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Trans-intervertebral osteotomy classification of posterior spinal corrective osteotomy procedures via the intervertebral space

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1. Introduction

With remarkable advances in the management of spinal deformities and novel surgical techniques widely used to address complex deformities (Wang et al., 2015; Smith et al., 2016, 2019; Berven et al., 2018; Silva and Lenke, 2010), novel techniques are presented to answer the question of future trends. The intervertebral space, including the disc, ligament and facet joints, is a common approach for degenerative disc disease and stenosis (de Kunder et al., 2018). Nevertheless, the intervertebral space was not properly described for the osteotomy procedure as an approach in spinal deformities, although the deformity apex frequently located at the intervertebral space and adjacent to the closure site could remain the origin of instability after traditional transpedicular osteotomy correction (Dickson et al., 2014; Luca et al., 2017).

Several posterior osteotomy procedures via the trans-intervertebral approach or involving the intervertebral space have been applied regionally to correct rigid spinal deformities, showing improved HRQoL in both the lumbar and thoracic spine (Huang et al., 2021; Zhang et al., 2011; Berjano et al., 2015; Obeid et al., 2018). In 2011, landmark paper by Wang et al. the authors' team (Zhang et al., 2011) reported a novel transpedicular technique for wedge resection of pedicle and extended rostral intervertebral disc managing posttraumatic kyphosis. In 2015, Berjano et al. (2015) and Bourghli et al. (2015) reported similar techniques correcting kyphotic deformities, while the fulcrum of the osteotomy closure was modified more dorsally for a larger correction angle. Afterwards, many other scholars reported similar techniques via the trans-intervertebral approach, while there were nuances between each technique in osteotomy correction geometry (Obeid et al., 2018; Liu et al., 2020). However, the terminology of these osteotomies was confusing and lies beyond the Schwab-SRS osteotomy classification. An appropriate classification system of these procedures was expected for evidence-based management and to facilitate technical communication among surgeons.

In the present study, a TIO classification of 3 main types with 2 subtypes was proposed, and the inter- and intrarater reliability and the validity of this classification system were evaluated.

2. Materials and methods

Following a sample size calculation, 40 consecutive patients who underwent posterior osteotomy procedures via the trans-intervertebral approach or involving the intervertebral space were allocated among the database of our surgical centre from January 2014 to December 2019. The study population included 14 (35.0%) males and 26 (65.0%) females with a mean age of 53.0 ± 9.4 years and a body mass index of 22.5 ± 2.8 kg/m^2 27 cases (67.5%) had cardiovascular, endocrine, urinary or immune background diseases. The etiology was degenerative scoliosis in the majority of patients (26 patients, 65%), Andersson's lesion for 5 cases (12.5%), ankylosing spondylitis kyphotic deformity for 4 cases (10%), posttraumatic deformity for 2 cases (5%), posttubercular kyphosis for 2

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Table 1
Demographic data and the characteristic features of patients.

Patient ID	Age	Gender	Etiology	BMI (kg/m2)	Comorbidity	TIO Classification	Osteotomy Level	δLK(°)
1	52	F	DS	24.4		I	L2/3	8.8
2	57	F	DS	26.2	HTN, DM, RA	I	L3/4	9.2
3	58	F	DS	22.1	HTN	I	L3/5	7.9
4	68	F	DS	23.7	HTN, DM	I	L3/4	5.5
5	50	F	DS	24.8	HTN	I[a]	L1/2, L2/3, L3/4	16.5
6	50	F	DS	23.7		I[a]	L2/3, L3/4	13.8
7	52	F	DS	26.4	HTN	I[a]	L1/2, L2/3, L3/4	18.5
8	52	F	DS	24.0		I[a]	L2/3, L3/4	16.7
9	54	F	DS	17.5	Anemia	I[a]	T12/L1, L1/2, L2/3	21.5
10	56	F	DS	18.2		I[a]	T12/L1, L1/2, L2/3	23.3
11	57	F	DS	22.5	HTN	I[a]	L1/2, L2/3, L3/4	20.5
12	58	M	DS	25.1	HTN	I[a]	L1/2, L2/3	18.0
13	58	F	DS	23.4		I[a]	L1/2, L2/3	17.5
14	58	F	DS	26.2	HTN, DM	I[a]	L1/2, L2/3, L3/4	22.5
15	59	M	DS	24.6		I[a]	L1/2, L2/3	18.5
16	62	F	DS	22.4		I[a]	L1/2, L2/3, L3/4	26.3
17	62	F	DS	22.7	HTN, DM	I[a]	T12/L1, L1/2, L2/3	25.5
18	64	M	DS	25.2	HTN, DM	I[a]	L2/3, L3/4	16.4
19	64	F	DS	23.5	HTN, DM	I[a]	L2/3, L3/4	18.6
20	65	F	DS	27.5	DM	I[a]	L1/2, L2/3, L3/4	25.3
21	66	F	DS	24.6		I[a]	L2/3, L3/4	21.3
22	69	F	DS	22.1	HTN, DM	I[a]	L1/2, L2/3, L3/4	26.5
23	32	M	ASKD	20.5	AS	II	L1/2	23.4
24	52	M	ASKD	23.9	AS	II	T10/11	25.8
25	49	F	DS	24.5		II	L1/2	23.3
26	50	F	DS	21.5	HTN, DM	II	L2/3	20.0
27	57	F	DS	26.6	HTN, DM	II	L1/2	18.9
28	48	M	PTrK	21.5		II	L1/2	19.5
29	37	M	AL	19.2	AS	II+	T12/L1	23.2
30	42	M	AL	18.1	AS, Anemia	II+	T11/12	25.8
31	43	M	AL	18.2	AS	II+	T12/L1	22.5
32	49	F	AL	17.6	AS	II+	L1/2	26.6
33	51	M	AL	25.5	AS	II+	T11/12	28.9
34	40	M	ASKD	17.8	AS	III	L1/2	35.5
35	45	M	ASKD	20.2	AS, HTN, DM	III	L1/2	32.5
36	55	F	DS	20.4	Anemia	III	L2/3	30.2
37	62	F	PTrK	22.7		III	T12/L1	33.0
38	29	M	CS	19.6		III+	L1/2	48.9
39	41	M	PTuK	20.5		III+	T9/10	57.5
40	48	F	PTuK	22.6	RI	III+	L1/2	58.8

AL: Andersson's lesion; AS: Ankylosing spondylitis; ASKD: Ankylosing spondylitis kyphotic deformity; CS: Congenital scoliosis; DM: Diabetes mellitus; DS: degenerative scoliosis; HTN: Hypertension; PTrK: Posttraumatic kyphosis; PTuK: Posttuberculosis kyphosis; RA: rheumatoid arthritis; RI: Renal insufficiency.
[a] Multilevel osteotomy.

