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Analysis of measures against mechanical complications in circumferential minimally invasive surgery for adult spinal deformity

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Abstract

Aim: We evaluated the reduction of mechanical complications (MCs) in circumferential minimally invasive spinal surgery (c-MIS) to treat adult spinal deformity (ASD) using lateral lumbar interbody fusion and a percutaneous pedicle screw.

Methods: Patients with ASD who underwent c-MIS with a follow-up period of > 24 months were enrolled. Groups were as follows: c-MIS using 5.5 mm rods (P group), c-MIS using a 5.5 mm single rod with cement augmentations in the upper instrumented vertebra (UIV)/UIV + 1 (B group), c-MIS using 6 mm rods (6P group), and multi-rod c-MIS (M group). Terminal rod contour was optimized to prevent proximal junctional kyphosis (PJK) in the P, 6P, and M groups. Patients were divided into an MC group, consisting of 68 patients with MCs, and a non-MC group, consisting of 78 patients without MCs. We examined various spinopelvic- and implant-related parameters between the groups.

Results: Overall, 146 patients with ASD who underwent c-MIS were included. The incidence of PJK was significantly lower in the P and M groups than in the B group, and rod fracture was significantly lower in the M group than in the B and P groups. In the MC group, preoperative PT, postoperative PI-LL, and PSA were significantly larger than those in the non-MC group. Use of the 5.5 mm single rod and postoperative PI-LL were significant risk factors for MCs.

Conclusion: The complication incidence decreased with improvements in surgical techniques and measures. Use of the 5.5 mm single rod and postoperative PI-LL were significant risk factors for MCs.

Keywords: Adult spinal deformity, lateral lumbar interbody fusion, percutaneous pedicle screw, minimally invasive surgical procedures, proximal junctional kyphosis, rod fracture, mechanical complications

INTRODUCTION

The prevalence of adult spinal deformity (ASD) is increasing as the relative population of older individuals increases and corrective surgery becomes widespread. While surgical treatment significantly benefits patients with ASD[1,2], the incidence of complications from ASD surgery reportedly ranges from approximately 8.4%-68%, which is 4-8 times that of idiopathic scoliosis. The invasiveness of the surgery is a further concern[3,4].

In 2006, Ozgur *et al.* reported a novel approach to extreme lateral interbody fusion (XLIF®, Nuvasive Inc., San Diego, CA, USA), which enabled minimally invasive interbody release and interbody fusion[5]. In addition, circumferential minimally invasive surgery (c-MIS) with percutaneous pedicle screw (PPS) and lateral lumbar interbody fusion (LLIF) for ASD is gaining popularity[6,7]. However, various complications, such as proximal junctional kyphosis (PJK)/proximal junctional failure (PJF)[8,9], rod fracture (RF)[10-12], and coronal imbalance (CI)[13,14], still occur at a consistent rate; therefore, countermeasures are important. Yilgor *et al.* reported the importance of global alignment and proportion in the prevention of mechanical complications (MCs)[15]. According to the experience in our institution, corrective surgery for ASD has been improved by the addition of various specific countermeasures. We aimed to evaluate the effectiveness of such measures in reducing the MCs of c-MIS by investigating the incidence of MC with each surgical procedure in c-MIS for ASD as well as identifying the risk factors for MCs.

METHODS

Patient selection

This study was approved by the institutional review board of the Kansai Medical University Hospital (Approval No. 2020189) and was conducted after obtaining informed consent from all patients involved. Written informed consent was also obtained from the patients for the publication of this report and any accompanying images. The inclusion criteria were as follows: age > 45 years, sagittal vertical axis (SVA) > 50 mm, pelvic tilt (PT) > 25°, pelvic incidence (PI)-lumbar lordosis (LL) > 10°, fused middle or lower thoracic vertebrae to ilium, and standing full-length lateral and anteroposterior radiographs of the spine at preoperative baseline and final follow-up. Patients with spinal deformity who underwent corrective surgery combined with LLIF and PPS at our institution between March 2016 and August 2019 with a minimum follow-up period of 24 months were included. Patients who underwent surgeries from the upper thoracic vertebrae to the ilium and had incomplete or inadequate radiographs for complete analysis were excluded. Considering the surgical method, LLIF was performed from L1/2 (T11/12 or T12/L1 in some cases) to L4/5; after one week, posterior spinopelvic fixation with PPS and transforaminal lumbar interbody fusion in the L5/S1 were performed. The fixation range in all cases was from the middle or lower thoracic spine to the pelvis. A 10° lordotic titanium cage was used in all cases. The amount of bleeding, operative time, spinopelvic parameters, implant-related parameters, MCs, and revision rates were evaluated for each of the following surgical procedures: c-MIS using 5.5 mm rods (P group), c-MIS using a 5.5 mm single rod with cement augmentations in the upper instrumented vertebra (UIV)/UIV + 1 (B group), c-MIS using 6 mm rods (6P group), and multi-rod c-MIS (M group) [Figure 1]. In all cases, posterior spinopelvic fixation was performed using PPS from the UIV to the lower instrumented vertebra. The selection criterion for the

