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RESEARCH

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Deformity angular distance ratio independently predicts intraoperative neuromonitoring alerts in spinal deformity correction

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Abstract

Background Intraoperative neuromonitoring (IONM) alerts are critical concerns for surgeons performing spinal deformity corrective surgeries, as they indicate a heighteded risk of postoperative neurological deficits. Previous studies have demonstrated that patients with large Cobb angle or elevated deformity angular ratio (DAR) are at an increased risk of IONM alerts. However, spinal curves with similar Cobb angles and DARs may exhibit significantly different risks of IONM alerts during surgery. Current methods for evaluating spinal deformity fail to comprehensively and accurately reflect its severity. The purpose of this study was to investigate whether the deformity angular distance ratio (DADR) serves as an independent predictor of IONM alerts during corrective surgery for spinal deformity.

Methods This study analyzed a consecutive series of 404 patients undergoing corrective surgery at a single academic center. Preoperative radiographs were used to calculate the DAR and DADR. Twelve clinically relevant candidate variables were selected for univariable analysis. Multivariable logistic regression analysis was then conducted to identify independent predictors of IONM alerts.

Results The incidence of IONM alerts in this cohort was 25.2%. Univariable analysis identified several factors potentially associated with IONM alerts, including older age, type-III spinal cord morphology, location of apex, etiological diagnosis, preoperative sagittal Cobb angle, sagittal DAR, sagittal DADR, coronal DADR, total DAR, total DADR, three-column osteotomy, and preoperative neurological deficits. Multivariable analysis revealed that an apex location at C7-T4, preoperative neurological deficits, sagittal DADR, and total DADR were independent predictors of IONM alerts.

Conclusions Among patients undergoing corrective surgeries for spinal deformities, the DADR is a robust measure of spinal deformity severity and is strongly correlated with the risk of IONM alerts. Compared to other deformity parameters, DADR is an independent predictor of IONM alerts. Additional independent predictors include the location of the apex and the presence of preoperative neurological deficits.

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Keywords Spinal deformity, Deformity angular distance ratio, Corrective surgery, Intraoperative neuromonitoring alert, Neurological deficits

Introduction

Corrective surgery for spinal deformities is a complex and technically demanding procedure, with a significant concern being the potential for neurological deficits resulting from intraoperative spinal cord compression, hypoperfusion, traction, or direct mechanical injury. Such injuries may occur during pedicle screw placement, osteotomy, or corrective procedures involving misguided instrumentation [1–3]. According to the literature, the incidence of transient neurological deficits following spinal deformity correction surgery ranges from 1.2 to 19.0% [2, 4–11], while the incidence of permanent neurological deficits varies between 0% and 4.8% [4–6, 11]. Given the high risk of neurological deficits, intraoperative neuromonitoring (IONM), which is suggested to be a raliable predictor of imminent spinal cord injury, has become a critical real-time tool for assessing nerve function during surgery [12]. However, IONM alerts, which indicate potential nerve compromise, are undesirable events, with reported incidences ranging from 5.3 to 32.9% [2, 4, 8, 9, 13, 14]. Furthermore, despite established protocols for managing IONM alerts, 15.6–51.0% of these events ultimately result in postoperative neurological deficits [2, 8, 9]. Although IONM alerts indicate an increased risk of neurological deficits, they do not always lead to postoperative neurological deterioration, as timely intraoperative interventions can influence outcomes. Nevertheless, further investigation into the risk factors associated with IONM alerts remains crucial for surgical decision-making, enabling prompt intraoperative adjustments and potentially reducing the risk of neurological injury.

Known risk factors for IONM alerts during corrective surgery include older age, larger curve magnitudes, apex location in the upper thoracic spine, post-tuberculosis or congenital deformities, type-III spinal cord morphology, three-column osteotomy (3CO), and preoperative neurological deficits [1, 8, 15–17]. Regarding preoperative imaging parameters, previous studies have found that large Cobb angles are associated with a higher risk of IONM alerts [14]. However, curves with similar Cobb angles and location can exhibit significantly different risks of IONM alerts or neurological deficits during surgery [18, 19]. It is intuitive that sharp, angulated deformities are at a higher risk for IONM alerts compared to more globally rounded curves. To quantify this, Wang et al. introduced the deformity angular ratio (DAR), defined as the curve magnitude per spinal level, which combines both the magnitude and sharpness of the deformity [20]. Current studies have confirmed that a high DAR is significantly correlated with an increased incidence of IONM alerts [1, 5].

Unlike the Cobb angle, which only quantifies the deformity angle, DAR partially reflects the spatial distribution of the deformity by considering the ratio of the Cobb angle to the number of affected vertebrae. However, DAR assumes uniform vertebral height and regular morphology, making it less suitable for evaluating the sharpness of deformities in cases of vertebral fusion or developmental anomalies. In clinical practice, we have observed that DAR may underestimate the severity of deformity in cases involving significant vertebral abnormalities or vertebral fusion, particularly in congenital and post-tuberculous spinal deformities. To address this limitation, Ni et al. proposed the deformity angular distance ratio (DADR), defined as the Cobb angle divided by the distance (in centimeters) between the midpoint of the upper endplate of the upper vertebrae and the midpoint of the lower endplate of the lower vertebrae, which can directly quantify the angular density per unit length [19]. The DADR provides a more accurate reflection of deformity severity and has been identified as a potential predictor of postoperative neurological deficits. However, due to a limited number of positive cases, the authors did not perform multivariate analysis to determine whether DADR is an independent predictor of postoperative neurological dysfunction. Therefore, the purpose of the present study is to investigate whether DADR is an independent influencing factor for IONM alerts in patients undergoing spinal deformity corrective surgery.

Methods

Patient population

The records of patients with spinal deformities who underwent corrective surgery at a single academic center between April 2010 and June 2024 were retrospectively reviewed. Patients were included in the study if they had complete medical records, imaging data, and IONM data. The exclusion criteria were as follows: (1) Patients with severe spinal trauma within three months prior to surgery; (2) Patients with a history of drug dependence, mental disorders, or malignancy; (3) Patients with active infection; (4) Patients with deformity apex locating below L2 or above C7; (5) Patients with mild deformities (Cobb < 20° or 20°–45° without symptoms/progression); and (5) Patients with insufficient baseline neuromonitoring data.

Demographic data, including age, sex, and etiological diagnosis, were collected. Based on established clinical and radiological criteria, etiological diagnoses were categorized as congenital, post-tuberculous, or others (e.g., idiopathic, post-traumatic, degenerative, etc.). All patients underwent posterior-based osteotomy, instrumentation and fusion using pedicle screw/rod constructs, with the primary goals of deformity correction or neurological improvement. Preoperative X-rays and magnetic resonance imaging (MRI) were obtained within three months before surgery. This study received ethical approval from Medical Science Research Ethics Committee of our hospital (M2024619).

Imaging evaluation

Preoperative and postoperative X-rays of the entire spine in both anteroposterior and lateral positions were obtained for all patients. Using the Picture Archiving and Communication System (PACS) (GE Healthcare, Mount Prospect, IL), the following parameters were measured from the X-rays: major sagittal and coronal Cobb angles, DAR (defined as the Cobb angle divided by the number of vertebrae spanning from the upper to the lower end vertebra), including coronal DAR (C-DAR), sagittal DAR (S-DAR), and total DAR (T-DAR = C-DAR + S-DAR), as well as the DADR. The DADR is defined as the Cobb angle divided by the distance (in centimeters) between the midpoint of the upper endplate of the upper end vertebrae and the midpoint of the lower endplate of the lower end vertebrae, which includes coronal DADR (C-DADR), sagittal DADR (S-DADR), and total DADR (T-DADR = C-DADR + S-DADR) (Fig. 1). In the present investigation, we used the maximum DAR and DADR values from each coronal curves as the patient's "coronal" DAR and DADR when multiple curves were present. Similarly, the DAR and DADR calculated from the maximum kyphosis were used as the patient's "sagittal" DAR and DADR to represent the acuteness of the spinal deformity. Additionally, the location of the deformity apex was recorded and categorized into three regions: C7-T4, T5-T8, and T9-L2.

Preoperative MRI was performed in all patients using either a 1.5T or 3.0T system (Siemens, Germany or General Electric, Boston, MA) to detect occult neurological abnormalities and mitigate perioperative neurological risks. Spinal cord morphology at the apex of the curve was classified according to the spinal cord shape classification system (SCSCS) described by Sielatycki et al. [21]. Based on T2-weighted axial MRI, we classified spinal cord morphology into three types: Type I, with a symmetrical spinal cord shape and visible cerebrospinal fluid (CSF) between the spinal cord and osseous structures; Type II, with a symmetrical spinal cord shape but no visible CSF between the spinal cord and osseous structures; and Type III, where the spinal cord is deformed against the apical concave pedicle/vertebral body, with no CSF between the spinal cord and the osseous structures (Fig. 2).