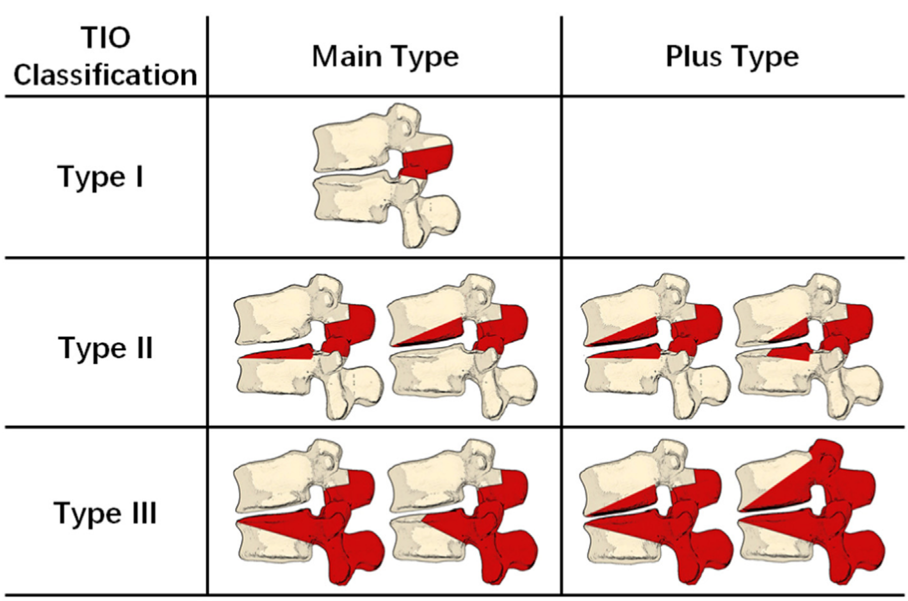

Fig. 1. Graphical illustration of the TIO classification. Type I: posterior element and PLL resections with or without discectomy; type II: wedge resection of either adjacent endplate with disc and posterior elements; type II + osteotomy: additional wedge resection of the other adjacent partial/whole endplate based on type II; type III: discectomy and extended distal trans-pedicular wedge osteotomy; type III + osteotomy: wedge resection of rostral inferior endplate or pedicles of the proximal vertebra based on type III.

