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COMPLICATIONS IN SPINE SURGERY (E KLINEBERG, SECTION EDITOR)

Neurological complications in adult spinal deformity surgery

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Abstract The number of surgeries performed for adult spinal deformity (ASD) has been increasing due to an aging population, longer life expectancy, and studies supporting an improvement in health-related quality of life scores after operative intervention. However, medical and surgical complication rates remain high, and neurological complications such as spinal cord injury and motor deficits can be especially debilitating to patients. Several independent factors potentially influence the likelihood of neurological complications including surgical approach (anterior, lateral, or posterior), use of osteotomies, thoracic hyperkyphosis, spinal region, patient characteristics, and revision surgery status. The majority of ASD surgeries are performed by a posterior approach to the thoracic and/or lumbar spine, but anterior and lateral approaches are commonly performed and are associated with unique neural complications such as femoral nerve palsy and lumbar plexus injuries. Spinal morphology, such as that of hyperkyphosis, has been reported to be a risk factor for complications in addition to three-column osteotomies, which are often utilized to correct large deformities. Additionally, revision surgeries are common in ASD and these patients are at an increased risk of procedure-related complications and nervous system injury. Patient selection, surgical technique, and use of intraoperative neuromonitoring may reduce the incidence of complications and optimize outcomes.

Keywords Adult spinal deformity · Surgery · Neurological complications · Nerve injury · Revision · Osteotomies

Introduction

Adult spinal deformity (ASD) consists of a range of disorders that are categorized by abnormal spinal alignment in the axial, coronal, and sagittal planes [1]. The prevalence of ASD is greater than 60 % in people over the age of 60 years [2] and is projected to increase over the next several decades due to an aging population, longer life expectancy, and greater awareness [3]. Symptomatic patients commonly complain of pain and disability evidenced by poor health-related quality of life (HRQOL) scores [4]. The recognition of key spinopelvic parameters and disability thresholds [5–7], in conjunction with new classification systems [8, 9], has helped guide the treatment of ASD. Operative intervention has been shown to improve HRQOL [10]. However, surgery can be associated with high complication rate [11–15], which increases in older age groups [16, 17]. Despite higher complication rates, older patients may improve disproportionately compared to younger patients who have undergone surgery [4] in several assessments including the Oswestry Disability Index (ODI), Scoliosis Research Society (SRS)-22, and back and leg pain numerical rating scales.

We review neurological complications related to ASD surgery. Several independent factors influence the likelihood of complications, including surgical approach (anterior, lateral, or posterior), use of osteotomies, kyphosis, spinal region, patient characteristics, and revision surgery status [18, 19]. Intraoperative neuromonitoring (IONM) may also have a role in identifying and preventing neurological complications.

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Patient selection

Age and comorbidities

Age and various comorbidities influence complication rates in deformity surgery. Advanced age has been shown to correlate with increased rates of major complications and mortality. No studies have demonstrated a link between age and neurologic complications. Pulmonary disorders, renal failure, coagulopathy, and congestive heart failure have also been demonstrated to increase patient morbidity and mortality rates. No studies have yet demonstrated a significant correlation between general health or particular comorbidity and neurologic complications. While there may be a relationship between neurologic compromise and age or comorbidity in ASD, it is more likely confounded by the magnitude of deformity with which these patients present [20, 21•].

Revision surgery

Revision surgery may be a risk factor for neurological complications because of altered anatomy, requirement for osteotomies through fusion masses, scar tissue, and the existence of preoperative neurological deficits compared to primary surgery patients [21•]. In a nationwide study of 10,912 ASD patients, those who underwent revision surgery had a higher rate of procedure-related complications (72 vs. 47 %, *p* = 0.0001) and increased risk of nervous system injury (odds ratio (OR) = 1.34 [1.10–1.60]) and accidental vessel or nerve puncture (OR = 1.44 [1.29–1.61]) [21•]. This increased risk of neural complications is supported by other studies [22, 23] including an SRS review of 108,419 spine surgeries that reported a 41 % higher rate of neural complications after revision compared to primary surgery [24]. However, Hassanzadeh et al. [25] compared complications of 167 primary and revision ASD surgeries and did not find a statistically significant increased rate of major complications in the revision group, despite requiring significantly more three-column osteotomies (3-COs) than the primary cohort. Postoperative motor deficits in the revision compared to the primary group occurred in 3.7 and 0 % of patients, respectively.