IONM and standardized intraoperative procedures for IONM alerts

IONM, including motor evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs), was performed and recorded for all patients. At our institution, IONM alerts were defined as: (1) a $\geq$50% reduction in amplitude and/or a $\geq$10% increase in latency in SSEPs, and/or (2) a $\geq$80% reduction in amplitude in MEPs despite a sustained increase of 100 V above baseline stimulation. These thresholds align with consensus guidelines [1, 8, 16]. Suspected false positives underwent a three-step protocol: technical troubleshooting, repeated stimulation, and clinical correlation via wake-up tests or postoperative neurological exams. Alerts resolved without intervention or unrelated to deficits were classified as false positives.

All IONM alerts were systematically managed through a standardized protocol adapted from consensus guidelines and prior studies [6, 8, 9, 22]. First, technical integrity was verified, including electrode positioning and signal baseline stability. Second, physiological parameters were optimized: mean arterial pressure (MAP) was elevated to >80 mmHg, hemoglobin maintained >10 g/dL, and reduced the anesthetic depth. Third, surgical interventions were implemented if alerts persisted, including reversal of corrective forces, localized decompression, or osteotomy completion. Unresolved alerts prompted wake-up test to confirm motor function.

Additionally, preoperative and postoperative neurological symptoms, somatic sensations, lower limb muscle strength, tendon reflexes, pathological signs, lower extremity motor score (LEMS) [19], and urinary and bowel function were assessed for all patients by reviewing their medical records. Postoperative neurological deficit was defined by the presence of at least one of the following criteria, excluding neurological symptoms caused by postoperative epidural hematoma formation: (1) a loss of 5 or more points in LEMS; (2) a score loss of 2 or more points in any lower extremity key muscle group; or (3) new urinary or bowel dysfunction.

Statistical analysis

Data were analyzed using SPSS software version 26 (SPSS Inc., Chicago, IL). The normality of the data was assessed using the Kolmogorov-Smirnov test (K-S test) or the Shapiro-Wilk test (S-W test). Continuous variables that followed a normal distribution were presented as the mean and standard deviation (SD), while non-normally distributed variables were described as the median and interquartile range (IQR). Categorical data were reported as frequencies and percentages. Twelve candidate variables

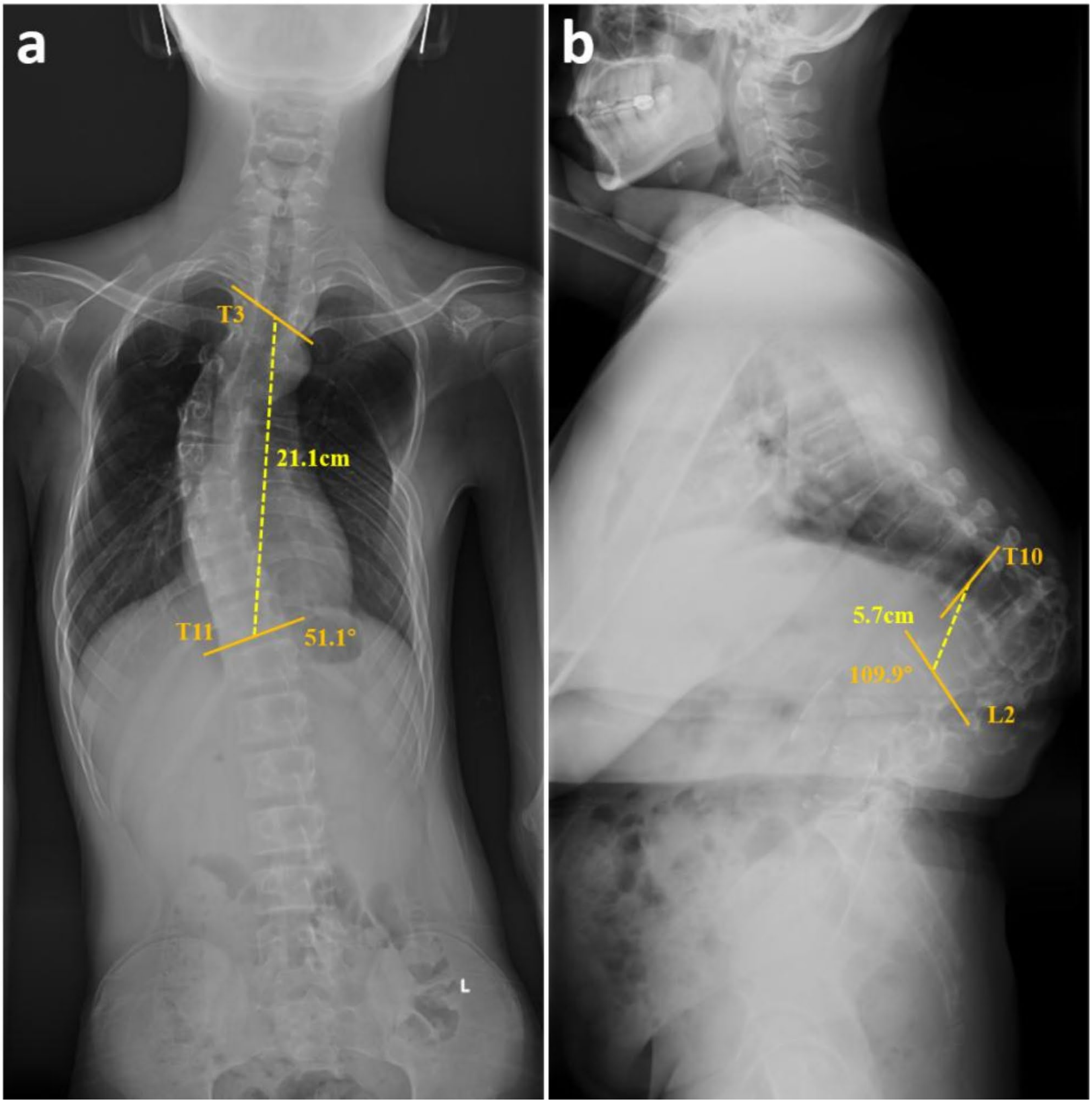

Fig. 1 **(a)** a 15-year-old male patient with congenital scoliosis. Anterior-posterior x-ray showing a 51.1° coronal main curve from T3 to T11, including 9 vertebrae, and the distance between the upper and lower vertebrae was 21.1 cm. Coronal deformity angular ratio (C-DAR) is 5.7 (51.1 divided by 9) and coronal deformity angular distance ratio (C-DADR) is 2.4 (51.1 divided by 21.1). **(b)** a 62-year-old female patient with post-tuberculous kyphosis. Lateral x-ray showing a 109.9° kyphotic angle from T10 to L2, including 5 vertebrae, and the distance between the upper and lower vertebrae was 5.7 cm. Sagittal deformity angular ratio (S-DAR) is 22.0 (109.9 divided by 5) and sagittal deformity angular distance ratio (S-DADR) is 19.3 (109.9 divided by 5.7)

were selected for univariable analysis based on clinical relevance and previous literature [1, 5, 8, 15, 16]. Variables with $p < 0.20$ in univariate analysis were included in the multivariate model. The discriminative ability of significant continuous risk factors was assessed using receiver operating characteristic (ROC) curve analysis, and the area under the curve (AUC) with 95% confidence intervals (CI) was calculated. The optimal cut-off values were determined by maximizing Youden's index. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated for each cut-off. A p-values of less than 0.05 was considered statistically significant.