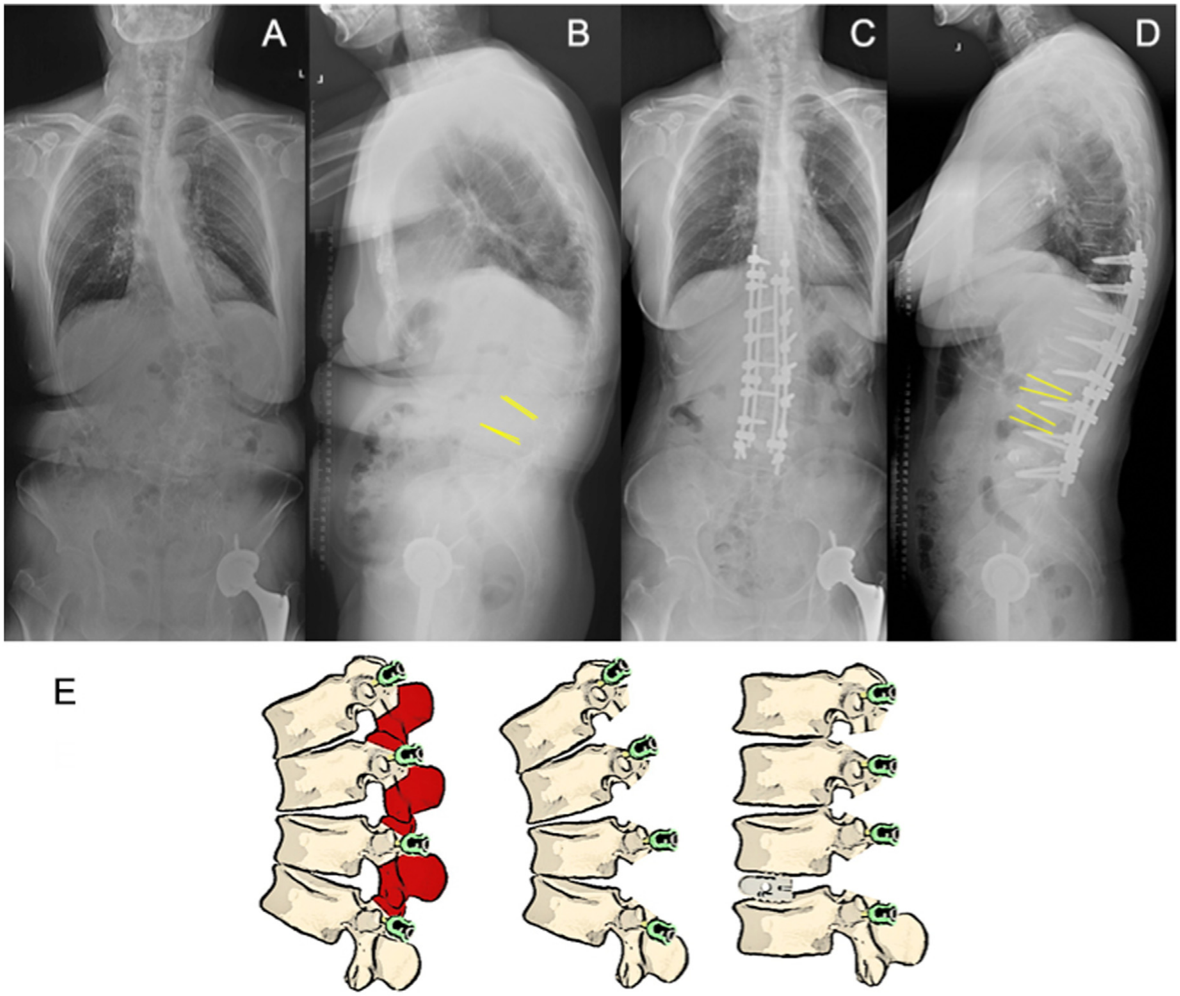

Fig. 2. A 66-year-old female with rigid lumbar scoliosis complained of severe axial pain. Multilevel type I TIO was performed, instrumented from T10 to L5, with a cage inserted in the L4/5 intervertebral space. Preoperative (**A**) anteroposterior and (**B**) lateral radiographs showed a mild lumbar curve in the coronal plane and rigid malalignment in the sagittal plane. (**C**) Anteroposterior and (**D**) lateral radiographs at 24 months postoperatively showed over 50% reduction in the lumbar curve and improved sagittal alignment, without recurrence of back pain. (**E**) Schematic of the multilevel type I TIO.

cases (5%) and congenital scoliosis for 1 case (2.5%), as shown in Table 1. Local kyphosis was measured using the PACS workstation (Picture Archiving and Communications Systems, PACS) as the angle between bilateral vertebral endplates adjacent to the osteomized intervertebral space in standing lateral radiographs taken preoperatively and postoperatively. δLK was calculated by preoperative LK minus postoperative LK for a rough estimation of deformity correction.

2.1. Definition of TIO and TIO classification

For the nonuniform terminology of spinal osteotomy procedures via the trans-intervertebral approach or involving the intervertebral space, a common characteristic is the correction resulting from the intervertebral space. In the present study, it is concluded that the above procedures are trans-intervertebral osteotomies and are defined as spinal osteotomy procedures meeting the following three criteria: a) osseous resection is centred around the intervertebral space, b) the centre of rotation is located at the intervertebral level and c) the instrumentation is centred in the intervertebral space.

Based on the experience of the authors' team and surgical methods reported by previous studies (Zhang et al., 2011; Wang et al., 2010; Liang et al., 2017), we propose a TIO classification by determining the surgical osseous resection extent as follows (the general classification diagram of TIO is shown in Fig. 1):

Type I: The resection of the TIO procedure included the posterior element and posterior longitudinal ligament (PLL) with or without discectomy (Fig. 2).
Type II: The wedge resection of the TIO procedure enlarged to either the adjacent rostral or caudal endplate (Fig. 3).
Type II+: The wedge resection of the TIO procedure included both endplates on the basis of type I TIO with discectomy (Fig. 4).
Type III: The wedge resection of the TIO procedure enlarged to caudal pedicles and partial vertebra (Fig. 5).