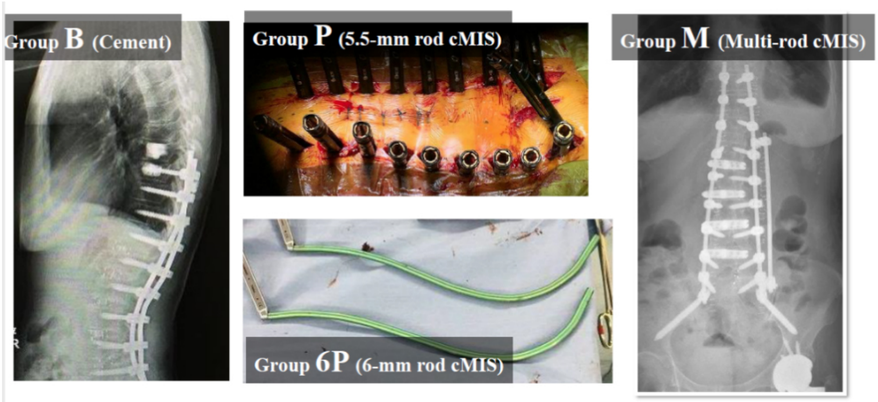

Figure 1. Representative photographs of each surgical procedure. c-MIS: Circumferential minimally invasive surgery.

above-mentioned surgical procedures was an improvement in surgical technique over time. Surgical techniques were not selected according to the spinal pathology and deformity. Patients were divided into two groups: an MC group consisting of 68 patients with MCs and a non-MC group consisting of 78 patients without MCs. We examined and compared various spinopelvic- and implant-related parameters between the two groups.

Radiological evaluation

Standing posteroanterior and lateral whole-spine radiographs were recorded at preoperative baseline and final follow-up. The following spinopelvic parameters were investigated using the current standard method: PI, LL, lower LL (LLL), PT, thoracic kyphosis, and SVA [Figure 2]. The following implant-related parameters were also investigated with reference to the report by Ishihara *et al.*[16]: the kyphotic angle of the rod in the UIV-L1 rod kyphotic angle (RKA), the angle between the pedicle screw (PS) and cranial endplate in the UIV [pedicle screw angle (PSA)], and the length of PS in the UIV [length of PS (LPS); Figure 3]. PJK was defined as the postoperative proximal junctional angle (PJA) between the caudal endplate of the UIV and the cephalad endplate of the UIV + 2 ≥ 10° and at least 10° greater than the preoperative measurements[17].

Statistical analysis

Radiographic and clinical parameters were analyzed using the Mann-Whitney U test or Wilcoxon signed-rank test for continuous data and the Chi-squared test for categorical data. Furthermore, logistic regression analysis was performed based on the results of the univariate analysis. Statistical significance was set at $P < 0.05$. All analyses were performed using JMP software (SAS Institute Inc., Cary, NC, USA).

RESULTS

Demographics

Based on the selection criteria, 156 patients were initially included in the study. As 10 patients were subsequently excluded (five underwent surgeries from the upper thoracic vertebrae to the ilium and five did not have sufficient radiological data), 146 patients were enrolled for the analysis. Demographic data are shown in Table 1. The mean age at surgery was 73.3 years (range, 48-83 years), and the mean follow-up period was 42.3 ± 18.2 months (range, 26-96 months). Female patients accounted for 75% of the study population (male:female = 1:3). No significant difference in age and sex was identified among the four groups; however, there was a significant difference in the follow-up period. Titanium alloy (TA) was used as the rod material only in the P, 6P, and M groups, whereas cobalt chromium (CCr) was used in more than half of the cases in the B group. The average bleeding volume was 732.0 ± 432.1 mL (anterior,

Table 1. Demographic data

		B group	P group	6P group	M group	Total	*P*-value
Cases		17	51	45	33	146	
F/U (months)		52.7 ± 3.8	45.4 ± 5.6	40.2 ± 1.8	34.3 ± 2.6	42.3 ± 18.2	$P < 0.001$*
Age (years)		72.1 ± 4.4	72.8 ± 6.8	73.2 ± 7.1	72.0 ± 6.2	72.3 ± 6.5	n.s.
Sex (male:female)		5:12	12:39	12:33	8:25	36:108	n.s.
Rod material (CCr:TA)		17:0	0:51	0:45	0:33	15:131	**(B *vs.* P, 6P, M)
Operative time	Ant (min)	156.6 ± 40.9	133.3 ± 31.5	115.7 ± 26.6	103.7 ± 25.3	130.7 ± 45.9	*(6P *vs.* M) *(B *vs.* P) **(B,P *vs.* M)
	Post (min)	318.8 ± 48.1	261.3 ± 39.4	222.3 ± 26.6	202.5 ± 42.9	242.7 ± 76.5	*(P *vs.* M) **(B *vs.* P, 6P, M)
	Total (min)	475.4 ± 65.0	392.7 ± 52.6	354.1 ± 37.1	315.2 ± 132.1	365.7 ± 158.2	*(6P, P *vs.* M) **(B *vs.* P, 6P, M)
Blood loss	Ant (mL)	145.8 ± 166.6	115.8 ± 167.6	128.4 ± 148.8	124.1 ± 77.6	129.1 ± 155.0	n.s.
	Post (mL)	912.8 ± 544.6	650.3 ± 309.4	506.6 ± 218.4	412.1 ± 296.2	603.2 ± 309.2	*(B *vs.* P) **(B *vs.* 6P, M)
	Total (mL)	1058.7 ± 6.8.6	760.1 ± 372.1	635.1 ± 320.8	437.3 ± 289.4	732.0 ± 432.1	*(P *vs.* M, B) **(B *vs.* 6P, M)