Cervical deformity

The majority of ASD correction is performed in the thoracic and lumbar spine. However, there has been increasing interest in cervical parameters, the effect of thoracic and lumbar osteotomies on the cervical spine [26], and cervical deformity correction. A prospective multicenter center of 78 patients who underwent surgery for adult cervical deformity reported a 24 % major complication rate, 6.4 % of which were C5 motor palsies [27•]. He et al. [28] reviewed 316 patients who received posterior cervical fusions for mixed etiologies of deformities including post-traumatic and congenital. The intraoperative spinal cord injury (SCI) rate was 1.3 % and was most often secondary to direct injury and reperfusion after decompression. Nerve root injury, as confirmed by electromyography (EMG) monitoring, occurred in 1 % of cases and was due to improper lateral mass screw placement. SCI has also been reported as a sequelae of cervical hyperextension during intubation [29]. Alternative intubation techniques should be performed in patients with cervical myelopathy, post-traumatic deformities, instability, or other risk factors for SCI.

Vertebral artery injury (VAI) is a clinically significant complication that may result in neurological consequences during anterior or posterior approaches to the cervical spine. Lall et al. [30] reviewed complications associated with 2274 craniocervical fusion surgeries and found a VAI injury rate of 1.3–4.1 % during placement of C1–2 transarticular screws. The authors emphasized the recognition of a high-riding vertebral artery because injury occurred most commonly in these cases. Identification of other anomalies including a persistent first intersegmental artery, tortuous VA, and high entrance level into the transverse foramen is also important. Neurological sequelae occurred in 3.7 % of patients with unilateral VAIs in another study [31]. Nerve injuries and their incidences after anterior cervical surgery have been well-reported, including the recurrent laryngeal nerve (1.3–13.3 %) [32], superior laryngeal nerve (1 %), hypoglossal nerve (<1 %) [33], and cervical sympathetic chain (0.2–4 %) [34].

Thoracolumbar deformity

Surgery for ASD commonly involves multiple levels of the thoracic and lumbar spine within the same patient. Within each region, deformities may occur in the sagittal and/or coronal planes; require posterior, anterior, and/or lateral approaches; posterior spinal fusion (PSF)-only or circumferential fusion via interbody grafts; or osteotomies ranging from partial posterior resection to three-column osteotomies. Treatments are complex and heterogeneous among patients; thus, thoracic and lumbar regions are discussed within several sections below.

Neurologic complications based on surgical approach

Posterior

Posterior surgical techniques are the mainstay of treatment for ASD and may include decompression, fusion with instrumentation, and osteotomies for the correction of spinal alignment. Neural injury is relatively low for decompression and fusion [35], but the rate may be significantly higher when osteotomies are performed [17, 36–39] (Table 1). A retrospective study of 103 ASD patients who underwent posterior arthrodesis of at least seven levels (from the thoracic spine to pelvis) reported a 17 % incidence of new neurologic deficits which persisted at the final follow-up visit [40]. Deficits were defined as a motor score of less than 4 out of 5 or persistent pain confirmed by EMG. Of the 17 deficits, 9 were radiculopathies and 8 were incomplete spinal cord injuries. Motor weakness following spine surgeries has a variable recovery rate. SCI, a devastating complication, has a worse prognosis.

