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Characteristics of cage migration cases following combined anterior-posterior spinal reconstruction surgery using an adjustable wide footprint plate cage

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ABSTRACT

Anterior-posterior vertebral reconstruction is indicated for unstable spinal fractures, but cage subsidence and migration remain concerns. Adjustable wide footprint plate (AWFP) cages were developed to enhance anterior column stability; however, postoperative migration and breakage have been reported. This study evaluated the radiographic characteristics of AWFP cage migration. We retrospectively reviewed 21 patients with single-level AO type A2-A4 or B4 fractures who underwent combined anterior-posterior reconstruction using an AWFP cage and pedicle screw-rod fixation between 2019 and 2024, with ≥6 months of follow-up. Demographics, vertebral computed tomography (CT) values, cage lift-up, subsidence, screw loosening, bone fusion, coronal AWFP angle, and hardware failure were assessed. Patients were classified into migration (≥3 mm displacement) and non-migration groups. Eleven patients showed cage migration. Demographics, CT values, and posterior fixation levels did not differ between groups. Anterior and posterior cage lift-up were significantly greater in the migration group (6.2 vs 2.1 mm, p = 0.03; 3.2 vs 0.7 mm, p = 0.04). Migration was associated with higher rates of subsidence and screw loosening. Progressive increases in the coronal AWFP angle were observed at 1 week (4.6° vs 1.5°, p = 0.001) and 6 months (7.3° vs 2.1°, p = 0.001). Plate breakage occurred in two cases, including one requiring revision surgery. AWFP cage migration is associated with excessive lift-up, subsidence, and progressive coronal angle changes. Monitoring coronal angle changes may facilitate early detection of mechanical failure.

Keywords: adjustable wide footprint plate cage, anterior-posterior combined spinal reconstruction surgery, vertebral fracture

INTRODUCTION

Vertebral fractures are frequently caused by high-energy trauma, such as motor vehicle collisions and falls from height. With the aging of society, the incidence of osteoporotic vertebral

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fractures associated with low-energy falls is increasing, imposing a major clinical and socioeconomic burden.[1] These fractures are often associated with progressive kyphotic deformity, persistent pain, and spinal cord injury, thereby causing functional impairment and reduced quality of life.[2] Although conservative management is often the initial approach, surgical intervention should be considered in patients with instability, severe vertebral collapse, or neurological risk.

Surgery is generally indicated for unstable vertebral fractures, particularly for patients with a Thoracolumbar Injury Classification and Severity Score[3] of ≥5. Severe vertebral body destruction (load-sharing score ≥7) requires anterior column reconstruction, and combined anterior-posterior spinal reconstruction is often indicated.[4] Autologous iliac crest or fibular grafts have traditionally been used for anterior reconstruction. However, they are frequently associated with donor-site complications, leading to an increasing preference for vertebral body replacement cages.[5] Recently, expandable cages that provide improved anterior column stability have become available.[6] Furthermore, the advent of adjustable wide footprint plate (AWFP) cages, which allow intraoperative adjustment of cage height and angulation, has enabled more robust fixation and improved biomechanical conformity with vertebral endplates.[7]

Despite these advantages, early postoperative complications, such as cage migration, plate tilting, and breakage, have been encountered in clinical practice. To the best of our knowledge, no study has reported plate tilting or failure associated with AWFP cages. Therefore, this study aimed to investigate the characteristics and clinical outcomes of patients with cage migration after combined anterior-posterior spinal reconstruction using AWFP cages. In observing cases of cage breakage, we hypothesized that such adverse outcomes are associated with cage migration during postoperative follow-up. Therefore, we focused our analysis on postoperative cage migration. Because cage migration typically occurs along the insertion path, we decided to stratify the study population by examining anteroposterior radiographs. Identifying features associated with migration and breakage can promote safer and more appropriate application of AWFP cages and improve patient outcomes.