Values are presented as mean ± standard deviations. Mann-Whitney U test, Chi-squared test. **$P < 0.001$, *$0.001 \leq P < 0.05$. B group: Balloon kyphoplasty in the upper instrumented vertebra (UIV)/UIV + 1 to prevent proximal junctional kyphosis; P group: circumferential minimally invasive surgery (c-MIS) using 5.5 mm rods; 6P group: c-MIS using 6 mm rods; M group: multi-rod c-MIS; CCr: cobalt chrome; TA: titanium alloy; F/U: follow-up; c-MIS: circumferential minimally invasive surgery.

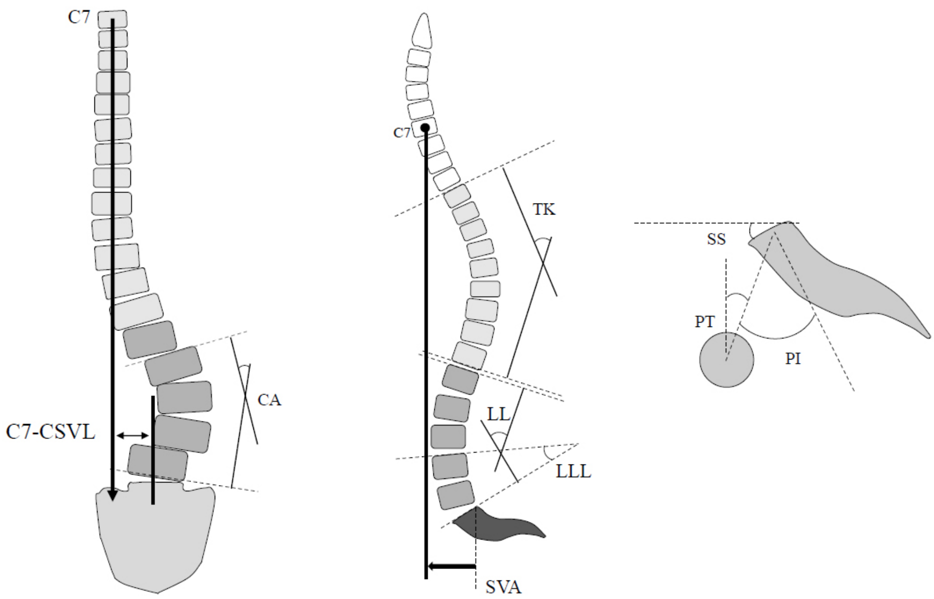

Figure 2. Spinopelvic parameters. LL: Lumbar lordosis; LLL: lower LL; TK: thoracic kyphosis; SS: sacral slope; PT: pelvic tilt; PI: pelvic incidence; SVA: sagittal vertical axis; CSVL: central sacrum vertical line; CA: cobb angle.

129.1 ± 155.0 mL; posterior, 603.2 ± 309.2 mL). The amount of intraoperative bleeding volume in posterior surgery gradually decreased with improvements in the surgical technique; in contrast, the same effect on intraoperative bleeding volume could not be observed in anterior surgery despite improvements in the surgical procedure. Both anterior and posterior operative time gradually decreased with improvements in the surgical technique [Table 1].

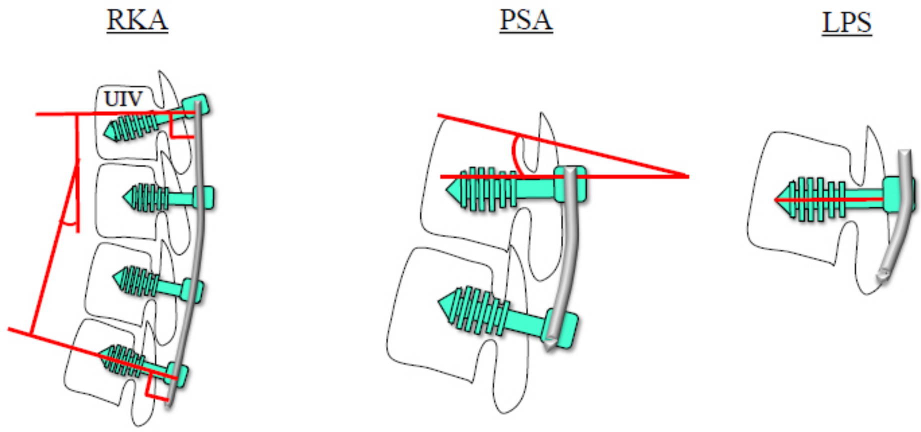

Figure 3. Implant-related parameters. RKA: Rod kyphotic angle in the upper instrumented vertebra (UIV)-L1; PSA: pedicle screw angle (angle between the pedicle screw and cranial endplate in the UIV); LPS: length of the UIV pedicle screw; UIV: upper instrumented vertebra.

