Review

Anaesthesia for Correction of Scoliosis in Children

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SUMMARY
Surgical correction of spinal deformities in children presents a challenge to the anaesthetist because of the extensive nature of the surgery, the co-morbidities of the patients and the constraints on anaesthetic techniques of intraoperative neurophysiological monitoring of the spinal cord. Adolescent idiopathic scoliosis is the most common deformity. Patients with scoliosis secondary to neuromuscular conditions are at greatest risk of perioperative problems, particularly excessive blood loss and respiratory failure. The risk of spinal cord damage can be decreased by the use of intraoperative spinal cord monitoring, particularly monitoring of the lower limb compound muscle action potential evoked by transcranial electrical stimulation. Specific anaesthetic techniques are required for this monitoring to be reliable. Because of concerns about spinal cord perfusion there is now less reliance on induced hypotension and haemodilution to reduce blood loss, with emphasis on proper patient positioning, controlled haemodynamics and antifibrinolytic therapy. Effective postoperative pain management requires a multimodal approach.

Key Words: Scoliosis, spine, anaesthesia, monitoring, complications

Spinal deformities have been known since ancient times. The Greek physician Galen introduced the terms scoliosis, kyphosis and lordosis1. Scoliosis refers to lateral curvature of the spine though is often used generically to refer to all spinal deformities in children. Kyphosis refers to posterior curvature and lordosis to anterior curvature2. Many curves are mixed and scoliosis etymologically refers to the torsion or twisting of the spinal column which underlies many deformities.

Hippocrates noted that spinal deformities compromised respiratory function3. He developed traction as a treatment, albeit ineffectually. An orthosis to be used as a brace was developed in the 16th century by Pare. Modern bracing techniques, particularly the Milwaukee brace developed by Blount, are effective at preventing progression of curvature in some cases and still have a place in management.

Hibbs performed the first spinal fusion for scoliosis in 19114, but operative treatment had poor results until the development of an internal fixation system, the Harrington Rod in 19625. Prolonged casting to allow the fusion mass to become solid was still required. Modern internal fixation systems allow early mobilization without casting.

Anaesthesia for correction of scoliosis is a challenge because of the frequent co-morbidities of the patients presenting for surgery, the extensive nature of the surgery and the constraints put on the available anaesthetic techniques because of intraoperative spinal cord monitoring. The postoperative period may be complicated by problems common to any major surgery such as continued blood loss, ileus, ventilatory failure and the syndrome of inappropriate anti-diuretic hormone secretion (SIADH), but also by unique complications such as superior mesenteric artery (SMA) syndrome6. Postoperative pain can be severe and its management requires a multimodal approach.

This review will describe the pathophysiology of scoliosis, the techniques of surgical correction and spinal cord monitoring and the implications of these for anaesthetic management. The protocol for perioperative anaesthetic management of these patients developed at The Children’s Hospital at Westmead (CHW) will be described.

Classification of Scoliosis
The aetiology of most cases of scoliosis is idio-


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pathic but scoliosis can be associated with a variety of conditions. A system of classification of scoliosis with its disease associations is shown in Table 1.3.

Pathophysiology

Idiopathic scoliosis is a complicated deformity involving the thoracic and/or lumbar spine, with lateral curvature, vertebral rotation and rib cage deformity. It may be associated with kyphosis and lordosis. As the curvature increases, rotation progresses and the chest cavity becomes narrowed resulting in a restrictive lung defect. This is rarely significant for curves of <65 degrees. With severe curves, restriction increases, V/Q mismatching occurs and respiratory failure and pulmonary hypertension may result. This severe respiratory compromise probably only occurs in curves >100 degrees. After skeletal maturity, curves <30 degrees do not progress but more severe curves may continue to progress another 10-15 degrees. Surgical correction does not reverse the restrictive lung deficit but will halt its progression2,3.

In scoliosis associated with neuromuscular disease, the underlying disease often further compromises respiratory function because of inability to cough, reduced protection against aspiration because of bulbar palsy and reduced ventilatory capacity. Neuromuscular scoliosis tends to involve most of the thoracolumbar spine in a long C shaped curve that includes an oblique pelvis.

The most popular and reproducible method to measure the curve is that described by Cobb. A line is drawn parallel to the superior border of the highest vertebral body that points most to the concavity of the curve and similarly from the inferior border of the lowest vertebral body. Perpendiculars from these lines are drawn and the angle of intersection measured. The greater the angle measured the more severe the curve (Figure 1).