MATERIALS AND METHODS

Study design and patient selection

This study was conducted in accordance with Declaration of Helsinki guidelines and approved by Institutional Review Board of Nagoya University Graduate School of Medicine (2019-0094). Informed consent was obtained in an opt-out form. This was a single-center retrospective study including 21 consecutive patients who underwent combined anterior-posterior spinal reconstruction for single-level AO classification A2, A3, A4, or B4 vertebral fractures[8] between 2019 and 2024. All patients underwent anterior reconstruction using a T2 Stratosphere cage with AWFPs (Medtronic, Minneapolis, MN, USA) and were followed for ≥6 months. The surgical indications included severe vertebral collapse (load-sharing score ≥7) and fractures deemed unsuitable for percutaneous vertebroplasty. Patients were categorized into two groups: the migration group, which included patients with ≥3 mm cage migration within 6 months after surgery, and the non-migration group, which included the remaining patients.

Surgical technique

Generally, posterior fixation was performed first. However, anterior reconstruction preceded posterior fixation in some cases at the lead surgeon's discretion. Posterior fixation was performed using Solera Voyager pedicle screws (Medtronic) with 4.75 or 5.5 mm cobalt-chromium rods. In principle, one vertebral level above and one level below the fracture were instrumented. However, fixation was extended when necessary.

Anterior reconstruction was performed using a T2 Stratosphere cage with AWFPs (Medtronic). During cage insertion, the AWFP is not fixed to the cage cylinder at a predetermined angle. Instead, cage expansion allows passive angulation of up to 8° using a self-adjusting end cap mechanism optimized for vertebral endplate conformity. Cage expansion and AWFP angulation were locked after the appropriate lift-up was achieved. Fluoroscopic guidance was used to ensure adequate distraction. All patients were fitted with a rigid orthosis after surgery, and rehabilitation was initiated.

Variables

Cage migration was defined as a displacement of ≥3 mm in anteroposterior radiographs, which exceeds radiographic measurement error and corresponds to a clinically meaningful threshold, as mechanical changes such as increased cage lift-up and early angular changes were observed beyond this level.[9,10] The distance between the center of the cage and the midpoint between the superior and inferior endplates, measured along a line connecting the spinous processes of the adjacent vertebrae, was evaluated (Fig. 1A). The change from the immediate postoperative measurement was defined as the amount of migration. As mentioned above, to minimize the effects of rotation and non-standard X-ray images, the measurement of migration is based on the midline distance from the spinous processes of adjacent vertebrae. Furthermore, because images showing obvious rotation or poor positioning are retaken during the image review process, the dataset did not include any images that would compromise the accuracy of the measurements.

Variables, including age, sex, body mass index (BMI), computed tomography (CT) values of adjacent vertebrae (Hounsfield unit [HU]), number of posterior instrumented levels, rod diameter, cage-induced intervertebral distraction (lift-up), cage subsidence, pedicle screw loosening, bone fusion, AWFP breakage, and failure of the cage locking mechanism, were collected.

CT values were measured on axial CT images at the upper, middle, and lower thirds of the

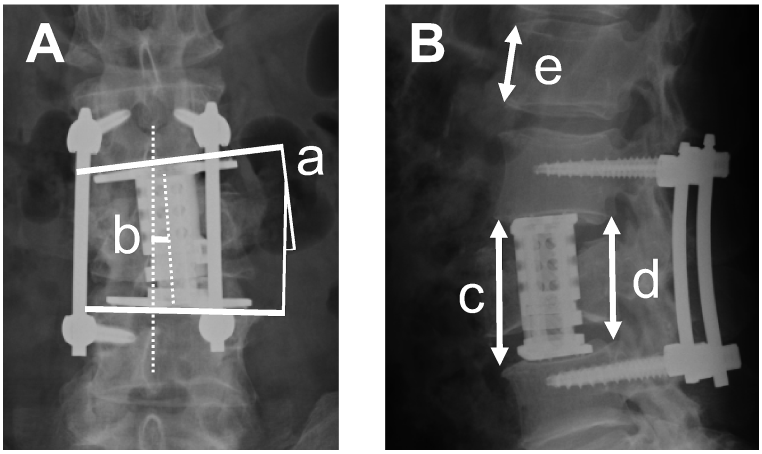

Fig. 1 Measurement on radiographs

Fig. 1A: Coronal AWFP angle (a); the angle formed between the cranial and caudal AWFP. The distance between the cage and the intervertebral midpoint (b).

Fig. 1B: Cage lift-up. Anterior distance (c), posterior distance (d), and reference for correction (e). Anterior vertebral lift-up was calculated as the difference in (c) corrected by (e). Posterior vertebral lift-up was calculated as the difference in (d) corrected by (e).