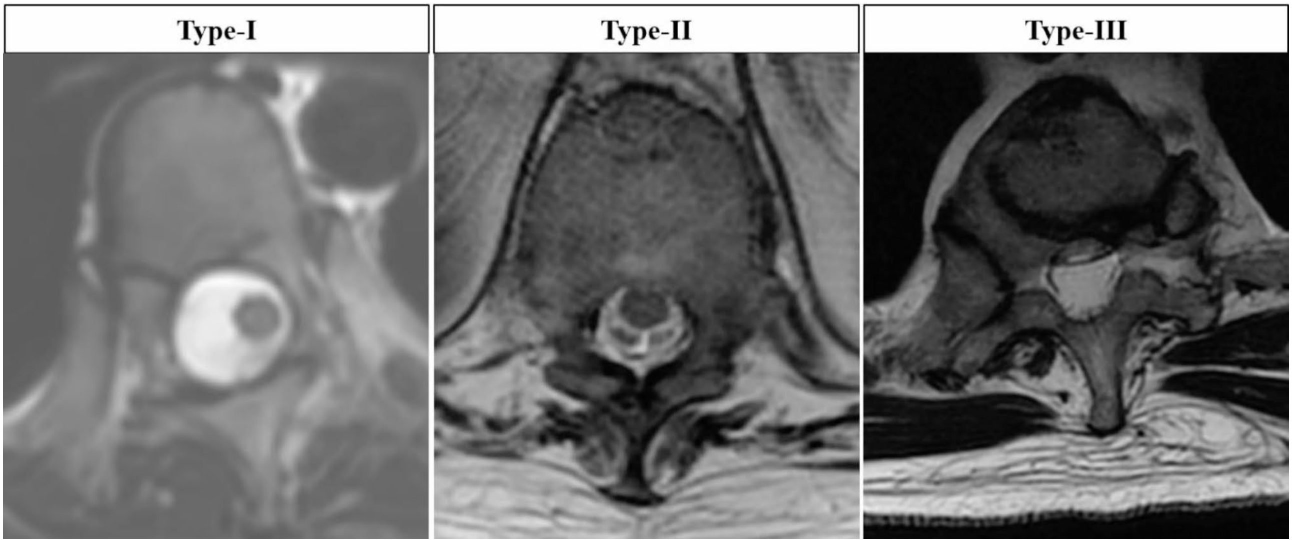

Fig. 2 T2-weighted magnetic resonance imaging (MRI) illustrate the three types of spinal cord morphology based on the spinal cord shape classification system (SCSCS). Type I, with a symmetrical spinal cord shape and visible cerebrospinal fluid (CSF) between the spinal cord and osseous structures; Type II, with a symmetrical spinal cord shape but no visible CSF between the spinal cord and osseous structures; and Type III, where the spinal cord is deformed against the apical concave pedicle/vertebral body, with no CSF between the spinal cord and the osseous structures

Results

Basic descriptive

A total of 404 patients were enrolled in our study, with a median age of 33.0 (15.0, 55.8) years, consisting of 229 females and 175 males. According to the SCSCS, 97 patients were classified as type I, 120 as type II, and 187 as type III. The most common locations of the deformity apex were T9-L2 (67.1%), followed by T5-T8 (27.7%) and C7-T4 (5.2%). Among the 404 enrolled patients, 78 presented with congenital deformities, 98 presented with post-tuberculous deformities, and 228 had deformities caused by other reasons, including 115 idiopathic spinal deformities, 52 post-traumatic deformities, 19 cases of kyphosis due to ankylosing spondylitis, 14 related to Scheuermann's disease, 10 associated with neurofibromatosis type-1, 7 with syndromic spinal deformities, 7 with degenerative spinal deformities, and 4 with neuromuscular deformities. Among the included patients, 204 had kyphosis, 160 had scoliosis, and 40 had kyphoscoliosis. The preoperative sagittal Cobb angle for these 244 patients was 70.6° (55.7°, 93.2°), which improved to 21.5° (12.2°, 33.0°) immediately after surgery, resulting in a kyphosis correction rate of 69.5%±13.3%. The S-DAR was 12.9 (10.7, 16.3), and the S-DADR was 7.7 (4.3, 14.9). Among the 200 patients with coronal deformities, the preoperative coronal Cobb angle was 56.9° (49.2°, 71.8°), which decreased to 15.9° (10.4°, 24.0°) postoperatively, with a scoliosis correction rate of 70.6%±11.9%. The C-DAR of these patients was 8.9 (7.3, 11.6), and the C-DADR was 4.1 (3.3, 5.9). The T-DAR for the entire cohort was 11.4 (8.7, 15.8), and the T-DADR was 5.4 (3.8, 10.8). All patients underwent osteotomies, with 141 receiving posterior column osteotomy (PCO) and 263 receiving 3CO. Of these, 141 patients presented with preoperative neurological deficits, while 263 did not. Postoperatively, 34 patients developed postoperative neurological deficits, while 370 did not (Table 1).

Table 1 also summarized the results of two groups of patients: those without IONM alerts and those with IONM alerts. There were no significant differences in the preoperative coronal Cobb angle ($P = 0.513$) or C-DAR ($P = 0.173$) between the two groups. However, compared with patients without IONM alerts, those with IONM alerts were older [23.5 (14.0, 56.0) versus 44.0 (32.3, 54.0), $P = 0.001$) and had a higher proportion of congenital and post-tuberculous deformities ($P < 0.001$). Additionally, a significantly higher proportion of patients in the IONM alerts group received 3CO ($P < 0.001$). A larger proportion of patients in the IONM alerts group also had preoperative neurological deficits compared to the IONM non-alerts group ($P < 0.001$). Moreover, there were statistically significant differences in SCSCS and the location of the deformity apex between the two groups.

Preoperative imaging parameters

The preoperative sagittal Cobb angle of patients without IONM alerts was 61.2° (52.4°, 78.3°), which improved to 16.8° (9.2°, 26.4°) postoperatively, resulting in a kyphosis correction rate of 72.7% ±13.3%. In contrast, patients with IONM alerts had a preoperative sagittal Cobb angle of 92.5° (70.7°, 115.5°), which improved to 31.6° (22.5°, 41.7°) postoperatively, yielding a kyphosis correction rate of 64.0%±11.4%. The preoperative coronal Cobb angle for patients without IONM alerts was 57.0° (49.8°,

Table 1 Characteristics of patients with and without IONM alerts

Variable	Overall	IONM Alerts		p-value
		No	Yes	
N (%)	404	302 (74.8)	102 (25.2)	-
Age (years)	33.0 (15.0, 55.8)	23.5 (14.0, 56.0)	44.0 (32.3, 54.0)	**0.001**
Gender (male/female)	175/229	117/185	58/44	**0.001**
SCSCS				**<0.001**
Type-I	97 (24.0)	87 (28.8)	10 (9.8)	-
Type-II	120 (29.7)	106 (35.1)	14 (13.7)	-
Type-III	187 (46.3)	109 (36.1)	78 (76.5)	-
Location of apex				**<0.001**
C7-T4	21 (5.2)	7 (2.3)	14 (13.7)	-
T5-T8	112 (27.7)	76 (25.2)	36 (35.3)	-
T9-L2	271 (67.1)	219 (72.5)	52 (51.0)	-
Etiological diagnosis (%)				**<0.001**
Congenital	78 (19.3)	52 (17.2)	26 (25.5)	-
Post-tuberculous	98 (24.3)	38 (12.6)	60 (58.8)	-
Others §	228 (56.4)	212 (70.2)	16 (15.7)	-
Sagittal Cobb angle (°)				
Preoperative	70.6 (55.7, 93.2)	61.2 (52.4, 78.3)	92.5 (70.7, 115.5)	**<0.001**
Postoperative	21.5 (12.2, 33.0)	16.8 (9.2, 26.4)	31.6 (22.5, 41.7)	**<0.001**
Correction rates	0.695 (±0.133)	0.727 (±0.133)	0.640 (±0.114)	**<0.001**
S-DAR	12.9 (10.7, 16.3)	12.0 (10.0, 15.0)	15.4 (12.2, 18.2)	**<0.001**
S-DADR	7.7 (4.3, 14.9)	5.1 (4.0, 8.9)	14.9 (10.0, 20.0)	**<0.001**
Coronal Cobb angle (°)				
Preoperative	56.9 (49.2, 71.8)	57.0 (49.8, 70.9)	55.5 (44.3, 105.4)	0.513
Postoperative	15.9 (10.4, 24.0)	15.6 (10.1, 22.7)	20.2 (13.0, 46.2)	**0.006**
Correction rates	0.706 (±0.119)	0.723 (±0.107)	0.617 (±0.141)	**<0.001**
C-DAR	8.9 (7.3, 11.6)	8.9 (7.3, 11.2)	10.4 (7.3, 13.3)	0.173
C-DADR	4.1 (3.3, 5.9)	4.0 (3.3, 5.5)	5.8 (3.5, 10.4)	**0.001**
T-DAR	11.4 (8.7, 15.8)	10.4 (8.0, 13.5)	15.7 (11.5, 19.8)	**<0.001**
T-DADR	5.4 (3.8, 10.8)	4.5 (3.5, 7.1)	14.6 (9.4, 23.8)	**<0.001**
Osteotomy type (%)				**<0.001**
PCO	141 (34.9)	134 (44.4)	7 (6.9)	-
3CO	263 (65.1)	168 (55.6)	95 (93.1)	-
Preoperative neurological deficits				**<0.001**
Yes	141 (34.9)	67 (22.2)	74 (72.5)	-
No	263 (65.1)	235 (77.8)	28 (27.5)	-
Postoperative neurological deficits				**<0.001**
Yes	34 (8.4)	3 (1.0)	31 (30.4)	-
No	370 (91.6)	299 (99.0)	71 (69.6)	-

Data is presented as mean ± SD, or median (IQR), or number (%)