Indications for Surgery

The indications for surgery in idiopathic scoliosis are usually given as progression in a curve over 40 degrees with nonoperative treatment, a 40-45 degree curve in a patient not skeletally mature, and curves over 50 degrees in a mature adolescent. Juvenile scoliosis may progress to severe curves with resulting severe restrictive lung defects. Follow up of untreated adolescent idiopathic scoliosis over 50 years failed to show major disability related to the scoliosis. Only patients with apical thoracic curves of over 100 degrees are at risk of death from cor pulmonale and respiratory failure. A large multi-centre follow-up of patients with idiopathic scoliosis who have had surgery found decreased back pain, improved self-image, and increased levels of activity as compared with preoperative status. Overall, patients were highly satisfied with the results of surgery7. The indications for surgery in congenital scoliosis depend on the underlying anomaly and the prediction for progression.

For scoliosis secondary to neuromuscular disease, surgery may be indicated to improve wheelchair posture and aid nursing care as well as to prevent progression of restrictive lung defect in patients with already compromised respiratory function. The inevitable decline in respiratory function in patients with progressive weakness due to diseases such Duchenne muscular dystrophy, (DMD) or spinal muscular atrophy, may be slowed but is not halted. A large multi-centre follow-up of patients with idiopathic scoliosis who have had surgery found decreased back pain, improved self-image, and increased levels of activity as compared with preoperative status. Overall, patients were highly satisfied with the results of surgery7. The indications for surgery in congenital scoliosis depend on the underlying anomaly and the prediction for progression.

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their families report an improved quality of life following surgery and would undergo the procedure again\textsuperscript{9,11}.

Surgical Technique

Surgical techniques for correction of scoliosis have evolved over the last 40 years after the development of the Harrington rod instrumentation. The technique chosen depends on the aetiology and severity of the curve and the skeletal maturity of the patient. Modern correction techniques aim to prevent progression of the curve and to correct the three-dimensional deformity taking into account the rigidity of the spine and the risk of neurological injury\textsuperscript{1,2}.

A posterior approach is most commonly utilized. Combined anterior and posterior approaches are utilized in more severe and rigid curves or where there is a need to prevent anterior growth. The combined approaches may be staged over one to two weeks, or done as one operation. Staged operations result in less morbidity and mortality in patients at high risk\textsuperscript{12}. For some congenital curves, or curves confined to the lumbar spine, an anterior approach only is used.

Systems used for the posterior approach are extensions of the Cotrel-Dubousset design\textsuperscript{13}. These involve multi-level fixation with pedicle screws or laminar hooks, two contoured rods to correct deformity in all planes and allow distraction and compression on each rod and cross bracing to provide stability\textsuperscript{2}. For smaller children, or patients with bones unable to support the laminar hooks, including most of the patients with neuromuscular curves, Luque rods and sub-laminar wires are used for fixation\textsuperscript{1}. Fusion alone with cast bracing is used occasionally in small children with congenital deformities.

The surgery is extensive. For posterior fusion the skin and supraspinous ligament are incised and the paraspinal muscles reflected. The spinous processes and interspinal ligaments are removed and the facet joints destroyed. After instrumentation and correction of deformity, bone graft is applied to the entire fusion area. The instrumentation is designed to provide stability allowing early postoperative mobilization before bony fusion is complete.

An anterior approach involves retroperitoneal dissection through a large thoraco-abdominal or flank incision. Single lung ventilation may aid surgical access. After exposure of the vertebral bodies, the intervertebral discs are removed on the convex side, shortening that side and increasing flexibility, allowing correction with less chance of neurological injury. Bone grafts are placed and instrumentation with vertebral screws and rods may be utilized if there is to be no posterior correction.

Preoperative Assessment and Preparation

The preoperative evaluation is a multidisciplinary process where staff from all disciplines involved both assess the patient for surgery and anaesthesia and

\textsuperscript{1}P. R. J. Gibson, Anaesthesia and Intensive Care, Vol. 32, No. 4, August 2004

\textbf{Figure 1}: Measurement of Cobb angle. (See fine lines and measured angles in lower thoracic region in particular.)
explain the complex nature of the surgery and perioperative care. Anaesthesia procedures such as invasive cardiovascular monitoring, urinary catheterization, neurophysiological monitoring, postoperative analgesic regimes and the wake-up test are explained. Patients and families may benefit from talking to patients who have been through the procedure. Unless contraindicated, patients at CHW are premedicated with oral midazolam 0.5 mg/kg to a maximum of 15 mg.