AWFP: adjustable wide footprint plate

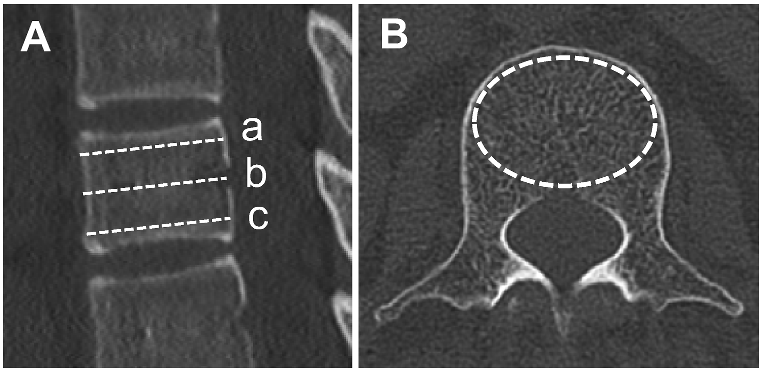

Fig. 2 Measurement points for CT values in vertebrae adjacent to the fractured vertebral body
Fig. 2A: CT values were measured on axial images at three levels of the adjacent vertebral bodies: just below the superior endplate (a), at the mid-vertebral level (b), and just above the inferior endplate (c).
Fig. 2B: At each level, an elliptical region of interest was placed to cover as much trabecular bone as possible while excluding the cortical bone.
The mean value of the three measurements was used for analysis.
CT: computed tomography

vertebral body, and the mean values were recorded[11] (Fig. 2). Cage lift-up was calculated as the change in anterior and posterior intervertebral heights on radiographs by comparing measurements obtained immediately after the final surgical procedure with those obtained after posterior fixation. The obtained values were adjusted using the anterior vertebral body height of the adjacent level to correct for inter-image magnification errors (Fig. 1B). Cage subsidence was defined as endplate depression of ≥3 mm. Screw loosening was defined as radiolucency of ≥1 mm around the screws.[12] Bone fusion was defined as trabecular bone bridging through or adjacent to the cage on CT.[13] AWFP breakage was defined as abnormal plate bending. Coronal AWFP angle was measured immediately after surgery, 1 week after surgery, and 6 months after surgery (Fig. 1A). CT values were compared between patients with and without cage subsidence.

Statistical analysis

All statistical analyses were performed using EZR software.[14] Categorical variables were compared using Fisher's exact test, whereas continuous variables were compared using Welch's *t*-test. A *p*-value <0.05 indicated statistical significance. For each measured and calculated parameter, intra- and inter-rater reliability was assessed using the intraclass correlation coefficient (ICC).

RESULTS

Of the 21 patients, 11 were included in the migration group, and 10 were included in the non-migration group. The mean ages of the migration and non-migration groups were 63.6 and 61.5 years, respectively, with 7 males in the migration group and 5 in the non-migration group. The mean BMI was 22.6 kg/m^2 in the migration group and 25.7 kg/m^2 in the non-migration group. No significant differences in any of these parameters were observed between the two groups. The fracture levels were T11 (n = 1), T12 (n = 1), L1 (n = 3), L2 (n = 3), and L3 (n = 3) in the migration group and T12 (n = 3), L1 (n = 4), L2 (n = 1), L3 (n = 1), and L4 (n = 1) in the non-migration group. The mean CT values of the cranial adjacent vertebrae in the migration and non-migration groups were 116 and 120 HU, respectively, and those of the caudal vertebrae were 119 and 113 HU, respectively. The mean number of posterior instrumented levels was 2.8 and 3.1 in the migration and non-migration groups, respectively. The rod diameters were 4.75 mm (n = 7) and 5.5 mm (n = 4) in the migration group and 4.75 mm (n = 6) and 5.5 mm (n = 4) in the non-migration group (Table 1).