IONM, intraoperative neuromonitoring; N, number; SCSCS, spinal cord shape classification system; S-DAR, sagittal deformity angular ratio; S-DADR, sagittal deformity angular distance ratio; C-DAR, coronal deformity angular ratio; C-DADR, coronal deformity angular distance ratio; T-DAR, total deformity angular ratio; T-DADR, total deformity angular distance ratio; PCO, posterior column osteotomy; and 3CO, three-column osteotomy. § Includes idiopathic, post-traumatic, ankylosing spondylitis, Scheuermann's disease, neurofibromatosis type-1, syndromic, degenerative, and neuromuscular deformities

Bold *p*-values represent statistical significance

70.9°), which improved to 15.6° (10.1°, 22.7°) postoperatively, with a scoliosis correction rate of 72.3%±10.7%. For patients with IONM alerts, the preoperative coronal Cobb angle was 55.5° (44.3°, 105.4°), which improved to 20.2° (13.0°, 46.2°) postoperatively, yielding a scoliosis correction rate of 61.7%±14.1%. Patients with IONM alerts exhibited a larger postoperative coronal Cobb angle ($P=0.006$) and smaller scoliosis correction rates ($P<0.001$) compared to those without IONM alerts. Significant differences were also observed between the two groups in the following parameters: preoperative S-DAR [12.0 (10.0, 15.0) versus 15.4 (12.2, 18.2), $P<0.001$], S-DADR [5.1 (4.0, 8.9) versus 14.9 (10.0, 20.0), $P<0.001$], C-DADR [4.0 (3.3, 5.5) versus 5.8 (3.5, 10.4), $P=0.001$], T-DAR [10.4 (8.0, 13.5) versus 15.7 (11.5, 19.8), $P<0.001$], and T-DADR [4.5 (3.5, 7.1) versus 14.6 (9.4, 23.8), $P<0.001$] (Table 1).

Results of univariate and multivariate analysis

Univariate binary logistic regression analysis identified 12 potential factors influencing IONM alerts: age, SCSCS, location of the apex, etiological diagnosis, preoperative sagittal Cobb angle, S-DAR, S-DADR, C-DADR, T-DAR, T-DADR, osteotomy type, and preoperative neurological deficits (Table 2).

Due to collinearity between the sagittal deformity parameters (sagittal cobb angle, S-DAR, and S-DADR) and the total deformity parameters (T-DAR and T-DADR), multivariate binary logistic regression analyses were performed separately for each set of parameters. The multivariate binary logistic regression analysis involving sagittal deformity parameters revealed that the location of the apex at C7-T4 (OR = 8.970, 95% CI 1.884–42.703, $P=0.006$), S-DADR (OR = 1.200, 95% CI 1.055–1.365, $P=0.006$), and preoperative neurological deficits (OR = 4.096, 95% CI 1.429–11.740, $P=0.009$) were independent predictors of IONM alerts (Table 3). The multivariate binary logistic regression analysis including total deformity parameters showed that the location of the apex at C7-T4 (OR = 4.512, 95% CI 1.409–14.444, $P=0.011$), T-DADR (OR = 1.195, 95% CI 1.100-1.299, $P<0.001$), and preoperative neurological deficits (OR = 3.264, 95% CI 1.322–8.060, $P=0.010$) were independent predictors of IONM alerts (Table 4).

Optimal thresholds for DADR

To determine optimal thresholds for deformity parameters, we performed ROC curve analysis for S-DADR and T-DADR (Fig. 3). The analysis revealed strong predictive performance, with an AUC of 0.842 (95% CI: 0.789–0.894) for S-DADR and 0.848 (95% CI: 0.801–0.894) for T-DADR. The optimal cut-off values, determined by maximizing Youden's index, were 7.35 for S-DADR (sensitivity 84.2%, specificity 76.5%) and 8.30 for T-DADR (sensitivity 82.7%, specificity 81.3%). Although the PPV were moderate (62.1% for S-DADR and 56.3% for T-DADR), the NPV exceeded 90% for both parameters (90.0% for S-DADR and 92.0% for T-DADR), indicating their utility in ruling out low-risk cases. Patients with values below these thresholds had a less than 10% probability of experiencing IONM alerts. These findings suggest that S-DADR and T-DADR thresholds can effectively stratify patients into high- and low-risk groups, aiding in preoperative planning and intraoperative decision-making.

Outcomes of IONM alerts

In our study, 102 patients experienced IONM alerts. Among these, standardized intraoperative interventions resulted in signal recovery in 67 cases (65.7%), with only

Table 2 Univariate binary logistic regression analysis of risk factors for IONM alerts

Variables	Group	B	S.E.	Wald	OR (95%CI)	*p*-value
Age (years)		0.019	0.006	12.174	1.020 (1.009, 1.031)	**<0.001**
SCSCS	Type-I*					
	Type-II	0.139	0.439	0.100	1.149 (0.486, 2.714)	0.751
	Type-III	1.829	0.365	25.051	6.226 (3.042, 12.740)	**<0.001**
Location of apex	T9-L2*					
	C7-T4	2.131	0.488	19.073	8.423 (3.237, 21.918)	**<0.001**
	T5-8	0.691	0.254	7.368	1.995 (1.212, 3.285)	**0.007**
Etiological diagnosis	Others *					
	Congenital	1.891	0.353	28.623	6.625 (3.314, 13.244)	**<0.001**
	Post-tuberculosis	3.041	0.332	83.904	20.921 (10.915, 40.101)	**<0.001**
Preoperative sagittal Cobb angle		0.040	0.006	42.129	1.041 (1.028, 1.053)	**<0.001**
S-DAR		0.141	0.032	19.306	1.151 (1.081, 1.226)	**<0.001**
S-DADR		0.207	0.029	52.039	1.230 (1.163, 1.301)	**<0.001**
C-DADR		0.237	0.058	16.683	1.268 (1.131, 1.420)	**<0.001**
T-DAR		0.115	0.019	36.783	1.121 (1.081, 1.164)	**<0.001**
T-DADR		0.198	0.023	73.734	1.219 (1.165, 1.275)	**<0.001**
Osteotomy type	PCO*					
	3CO	2.382	0.408	34.012	10.825 (4.862, 24.102)	**<0.001**
Preoperative neurological deficits	No*					
	Yes	2.227	0.262	72.483	9.270 (5.552, 15.477)	**<0.001**

IONM, intraoperative neuromonitoring; B, regression coefficient; S.E., standard error; OR, odds ratio; CI, confidence interval; SCSCS, spinal cord shape classification system; S-DAR, sagittal deformity angular ratio; S-DADR, sagittal deformity angular distance ratio; C-DADR, coronal deformity angular distance ratio; T-DAR, total deformity angular ratio; T-DADR, total deformity angular distance ratio; PCO, posterior column osteotomy; and 3CO, three-column osteotomy

* Reference category. Bold *p*-values represent statistical significance

Table 3 Multivariate analysis of risk factors for IONM alerts: sagittal deformity parameters

Variables	Group	B	S.E.	Wald	OR (95%CI)	*p*-value
Age (years)		-0.014	0.013	1.275	0.986 (0.962, 1.011)	0.259
SCSCS	Type-I*					
	Type-II	-0.524	0.648	0.654	0.592 (0.166, 2.108)	0.419
	Type-III	-0.481	0.658	0.533	0.618 (0.170, 2.248)	0.465
Location of apex	T9-L2*					
	C7-T4	2.194	0.796	7.594	8.970 (1.884, 42.703)	**0.006**
	T5-8	0.664	0.511	1.689	1.942 (0.714, 5.287)	0.194
Etiological diagnosis	Others *					
	Congenital	-0.461	0.640	0.519	0.631 (0.180, 2.210)	0.471
	Post-tuberculosis	-0.879	0.680	1.669	0.415 (0.110, 1.575)	0.196
Preoperative sagittal Cobb angle		0.014	0.014	1.020	1.015 (0.987, 1.043)	0.313
S-DAR		-0.042	0.055	0.591	0.958 (0.860, 1.068)	0.442
S-DADR		0.182	0.066	7.671	1.200 (1.055, 1.365)	**0.006**
Osteotomy type	PCO*					
	3CO	0.994	1.180	0.710	2.702 (0.268, 27.272)	0.399
Preoperative neurological deficits	No*					
	Yes	1.410	0.537	6.891	4.096 (1.429, 11.740)	**0.009**

IONM, intraoperative neuromonitoring; B, regression coefficient; S.E., standard error; OR, odds ratio; CI, confidence interval; SCSCS, spinal cord shape classification system; S-DAR, sagittal deformity angular ratio; S-DADR, sagittal deformity angular distance ratio; PCO, posterior column osteotomy; and 3CO, three-column osteotomy