The focus in the medical assessment is on cardiorespiratory function. For most patients with idiopathic scoliosis a good exercise tolerance is the best guide to cardiorespiratory status. These patients have a 25% incidence of mitral valve prolapse\textsuperscript{14}, but this is rarely of haemodynamic significance and appropriate antibiotic cover is given to all patients. Spirometry is routinely performed and most often shows a moderate restrictive defect. Postoperative ventilation is rarely required unless the defect is severe, such as an FVC <30\% predicted\textsuperscript{1}. A full blood count is assessed and either crossmatch or group and screen done depending on patient size and preoperative haematocrit.

The cost effectiveness of autologous predonation in adults has been questioned\textsuperscript{15}. In adolescent idiopathic scoliosis, preoperative autologous donation reduces allogenic blood exposure and seems cost effective. In scoliosis patients most at risk of needing perioperative transfusion, smaller children and children with scoliosis secondary to neuromuscular disease, predonation does not reduce the need for allogenic blood\textsuperscript{14,17}. Preoperative anaemia may be a problem unless iron and erythropoietin therapy is also used\textsuperscript{18}. The small number of suitable patients, and problems due to timing of donations with surgery, limits the use of autologous predonation in our unit.

Patients with scoliosis secondary to neuromuscular disease have a higher incidence of complications and assessment of cardiorespiratory status is more difficult. They may be unable to perform spirometry and relatively immobile. Anaesthesia for patients with cerebral palsy has recently been reviewed\textsuperscript{19}.

Cardiomyopathy complicates many progressive muscle diseases such as DMD and myotonic dystrophy and should be assessed by ECG and transthoracic echocardiography (echo) or radionuclide imaging if echo is technically difficult. The value of normal resting values to predict intraoperative events has recently been questioned\textsuperscript{20}. Acute intraoperative heart failure has occurred in a DMD patient with a normal preoperative echo and stress echocardiography has been recommended. Intraoperative monitoring with transoesophageal echo (TOE) may be warranted.

Determining the point at which the risks of surgical complications outweigh the benefits of scoliosis surgery is difficult, particularly in patients whose life expectancy is limited by the progressive nature of the disease. Ramirez et al examined complications in 30 patients with DMD who underwent posterior spinal fusion. No patients were symptomatic of cardiomyopathy preoperatively and only two had FVC <40\% predicted. Four patients died in the first postoperative year and three more in the second year of follow-up. Eight patients suffered major complications resulting in significant morbidity. Fifteen of the twenty-one patients and families who could be surveyed over several years postoperatively said surgery had improved their quality of life\textsuperscript{21}. Morris, in a recent editorial quoting extensive experience in anaesthesia and DMD, considered a left ventricular ejection fraction of less than 50\% and a forced vital capacity (FVC) of less than 25\% of predicted contraindicated elective surgery\textsuperscript{22}.

Rawlins et al looked at complications in 32 patients undergoing spinal fusion with FVC <40\% predicted\textsuperscript{23}. There were no perioperative deaths. Six patients had major pulmonary complications and three patients required tracheostomy. They concluded that reduced FVC alone should not contraindicate surgery, but emphasized the need for intense multidisciplinary approach to the perioperative care of these patients. Most of the patients in this review had a congenital cause for their scoliosis and only one had DMD. Wazeka et al looked at twenty-one patients with spinal deformities with an average FVC of 32\%\textsuperscript{21}. The deformities had a variety of aetiologies, including four due to myopathy. Four patients were on assisted home ventilation preoperatively, including two of the myopathy patients. They also had no perioperative deaths. The four patients on assisted ventilation preoperatively continued it postoperatively and two additional patients required assisted ventilation postoperatively for up to three months. The authors concluded that major spinal surgery is feasible in these patients with severe restrictive lung disease and again emphasized the need for a multidisciplinary approach, including particular attention to nutritional status.

With modern perioperative care it seems that low values for FVC alone should not contraindicate surgery. In patients with progressive weakness however such as DMD the guidelines of Morris mentioned above would seem wise\textsuperscript{21}.

It is now thought that DMD and other dystrophinopathies are not associated with malignant

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hyperthermia. Suxamethonium is contraindicated in patients with a dystrophinopathy as it may cause rhabdomyolysis and hyperkalaemic cardiac arrest. Volatile agents may also cause rhabdomyolysis in these patients though this is often subclinical. While some units with vast experience report no problems with the use of volatile agents in patients with dystrophinopathies, minimizing the risk of rhabdomyolysis by avoiding volatile agents seems reasonable.