Table 1 Patients' demographics

	Migration group (N = 11)	**Non-migration group (N = 10)**	***p*-value**
Age, years	63.6 ± 18.4	61.5 ± 22.1	0.82
Sex, men, n	7 (63.6%)	5 (50%)	0.67
BMI, kg/m^2	22.6 ± 4.6	25.7 ± 7.8	0.27
Vertebral CT value, HU			
Superior vertebra	116.1 ± 54.9	121.0 ± 71.5	0.86
Inferior vertebra	119.0 ± 61.3	113.3 ± 63.9	0.84
Number of fused vertebrae	2.8 ± 1.0	3.1 ± 1.0	0.52
Rod diameter 4.75 mm/5.5 mm, n	7/4	6/4	1

BMI: body mass index
CT: computed tomography
HU: Hounsfield unit

Intra-rater and inter-rater reliability in image measurements were adequate (ICC, 0.799–0.963 and 0.717–0.963, respectively; Supplementary Tables 1–3). The anterior and posterior cage lift-up were significantly greater in the migration group than in the non-migration group (6.2 vs 2.1 mm, $p = 0.03$; 3.2 vs 0.7 mm, $p = 0.04$). Cage subsidence was observed in 7 patients in the migration group and 3 in the non-migration group, and screw loosening was observed in 4 patients in the migration group and 2 in the non-migration group. Bone fusion was observed in 9 patients in the migration group and 9 in the non-migration group (Table 2). The coronal AWFP angle was similar between the two groups (1.6° vs 1.4°) immediately after surgery. However, it was significantly greater in the migration group at 1 week (4.6° vs 1.5°, $p = 0.001$) and continued to increase at 6 months (7.3° vs 2.1°, $p = 0.001$) (Fig. 3). AWFP breakage occurred in two patients in the migration group (Table 3). Additionally, the mean CT values of the cranial and caudal vertebrae were relatively lower in patients with cage subsidence (109.3 vs 126.7 HU, $p = 0.53$; 108.0 vs 123.8 HU, $p = 0.57$, respectively).

Table 2 Radiographic evaluation

	Migration group (N = 11)	**Non-migration group (N = 10)**	***p*-value**
Anterior cage lift-up height, mm	6.2 ± 5.0	2.1 ± 1.4	**0.03**
Posterior cage lift-up height, mm	3.2 ± 2.3	0.7 ± 2.6	**0.044**
Cage subsidence, n	7 (63.6%)	3 (30.0%)	0.20
PS loosening, n	4 (36.4%)	2 (20.0%)	0.64
Bone fusion, n	9 (81.8%)	9 (90.0%)	<0.99
AWFP breakage, n	2 (18.2%)	0 (0%)	0.48

PS: pedicle screw
AWFP: adjustable wide footprint plate

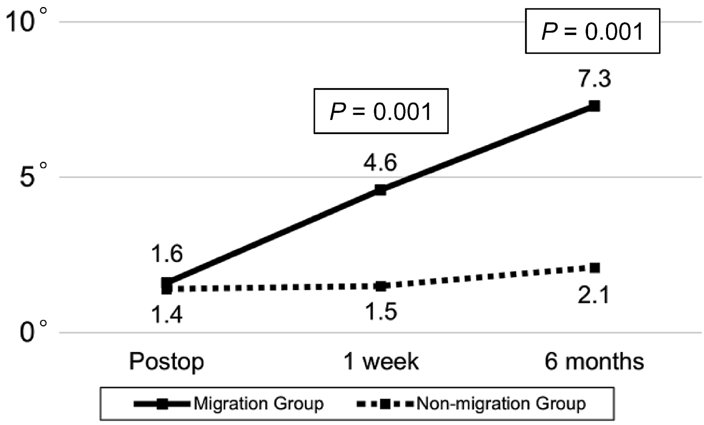

Fig. 3 Change in coronal AWFP angle at three postoperative time points
AWFP: adjustable wide footprint plate

Table 3 List of the migration group

	Age/ Sex	Fracture level/ AO type	Fusion levels	Anterior/ Posterior order	Change in plate angle at 1-week postop, °	Change in plate angle at 6-month postop, °	Cage lift-up, mm	Cage subsid-ence	Bone fusion	PS loosening	AWFP breakage
1	26/M	L1/A4	T12-L2	PA	3	6	11.6	−	+	−	−
2	65/M	L3/A2	L2-L4	PA	4	4	5.6	−	−	−	+
3	82/M	L2/A4	T12-L5	AP	6	10	NA*	+	+	−	−
4	75/M	L2/A3	L1-L3	PA	2	6	13.4	−	+	−	−
5	38/F	L2/A4	L1-L3	PA	−1	4	3.2	+	+	−	−
6	71/F	L1/A4	T11-L2	PA	1	2	0.0	+	+	−	−
7	78/F	T11/A4	T9-T12	PA	5	6	0.0	+	+	+	−
8	59/M	T12/A3	T10-L1	PA	6	11	6.5	+	+	+	−
9	55/F	L1/A3	T11-L2	PA	1	1	6.4	−	+	−	−
10	86/M	L3/A4	L2-L4	PA	5	11	12.6	+	+	+	−
11	64/M	L3/A3	L1-L5	PA	1	NA†	2.1	+	−	+	+