* Reference category. Bold *P*-values represent statistical significance

Table 4 Multivariate analysis of risk factors for IONM alerts: T-DAR and T-DADR

Variables	Group	B	S.E.	Wald	OR (95% CI)	*p*-value
Age (years)		-0.012	0.012	1.031	0.988 (0.966, 1.011)	0.310
SCSCS	Type-I*					
	Type-II	-0.718	0.534	1.807	0.488 (0.171, 1.389)	0.179
	Type-III	-0.338	0.526	0.412	0.714 (0.255, 1.999)	0.521
Location of apex	T9-L2*					
	C7-T4	1.507	0.594	6.441	4.512 (1.409, 14.444)	**0.011**
	T5-8	0.550	0.388	2.010	1.734 (0.810, 3.710)	0.156
Etiological diagnosis	Others *					
	Congenital	0.219	0.522	0.175	1.244 (0.447, 3.465)	0.675
	Post-tuberculosis	0.006	0.602	0.000	1.006 (0.309, 3.271)	0.992
T-DAR		-0.048	0.039	1.486	0.953 (0.882, 1.030)	0.223
T-DADR		0.178	0.042	17.732	1.195 (1.100, 1.299)	**<0.001**
Osteotomy type	PCO*					
	3CO	1.039	0.608	2.920	2.827 (0.858, 9.310)	0.087
Preoperative neurological deficits	No*					
	Yes	1.183	0.461	6.577	3.264 (1.322, 8.060)	**0.010**

IONM, intraoperative neuromonitoring; T-DAR, total deformity angular ratio; T-DADR, total deformity angular distance ratio; B, regression coefficient; S.E., standard error; OR, odds ratio; CI, confidence interval; SCSCS, spinal cord shape classification system; PCO, posterior column osteotomy; and 3CO, three-column osteotomy

* Reference category. Bold *p*-values represent statistical significance

3 patients (4.5%) subsequently developing new postoperative neurological deficits, underscoring that prompt intervention can significantly mitigate risk. In contrast, among the 35 patients (34.3%) with unresolved alerts, 28 (80.0%) develop neurological deficits while 7 patients remained neurologically intact, classifying these 7 cases as false positives. Notably, 3 patients without intraoperative alerts also exhibited postoperative neurological deficits, suggesting potential limitations of IONM in detecting subtle injuries. These findings reinforce that an alert does not invariably lead to neurological deterioration. Instead, timely and effective intraoperative interventions play a critical role in reducing the incidence of postoperative neurological deficits. Representative cases are shown in Figs. 4, 5, 6 and 7.

Discussion

Postoperative neurological deficit is a significant concern for patients undergoing spinal corrective surgery. In our study, the incidence of postoperative neurological

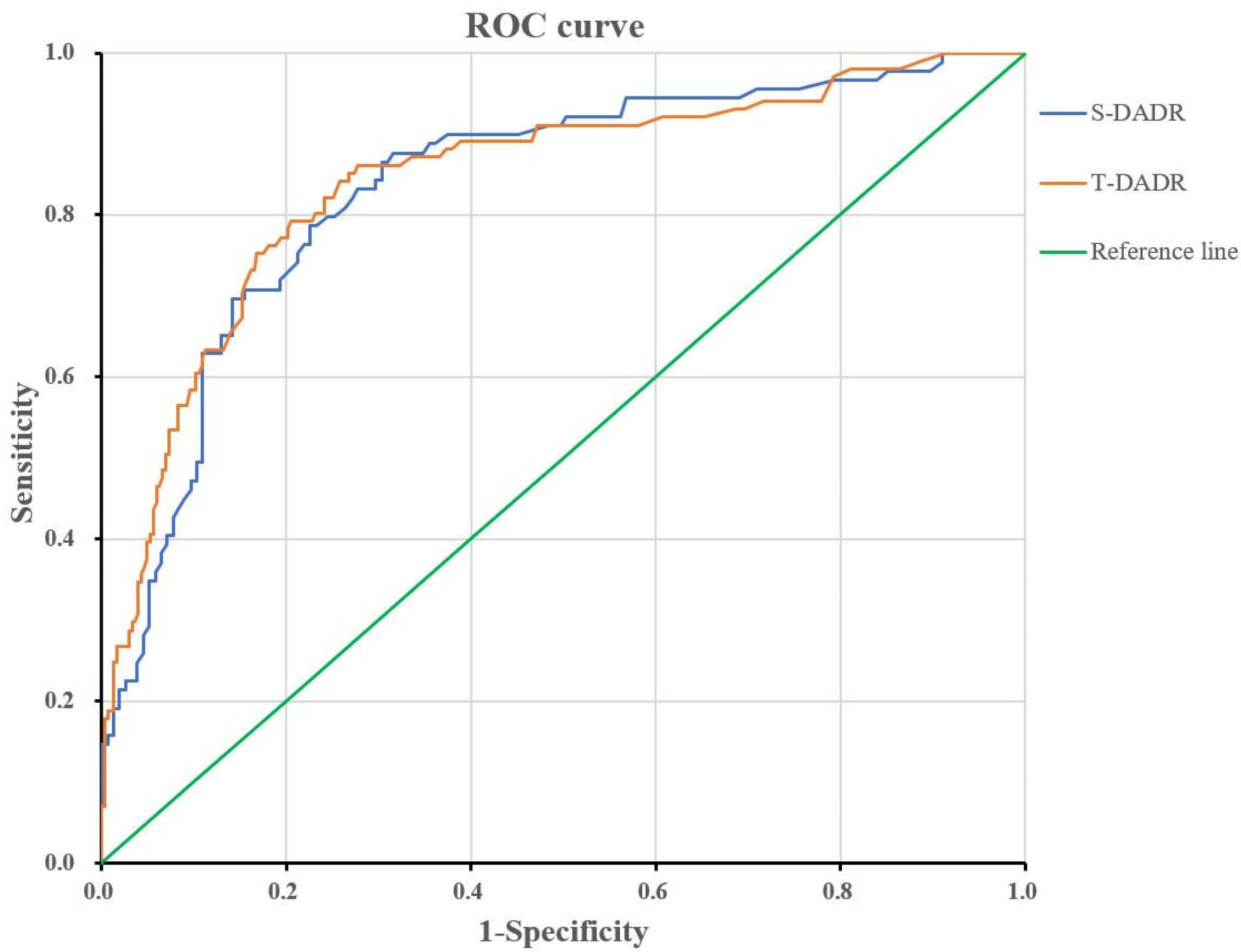

Fig. 3 The receiver operating characteristic (ROC) curve of sagittal deformity angular distance ratio (S-DADR) and total deformity angular distance ratio (T-DADR) in assessing IONM alerts risk. The area under ROC curve (AUC) were 0.842 (95% CI: 0.789–0.894) for S-DADR and 0.848 (95% CI: 0.801–0.894) for T-DADR

deficits was 8.4% among individuals undergoing corrective procedures. The reported incidence of neurological deficits following spinal corrective surgery varies widely in the literature. For instance, a study involving 253 pediatric patients with spinal deformities who underwent posterior spinal fusion found a postoperative neurological deficit incidence of 1.2% [5]. Liu et al. reported new neurological deficits in 9.1% of patients following 3CO [8]. A study of 205 patients with severe spinal deformities found a posteoperative neurological deficits rate of 19.5% [6]. Furthermore, in a case series involving 84 patients with severe and complex spinal deformities, 82 of whom underwent single-segment or multi-segment vertebral column resection (VCR), neurological complications were observed in 23.8% of cases [11].

In current clinical practice, IONM, including SSEPs and MEPs, is highly recommended to reduce the incidence of new neurological deficits. IONM provides continuous real-time information regarding the integrity of the posterior column pathway and motor pathways of the spinal cord, thereby enhancing patient safety during surgery [23, 24]. A meta-analysis of 16 studies involving 3778 patients with idiopathic scoliosis in children showed that changes in SSEPs had a sensitivity of 72.9% and a specificity of 96.8%, while SSEPs loss had a sensitivity of 41.8% and a specificity of 99.3% in predicting new neurologic deficits [23]. Zuccaro et al. observed a sensitivity of 13.2% and a specificity of 100% for SSEPs monitoring, and a sensitivity of 100% with a specificity ranging from 93 to 100% for MEPs monitoring in detecting new postoperative neurological deficits [24]. A study of 87 patients with kyphoscoliosis and intraspinal abnormalities undergoing posterior spinal fusion showed that the sensitivity and specificity for SSEPs were 100% and 97.3%, respectively, and for MEPs were 100% and 98.8% [25]. In a report by Bhagat et al. on 315 spinal deformity patients undergoing corrective surgery, multimodal monitoring