Complications During Surgery and their Implications for Anaesthesia

Scoliosis has complications common to other extensive operations including problems of temperature maintenance and compression neuropathies from positioning. The problems of perioperative hypothermia have been extensively reviewed. Active warming measures should be commenced before induction of anaesthesia and continued throughout. Positioning prone on the four-post frame commonly used for posterior fusions is a team responsibility. Care should be taken not to extend the arms more than 90 degrees in abduction or forward flexion, and to avoid compression of the axilla, the ulnar nerves at the elbow and the lateral cutaneous nerves in the upper thigh. Correct positioning on the frame should allow free movement of the abdomen, ensuring adequate ventilation, and avoid elevated venous pressure, which contributes to bleeding. The eyes should be protected and checked frequently throughout surgery to make sure there is no external pressure. Other complications, including major neurological injury, blood loss, coagulopathy, venous air embolism and postoperative visual loss are reviewed below.

Neurological Injury

The risk of spinal cord injury from surgery to correct spinal deformities varies from 0.3-0.6% according to data from surveys of the Scoliosis Research Society. Scoliosis correction for congenital kyphosis, neurofibromatosis, skeletal dysplasias and post-infectious scoliosis carry higher neurologic risk. Neurological injury can be due to:
1) direct contusion of the cord by implant or instrument.
2) reduction of spinal cord blood flow by stretching or compression of vessels or direct interruption of radicular blood flow.
3) distraction injury of the spinal cord
4) epidural haematoma.

Risk factors may be additive. Ischaemic injury is the most common and the areas of the cord most vulnerable to ischaemic injury are the motor pathways supplied by the anterior spinal artery. Intraoperative spinal cord monitoring has been developed to decrease the risk of neurological injury. With early detection by monitoring it is hoped intervention may prevent irreversible damage. Despite this, occasional patients may be neurologically normal immediately postoperatively, yet develop paralysis over the next 48 hours due to spinal cord ischaemia.

Methods of spinal cord monitoring

Wake-up test

The wake-up test allows intraoperative emergence sufficient to test lower limb motor, but not sensory, function for early detection of spinal cord injury after correction of deformity. Although confirmation of function is reassuring, loss of function may already be irreversible. The single window of observation does not allow correlation of loss of function with surgical events. If positive, the surgeon is obliged to remove all the implants. Patient cooperation is needed and gross patient movement may result in accidental extubation or loss of IV access, while inspiratory efforts may promote venous air embolism.

Clonus test

Clonus can normally be elicited in patients with intact spinal reflexes and lack of central inhibition. It is possible to elicit clonus in a neurologically normal patient just awakening from general anesthesia, because anaesthesia has reduced cortical inhibition. This has been utilized in the clonus test. Eliciting clonus of the ankles is attempted just prior to wake-up. If clonus is present spinal cord integrity is assumed, if absent the full wake-up test is performed. Although it does not require patient cooperation there is only a small window when clonus can be elicited and the absence of clonus does not reliably predict injury.

Continuous Intraoperative neurophysiologic monitoring

Intraoperative neurophysiologic monitoring involves stimulating one part of the nervous system and measuring a response (an evoked potential) in a distant part across the area of the spinal cord at risk. The two modalities that have been developed are somatosensory evoked potentials (SSEPs) and motor evoked potentials (MEPs). SSEP monitoring involves stimulation of a peripheral nerve, usually the posterior tibial nerve, and detecting a spinal response with epidural electrodes or a cortical response with scalp electrodes. MEP monitoring involves stimulating the motor cortex by electrical impulses transcranially and detecting the resulting signal at spinal
level with epidural electrodes or from muscles as a compound muscle action potential (CMAP). These modalities of monitoring are now the accepted standard of care for spinal corrective surgery\textsuperscript{36}. Anesthesia and intensive care, Vol. 32, No. 4, August 2004

SSEP monitoring

The SSEP response is small compared to background noise, so signal averaging techniques are used with a 2-3 minute delay in processing information. There may also be a delay between onset of ischaemia and changes in potentials\textsuperscript{37}. Only the dorsal sensory with a 2-3 minute delay in processing information. Transcranial magnetic stimulation of MEP’s has been described but is now rarely used.

MEP monitoring

In response to false negatives with SSEP monitoring, motor evoked potential monitoring was developed\textsuperscript{38}. MEPs monitor the more vulnerable anterior cord. Stimulation of the motor cortex results in direct stimulation of pyramidal cells and conduction down spinal pathways resulting in a “D” wave that can be recorded from the spinal cord via epidural electrodes. Stimulation also results in polysynaptic transmission recorded as subsequent “I” waves. Summation of these waves results in firing of the anterior horn cell and peripheral transmission via motor nerves to the muscle. Muscle depolarization results in the CMAP\textsuperscript{39}. CMAPs may also be generated by surgical manoeuvres that result in irritation of nerve roots or cord concussion. Transcranial stimulation with recording of potentials from peripheral nerves has also been used. These recordings result predominantly from conduction via the dorsal columns. They are not true MEPs and have the same false negative problems as SSEPs monitoring\textsuperscript{38}.