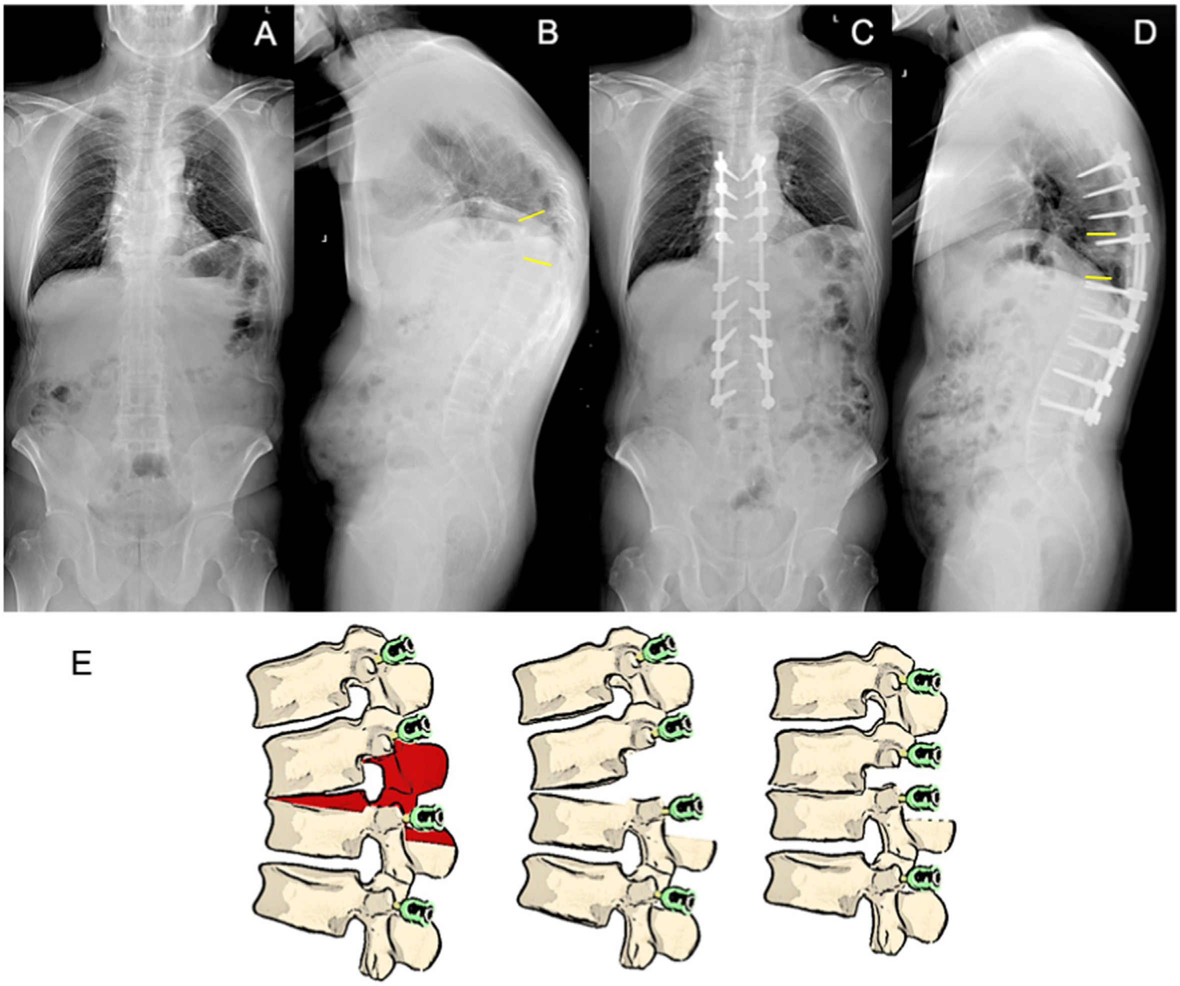

Fig. 3. A 52-year-old male patient with ankylosing spondylitis suffering from persistent back pain and kyphosis progression after trauma was diagnosed with T11 superior endplate damage. Type II TIO at the T10/11 level was performed for a major caudal endplate impaired, with direct osteotomy of the impaired caudal endplate, and osteotomy closure was implemented without cage insertion and segmental fixation. Preoperative (**A**) lateral and (**B**) anteroposterior radiographs showed malalignment in the sagittal plane, and the lesion was located at the apex of the kyphosis. Postoperative (**C**) lateral and (**D**) anteroposterior radiographs showed improved sagittal alignment. (**E**) Schematic of the type II TIO.

Type III+: The wedge resection of the TIO procedure included both pedicles on the basis of type I TIO with discectomy (Fig. 6).

2.2. Reliability and validity test and statistics

To evaluate the reliability and validity of the proposed classification, the above 40 cases including pre- and postoperative CT scans (compulsory), full-length standing radiographs (compulsory) and magnetic resonance imaging scans (optional) from a single-center database were analysed and compared with surgical records with detailed information of the osseous resection portion. Five practiced spine surgeons from two institutions were trained with TIO classification and then classified all 40 cases according to the proposed classification with CT scans and other radiological data in a blinded fashion to assess interobserver reliability. Approximately 2 weeks after the first classifying test, the process was repeated with the same cases in a different order to assess intraobserver reliability. Additionally, the validity was assessed by comparing the first classification results to detailed surgical records.

Interobserver and intraobserver reliability were measured by calculating ICC (interclass correlation coefficient), and validity was measured by κ correlation coefficient, all by IBM SPSS (version 26.0, IBM Corp.). The mean value and 0.95 confidence interval were used. ICC values are interpreted as follows: values ≤ 0.50 indicate poor, 0.50–0.75 moderate, 0.75–0.90 good, and above 0.90 excellent (Koo and Li, 2016). κ values of 0.00–0.20 were considered slight agreement, 0.21 to 0.40 fair agreement, 0.41 to 0.60 moderate agreement, 0.61 to 0.80 substantial agreement, and 0.81 to 1.00 almost perfect agreement (Landis and Koch, 1977).

3. Results

The characteristic features of patients and classification results are shown in Table 1. According to the TIO classification, the osteotomy procedures of these 40 cases were classified, 22 for type I TIO and 18 of which were multilevel, 6 for type II TIO, 5 for type II + TIO, 4 for type III TIO and 3 for type III + TIO. Only patients with degenerative scoliosis