Radiographic parameters

Spinopelvic parameters

The spinopelvic parameters revealed no statistically significant differences between the four groups [Table 2].

Implant-related parameters

RKA in the P, 6P, and M groups was significantly larger than that in the B group ($P < 0.001$). PSA and LPS in the 6P and M groups were significantly larger than those in the other groups ($P < 0.001$; Table 2).

Complications

The incidence of PJK decreased in the P, 6P, and M groups, and the incidence of PJK in the P and M groups was significantly lower than that in the B group [$P = 0.029$ (B *vs.* M) and 0.017 (B *vs.* P)]. The incidence of RF in the M group was significantly lower than that in the B and P groups [$P = 0.004$ (B *vs.* M) and 0.013 (P *vs.* M)]. The incidence of RF in the 6P group appeared to be lower than that in the P group; however, the difference was not significant ($P = 0.051$). The union failure rate was 26%. In most cases with RF, union failure was confirmed; however, only three cases reported RF after the union. The re-surgery rate decreased with changes in the surgical procedure. The re-surgery rate in the M group was significantly lower than that in the B group ($P = 0.017$; Table 3 and Figure 4).

Risk factors for MCs

In the MC group, 5.5 mm single rods were used more frequently than 6 mm single rods and 5.5 mm multi-rods, and CCr rods were used more often than TA rods [Table 4]. Among the various parameters, those in the MC group were significantly larger in terms of preoperative PT, postoperative PI-LL, and PSA [Table 5] compared with the non-MC group. Logistic regression analysis identified the use of a single 5.5 mm rod and postoperative PI-LL as significant risk factors for MCs. Receiver operating characteristic analysis of MCs using postoperative PI-LL revealed a cutoff value of 7° [area under the curve (AUC), 0.599].

DISCUSSION

Global alignment and mechanical complications

Yilgor *et al.* reported the importance of global alignment and proportion in the prevention of MCs[15]. Pizones *et al.* and Sebaaly *et al.* reported that restoring the ideal Roussouly sagittal alignment in ASD

Table 2. Spinopelvic parameters and implant-related parameters

	B group (*n* = 17)	P group (*n* = 51)	6P group (*n* = 45)	M group (*n* = 33)	*P*-value
Preop. PI (°)	43.5 ± 13.1	46.1 ± 11.7	43.3 ± 12.1	46.5 ± 11.1	n.s.
Postop. PI (°)	43.8 ± 12.7	47.0 ± 10.9	44.5 ± 11.9	45.2 ± 12.1	n.s.
Preop. LL (°)	7.2 ± 13.5	6.2 ± 12.1	7.2 ± 12.8	4.0 ± 13.1	n.s.
Postop. LL (°)	46.2 ± 9.8	48.8 ± 10.2	46.2 ± 11.1	48.8 ± 10.2	n.s.
Preop. PI-LL (°)	33.9 ± 12.5	38.5 ± 15.3	36.9 ± 14.8	42.5 ± 15.4	n.s.
Postop. PI-LL (°)	1.2 ± 14.3	2.6 ± 13.4	1.2 ± 12.3	2.6 ± 11.2	n.s.
Preop. PT (°)	29.5 ± 7.2	30.7 ± 6.8	29.5 ± 8.5	30.7 ± 7.5	n.s.
Postop. PT (°)	18.9 ± 6.2	20.9 ± 6.9	20.2 ± 7.1	18.9 ± 6.8	n.s.
Preop. TK (°)	21.3 ± 8.7	16.2 ± 9.4	22.5 ± 9.9	16.2 ± 7.2	n.s.
Postop. TK (°)	38.8 ± 9.3	37.7 ± 10.1	39.8 ± 8.3	36.7 ± 7.5	n.s.
RKA (°)	10.5 ± 7.2	18.9 ± 8.9	19.2 ± 9.3	18.7 ± 9.2	$P < 0.001$***
PSA (°)	2.5 ± 5.2	4.1 ± 3.8	18.1 ± 5.6	19.3 ± 6.2	$P < 0.001$**
LPS (mm)	36.4 ± 2.3	35.7 ± 2.4	42.5 ± 2.7	43.1 ± 2.6	$P < 0.001$**

Values are presented as mean ± standard deviation. Mann-Whitney *U* test. **Statistically significant (B and P *vs.* 6P and M); ***Statistically significant (B *vs.* P, 6P, and M); **/****P* < 0.001. B group: Balloon kyphoplasty in the upper instrumented vertebra (UIV)/UIV + 1 to prevent proximal junctional kyphosis; P group: c-MIS using 5.5 mm rods; 6P group: c-MIS using 6 mm rods; M group: multi-rod c-MIS; LL: lumbar lordosis; PI: pelvic incidence; TK: thoracic kyphosis; PT: pelvic tilt; SVA: sagittal vertical axis; RKA: rod kyphotic angle; PSA: pedicle screw angle; LPS: length of the upper instrumented vertebra pedicle screw; c-MIS: circumferential minimally invasive surgery.