Anaesthetic agents and Spinal cord monitoring

The impact of anaesthetic agents on spinal cord monitoring increases with the number of synapses in the pathway to be monitored. Volatile anaesthetic agents and propofol depress SSEPs and MEPs in a dose-dependent manner in parallel to their effects on the EEG, probably due to inhibitory effects on polysynaptic pathways. Ketamine and etomidate may enhance recordings\textsuperscript{40}. Epidural recordings of MEPs and SSEPs are more robust than both cortical SSEPs and CMAPs because they rely less on polysynaptic transmission. Nitrous oxide profoundly depresses SSEPs and MEPs unless epidural recordings are used\textsuperscript{40}. Opioids, including intrathecal opioids, have little effect on either modality except in large bolus doses. Muscle relaxants reduce background noise enhancing SSEP recordings. Profound degrees of muscle relaxation abolish CMAPs but not epidural MEPs. Recordings of CMAPs are possible with minor degrees of relaxation corresponding to train of four (TOF) counts of 2-3\textsuperscript{41}. A technique using relaxant, moderate to high dose opioid, and sub MAC volatile agent or propofol infusion is usually used for SSEP monitoring. Nitrous oxide may be used if epidural rather than cortical evoked potentials are monitored. Once baseline SSEPs are recorded it is important to avoid boluses of depressive agents to avoid false positive results\textsuperscript{37,39,40}.

The effects of general anaesthetic agents and muscle relaxants frustrated early attempts at MEP monitoring particularly of CMAPs. Using multi-burst transcranial stimulation and epidural recording of spinal signals, which are relatively robust in the face of standard anaesthetic regimes, overcame some of the problems\textsuperscript{40}. Epidural electrodes create some difficulties. They reduce the epidural space, clutter the surgical field and require extension of the surgical field cranially and caudally. Accidental dislodgement results in loss of presurgical baseline. Epidural recordings are less sensitive to the effects of ischaemia and change later than CMAPs\textsuperscript{40}. CMAPs may also be generated by nerve root irritation or cord concussion. If only epidural recordings are used these additional warning signs are lost.

A protocol for reliable MEP monitoring

By blocking arousal stimuli, high dose opioid, as a component of anaesthesia allows marked reductions in both volatile concentrations and propofol doses used\textsuperscript{40,41}. Remifentanil may also have a small hypnotic effect\textsuperscript{40}. Reducing the concentration of volatile agent or propofol dose needed for anaesthesia allows reliable recording of CMAPs and eliminates the need for epidural recordings. There is no logical reason to prefer propofol to volatile agents as the sedative component of anaesthesia as has been advocated\textsuperscript{40} because the effects of both on CMAPs are dose-dependent and the dose of both required in a...
balanced anaesthesia regime is greatly reduced by remifentanil. The great advantage of volatile agents is that end-tidal concentrations can be readily measured and rapidly titrated to a level that results in satisfactory recordings usually in the 0.4–0.7 MAC range. Sevoflurane or desflurane may be preferable volatile agents because they are the most rapidly titratable. Volatile agents and propofol may also be titrated to bispectral index (BIS) though this is awaiting validation in children. The addition of nitrous oxide (N2O) offers no advantages when using remifentanil and it profoundly depresses CMAPs so should be avoided.

The CHW anaesthetic protocol consists of high dose remifentanil and 0.4–0.7 MAC end-tidal sevoflurane without N2O or muscle relaxants. Others have developed similar protocols utilizing propofol48. Etomidate and ketamine as supplements to N2O/oxytocin anaesthesia also seem compatible with reliable monitoring49.

High dose opioid anaesthesia leads to the development of acute tolerance and possibly to postoperative hyperalgesia50, an effect abolished by low dose ketamine41. Ketamine also fortuitously may enhance the generation of CMAPs with transcranial stimulation, so we usually include low dose intraoperative ketamine (initial dose of 0.15 mg/kg followed by 2 µg/kg/min) in our protocol.