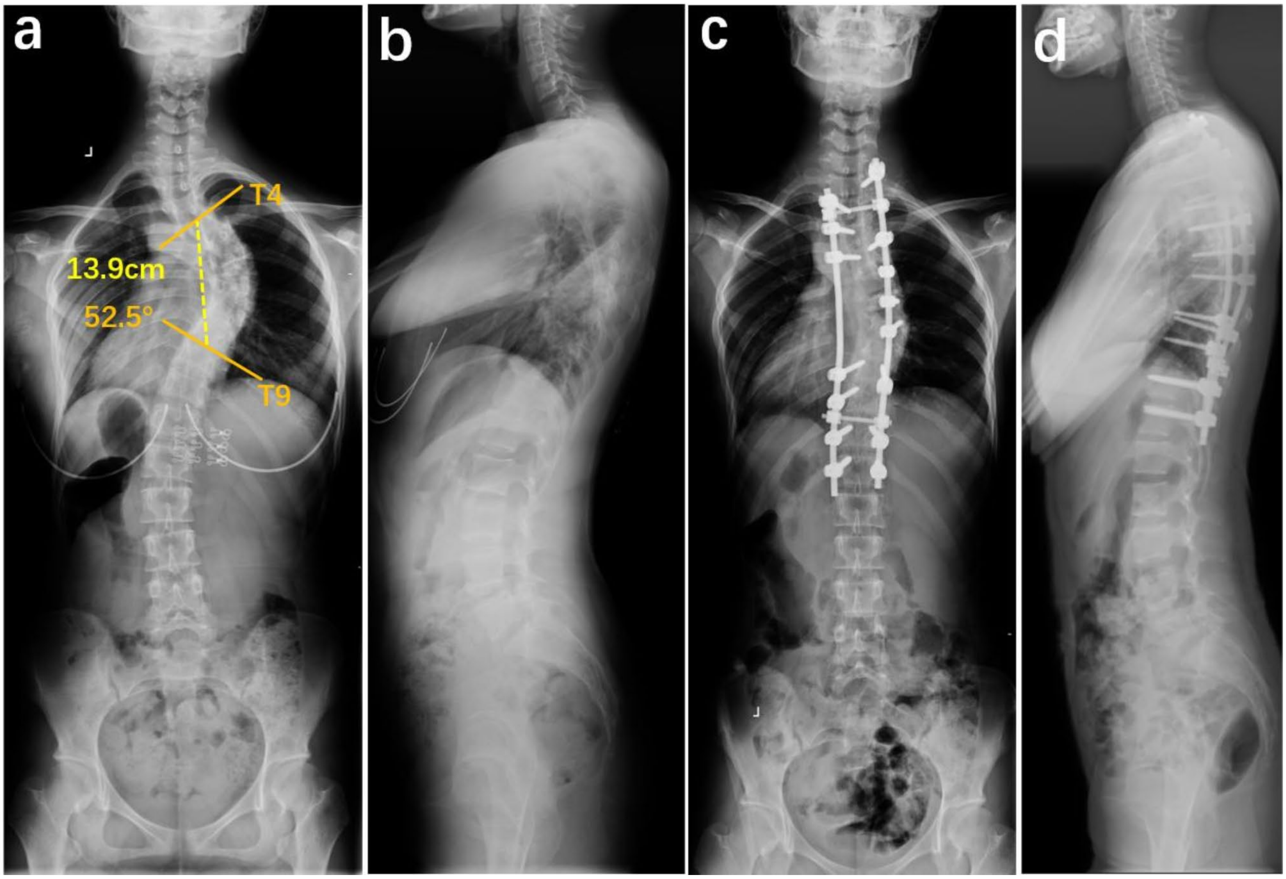

Fig. 4 A 25-year-old female with idiopathic scoliosis underwent posterior column osteotomies (PCO) at T5–T8 and posterior spinal instrumentation from T3 to T12. Intraoperative neuromonitoring (IONM) remained stable, with no new postoperative neurological deficits. (**a**) Preoperative anterior-posterior and (**b**) lateral whole-spine radiographs demonstrate a T4–T9 coronal curve measuring 52.5°, with preserved sagittal alignment. The coronal deformity angular ratio (C-DAR) was calculated as 8.8 (52.5/6), and the coronal deformity angular distance ratio (C-DADR) was calculated as 3.8 (52.5/13.9). Postoperative day 5 (**c**) anterior-posterior and (**d**) lateral radiographs show successful correction of the major curve to 13.1°

(SSEPs + MEPs) achieved a sensitivity of 100% and a specificity of 99.3% [26].

IONM alerts are considered reliable indicators of impending neurological deficits, although the reported incidence of these alerts varies widely in previous literature. In our study, the incidence of IONM alerts was 25.2% among patients undergoing corrective surgery, which is higher than that reported in most retrospective studies. Samdani et al. reporting on data of 676 patients with adolescent idiopathic scoliosis, cited a 5.3% rate of IONM alerts during corrective surgery [14]. Bakhsheshian et al. observed that 11.7% of patients experienced IONM alerts in a cohort of 256 patients with a major curve located in the spinal cord region [1]. The high incidence of IONM alerts in our study may be attributed to the inclusion of patients with spinal deformities involving the spinal cord region and a larger proportion of patients with kyphosis or kyphoscoliosis (244/404, 60.4%). In another study of 114 patients undergoing surgical correction for kyphotic deformity, the incidence of IONM alerts was 28.9% [15], which is similar to the rate reported in our study. A case series involving 82 patients with severe thoracic deformities found that IONM alerts occurred in 32.9% of cases [9]. Given the high incidence of IONM alerts during corrective surgery and the potential neurological damage they signify, further investigation into their clinical risk factors remains essential. The present study identified the location of the apex, preoperative neurological deficits, S-DADR, and T-DADR as independent factors influencing IONM alerts.

Our findings indicate that both preoperative neurological deficits and the location of the deformity apex in the upper thoracic spine are independent risk factors for IONM alerts during corrective surgery, which aligns with the findings of several previous studies. Jin et al. identified preexisting neurologic dysfunction as an independent risk factor for IONM alerts during surgical correction [12]. A study of 87 patients with severe kyphoscoliosis and intraspinal abnormalities undergoing posterior corrective surgery showed that patients with preoperative neurological deficits were at higher risk of IONM alerts [25]. This suggests that pathologically