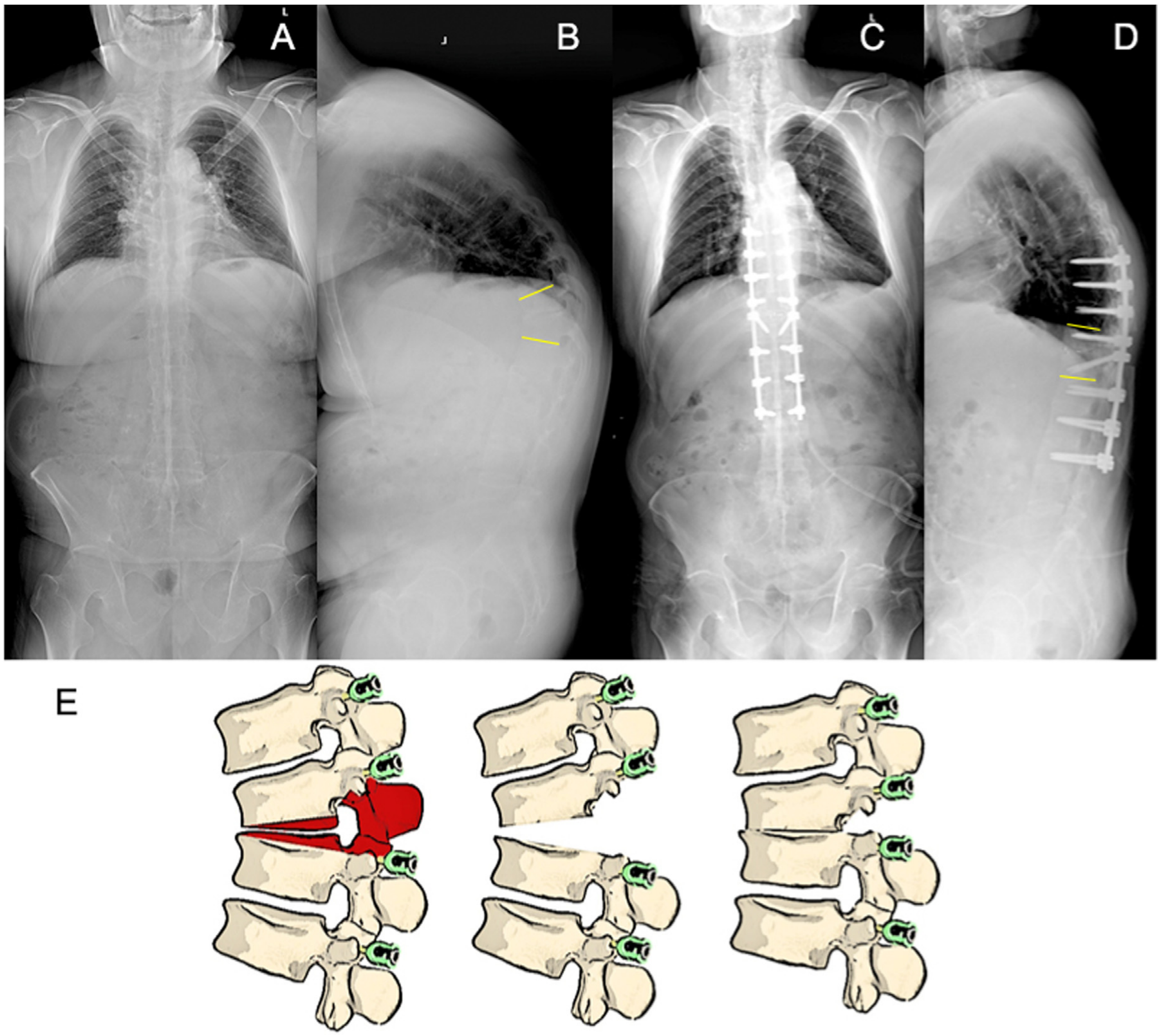

Fig. 4. A 51-year-old male patient with ankylosing spondylitis suffered from a back patient without obvious cause, and Andersson's lesion was detected at T11/12 with erosion of both adjacent endplates of the intervertebral space. Type II + TIO at the T11/12 level was performed with segmental fixation adjacent to the osteotomy intervertebral space and cage insertion. Preoperative (**A**) lateral and (**B**) anteroposterior radiographs showed large pelvic tilt and decompensation in the sagittal plane. Postoperative (**C**) lateral and (**D**) anteroposterior radiographs showed improved sagittal alignment after a less invasive surgery. (**E**) Schematic of the type II + TIO.

(100%) were treated with type I TIO, despite single-level (18.2%) or multilevel (81.8%) application. For type II TIO, this procedure was preserved for DS (50%), ankylosing spondylitis kyphotic deformity (33.3%) and posttraumatic deformity (16.7%). All patients with Andersson's lesion (100%) were treated with type II + TIO. Type III TIO was applied in cases with ASKD (50%), DS (25%) and PTrK (25%), and type III + TIO was applied in cases with congenital scoliosis (33.3%) and post-tuberculosis kyphosis (66.7%). According to the δLK, the type I TIO obtained correction angles ranging from 5.5° to 10.7° per level, 18.9°–25.8° for type II, 22.5°–28.9° for type II+, 30.2°–35.5° for type III and 48.9°–58.8° for type III+.

The interobserver reliability of the TIO classification among the two tests of each surgeon was “excellent with the ICC average of 0.915 (95% CI 0.859–0.971), and the ICC improved to 0.943 (95% CI 0.887–0.999) from the first to the second classifying tests among the five surgeons (Table 2). The intraobserver ICC values for five individual spine surgeons ranged from 0.927 to 0.964 (Table 3), also showing an “excellent” result that indicated a high degree of agreement beyond chance. For the validity test, the κ values ranged from 0.893 to 0.964, indicating almost perfect agreement with the original record (Table 3).

4. Discussion

Spinal osteotomy via the trans-intervertebral approach has been reported due to its potential advantage in correction geometry and surgery complications (Huang et al., 2021; Zhang et al., 2011; Berjano et al., 2015), because some type of this procedure theoretically provides a direct bone-to-bone contact surface at the anterior and middle columns (Cunningham and Polly, 2002). Osteotomy classifications could help preoperative surgical planning and prediction of postoperative alignment (Koller et al., 2018). The present study first analysed the panorama of the spinal osteotomy procedure via the trans-intervertebral approach,