Surgery of the lumbar spine for ASD has a neurologic complication rate between 0.5 and 17 % and is dependent upon approach (anterior, lateral, or posterior), number of fusion levels, case complexity, and the study's ability to capture complications [41]. In a review of 2783 patients, the incidence of neurological deficits after posterior decompression and fusion was 1.9; 60 % of deficits were secondary to malpositioned screws (30 %) and bone morphogenetic protein (BMP)-radiculitis (30 %) [41]. Of the 1.9 % neural injury rate, 24 % were from radiculopathy or SCI after graft placement, sublaminar wires, or deformity correction. Pedicle screws are a known risk factor for new neural deficits due to extrapedicular placement [42].

In contrast, a review of 4980 cases from the SRS Morbidity and Mortality database found an overall neurological complication rate of 1.8 % ($n = 90$) without differences between anterior and posterior approaches [18]. Of these 90 deficits, 46.7 % were identified greater than 24 h after surgery and smaller percentages were determined either intraoperatively (13.3 %) or within 24 h of surgery (41.1 %). The majority (71/90 or 78.9 %) of deficits was secondary to nerve root injuries and had at least partial recovery. Of the 90 patients, 75 had documentation of their clinical course. Regarding nerve root injuries, 23 had complete recovery, 33 had partial recovery, and 2 had no recovery. Six of 11 patients with incomplete SCIs experienced complete relief and the remainder had partial relief. Three patients with cauda equina syndrome had partial relief, 1 patient had complete relief, and 1 had no recovery. However, functional outcome data was not available and detailed follow-up information was not reported. The authors also did not find an increased rate of neurological deficits in patients who were older, underwent revision procedures, or had osteotomies, which is in contrast to other studies [19].

Table 1 Risk factors for neurological complications

Malpositioned screws
BMP
EBL >3 L
Preoperative neural deficit
Age >60 years
Revision surgery
Hyperkyphosis
Large coronal plane deformities
PSF >5 levels
Multilevel LLIF and LLIF at L4–5
Prolonged surgical exposure (LLIF)
Thoracic level 3-CO (compared to lumbar)
Multilevel 3-COs (2 or more)
Prolonged surgery (<200 min)
Spinal cord shortening >100 % of one VB height

BMP bone morphogenetic protein, *3-CO* three-column osteotomy, *PSF* posterior spinal fusion, *EBL* estimated blood loss, *VB* vertebral body, *LLIF* lateral lumbar interbody fusion

Osteotomies are often performed via a posterior-only approach for correction of sagittal and coronal plane deformities. Osteotomies are classified by anatomic grades of resection [43] and increase in complexity from partial facet resection to complete removal of the vertebral body. The risk of neural injury may increase with bony resection and has been found to be greater with three-column (3COs) compared to posterior column-only osteotomies in some studies [44, 45], but not in others [46•].

Anterior

Anterior-posterior approaches in the thoracic spine have become less common than posterior-only techniques because of the difficulty approaching the curve concavity in large deformities, pulmonary complications from transthoracic approaches, and concern of SCI from anterior distraction forces [47]. Additionally, posterior-only procedures with instrumented fusion have been shown to provide adequate deformity correction with lower neural complications than combined approaches [41, 48]. However, anterior surgery of the lumbar spine is commonly performed in adult deformity patients and affords higher fusion rates than posterior-only procedures without iliac screw fixation [3].

Ghobrial et al. [41] reviewed studies from 2004 to 2015 which delineated the outcomes, cause, and follow-up of neurological complications after lumbar spine surgery. The pooled incidence of new neural deficits in the 12 included studies (2873 patients) after anterior or lateral lumbar interbody fusion (ALIF and LLIF, respectively) was 4.1 % and the most common complication was immediate radiculopathy with motor deficit after LLIF. ALIF has been associated with injury to the presacral superior hypogastric plexus and lumbar sympathetic trunk during exposure (Table 2). Ilioinguinal, iliohypogastric, and thoracoabdominal nerve injury, respectively, result in numbness of the upper inner thigh and perineum, lateral gluteal numbness, and paralysis of the internal and transverse abdominal muscles, and anterior abdominal numbness and rectus paralysis.