Table 3. Complications

	B group (*n* = 17)	P group (*n* = 51)	6P group (*n* = 45)	M group (*n* = 33)	Total (*n* = 146)	*P*-value
PJK/PJF	8 (47.1%)	8 (16.6%)	9 (20.9%)	9 (18.7%)	33 (22.6%)	*(B *vs.* P, M)
RF	11 (64.7%)	16 (33.3%)	7 (16%)	6 (12.5%)	40 (27.8%)	*(B, P *vs.* M)
Union failure	9 (52.0%)	14 (33.3%)	7 (16%)	6 (12.5%)	36 (26.5%)	*(B, P *vs.* M)
Total revision rate	11 (64.7%)	15 (31.2%)	9 (20.9%)	8 (16.6%)	43 (29.9%)	*(B, *vs.* M)
PJK/PJF	7 (41.2%)	6 (12.5%)	6 (13.9%)	3 (6.2%)	22 (15.0%)	*(B *vs.* P, M, 6P)
RF	10 (58.8%)	12 (25.0%)	5 (11.6%)	4 (8.3%)	31 (21.0%)	* (B *vs.* 6P, M)

Values are presented as mean ± standard deviation. Chi-squared test. *$0.001 \leq P < 0.05$. B group: Balloon kyphoplasty in the upper instrumented vertebra (UIV)/UIV + 1 to prevent proximal junctional kyphosis; P group: c-MIS using 5.5 mm rods; 6P group: c-MIS using 6 mm rods; M group: multi-rod c-MIS; PJK: proximal junctional kyphosis; PJF: proximal junctional failure; RF, rod fracture; c-MIS: circumferential minimally invasive surgery.

surgery decreases the risk of mechanical complications[18,19]. All these reports combine PJK and RF under the definition of MCs and describe the importance of global spinal proportions in the prevention of MCs. However, Kwan *et al.* reported that spinal alignment based on the global alignment and proportion score is not associated with an increased risk of MCs[20]. We previously reported risk factors for PJK[16]. In that study, we reported that the occurrence of PJK was not associated with inflection point height and restoration to alignment based on the Roussouly classification. In the present study, postoperative PI-LL was a risk factor for MCs with a cutoff value of 7°. This result indicates that sufficient alignment correction is important in the prevention of MCs. Conversely, there was no significant difference in LLL between the two groups, and the spinal proportions between the two groups were similar. From the above results, we can speculate that

Table 4. Demographic data (MC group *vs.* non-MC group)

		Whole Group (*n* = 146)	Group non-MCs (*n* = 85)	Group MCs (*n* = 61)
Age (years)		72.3 ± 6.5 (48-83)	72.1 ± 6.9	73.2 ± 7.7
Rate of women (%)		77.3	80.1	77.1
Period of follow-up (months)		42.3 ± 18.2 (26-69)	40.7 ± 6.3	40.6 ± 6.2
Rod diameter/ number in construct	5.5 mm/2 rods	66(45%)	30	36*
	6 mm/2 rods	45(31%)	31	14
	5.5 mm/3 rods	35 (24%)	24	11
Rod material	CCr	17	3	14**
	TA	131	83	48
Number of levels fused		10.3 ± 0.5 (10-13)	10.3 ± 0.5	10.4 ± 05
Cement augmentation in UIV/UIV+1		17	3	14**
Number of LLIF		4.0 ± 0.5 (3-6)	4.0 ± 03	4.1 ± 05
UIV (case)	T8	3 (2%)	2	1
	T9	39 (27%)	20	19
	T10	104 (71%)	63	41

Values are presented as mean ± standard deviation. Wilcoxon signed-rank test. *Statistically significant. UIV: Upper instrumented vertebra; LLIF: lateral lumbar interbody fusion; CCr: cobalt chrome; TA: titanium alloy; MC: mechanical complication. *$P < 0.05$, **$P < 0.001$ compared with non-MC group.

Table 5. Spinopelvic parameters and implant-related parameters (MC group *vs.* non-MC group)

	Group MCs (*n* = 85)	Group non-MCs (*n* = 61)	*P*-value
Pre-PI (°)	48.8 ± 11.6	46.7 ± 11.6	0.185
Post-PI (°)	50.0 ± 10.7	47.2 ± 9.2	0.057
Pre-LL (°)	9.7 ± 16.5	7.2 ± 15.8	0.224
LL after LLIF (°)	32.6 ± 10.7	31.8 ± 10.9	0.489
Post-LL (°)	44.8 ± 9.8	46.8 ± 10.6	0.409
Pre-PI-LL (°)	38.1 ± 18.8	39.6 ± 15.0	0.520
Post-PI-LL (°)	4.0 ± 11.4	0 ± 10.2	*0.035
Pre-PT (°)	32.2 ± 11.54	30.6 ± 10.2	0.480
Post-PT (°)	18.9 ± 9.7	16.1 ± 8.6	*0.049
Pre-TK (°)	21.6 ± 14.2	20.8 ± 8.6	0.895
Post-TK (°)	37.4 ± 10.1	37.9 ± 10.6	0.724
Pre-LLL (°)	20.4 ± 12.5	24.0 ± 9.8	0.092
Post-LLL (°)	30.4 ± 8.7	30.8 ± 7.3	0.991
RKA (°)	18.8 ± 6.9	20.1 ± 6.0	0.101
PSA (°)	6.4 ± 8.2	8.9 ± 6.8	*0.019
LPS (mm)	19.3 ± 6.0	22.0 ± 4.3	*0.037