PS: pedicle screw
AWFP: adjustable wide footprint plate
PA: posterior-anterior
AP: anterior-posterior
NA: not applicable
* Cage lift-up height was evaluated in patients who underwent surgery in the PA order.
† Reoperation performed due to implant failure within 6 months.

AWFP breakage cases

The first case was a 65-year-old male patient who sustained an L3 AO type A2 fracture. Staged surgery with L2-4 posterior fixation and L3 cage reconstruction was performed. Cage migration (4 mm) and AWFP angle change (10°) were observed 1 week after surgery. Although bony fusion was confirmed at 3 years after surgery, marked caudal plate bending indicated plate breakage. However, no symptoms were observed (Fig. 4).

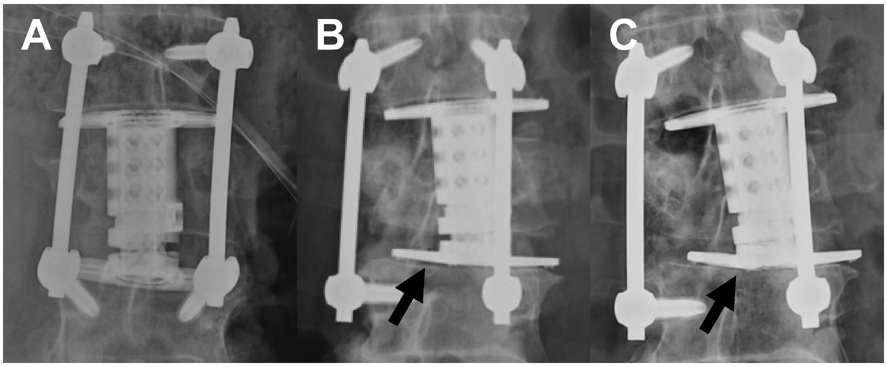

Fig. 4 Case 1 of AWFP breakage
Fig. 4A: Immediately after surgery
Fig. 4B: One month after surgery; cage migration and increased coronal AWFP angle were observed (arrow).
Fig. 4C: Three years after surgery; despite AWFP breakage (arrow), bone union was achieved.
AWFP: adjustable wide footprint plate

The second case was a 64-year-old male patient who suffered an L3 AO type A3 fracture. Staged surgery with L1-5 posterior fixation and L3 cage reconstruction was performed. Progressive cage migration from 3 mm at 1 week to 12 mm at 6 weeks was observed. Cranial plate breakage was observed at 4 months. No endplate injury was evident intraoperatively. However, cranial endplate damage was observed when plate breakage occurred. Revision surgery, including cage removal, iliac bone grafting, and extended T11-S1 posterior fixation, was performed. The explanted cage demonstrated cranial AWFP fracture and caudal AWFP cracking, whereas the locking mechanism remained intact (Fig. 5).