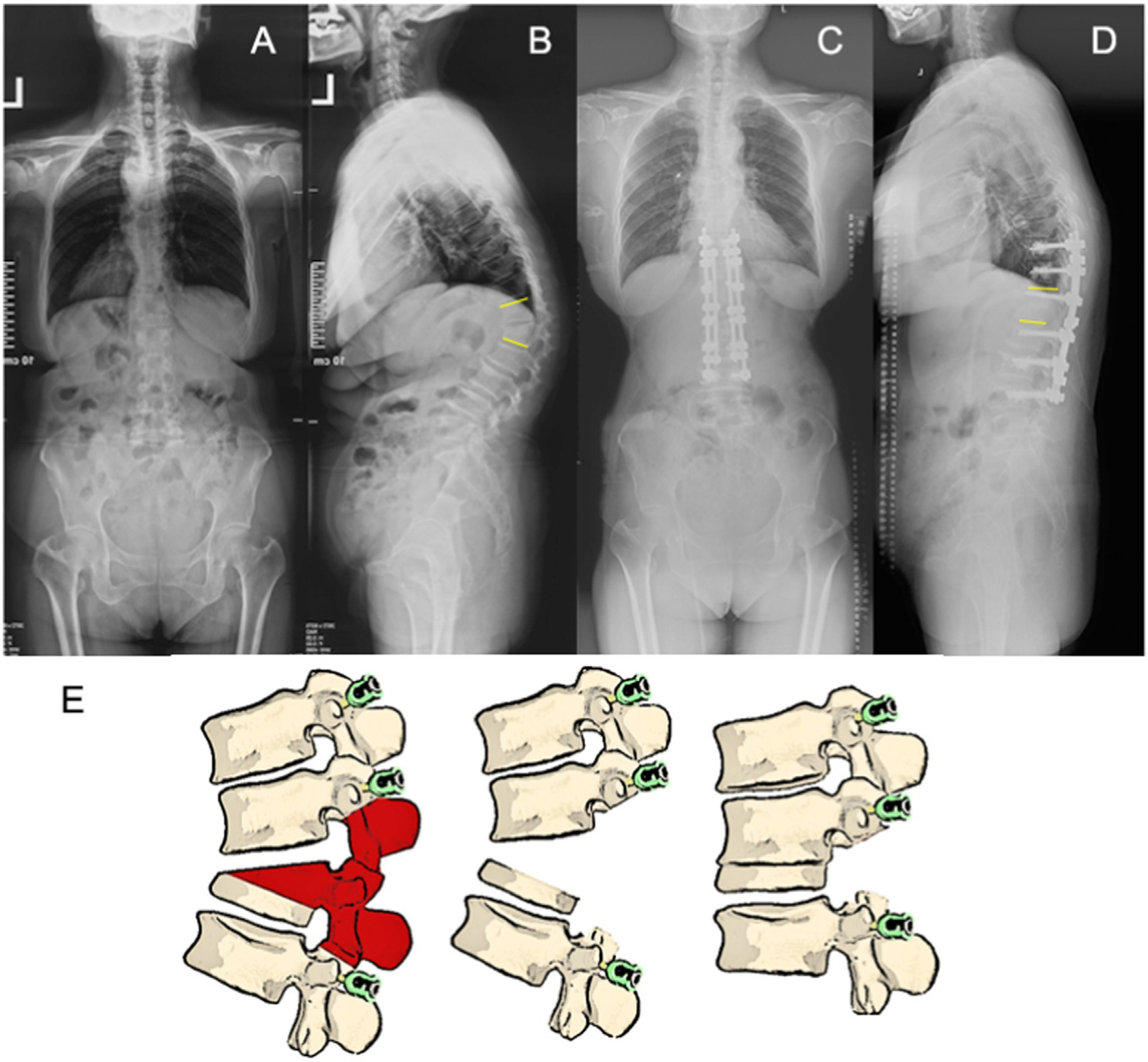

Fig. 5. A 62-year-old female patient complained about progressive axial back pain during standing or sitting, with a history of trauma 10 months ago causing a wedge-shaped L1 vertebra and posttraumatic kyphosis. Type III TIO was performed at the T12/L1 level. Preoperative (**A**) lateral and (**B**) anteroposterior radiographs showed wedge-shaped L1 vertebra and the apex of kyphosis located at T112/L1 intervertebral space. Postoperative (**C**) lateral and (**D**) anteroposterior radiographs showed improved sagittal alignment with a correction angle of 33°, and the direct bony contact of the inferior endplate of T12 and the remaining L1 vertebra is shown in box. (**E**) Schematic of the type III TIO.

defined it as trans-intervertebral osteotomy (TIO) and proposed a TIO classification. Some scholars advise that these procedures should be named "trans-discal" osteotomies, while this name fails to contain the meaning that facet joints are a part of the intervertebral structure, which is not a "discal" portion. Because the widely used Schwab-SRS osteotomy classification rarely covers all these techniques (Ramey et al., 2021; ZÁrate-KalfÓpulos et al., 2020), Bourghli et al proposed a complementary part to the SRS-Schwab osteotomy classification to subdivide the existing SRS-Schwab grade 3 and 4 osteotomies (Bourghli et al., 2021). While the present TIO classification generalized the essence of the above techniques and emphasized the intervertebral space in improving correction.

In TIO classification, the osteotomy procedures along all histories were investigated, and finally, an anatomical definition was proposed, which is intuitional and had excellent inter- and intraobserver reliability and excellent validity compared with the surgical records. Regarding our present definition of TIO, the osteotomy procedure via the trans-intervertebral approach was reported early since the popularity of interbody fusion surgery, while the correction ability of instrumented PLIF was recognized five decades later than its initial introduction by Cloward et al., in 1953 (Cloward, 1953). It is recognized in the present study that PLIF, SPO and Ponte osteotomy techniques are the prototype of type I TIO (Fig. 7). Spinal osteotomy correction by the trans-intervertebral approach was first reported by Wang et al., in 2010 managing severe ankylosing spondylitis kyphotic deformity (Wang et al., 2010), and in 2011 managing posttraumatic thoracolumbar kyphosis