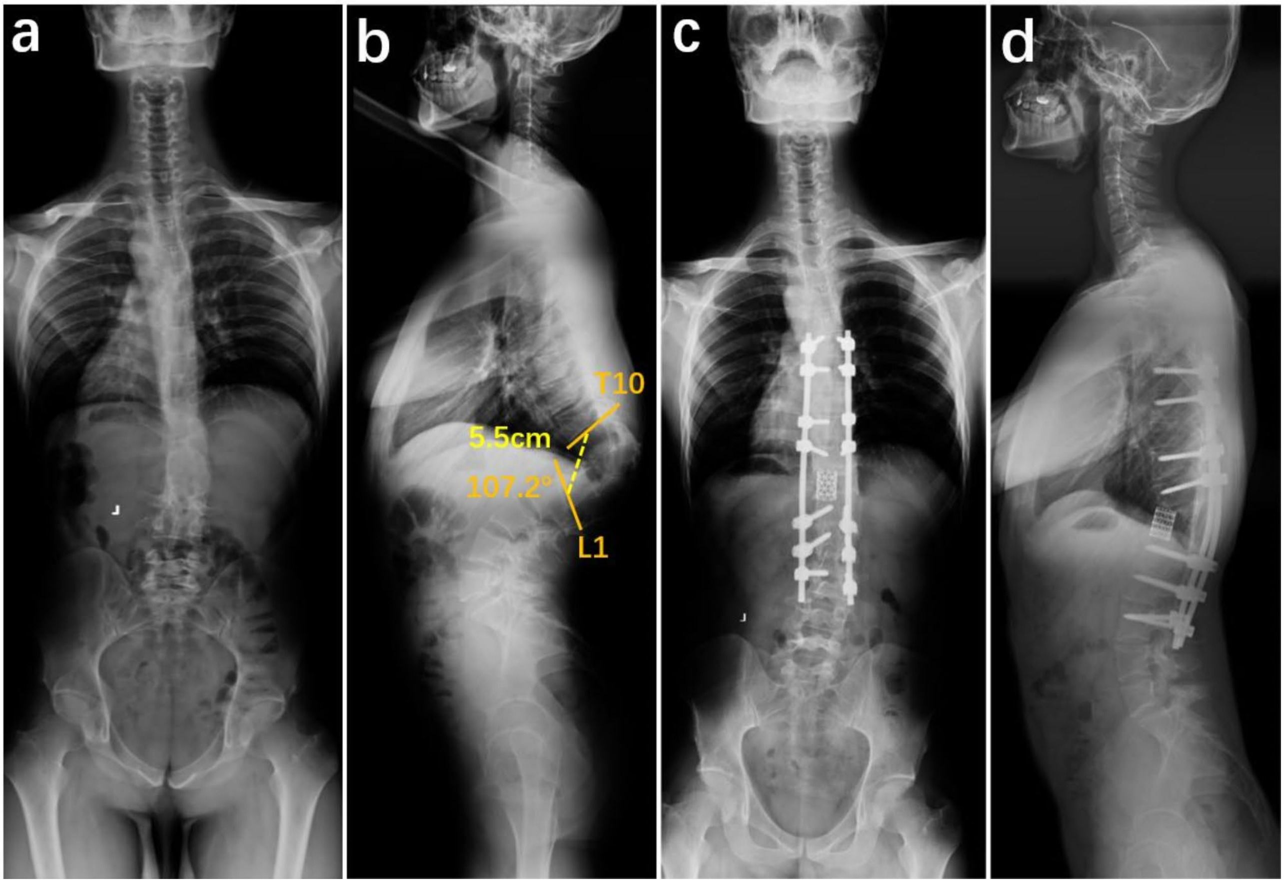

Fig. 5 A 26-year-old male with congenital kyphosis underwent vertebral column resection (VCR) at T11–T12 and posterior spinal instrumentation from T6 to L3. Intraoperative neuromonitoring (IONM) remained stable, with no new postoperative neurological deficits. (**a**) Preoperative anterior-posterior and (**b**) lateral whole-spine radiographs demonstrate a T10–L1 kyphotic curve measuring 107.2°, with preserved coronal alignment. The sagittal deformity angular ratio (S-DAR) was calculated as 26.8 (107.2/4), and the sagittal deformity angular distance ratio (S-DADR) was calculated as 19.5 (107.2/5.5). Post-operative 7-month (**c**) anterior-posterior and (**d**) lateral radiographs show successful correction of the kyphotic curve to 30.2°

decompensated spinal cord, due to chronic compression or traction from spinal deformities, is more susceptible to IONM alerts during surgery. The upper thoracic spinal cord, with its insufficient blood supply, is particularly vulnerable to direct compression and passive tension generated by the apex of the curve, making it more prone to secondary spinal cord injury during corrective surgery [27]. Furthermore, an analysis of 114 cases of kyphotic deformities showed that preoperative neurological status, the presence of myelopathy signs, and the apex of the curve located above T5 were significant predictors of IONM alerts during kyphosis corrective surgery [15], which is consistent with the findings of our study.

When diagnosing and treating spinal deformities, it becomes evident that the DAR may underestimate the severity of deformities, particularly in cases involving vertebral fusion or dysplasi, such as congenital, post-traumatic, and post-tuberculous spinal deformities. Previous studies have indicated that there is no significant difference in neurological deficits between patients with higher and lower DAR values after posterior VCR (PVCR) surgery [28]. To address this limitation, Ni et al. proposed a novel evaluation parameter, the DADR, to more accurately reflect the degree of spinal deformity, and their study found that DADR is a potential predictor of postoperative neurological deficits [19]. In our study, univariate regression analysis revealed that the sagittal Cobb angle, DAR, and DADR were potential predictors of IONM alerts during corrective surgery. However, multivariate binary logistic regression analysis identified only S-DADR and T-DADR as independent factors influencing IONM alerts. The association between DADR and IONM alerts may be attributed to two interrelated factors: biomechanical stress on the spinal cord and procedural complexity. A higher DADR signifies either a larger Cobb angle (indicating severe angular deformity) or a shorter distance between end vertebrae (reflecting focal apex curvature), both increasing cord vulnerability to intraoperative compression or stretch. Furthermore, correcting high-DADR deformities often requires complex

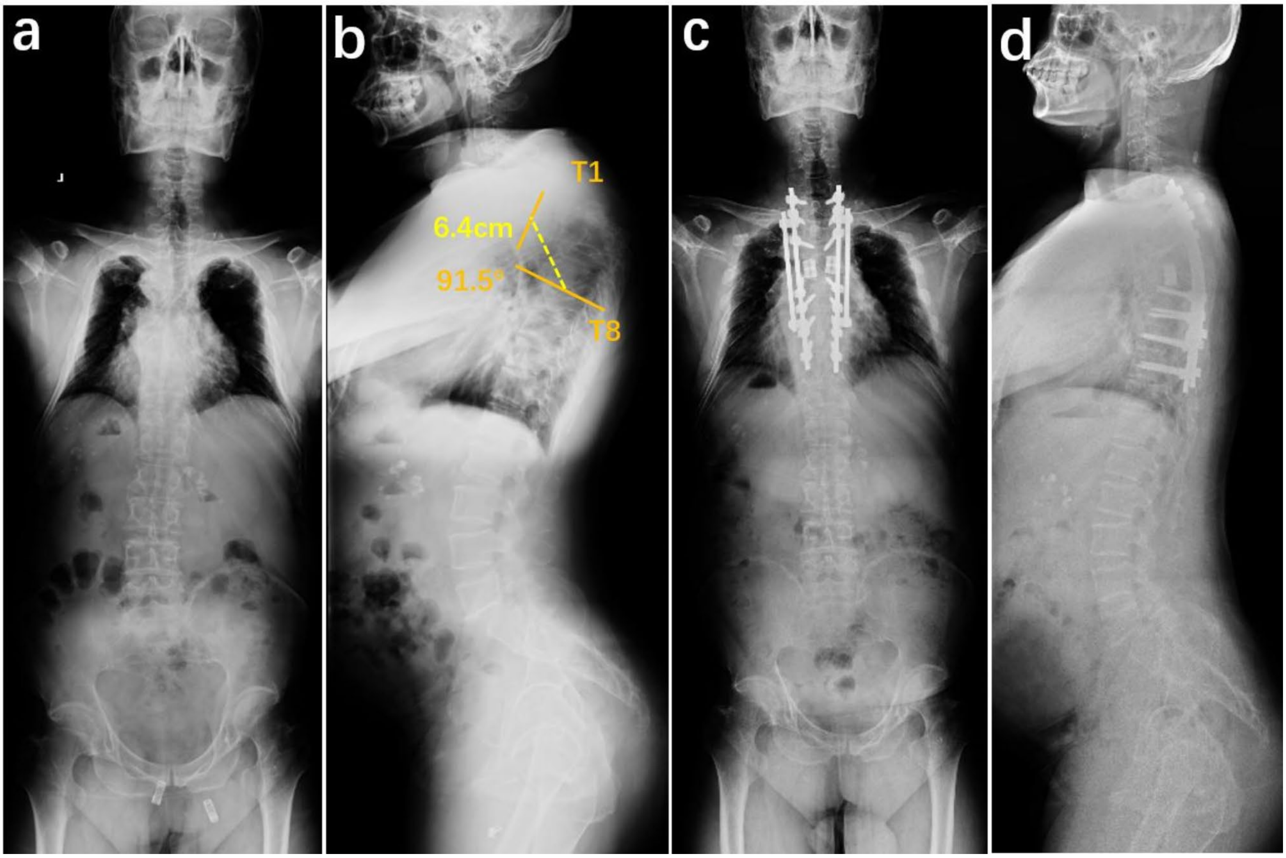

Fig. 6 A 49-year-old male with post-tuberculous kyphosis underwent vertebral column resection (VCR) at T3–T6 and posterior spinal instrumentation from C7 to T10. During pedicle screw placement, transient bilateral lower extremity somatosensory evoked potentials (SSEPs) alerts occurred, which resolved following blood pressure elevation and intravenous methylprednisolone administration. No new neurological deficits were observed postoperatively. (**a**) Preoperative anterior-posterior and (**b**) lateral whole-spine radiographs demonstrate a T1–T8 kyphotic curve measuring 91.5°, with preserved coronal alignment. The sagittal deformity angular ratio (S-DAR) was calculated as 11.4 (91.5/8), and the sagittal deformity angular distance ratio (S-DADR) was calculated as 14.3 (91.5/6.4). Postoperative 7-month (**c**) anterior-posterior and (**d**) lateral radiographs show successful correction of the kyphotic curve to 17.7°

osteotomies, which involve prolonged manipulation near the compromised spinal cord. Future studies integrating intraoperative imaging with real-time cord perfusion monitoring could elucidate the precise mechanisms underlying this relationship. These findings further emphasize the advantages and clinical applicability of DADR as a more reliable parameter for assessing deformity severity and predicting neurological risk.

Beyond its predictive value, DADR may have significant implications for intraoperative decision-making. High DADR values, which reflect a higher angular density of deformity per unit length, signal an increased risk for IONM alerts and subsequent neurological injury. In such cases, we suggest several measures: preoperative traction to improve the deformity angle and potentially reduce the osteotomy grade; comprehensive preoperative preparation, including ensuring sufficient blood availability and optimal control of comorbid conditions; and more precise intraoperative techniques such as navigation-assisted screw placement and digital technology-assisted osteotomy and correction. Additionally, enhanced multimodal neuromonitoring with a lowered IONM alert threshold, maintenance of appropriate MAP to prevent spinal cord hypoperfusion, and, when necessary, staged osteotomy and correction procedures, may further mitigate the risk of neurological complications. These strategies highlight how high DADR values could inform tailored surgical approaches and intraoperative precautions, ultimately aiming to improve patient outcomes.