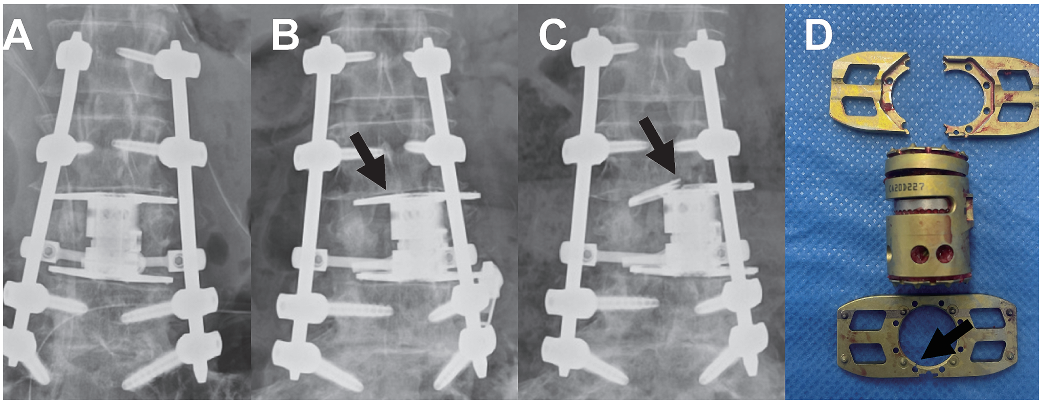

Fig. 5 Case 2 of AWFP breakage
Fig. 5A: Immediately after surgery
Fig. 5B: Two months after surgery; cage migration was observed (arrow).
Fig. 5C: Four months after surgery; AWFP breakage was observed (arrow).
Fig. 5D: A broken implant was retrieved during the revision surgery.
AWFP: adjustable wide footprint plate

DISCUSSION

This study evaluated the postoperative outcomes of combined anterior-posterior spinal reconstruction using AWFP cages and identified the characteristics associated with cage migration. Although no significant differences in age, sex, BMI, adjacent vertebral CT values, number of levels fixed posteriorly, or rod diameter were observed between the migration and non-migration groups, the migration group demonstrated significantly greater cage lift-up and higher incidence of cage subsidence than the non-migration group. Furthermore, the coronal AWFP angle progressively increased in the migration group, and some plate breakage was observed.

Early cage migration can be a potential cause of reoperation in spinal reconstruction using an expandable vertebral body replacement cage.[6] Endplate injury is a known cause of cage migration in lateral lumbar interbody fusion (LLIF) procedures, which involve a similar cage placement procedure.[15] Therefore, the relatively high incidence of endplate injury and subsidence observed in the migration group indicates that AWFP cage migration shares biomechanical features with LLIF cage migration. Older age (>65 years), female sex, low bone density, and excessive cage height are risk factors for LLIF-associated endplate injury.[16] Expandable cylindrical cages without a wide footprint are more likely to cause subsidence than non-expandable cages.[17] Furthermore, excessive cage expansion increases the risk of adjacent vertebral fractures and endplate injury.[18] The AWFP system increases the endplate contact area and allows passive angular adjustment up to 8°, theoretically reducing stress concentration at the cage ends and improving the endplate fit. Therefore, the AWFP cage may better prevent endplate damage and cage subsidence than cylindrical cages.[7]

However, AWFP cage subsidence occurred in 10 of the 21 patients included in this study. Patients with endplate injury tended to have lower CT attenuation values. However, the difference was not statistically significant due to the small sample size. Low CT values have been reported to be a predictor of endplate injury in LLIF.[19] Therefore, low adjacent vertebral CT values are likely associated with an increased risk of subsidence even with AWFP cages. Therefore, minimizing cage lift-up is essential, particularly in patients with low CT values. Furthermore, the AWFP cage features plates that allow a maximum circumferential tilt angle of 8°. Although an 8° tilt angle is sufficient for the thoracolumbar junction, it may be insufficient for the lumbar spine, resulting in a mismatch between the AWFP and the vertebral endplates. In this study, migration occurred in 5 cases at the thoracolumbar junction (T11-L2), whereas it occurred in 6 cases at the lower lumbar level (L3-L4), indicating a higher incidence of migration at the lower lumbar level, where sagittal endplate inclination may exceed the maximum 8° adjustment allowed by the AWFP. Insufficient angular compatibility may result in stress concentration, leading to endplate damage and migration.

Insufficient posterior fixation strength has been reported to contribute to cage migration in LLIF.[20] In this study, three cases in the migration group did not show cage subsidence. These cases had posterior fixation limited to one level cranially and caudally, and relatively thin 4.75 mm rods were used in all of them. Excessive anterior expansion under inadequate posterior fixation may have induced alignment changes without vertebral endplate damage exceeding the limits tolerable by the screw-rod system, leading to pedicle screw microloosening and biomechanical instability. Therefore, extending the posterior fixation levels or using fenestrated screws with cement augmentation may improve stability. Minimizing cage lift-up is important when posterior fixation is limited, and using thicker rods, such as 5.5 mm or 6.0 mm, may be preferable.

