia
Chiari Type III
Occipital encephalocele containing dysmorphic cerebellar and brainstem tissue
Chiari Type IV
Hypoplasia or aplasia of the cerebellum

Manipulation of the skull vault alters the skull shape to promote uniform growth in sagittal and coronal planes. The management of more complex multiple suture craniosynostosis with craniofacial anomalies at a supraregional centre has been shown to be beneficial.

Anaesthetic implications of craniofacial surgery are as follows:

(i) Blood loss—surgery often occurs at the nidus of physiological anaemia between 2 and 6 months. Bleeding is from scalp wounds and bone, making it difficult to quantify accurately. Blood products are invariably required perioperatively.

(ii) VAE—the patient is at risk during retraction of the scalp over the orbital ridge.

(iii) Oculocardiac reflex—profound bradycardia may result from orbital manipulation. It usually responds to removal of the stimulus and administration of anti-muscarinic agents.[8]

(iv) Airway—surgery below the orbital ridge is associated with excessive facial oedema and may involve the use of a rigid extraction device frame. This may present the anaesthetist with problems at the initial and subsequent surgeries. Occasionally, a preoperative tracheostomy may be required.[8]

(v) Positioning—this will vary for individual procedures, particular care is needed around the eyes and to guard against excessive neck extension/flexion.

Conflict of interest

None declared.

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Please see multiple choice questions 5–8.