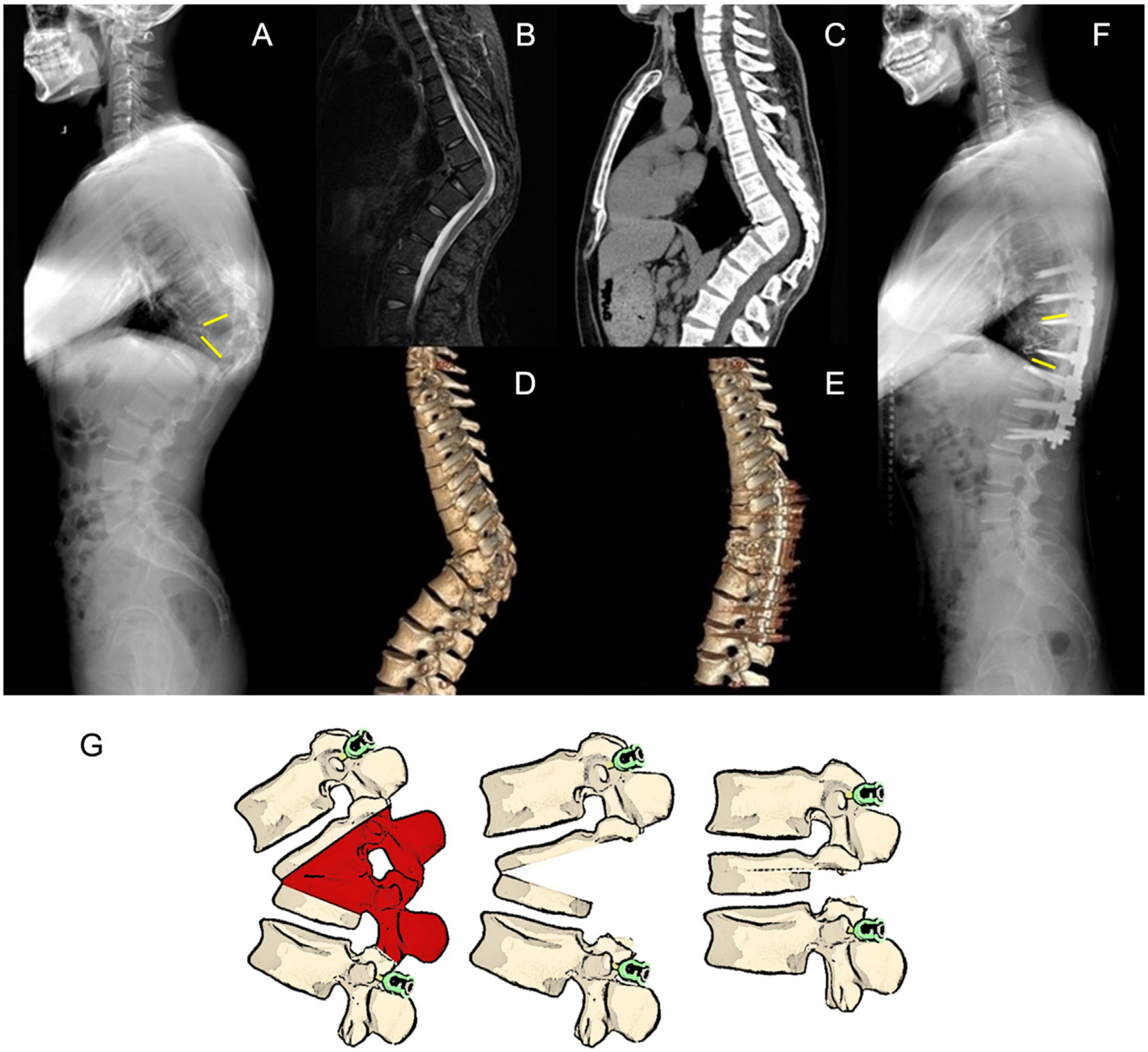

Fig. 6. A 41-year-old male patient presented with severe back and radicular pain without symptomatic myelopathy. Anterior column collapse was observed at T9/10, with the diagnosis of post-tubercular kyphosis. Type III + TIO at the T9/10 level was performed. Preoperative lateral (**A**) radiograph, (**B**) STIR MRI, (**C**) CT and (**D**) three-dimensional reconstruction showed anterior column collapse in the lower thoracic region. The kyphotic angle of T9-11 was 80.6°, and the SVA was measured 1.0 cm preoperatively. Postoperative lateral (**E**) CT reconstruction and (**F**) radiography showed improved sagittal alignment and solid fusion, with the kyphotic angle diminished to 23.1°. (**G**) Schematic of the type III + TIO.

Table 2
The ICC values of interobserver reliability.

	The ICC value	95%CI	P-value
1st Test	0.915	0.859–0.971	<0.001
2nd Test	0.943	0.887–0.999	<0.001

Table 3
The ICC values of intraobserver reliability for classification results and mean κ values for validity.

	The ICC value	95%CI	The κ value
Surgeon 1	0.927	0.750–0.974	0.964
Surgeon 2	0.930	0.755–0.944	0.964
Surgeon 3	0.964	0.789–0.973	0.964
Surgeon 4	0.929	0.753–0.973	0.964
Surgeon 5	0.929	0.750–0.973	0.893

(Zhang et al., 2011) (Fig. 8). These two TIO techniques were then described as "bone disc osteotomy", "bone-disc-bone osteotomy", and "extended pedicle subtraction osteotomy" until Schwab defined it as "SRS-Schwab grade 4 osteotomy" in 2014, and the original schematic (Fig. 9) of the landmark paper in 2011 was frequently cited as a "grade 4 osteotomy". In 2015, "corner osteotomy" by Berjano et al. (2015) and "modified closing-opening wedge osteotomy" by Bourghli et al. (2015) were introduced to address rigid thoracolumbar kyphosis. In 2018, Obeid et al. (2018) initially reported that "proximal thoracic PSO" was safely applied in the upper thoracic region of 10 patients. Buell TJ et al. (Buell et al., 2018) reported their utilization of a technique named "extended PSO" for 10 patients with severe kyphotic deformities. Ramey et al. (2021) reported a novel technique for correcting kyphosis in an adult spinal deformity patient while preserving the anterior part of the endplate for placement of the cage. For the resection range that included both endplates adjacent to the osteotomy intervertebral space despite its preservation of the ventral part, this technique was classified as type II + TIO.

The correction angle increases from type I to type III + measured by

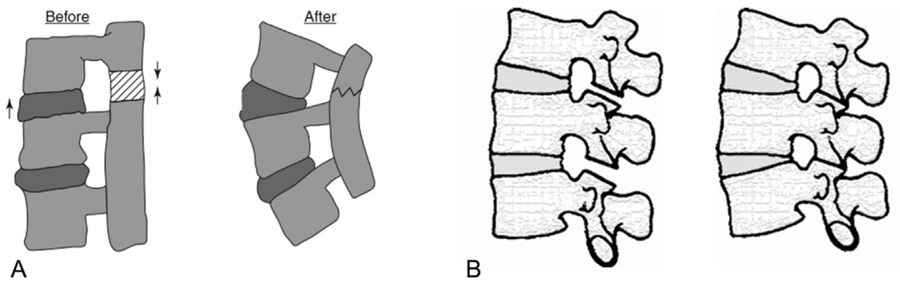

Fig. 7. (**A**) Smith Petersen osteotomy: anterior opening and closure of the posterior wedge via a trans-intervertebral approach. (**B**) Ponte osteotomy: fact resection and wedge osteotomy via a trans-intervertebral approach. These techniques are the prototype of type I TIO and are generally indicated for kyphotic deformities. The image is directed cited from Spinal Osteotomy by Wang et al. (Wang et al., 2015).