In this study, progressive coronal AWFP angle increases were observed in the migration group. In case 1, increased plate angulation was correlated with cage migration, indicating that migration leads to uneven load distribution on the AWFP plate and the self-adjusting end cap, resulting in locking mechanism loosening and increased coronal AWFP angle. An angle exceeding 8° likely subjected the plate to excessive force, resulting in breakage. In case 2, no increase in coronal AWFP angle was observed. However, the patient experienced AWFP failure. Because the locking mechanism remained functional, cage migration directly transferred uneven compressive load to one AWFP side, causing early plate fracture. We speculate that loosening of the locking mechanism, accompanied by an increase in the coronal AWFP angle, may contribute to load dispersion on the plate (Fig. 6). Conversely, if locking is maintained, cage displacement rapidly leads to uneven stress distribution on the plate. Therefore, early plate failure might have resulted from the vertical compressive forces applied to only one side of the plate, whereas the locking mechanism remained engaged.

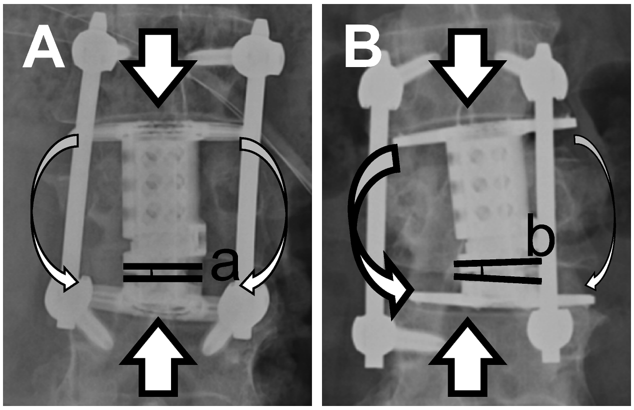

Fig. 6 Mechanism underlying the increased unilateral stress on the plate with cage migration
Fig. 6A: The cage is positioned at the midline, resulting in symmetric loading on both sides of the plate.
Fig. 6B: Cage migration leads to increased stress on one side. Therefore, the locking mechanism angle worsens from (a) to (b). Once this angle exceeds the mechanical limit of 8°, the load on the plate is expected to increase dramatically.

Based on these findings, it is desirable to utilize the increase in the coronal AWFP angle as a predictive parameter. The plate locked by a locking mechanism should not change in angle; therefore, it can be said that a change in the coronal AWFP angle itself indicates a high risk of implant failure. Considering measurement errors in imaging studies—specifically, a measurement error of approximately 3° for scoliosis curves,[21] if a 3° change in the coronal plane AWFP angle is observed, clinicians should judge this to indicate a high risk of implant failure and consider implementing more frequent follow-ups and extending the duration of external fixation. Although this study focuses on findings in anteroposterior radiographs, we consider displacement in the coronal plane to be an aspect of three-dimensional mechanical instability accompanied by sagittal displacement. A key point is that, given the characteristic shape of the AWFP and the ease of interpreting radiographic images, displacement or deformation of the AWFP cage in the coronal plane is considered clinically easy to detect.

Because this was a case series study with a limited number of cases, it was not designed to determine the optimal fixation construct; however, strategies that may help reduce the risk of cage migration and failure should be considered. Nevertheless, because of the small sample size, the statistical power was limited, and some variables may not have reached statistical significance despite potential associations. In addition, we were unable to clearly identify independent factors associated with cage migration, as multivariate analyses could not be performed. Therefore, based on the characteristics of the AWFP cage revealed in the current study and the key points clinicians should focus on, we propose several hypotheses regarding specific strategies to avoid problems. First, the cage lift-up should be minimized. While it would be ideal to specify recommended intraoperative target or safe range regarding cage lift-up for practical guidelines, this issue could not be resolved due to the small number of cases. However, the acceptable lift-up may be approximately 2 mm based on the observed lift-up in the non-migration group. Second, inadequate posterior fixation might contribute to cage migration by reducing overall construct stability. In particular, careful consideration may be required in patients with poor bone quality. Previous studies have suggested that vertebral CT values ≤110 HU are associated with an increased risk of pedicle screw loosening.[22] Screw loosening might compromise the rigidity of posterior fixation and could facilitate cage migration. Therefore, minimal posterior fixation might be avoided in patients with low CT values. In such cases, extending the posterior fusion levels to better distribute mechanical stress, using larger-diameter rods (eg, ≥5.5 mm) to increase construct stiffness, and considering cement augmentation of pedicle screws to enhance fixation strength might be reasonable strategies. These issues should be addressed in future clinical practice and through improvements in implant design.