Table 2 Neurological complications of anterior and lateral lumbar surgery

	Structure	Clinical Finding	Incidence (%)	Recovery
Anterior[a]	Superior hypogastric plexus	Retrograde ejaculation	1.7–6	Partial to full in 33 % at 1–2 years
	Lumbar sympathetic trunk	Hyperthermia of ipsilateral lower extremity	4–10	Partial to full recovery in 76 %
	Nerve root	Radicular pain	4	Partial to full recovery in 75 %
Lateral[b]	Psoas muscle	Hip flexion weakness	1.6–54	Full recovery expected
	Femoral nerve			
	Motor	Leg extension and hip flexion weakness	1.4–24	Motor: Partial recovery in 100 %, complete recovery in 33–100 %
	Sensory	Thigh and leg numbness	10–83	Sensory: Partial to full recovery in 67–90 %
	Individual nerve root	Sensory loss Motor weakness	1–24 3–17	Partial to full recovery in 10 to 75 %
	Thoracoabdominal nerve	Abdominal wall bulge	2.8–4.2	Partial to full recovery in 50 %

[a] Anterior approach performed via retroperitoneal approach

[b] Lateral approach reflects retroperitoneal transpsoas exposure

Lateral

LLIF is a useful adjunct to posterior techniques in ASD surgery and provides several advantages to posterior-only surgery: LLIF is performed without the retraction of nerve roots, does not cause epidural fibrosis, and spares the stabilizing effect of the anterior longitudinal ligament. LLIF also improves segmental sagittal and coronal alignment, but it does not improve global balance as a standalone procedure [49]. Supplemental posterior fusion is recommended for the treatment of ASD.

LLIF performed through a retroperitoneal transpsoas approach is associated with approach- and surgery-related complications. In 2014, Lykissas et al. [50•] reported on the largest series evaluating neurological complications after LLIF in patients with deformity or degenerative conditions. Complications were studied immediately postoperatively, at most recent follow-up (mean, 15 months; range, 6–53 months), and at minimum 18 months follow-up ($n = 87$ or 21 %). Of the 415 patients (919 levels) who underwent standalone or supplemental fixation with posterior instrumentation, the incidences of immediate complications were 39 % for thigh pain, 38 % for sensory deficits, and 24 % for extremity weakness. At most recent follow-up, 5 % of patient reported anterior thigh pain, 24 % had sensory deficits, and 17 % exhibited motor deficits as found on manual muscle testing. However, patients who underwent standalone LLIF ($n = 160$) had lower rates of sensory and motor deficits at last follow-up (11 and 4 %, respectively) and when patients with preoperative deficits were excluded, the rates of persistent sensory and motor deficits were only 9 and 3 %, respectively. Among the 335 patients with surgery-related complications, 87 (26 %) had a minimum 18 month follow-up and of this group, 10 and 2 % had persistent sensory and motor deficits, respectively. A risk factor analysis identified L4–5 fusion level, LLIF of ≥4 levels, and use of recombinant BMP-2 as significant factors of motor deficit at latest follow-up. Another study of neural complications after LLIF reported left-sided approaches, exposure of the L4–5 level, and fusion of multiple levels as risk factors [51].

Psoas weakness has a reported incidence as high as 55 % [41, 52, 53] and is often due to muscle dissection [54]. Tormenti et al. [55] reviewed complications of adult scoliosis patients following combined transpsoas LLIF and PSF. Twenty-five percent of patients experienced sustained motor radiculopathies and 75 % had thigh dysesthesias after LLIF. Seventy-five percent of motor palsies persisted for 3 months and 83 % of sensory symptoms were present at latest follow-up (mean, 10.5 months). In a review of 235 patients (444 levels), sensory deficits were observed in 1.6 %, psoas weakness in 1.6 %, and lumbar plexus-related deficits in 2.9 % of patients at 1 year follow-up after LLIF [56]. Duration of surgery (odds ratio 1.01, 95 % confidence interval (CI) 1.01–1.01, $p = 0.009$) was the only risk factor for lumbar plexus-related deficits and, in addition to female sex (odds ratio 3.86, 95 % CI 1.10–13.50, $p = 0.034$), was also a risk factor for psoas mechanical flexion deficits. Patient positioning has also been implicated in iatrogenic nerve injury; L4 neuropraxia may occur from excessive side bending of the patient during lateral positioning as a result of increased psoas tension and reduced nerve root perfusion [57].