Several previous studies have found that age, SCSCS, and etiological diagnosis are potential influencing factors for IONM alerts or postoperative neurological deficits during corrective surgery [1, 3, 8, 29]. However, our study did not find these factors to be independent predictors of IONM alerts. This discrepancy is understandable, as Ni et al. concluded in a study involving 244 patients with spinal deformities that age, SCSCS and etiological diagnosis were independent risk factors for preoperative neurological deficits [30]. In other words, age, SCSCS and etiological diagnosis may influence IONM alerts or

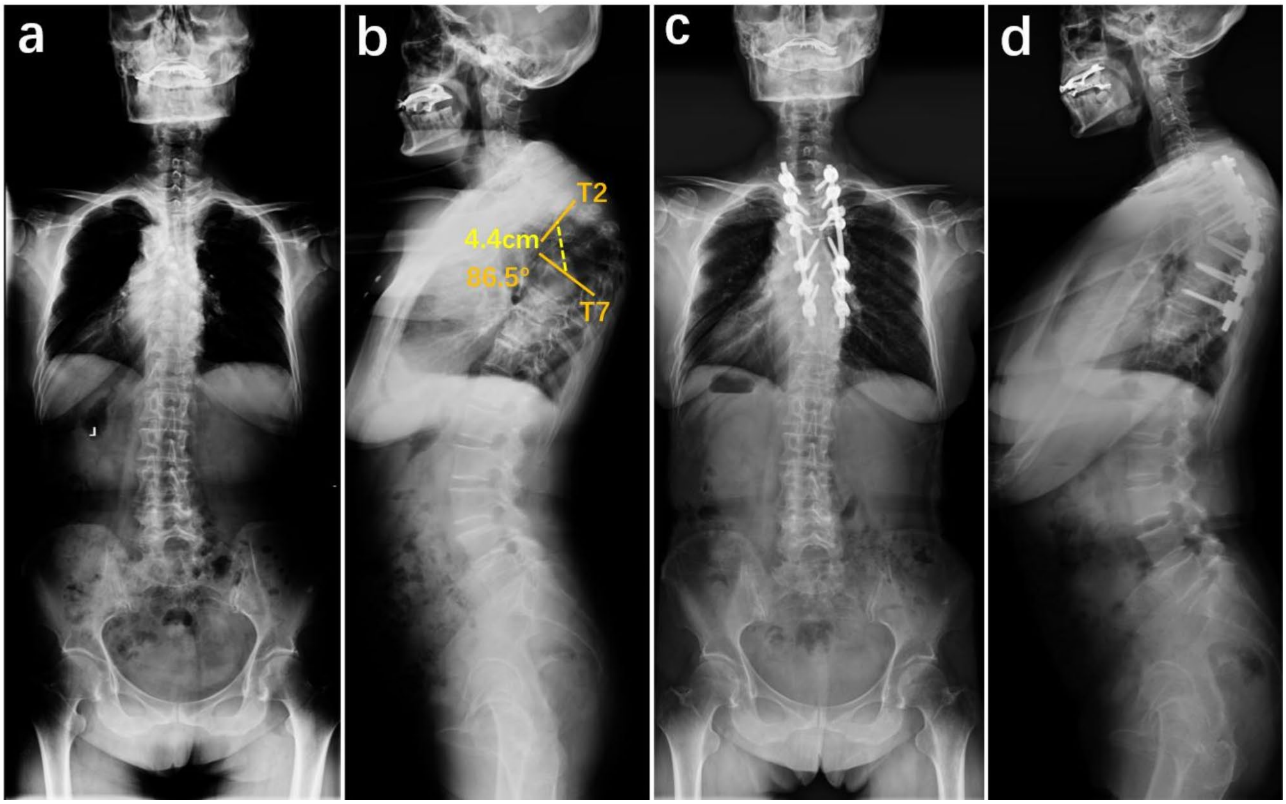

Fig. 7 A 66-year-old female with post-tuberculous kyphosis underwent vertebral column resection (VCR) at T4–T6 and posterior spinal instrumentation from T1 to T9. During decompression, transient loss of left lower extremity motor evoked potentials (MEPs) was observed, with subsequent recovery; however, right lower extremity MEPs were lost and did not recover by the end of surgery. Immediate postoperative examination revealed preserved left lower extremity motor strength, while the right lower extremity exhibited complete paralysis. By postoperative day 2, right iliopsoas and quadriceps strength improved to grade I, with other muscle groups at grade IV. Further recovery to grade III in the right iliopsoas and quadriceps (other muscles: grade IV) was noted by postoperative day 9. At 5-month follow-up, right lower extremity motor strength had returned to preoperative levels. (**a**) Preoperative anterior-posterior and (**b**) lateral whole-spine radiographs demonstrate a T2–T7 kyphotic curve measuring 86.5°, with preserved coronal alignment. The sagittal deformity angular ratio (S-DAR) was calculated as 14.4 (86.5/6), and the sagittal deformity angular distance ratio (S-DADR) was calculated as 19.7 (86.5/4.4). Postoperative 5-month (**c**) anterior-posterior and (**d**) lateral radiographs show correction of the kyphotic curve to 41.7°

postoperative neurological deficits indirectly, by affecting the preoperative neurological status, rather than being direct independent factors.

Several limitations exist in the present study. First, due to its retrospective nature, the precise causes of failed SSEPs/MEPs baseline and IONM alerts could not be fully determined. Patients without recordable SSEPs/MEPs baseline signals or during the entire surgical procedure were excluded from the analysis, which may introduce bias into the results. Second, the relatively low incidence of IONM alerts constrained our ability to comprehensively assess the risk factors. It is generally recommended to use no more than one variable per 10 events in multivariable analyses. Given the exploratory nature of this study, we expanded this limit to include 12 variables, based on clinical relevance and insights from the existing literature. However, numerous other factors, such as operation duration and estimated blood loss, were recorded in the database but not incorporated into the current investigation. To gain a more comprehensive understanding, large-scale studies, such as national databases, would be essential. Third, the inclusion of patients with diverse etiologies may introduce variability in the outcomes and limit the generalizability of the findings to specific patient subgroups. Fourth, as this is a single-center study, the external validity of our results is inherently limited. Finally, the study did not perform stratified analyses by deformity type (scoliosis, kyphosis, or kyphoscoliosis) due to insufficient IONM-positive cases in certain subgroups. Future multi-center prospective studies with larger patient cohorts are warranted to address these limitations by enabling more robust subgroup analyses and enhancing the applicability of the results to distinct patient populations. Despite these challenges, this study is the first to demonstrates that DADR is an independent influencing factor for IONM alerts during spinal deformity correction, and it holds potential as a valuable tool for risk stratification and management of IONM alerts in spinal corrective surgery.

Conclusions

In this cohort of patients undergoing spinal deformity corrective surgeries, the incidence of IONM alerts was 25.2%. Our findings suggest that S-DADR and T-DADR, novel parameters for evaluating the severity and complexity of spinal deformities, serve as independent predictors of IONM alerts during spinal deformity correction. Therefore, we recommend the inclusion of DADR as a key criterion for evaluating neurological risk and managing spinal deformity correction, contingent upon the completion of further reliability testing and subsequent publication of results. Additional independent predictors of IONM alerts identified in this study included the location of the apex at C7-T4 and the presence of preoperative neurological deficits.

Abbreviations

AUC	Area under the curve
B	Regression coefficient
C-DADR	Coronal deformity angular distance ratio
C-DAR	Coronal deformity angular ratio
CI	Confidence interval
CSF	Cerebrospinal fluid
DADR	Deformity angular distance ratio
DAR	Deformity angular ratio
IONM	Intraoperative neuromonitoring
IQR	Interquartile range
MAP	Mean arterial pressure
MEPs	Motor evoked potentials
MRI	Magnetic resonance imaging
OR	Odds ratio
PACS	Picture archiving and communication system
PCO	Posterior column osteotomy
PVCR	Posterior vertebral column resection
ROC	The receiver operating characteristic curve
SCSCS	Spinal cord shape classification system
SD	Standard deviation
S-DADR	Sagittal deformity angular distance ratio
S-DAR	Sagittal deformity angular ratio
S.E	Standard error
SSEPs	Somatosensory evoked potentials
T-DADR	Total deformity angular distance ratio
T-DAR	Total deformity angular ratio
VCR	Vertebral column resection
3CO	Three-column osteotomy

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Author contributions

JN designed the study, collected the data, analyzed the data, and wrote the manuscript. XG, ZS, and CZ collected the data. ZC supervised the study. YZ supervised the study and revised the manuscript. All authors have read and approved the submitted version of the manuscript.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to the privacy concerns of the data but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study received approval from Peking University Third Hospital Medical Science Research Ethics Committee (M2024619).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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