This study has several limitations, including a small sample size, single-center design and a relatively short follow-up period. However, this study included consecutive patients with well-defined indications who underwent a standardized surgical procedure, which enhances the internal validity. Additionally, since a single threshold was applied to cage migration (which is essentially a continuous variable), there is a possibility that information was lost due to the conversion to a binary endpoint. However, in the migration group, only one case showed migration of less than 4 mm, while in the non-migration group, all cases showed migration of 2 mm or less. Therefore, we believe that the loss of information due to group classification is minimal. Moreover, although the number of cases was limited, the migration group demonstrated clear increases in the coronal AWFP angle, underscoring the need for clinical attention during postoperative follow-up. To the best of our knowledge, this is the first case series to describe the structural failure of AWFP cages. The study's findings indicate that progressive AWFP angle changes may serve as an early radiographic predictor of implant breakage and poor clinical outcomes.

In conclusion, cage migration after spinal reconstruction using AWFP cages was significantly associated with greater cage lift-up and higher incidence of cage subsidence. Cage migration cases demonstrated progressive coronal AWFP angle increases and included cases of AWFP breakage. These findings indicate that avoiding excessive cage lift-up, which may cause endplate injury, and ensuring sufficient posterior fixation strength in spinal reconstruction using an AWFP cage are crucial to preventing postoperative anterior cage migration. When AWFP cage migration or changes in the AWFP angle in the coronal plane are observed, clinicians should consider the patient to be at high risk for implant failure and consider implementing more frequent follow-ups and extending the duration of external fixation.

AUTHOR CONTRIBUTIONS

KO and NS designed the study; KO, NS, and Y Okada collected the data; KO, NS, and TU analyzed the data; KO, NS, and HN wrote the manuscript; S Ito, JO, IY, and Y Ode reviewed and provided critical revisions to the manuscript; TU and S Imagama supervised the project.

DISCLOSURE STATEMENT

The authors declare that there is no financial support, funding, or personal or institutional relationship that could be construed as a potential conflict of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) for English language translation. After using this tool, the authors reviewed and revised the content as necessary and take full responsibility for the content of the published article.

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SUPPLEMENTARY INFORMATION

Table S1 Intra-rater reliability of radiographic measurements

	After posterior fixation	After combined anterior–posterior fixation	1 week after surgery	6 months after surgery
a	0.973 (0.928–0.990)	0.949 (0.866–0.981)	–	–
b	0.716 (0.373–0.887)	0.777 (0.484–0.913)	–	–
c	0.896 (0.736–0.961)	0.898 (0.742–0.962)	–	–
d	–	0.720 (0.427–0.878)	0.833 (0.633–0.929)	0.873 (0.714–0.947)
e	–	0.685 (0.370–0.859)	0.943 (0.865–0.977)	0.964 (0.914–0.985)

Values are presented as intraclass correlation coefficients, with 95% confidence intervals shown in parentheses.

Table S2 Inter-rater reliability of radiographic measurements

	After posterior fixation	After combined anterior–posterior fixation	1 week after surgery	6 months after surgery
a	0.941 (0.846–0.978)	0.887 (0.715–0.957)	–	–
b	0.768 (0.468–0.909)	0.907 (0.762–0.965)	–	–
c	0.898 (0.743–0.962)	0.801 (0.532–0.923)	–	–
d	–	0.892 (0.753–0.955)	0.912 (0.811–0.966)	0.925 (0.824–0.969)
e	–	0.912 (0.797–0.963)	0.969 (0.926–0.987)	0.956 (0.896–0.982)

Values are presented as intraclass correlation coefficients, with 95% confidence intervals shown in parentheses.

Table S3 Intra- and inter-rater reliability of measurement values

	Intraobserver	Interobserver
Anterior cage lift-up	0.799 (0.528–0.922)	0.717 (0.375–0.887)
Posterior cage lift-up	0.822 (0.576–0.932)	0.787 (0.504–0.917)
Cage migration	0.963 (0.912–0.985)	0.963 (0.910–0.985)

Values are presented as intraclass correlation coefficients, with 95% confidence intervals shown in parentheses.