Kyphosis

Wang et al. [58] evaluated the safety of posterior-only vertebral column resection (VCR) in 24 patients with sharp, angular kyphotic deformities. The patient sample was heterogeneous and included children, adults, intraspinal anomalies, revision surgeries, patients with preoperative incomplete SCIs, and curves with apices in different regions of the thoracic and lumbar spine. Prior to surgery, the average segmental kyphosis measured 87° and improved to 20° at latest follow-up. Two (8.3 %) patients suffered neurological injuries: one incomplete SCI and one nerve root injury. The incomplete SCI occurred during osteotomy closure in a patient with preoperative SCI (American Spinal Injury Association [ASIA] C), which resulted in deterioration to an ASIA B. The cause of the nerve root injury was not reported and CT imaging was negative for malpositioned implants. However, nerve root injuries may occur during osteotomies because of insufficient bony resection and sagittal translation of the vertebral bodies. Shortening of the cord is an additional risk factor for SCI. The only study that has evaluated the consequence of progressive spinal cord shortening on cord function during vertebrectomy used a pig model and concluded that shortening of 104 % of one vertebral body height at the thoracolumbar level caused SCI [59].

Papadopoulos et al. [47] reported on 45 hyperkyphotic patients treated by posterior-only VCR for congenital and post-tuberculous kyphosis. Average preoperative kyphosis measured 108° and improved to 60° postoperatively. IONM changes occurred during 22 % of the surgeries, but only 30 % of the patients with IONM changes developed neurological complications. One (2.2 %) patient developed a complete SCI and two patients had postoperative nerve root injuries (one transient L1 injury and one permanent S1 injury). IONM changes were the results of hypotension, cord manipulation, and osteotomy closure. Another study reported a 22-fold increased risk of developing a postoperative neural deficit in patients with preoperative kyphotic deformity compared to patients without kyphosis [37]. The reason is because the spinal cord is draped over the curve apex and under tension, which results in cord injury when the spine is extended via osteotomies. The spinal cord in double major curves in the setting of adult scoliosis is another situation in which the cord should be presumed to be under tension at the thoracolumbar transition zone.

The duration of spinal cord compression in hyperkyphotic patients prior to spinal realignment and decompression may be predictive of injury. All patients with IONM changes in the study by Papadopolous et al. [47] had chronic spinal cord compression. Another study found substantially better outcomes after decompression for hyperkyphosis secondary to Pott's disease in patients with active versus healed disease [60]. Zhang et al. [61] reviewed their series of 10 patients (adult and pediatric) with compressive myelopathy in severe angular kyphosis. No adult patients deteriorated in neurological status postoperatively; however, patients who underwent decompression and stabilization less than 2 years after symptom onset improved one to two ASIA grades whereas patients with longer durations between onset and surgery had either no improvement or only "slight improvement."

Large coronal plane deformities

A prospective, multicenter Scoli-RISK-1 study of 256 ASD patients with ≥80° of coronal and/or sagittal deformity reported a 22 % incidence of new lower extremity motor weakness at time of discharge [62•]. Seventy-six percent of patients underwent posterior-only surgery and 79 % were treated with 3-COs. Rates of lower extremity motor weakness significantly improved from time of discharge to 6 weeks (17.2 %, $p = 0.0042$) and from 6 weeks to 6 months after surgery (10.8 %, $p = 0.0011$) [62•]. Compared to patients with normal preoperative neurological function, those with preoperative deficits had a significantly greater rate of postoperative deficits (25.8 vs. 21.0 %, $p < 0.0001$). The reported neural complication rate is the highest to date [62•], surpassing rates in other studies of coronal deformities >80° [39, 63–65]. These rates more likely reflect the true incidence of neurological complications after complex ASD surgery because retrospective studies are limited by incomplete follow-up, imperfect documentation, and detection bias. The Scoli-RISK-1 study utilized a standardized outcome measure for lower extremity motor weakness and is the only prospective study [66–70] to quantify neural function both pre- and postoperatively.