CMAP monitoring results in patient movement because the stimulus causes muscle contraction. Reducing the stimulus intensity can reduce the vigour of the muscle contraction and movement. Some units use partial neuromuscular blockade as described above, though we have not found it necessary. Avoidance of muscle relaxants also makes awareness less likely52. Complications of CMAP monitoring are few but have included tongue lacerations or kinking of the endotracheal tube from biting (bite blocks are recommended), and the production of seizures in patients with poorly controlled epilepsy53. Contraindications to CMAP monitoring use include metallic cranial implants such as components of shunts, aneurysm clips, or cochlear implants.

We rely on CMAP monitoring alone. From our unreported series of over 300 patients at CHW and Westmead Hospital (WH) there have been no false negatives reported and two false positives (patients who had persistent abnormal traces intraoperatively, who had no postoperative deficit). In all neurologically normal patients and almost all patients with neuromuscular curves CMAPs have been recordable. (Dr Jim Lagopoulos PhD, neurophysiologist CHW, personal communication). Patients in whom we have been unable to obtain initial recordings have been paraplegic or had spinal muscular atrophy.

Combined SSEP and CMAP monitoring to cover sensory and motor areas has been recommended54. This requires epidural lead placement, as it is not possible to simultaneously measure cortical SSEPs and stimulate transcranially for CMAP monitoring. The gain from this combined monitoring would appear to be theoretical and has not been demonstrated clinically.

Managing neurological abnormalities detected by monitoring

Once a neurological abnormality is recognized, it is important to correct any contributing factors as soon as possible. Anaesthetic contribution to the loss of traces should be ruled out, the blood pressure normalized or even increased above normal values and anaemia corrected to maximize oxygen delivery to the spinal cord. If the loss of function can be attributed to a single event such as placing a sublaminar wire or hook this should be removed. If distraction has been applied it should be released. Doubts about the validity of monitoring may be by settled by a wake up test.

We perform the wake-up test as follows. An assistant at the patient’s feet watches for movement. The anaesthetist should be prepared to restrain the patient to prevent gross movement and accidental extubation. The volatile agent is turned off and the remifentanil infusion decreased to 0.1 µg/kg/min. When the end tidal volatile concentration falls to 0.2 MAC or below the patient is asked to squeeze hands and then wriggle toes. When this occurs the volatile agent is reintroduced and a small dose of hypnotic agent may be given, bearing in mind that this will interfere with spinal cord monitoring for some time. Using our current monitoring we perform about one wake-up test per year.

Methylprednisolone 30 mg/kg should be administered followed by infusion of 5.4 mg/kg/hr for any persistent deficits in line with accepted spinal cord injury protocols54,55. The same measures should be applied if deficits appear in the postoperative period. Reversal of paraplegia has been reported with restoration of normal blood pressure, correction of anaemia and release of distraction56.

From all of the above it is clear that successful intraoperative neurophysiological monitoring requires close cooperation between the surgeon, anaesthetist and neurophysiologist conducting the monitoring. The cost of monitoring at CHW includes an initial equipment set-up cost of A$60,000, a cost/case of A$200 in disposable electrodes and the hourly cost of the neurophysiologist.

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Blood loss and Coagulopathy

Scoliosis correction may be associated with major blood loss (>50% of blood volume) and the development of coagulopathy. Blood loss is related to length of procedure and number of segments fused. About a third of the blood loss occurs in the postoperative period. The 24 hour blood loss has been calculated at about 200 ml/segment fused. The coagulopathy is both dilutional and consumptive, and also related to the length of procedure and number of segments fused. Patients with neuromuscular disease may be particularly at risk because of a number of factors. They often have longer procedures with more segments fused. They have osteopenic bone which bleeds more and requires sublaminar wiring, rather than laminar hooks, prolonging the procedure. They may also have subclinical coagulation abnormalities.

Large bore intravenous access with an efficient fluid warmer and an intra-arterial line for monitoring arterial pressure and blood sampling is necessary for all patients. Careful monitoring of blood loss is important. Central venous access is indicated in patients who may need inotropic support, those having combined procedures and those in whom peripheral access is difficult. CVP may not accurately reflect cardiac filling in the prone position. Transoesophageal echocardiography (TOE) may be more useful for patients with cardiac defects to more accurately assess filling.

Many strategies to reduce blood loss have been described. Simple measures such as infiltration of skin with dilute local anaesthetics containing 1:500,000 adrenaline and ensuring free abdominal movement reducing venous pressure are important. Controlled hypotension has been widely advocated, and does reduce blood loss, at least intraoperatively, but may also be associated with increased risk of neurological deficit because of reduced spinal cord perfusion, particularly if this is compromised by distraction. Recommendations are now more conservative, with control of mean arterial pressure limited to 70 mmHg, a figure easily achieved with a regime of high dose remifentanil and sub-MAC volatile agent without the need to resort to other measures to induce hypotension described in standard texts.