Values are presented as mean ± standard deviation. Mann-Whitney *U* test. *Statistically significant. LLIF: Lateral lumbar interbody fusion; LL: lumbar lordosis; PI: pelvic incidence; TK: thoracic kyphosis; PT: pelvic tilt; LLL: lower LL; MC: mechanical complication.

insufficient alignment correction is more strongly related to MCs than to spinal proportion. We considered that the results may be expected to differ between the study in which PJK and RF were collectively analyzed as MCs and the study in which PJK and RF were analyzed separately. We further consider that PJK and RF occur for different reasons and that grouping both of them under the label of mechanical complications is a reason for the confusion in investigating the causes of each. Therefore, the causes of PJK and RF should be investigated separately.

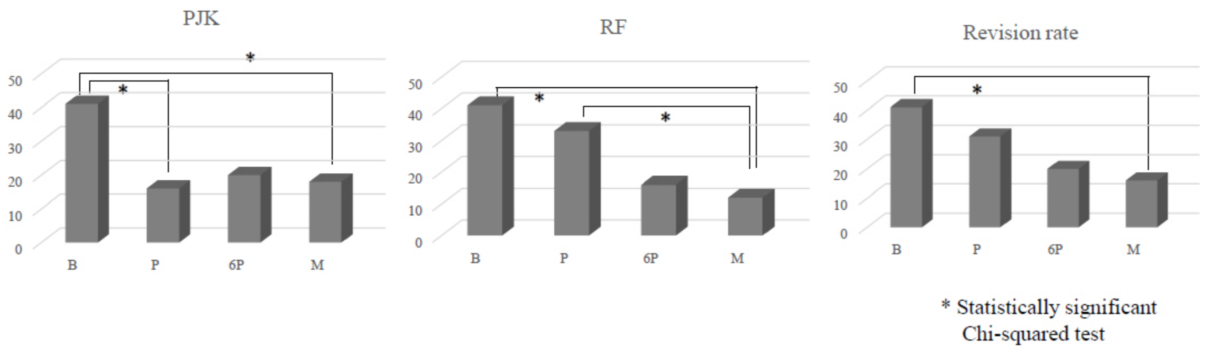

Figure 4. Complications: B group: Balloon kyphoplasty in the upper instrumented vertebra (UIV)/UIV + 1 to prevent proximal junctional kyphosis; P group: circumferential minimally invasive surgery (c-MIS) using 5.5 mm rods; 6P group: c-MIS using 6 mm rods; M group: multi-rod c-MIS. PJK: Proximal junctional kyphosis; RF: rod fracture.

PJK/PJF

Although PJK is asymptomatic in most cases, it sometimes presents with serious symptoms such as pain and paralysis[21]. PJK is believed to be caused by multiple factors including age, preoperative SVA, thoracolumbar spinal muscle mass, overcorrection, the level of the UIV, the type of anchored instrumentation for UIV fixation, soft tissue damage around the UIV, fixation to the pelvis, UIV tilt angle, and terminal rod contour[8,16,21-26]. Of these factors, we consider the terminal rod contour to be the most important. We previously reported that inadequate kyphosis of the terminal rod and overcorrection were risk factors for PJK[16]. To reduce PJK after c-MIS for the treatment of ASD using LLIF and PPS, we have also been undertaking the following four measures: (1) inserting a pedicle screw at the thoracic level using the PPS technique to preserve the posterior soft tissues such as the paraspinal muscle, facet joint capsule, supraspinous ligament, and interspinous ligament; (2) inserting longer pedicle screws in the caudal direction obliquely at the UIV to prevent PS back-out; (3) ensuring sufficient kyphosis of the terminal rod contour for postoperative reciprocal change[16]; and (4) targeting postoperative LL with satisfactory PI-10 < LL < PI to avoid overcorrection[16]. In the present study, the incidence rate of PJK was higher in group B than in the other groups. There are two reasons for this. The first is the high rigidity of the CCr rods. CCr rods were used in all cases in Group B. Han *et al.* reported that PJK occurs more frequently in patients with CCr rods than in those with TA rods[27]. They considered that when a more rigid CCr rod is used, the increased stiffness of the vertebral body at the proximal end of fixation and the consequent load on the adjacent disc becomes a factor in PJK. Lange *et al.* and Cammarata *et al.* reported that a more gradual transition from instrumented to non-instrumented vertebra is important[28,29], and that the use of transition rods is desirable. In this study, it is speculated that the incidence rate of PJK was higher in group B than in the other groups due to excessive stress applied between adjacent vertebrae due to more rigid fixation using CCr rods with cement augmentation.