Neurologic complications by surgical technique

Interbody grafts

Interbody grafts can be placed from anterior, lateral, or posterior approaches. Laterally placed grafts are biomechanically equivalent to those placed from an anterior approach [71], and ALIF grafts have larger cage footprints and greater biomechanical stability compared to posterior-based interbodies [72]. Both ALIF and LLIF indirectly decompress the neural foramina and avoid iatrogenic injury to the posterior musculature [3]. However, nerve root injury may be incurred by incomplete discectomy (displacement of disk material during implanting of interbody), encroachment of the interbody into neural foramina, and over distraction of the disk space by an excessively large graft [73].

Three-column osteotomies

Transient nerve root injuries are the most common neurological complication of 3-COs performed by a posterior-only approach [39, 47, 74, 75] although SCI is also an established complication. Bianco et al. [19] reported on 423 ASD patients who underwent three-column osteotomies at eight centers.

The rate of intra- and postoperative neurological deficits was 18.6 %; intraoperative complications had a 7 % incidence and were most commonly from SCIs (2.6 %). The incidence of postoperative neural complications was 17 % and were grouped by motor deficit or paralysis ($n = 51$), cauda equina syndrome ($n = 2$), and bowel or bladder dysfunction ($n = 20$). The most common postoperative complications were unplanned return to surgery (19.4 %), motor deficit or paralysis (12.1 %), and bowel or bladder dysfunction of which 4.5 % were secondary to neurological complications. Clinical outcome data was not reported. Patients with higher complication rates were more likely to have undergone two rather than one osteotomy (56 vs. 38 %, $p = 0.04$), thoracic versus lumbar osteotomies (16 vs. 6 %, $p = 0.03$), and be greater than 60 years of age. Daubs et al. [20] similarly concluded that patients over 60 years and those that had 3-COs were significantly more likely to experience a major complication. In their study of 46 patients, 20 % had at least one major complication and the majority was due to neurological deficits (44 %).

Kim et al. [37] found a postoperative neural complication rate of 14 % in a study of 233 patients who underwent 3-COs via a posterior-only approach. Eighteen percent of patients with neurological complications had permanent deficits and the remainder experienced only transient symptoms, which were most commonly caused by hematomas (56 %), lumbar nerve injury (26 %), and incomplete resection of bone at the osteotomy site (11 %). Hematomas have been implicated as a reversible cause of neurological deterioration and should be treated urgently to avoid catastrophic consequences [28]. Significant risk factors for postoperative neurological complications included preoperative neural deficit, instrumented fusion of greater than five levels, duration of surgery greater than 200 min, estimated blood loss greater than 3 L, and resection of two or more vertebrae ($p < 0.05$). Most notably, the presence of a preoperative neural deficit increased the risk of acquiring a postoperative deficit by a factor of over 20. Decancellation procedures (egg shell and pedicle subtraction osteotomies) had a similar rate of neurological complications as VCRs ($p > 0.05$).

Interestingly, a multicenter study of 207 prospectively collected ASD patients did not find a higher rate of neural complications in those undergoing 3-COs ($n = 132$, VCR or pedicle subtraction osteotomy [PSO]) compared to those who did not ($n = 75$, posterior spinal fusion-only) [46•]. The incidence of neurological deficits for those undergoing PSF-only was 6.7 versus 9.8 % ($p = 0.435$) for osteotomy patients. Regarding 3-CO patients, VCR compared to PSO was associated with a higher rate of medical complications, but postoperative neural deficits were similar (15.8 vs. 8.8 %, respectively; $p = 0.348$).