Antifibrinolytics have been shown to reduce blood loss during scoliosis surgery, particularly in patients with neuromuscular disease. The serine protease inhibitor aprotinin is the most studied and the most effective, halving blood loss in high-risk patients. There is a risk of hypersensitivity reactions, particularly with re-exposure within six months, so aprotinin should not be reused during staged procedures. We confine aprotinin use to high risk patients and use a dose of 15000 KIU/kg loading dose over 20 minutes and 7500 KIU/kg/hr for the duration of the operation.

Reduction in exposure to allogeneic blood transfusion can be achieved by preoperative autologous donation, acute normovolaemic haemodilution and intra-operative cell salvage. Preoperative autologous donation has been discussed. We do not use acute normovolaemic haemodilution because of the possible exacerbation of any spinal cord ischaemia by anaemia, although other units use it routinely. We do use cell salvage, particularly in patients at high risk. In small patients, allogeneic transfusion is often needed before there is enough processed blood from cell salvage to return to the patient.

Air embolism

Air embolism should be considered in the differential diagnosis of sudden cardiovascular collapse in patients operated on in the prone position. Initial management should follow standard lines of preventing further air entrainment, ventilation with 100% oxygen, fluid boluses, and attempts to aspirate air from the heart. In a report of two cases of fatal air embolism, central catheters were not able to aspirate air. Paradoxical air embolism has also been reported. Cardiac arrest in the prone position is difficult to manage, but successful resuscitation has been reported using posterior thoracotomy for both internal cardiac massage and defibrillation. External cardiac massage in the prone position has also been used successfully, but it is hard to see how effective compressions could be obtained on the four-poster frame commonly utilized for scoliosis surgery. If the spine is stable the wound should be covered and the patient turned onto a bed for resuscitation, if unstable then consideration given to left posterior thoracotomy and internal massage. Consideration should be given to the placing of external defibrillator pads in patients at particular risk of cardiac arrest such as those with DMD. Fat embolism has also been reported as a rare complication of scoliosis surgery.

Visual loss

The reports of visual loss in patients having prone spinal surgery have been in adults. The most common cause is thought to be ischaemia of the optic nerve. Optic nerve and retinal perfusion pressure depends on maintaining the difference between arterial pressure and intra-ocular pressure or CVP. The risk factors for postoperative visual loss are the same as those for vascular disease plus intra-operative hypotension, anaemia and prolonged surgery. Prone
Positioning is known to cause a rise in intraocular pressure related to the length of surgery\(^7\). Slight head up positioning may reduce somewhat the rises in intraocular pressure and the facial oedema that occurs with prolonged prone positioning. The eyes must be checked regularly throughout surgery to ensure there is no external pressure being applied, particularly as patient movement may change the initial head position.

**Postoperative Management**

**Pain Control**

Effective pain control and active rehabilitation following scoliosis correction requires a multimodal regimen of pain management\(^7\). Spinal and systemic opioids, local anaesthetic techniques and NSAIDs are the major components.

Intrathecal morphine has been shown to be associated with reduced intraoperative bleeding and better postoperative analgesia than systemic morphine alone in scoliosis surgery\(^2\). At CHW we use spinal morphine 5 µg/kg, to a maximum of 300 µg, administered intrathecally preoperatively by the anaesthetist or, if this is difficult, intraoperatively by the surgeon. If these routes are not feasible the drug may be administered caudally in a dose of 50 µg /kg to a maximum of 3 mg. Intrathecal morphine does not interfere with CMAP monitoring and seems to decrease the amount of intraoperative remifentanil required. It results in smooth emergence from high dose remifentanil anaesthesia. Patient controlled analgesia (PCA) with morphine is added to this regimen, initially with a small bolus dose of 10 µg /kg. After 12-24 hrs the bolus dose can be increased and a background infusion commenced if necessary. For patients incapable of using a PCA, nurse controlled analgesia (NCA) can be initiated.

Opioids used alone can result in excessive sedation, nausea, vomiting and ileus and do not alleviate pain on movement. For posterior spinal surgery, surgically placed epidural catheters can be utilized\(^71,72\). We prefer to use PCA systemic morphine, as described above, rather than continuing epidural or spinal opioids. For anterior corrections, a catheter can be placed in the paravertebral space, underneath the reconstituted parietal pleura, and used for a continuous infusion of local anaesthetics. In some patients we have found these infusions have provided very effective analgesia. In others, the blocks appear patchy, presumably because of interruptions to the epidural or paravertebral space by surgery.