In addition, Bess *et al.*, in their study on finite element analysis, reported that the use of a posterior tether rather than PS and hook is useful for the prevention of PJK[30]. The second reason for the higher PJK incidence is that RKA, PSA, and LPS were smaller in group B than in the other groups. We focused on kyphosis of the terminal rod to make the rod suitable for postoperative reciprocal change in the thoracic spine. Thoracic kyphosis, which had been compensated for preoperatively due to a decrease in LL, increased due to reciprocal changes after corrective surgery[16]. We speculate that kyphosis of the terminal rod was one of the reasons for the decreased PJK that made the rod suitable for postoperative reciprocal change of the thoracic spine. Insufficient RKA, as we reported in the past, is a cause of PJK because it is not compatible with postoperative reciprocal change. Increasing the PSA increases the strength of the pull-out of the screw and also prevents screw deviation to the cranial disc and cranial vertebral body when PJK occurs. Further, it is important to insert a longer PPS in the caudal direction rather than parallel to the endplate. The purpose of this is to increase pull-out strength and prevent screw penetration into the cranial disc and cranial vertebral body after a UIV fracture [Figure 5]. Oe *et al.* reported that longer screws can reduce the stress on the UIV and UIV fractures[31]. There are also some reports that the reduction of posterior soft tissue damage using PPS is useful in the prevention of PJK[22,32]. In all groups, posterior surgery was performed with PPS. However, RKA and PSA were significantly lower and LPS was significantly shorter in the B group than in the other groups. Therefore, in the present study, it is difficult to conclude whether preservation of the posterior soft tissue by using PPS is the primary factor that affects the prevention of PJK. It is speculated that these measures contributed to the prevention of PJF and its associated complications, such as PS back-out and secondary fractures of UIV + 1.

Theologis *et al.* and Martin *et al.* reported the usefulness of cement augmentation in PJK prevention[33,34]. In the B group in the present study, cement augmentation was performed in the UIV and UIV + 1 to prevent PJK. However, the incidence of PJK was 41.3%, which was higher than that in the other groups. Increasing the bone strength of the vertebral body with cement augmentation to prevent screw back-out and vertebral body fracture did not prevent PJK. Conversely, the RKA, PSA, and LPS in the B group were significantly smaller than those in the other groups. Furthermore, the PSA and LPS in the B groups were significantly smaller than those in the 6P and M groups. From the above results, we could expect that the terminal rod contour, PSA, and PSL are more important factors for determining the prevention of PJK than the increase in bone strength and rigidity of instrumentation.

The inflection point (IP) was also very important. According to Roussouly *et al.*, the spinal alignment of healthy people can be classified into four types, and the IP moves toward the cranial side as the PI increases[35]. Jakinapally *et al.* reported that the incidence of PJK in patients with inflection vertebra at T12 or cranially was significantly higher (69%) than that at L1 or caudally (26%)[36]. We reported that RKA in the UIV to L1 requires 13.5° or more to prevent PJK[16]. Based on the report by Roussouly *et al.*[35], we speculate that we should create a rod contour with the IP moved further cranially if the patient's PI is high and with the IP moved more caudally if the patient’s PI is low. Considering the findings of our previous report and Jakinapally *et al.*’s report[36], we need to create a rod contour with a thoracic kyphosis ≥ 13° and an IP of L1 or lower.

There are also some reports that suggest that overcorrection is a risk factor for PJK[16,27,37]. Mechanistically, this is expected to correct the global balance by developing PJK when overcorrection results in a negative SVA[16]. We consider that PI-10 < LL < PI is appropriate for the correction goal in ASD surgery[16].

RF

RF is a frequent implant-related complication following ASD surgery. Previous studies have shown a high incidence (range 6.8%-22%) of RF following corrective fusion surgery in patients treated for ASD[10,11,38,39]. Several risk factors have been reported for the development of RF, such as older age, higher BMI, history of previous spine surgery, performance of a pedicle subtraction osteotomy, use of CCr rods, greater baseline sagittal spinopelvic malalignment (SVA, PT, and PI-LL mismatch), and greater magnitude of sagittal spinopelvic malalignment correction with surgery (SVA and PI-LL mismatch)[10,11,39]. In c-MIS for the treatment of ASD, there is a significant risk that if the bone surface for grafting is narrow, bone grafting other than interbody fusion cannot be performed. Accordingly, the pseudarthrosis rate is higher than that of conventional open surgery[40]. Moreover, since the bone surface area available for bone fusion is narrow in c-MIS, bone fusion takes longer. RF in c-MIS develops because the durability of the rod decreases before