Intraoperative neuromonitoring

IONM provides information about neural functioning and may mitigate both temporary and permanent impairments [76]. Somatosensory-evoked potentials (SSEPs) are valuable in the direct monitoring of sensory pathways and provide indirect information about motor tracts. Motor-evoked potentials (MEPs) are commonly used in conjunction with SSEPs because they evaluate the corticospinal motor tracts and nerve roots better. In the series by Papadopoulos et al. [47], nearly 98 % of patients with IONM changes were managed by intraoperative protocols and avoided neurologic sequelae. IONM is invaluable in the management of ASD and especially in patients with hyperkyphosis, double major curve patterns, and other extreme curvatures.

However, understanding the limitations of IONM is essential to minimizing neurological complications. False negative SSEP readings can result in injury to motor tracts and nerve roots because SSEPs (1) indirectly assess motor pathways and (2) represent signal averaged data. A review of 38 adolescent idiopathic scoliosis patients with intraoperative signal changes found that SSEPs failed to identify motor deficits in nearly 60 % of patients with confirmed deficits, MEPs were more sensitive than SSEPs at detecting motor loss (100 vs. 43 %), and changes in SSEPs lagged behind MEPs by approximately 5 min [77]. Myelopathy, which may be present in ASD patients, can negatively affect the sensitivity of MEP recordings [78] and must therefore be considered in preoperative planning.

Management protocols for high-risk spine patients with IONM changes have been developed [79, 80]. Ziewacz et al. [79] published a checklist for IONM changes in ASD patients and emphasized the importance of a team approach. At time of signal change, the surgeon has several roles which include reducing compression or stretch on the spinal cord, stopping manipulative maneuvers, identifying misplaced implants, performing further decompression if stenosis is present, and reversing deformity correction. The anesthesia team should consider withholding inhalational agents, reducing intravenous anesthetics, confirming absence of neuromuscular blockade, applying a train of four twitches, maintaining hemoglobin to >9–10 g/dL, and increasing mean arterial pressures to at least 90 mmHg. The neurophysiologist's role is to repeat signals for ruling out false positive findings, confirm the correct placement of all leads, check for equipment malfunction, and assess for symmetric versus asymmetric changes which signifies anesthesia and blood pressure-related causes rather than spinal cord or nerve root injury, respectively.

Advancements in neuromonitoring have also focused on reducing iatrogenic nerve injury during transpsoas approaches. EMG without MEPs has been unsuccessful in preventing postoperative weakness caused by lumbar plexus injury [81]. Spontaneous and triggered EMG is sensitive for direct nerve injury, but is not reliable for indirect nerve injuries from prolonged compression of the nerves between the retractor blades and the transverse processes. MEPS, however, have recently shown promise [82, 83] and can be used with spontaneous and triggered EMG. Triggered EMG is recommended for transpsoas dissection and placement of retractor blades whereas MEPs can detect indirect nerve injury. However, the interpretation of MEPs is affected by radicular overlap (overlapping muscle innervation from adjacent roots) [82], limited sampling of motor neurons (MEPs measure about 4–5 % of motor axons in a muscle) [84], and variable excitability of neurons, anesthetics, and hypotension [85].

Conclusion

Surgical treatment of ASD patients is associated with relatively high neurological complication rates that range in severity from transient sensory dysesthesias to complete spinal cord injury. The large range of complications reported in the literature is likely affected by surgeon experience, study designs, lack of established definitions of complications [21•], variable approaches, and patient selection, among other factors. However, the continued identification and evaluation of neural complications, development of techniques to minimize neural injuries, and patient education will help to reduce and manage these complications.

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Compliance with ethical standards

Conflict of interest Justin Iorio and Patrick Reid declare that they have no conflicts of interest. Han Jo Kim is a consultant for K2M and Zimmer Biomet.

Human and animal rights and informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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