The use of NSAIDs in scoliosis surgery is controversial. NSAIDs provide effective pain relief and reduce opioid requirements\(^79\). A study in rats using high dose indomethacin showed interference with bone fusion\(^8\). The clinical relevance of this study has been questioned, due to the extremely high doses of indomethacin used. Nevertheless, a retrospective study of 288 patients undergoing instrumented lumbar spinal fusion showed a significantly higher number of failed fusions in the group given ketorolac for analgesia. The rate of failure seemed dose-related\(^75\). Ketorolac was given to those patients whose pain was not well controlled by opioids and perhaps pain was an indicator of failed fusion. A later prospective study of 35 adolescent patients showed the expected improvements in analgesia in the ketorolac group with no difference in failed fusion at two year follow up\(^3\). Failed fusion in adolescent idiopathic scoliosis surgery is extremely rare and a large prospective study would be required to demonstrate any effect of NSAIDs.

The COX-2 specific NSAIDs show similar analgesic efficacy and opioid sparing to conventional NSAIDs in adult spinal fusion patients\(^7\) and a parenteral preparation, parecoxib is available\(^8\). In an animal model, the COX-2 specific NSAID, celecoxib, did not affect the rate of bony fusion\(^3\), but celecoxib and rofecoxib resulted in non-union of fractures in another animal model and it seems COX-2 is needed for fracture healing\(^4\). The significance of these findings for short-term perioperative use is unknown. The COX-2 specific NSAIDS do not affect platelet function. As bleeding into drains can continue for some time following spinal corrective surgery the COX-2 specific agents would seem a logical choice of NSAID in these patients, though studies in children are lacking and they are yet to be licensed for use in children. The pharmacology of these agents of relevance to anaesthesia has recently been reviewed\(^8\).

Ketamine, as an opioid-sparing component of a postoperative analgesic regimen, has met with mixed results in clinical studies despite theoretical considerations and animal studies suggesting it should be effective\(^8\). A recent study showed that low doses in recovery were highly effective in treating morphine resistant pain\(^\)\(^8\). Other studies showed it to be ineffective when routinely added to PCA regimes for abdominal surgery\(^6\)\(^\)\(^7\). We reserve ketamine’s use postoperatively for patients with continued pain or opioid use resulting in excessive sedation with our usual protocol. It may be added to a PCA in a dose ratio of 1:1 with morphine\(^6\) or separately as a continuous infusion.

**Other Postoperative Complications**

The Superior Mesenteric Artery Syndrome is thought to arise because of compression of the third
part of the duodenum between the superior mesenteric artery and the aorta, the relationship between these structures having been distorted by correction of scoliosis. It has been reported after cast bracing and Harrington rod instrumentation, but is thought to be less common after modern instrumentation techniques. Symptoms consist of nausea and intermittent bilious vomiting occurring up to twelve days after surgery. Abdominal pain and distension may occur in 50% of cases. It usually settles with conservative management.

Problems with fluid management

Careful fluid management is required postoperatively with hourly urine measures and replacement of ongoing losses. Ileus is inevitable but can be minimized by avoiding nitrous oxide and utilizing a multi-modal analgesic regimen. We do not now routinely place nasogastric tubes. The postoperative period is associated with high levels of ADH, which may contribute to oliguria. Hypotonic fluid administration in the face of high ADH levels will lead to hyponatraemia and hypo-osmolality. Assessment of the patient’s volume status should precede fluid administration to correct oliguria if the problems associated with perioperative fluid excess are to be avoided.

Respiratory complications

Atelectasis and deterioration in respiratory function is common following surgery and an intense postoperative analgesic regimen should be utilized to provide frequent physiotherapy and early mobilization. Chylothorax has been reported rarely after anterior surgery along with other more usual post-thoracotomy complications of air-leak, haemothorax and persistent chest pain. Deterioration in bulbar function has been reported following surgery in patients with myotonic dystrophy.

CONCLUSION

Anaesthesia for scoliosis surgery has evolved over the last decade. New drugs and techniques allow continuous intraoperative monitoring of motor pathways, permitting safer correction. Modern perioperative care has enabled surgery in patients previously considered unsuitable. Because of concerns about spinal cord ischaemia there is now less emphasis on induced hypotension to reduce blood loss and allogeneic transfusion requirements with increased emphasis on antifibrinolytic therapy and cell salvage. The postoperative course of patients has been improved by multi-modal postoperative pain therapy. The success of this surgery requires a dedicated team approach.

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