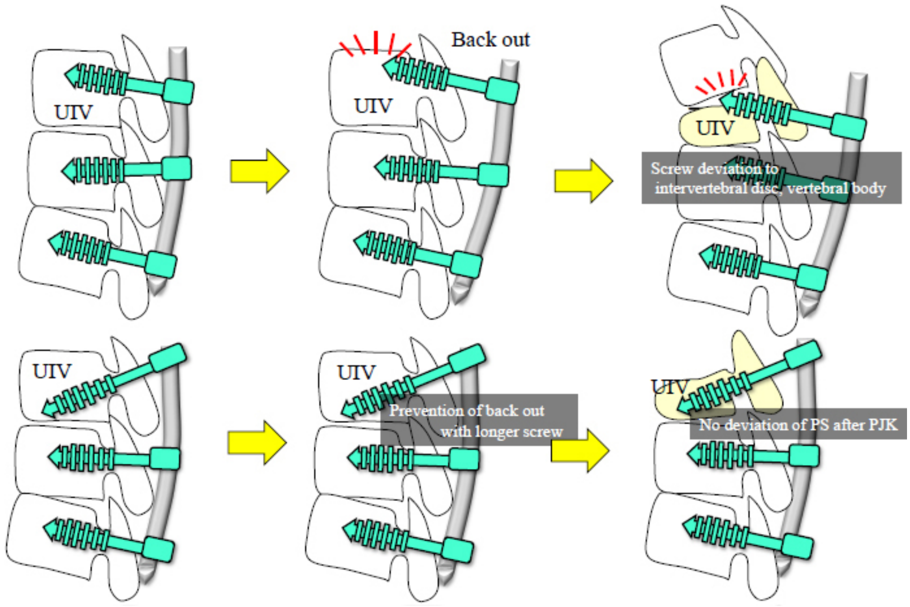

Figure 5. Inserting longer screws in the caudal direction obliquely at the UIV. UIV: Upper instrumented vertebra; PJK: proximal junctional kyphosis.

bone fusion is achieved. Therefore, it is important to increase rod durability by using additional rods to prevent the breakage that may occur before bone fusion to increase the bone fusion rate. Increasing the durability of the rod will promote spontaneous bone fusion of facet joint and intervertebral bridging[41]. Previous reports have shown that multiple rods reduce RF after ASD, and the benefit of multiple rods is gradually being recognized[42-44]. In the present study, the incidence of RF tended to decrease in the 6P group and significantly decreased in the M group, confirming the benefit of multiple rods for RF. Furthermore, in the logistic regression analysis in this study, the use of a 5.5 mm single rod and postoperative PI-LL were identified as significant risk factors for MCs. This result suggests that increasing the number of rods or rod diameter is more useful in the prevention of RF. Conversely, Pizones *et al.* and Sebaaly *et al.* reported that recovery to good alignment is important for the prevention of MCs[18,19]. In the present study, post PI-LL was detected as a risk factor for MCs, and the results were almost the same as in previous reports.

Surgical invasion/re-surgery rate

The amount of bleeding and the operation time peaked in group B and decreased with the improvement of the surgical procedure. The reason for this reduction in surgical invasion is due to the acquisition of surgical techniques and progression of the surgeon along the learning curve.

The re-surgery rate after open ASD surgery reportedly ranges from 9%-58%[9,45-49]. Hamilton *et al.* reported a 12% re-surgery rate after traditional open surgery; however, when less invasive procedures were employed, the rate increased to 27% in the HYB group but decreased to 11.1% in the c-MIS group[50]. In general, the re-surgery rate increases as follow-up durations increase, likely because failures such as RF, pseudoarthrosis, or adjacent segment disease may occur or become symptomatic several years after surgery. In the present study, the re-surgery rate was 41% in the B group; however, it was 20% in the 6P group and 16% in the M group, which is a significant decrease. The reason for this is that, although there are differences in the follow-up period, the above-mentioned measures against various complications were effective. However, further long-term follow-up is required in this regard.

Limitations

This study has four limitations. First, this was a retrospective, single-institution, historical study. In the future, a multi-center large-scale study would be desirable. Second, complications after surgery for ASD may have decreased as surgical techniques improved over time. The improvement of the surgical procedure produced a large bias in this study, and further detailed analysis using multivariate analysis or other methods is necessary in the future. Third, the effects of metal corrosion and corrosive products on tissues have not been investigated. Further investigation is needed in the future. Lastly, although bone mineral density (BMD) and its treatment may have significant impacts on PJK and RF, BMD was not evaluated in this study. Future studies should evaluate BMD in the context of osteoporosis treatment.

In conclusion, in the present study, we evaluated the effectiveness of measures against MCs from the clinical results of multiple surgical procedures to treat ASD, in addition to examining the risk factors for MCs. The incidence of MCs was highest in the B group and lowest in the M group. In the prevention of PJK, terminal rod contour, PSA, and LPS may be more important than tight fixation in the UIV. To reduce RF in c-MIS for ASD, it is necessary to obtain bone fusion before RF occurs, and it is important to increase the durability of the implant by using additional rods. The risk factors for MCs were the use of a single 5.5 mm rod and postoperative PI-LL.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design: Ishihara M
Performed data acquisition: Ishihara M
Investigation: Ishihara M, Adachi T, Tani Y, Paku M, Tanaka T, Masada K
Analyzed and interpreted the data: Ishihara M, Taniguchi S
Review and Editing: Taniguchi S, Kotani Y, Saito T
Supervision and Project Administration: Saito T
Supervised the study: Ishihara M
All authors approved the manuscript for publication.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

This study was approved by the institutional review board of the Kansai Medical University Hospital (approval no.: 2020189) and was conducted after obtaining the consent of all patients.

Consent for publication

Written informed consent was obtained from the patient for publication of this report and any accompanying images. A copy of the written consent form is available for review by the editor.

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