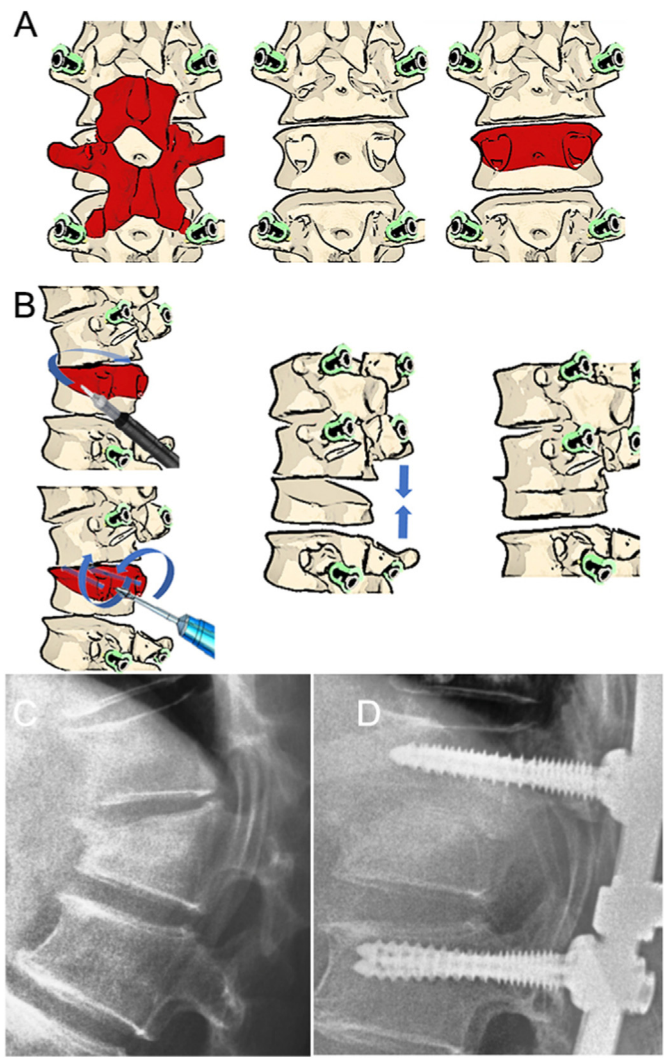

Fig. 8. (**A**) After pedicle screw insertion and adequate decompression with laminectomy, pediculotomy was performed on the pedicles caudal to the intervertebral space. Then, the wedge portion of the vertebra was clearly exposed. (**B**) Two possible methods were recommended for wedge resection after pediculotomy: with an ultrasound bone scalpel to perform a direct wedge resection from the base of the pedicles and dorsal vertebral body or with a probe to complete an egg-shell procedure. After wedge resection, the wedge osteotomy space is closed gradually with direct bony contact. (**C**) An ideal kyphosis indicated for type III TIO with apex at intervertebral space. (**D**) After osteotomy closure of type III TIO of this kyphosis, direct bony contact of the lower endplate of the rostral vertebra and the residual caudal vertebra can be observed.

δLK as shown in the present consecutive cohort, according to the osseous resection portion. In clinical practice, type I TIO could obtain less than 10° correction for each level, depending on the utilization of the interbody cage. Additionally, multilevel TIOs in the lumbar region could be realigned for lordosis. Type II/II + TIO could achieve almost 20°–25° correction per level, indicating kyphotic with endplate disruption. Some speculation was made that the degree of endplate erosion may affect the correction angle of type II/II + TIO. On the other hand, the ventral part of the endplate could be preserved for a larger correction angle compared to total endplate resection with or without a cage insertion (Fig. 10), and the correction geometry would be different for the variation of the COR. For the selection of cages, expandable or wedge-shaped products could be utilized for anterior support (Ramey et al., 2021). When inserting a cage, a disc spacer could be utilized to restore the height of the intervertebral disc space. Type III/III + TIO can obtain over 30° correction and is indicated for rigid kyphosis with spinal column deficiency or malformation, such as congenital kyphosis/kyphoscoliosis, post-tuberculosis kyphosis, posttraumatic thoracolumbar kyphosis (Huang et al., 2021; Zhang et al., 2011; Bourghli et al., 2015; Wang et al., 2008, 2009) and severe sagittal imbalance with thoracic hyperkyphosis (Obeid et al., 2018) or lumbar kyphosis (Berjano et al., 2015), especially severe ankylosing spondylitis kyphotic deformity (Wang et al., 2010; Zhao et al., 2015). Additionally, asymmetrical TIO (all types) in the coronal plane can also be directly performed to implement a three-dimensional deformity correction just filling the vacancy of systematic coronal plane correction in spinal osteotomy. Further cohort studies may investigate the feasibility of asymmetrical TIO compared with existing asymmetrical PSO or VCR techniques (Cecchinato et al., 2015; Toyone et al., 2012).

By analysing a consecutive cohort in a single centre, the results of the reliability and validity test confirmed that the TIO classification system is simple and consistent. However, this study was retrospective and single-centred, and the sample size was determined by reliability and validity tests. It is noteworthy that TIO procedures were not routinely applied for every case in our surgical centre and the main indications for TIO were rigid kyphoscoliosis, intervertebral kyphotic apex and kyphosis with damaged endplates. The radiological measurement in the present study was for consistency comparison with the proposed classification and the clinical outcomes of these patients were not included in this diagnostic study. Further study was recruited to investigate the complication rates of TIO compared with traditional osteotomy procedures.

5. Conclusions

Posterior osteotomy procedures via the trans-intervertebral approach or involving the intervertebral space could be classified into 3 main types and 2 plus subtypes by the proposed TIO classification. Based on both pre- and postoperative CT scans, TIO classification has excellent reliability and validity and is a reliable tool to help manage rigid malalignment and spinal deformities of various etiologies.

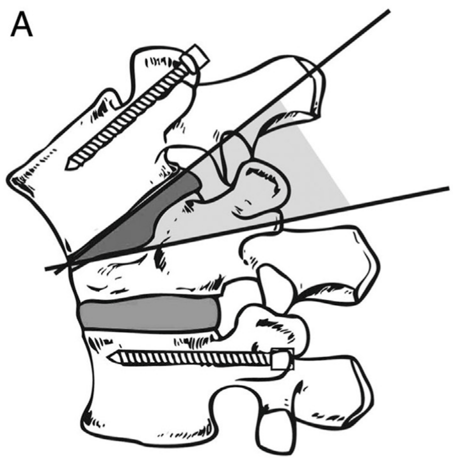

Fig. 9. Original schematic of type III TIO. (**A**) The injured intervertebral cartilage is removed, and a portion of the compressed wedge vertebra is left. (**B**) The anterior spinal column achieves bone-on-bone solid fusion. This picture was directly cited from the study by Zhang X et al. (Zhang et al., 2011). This technique was classified as type III TIO because its osseous resection included caudal pedicles, and this original diagram was widely used in later studies.

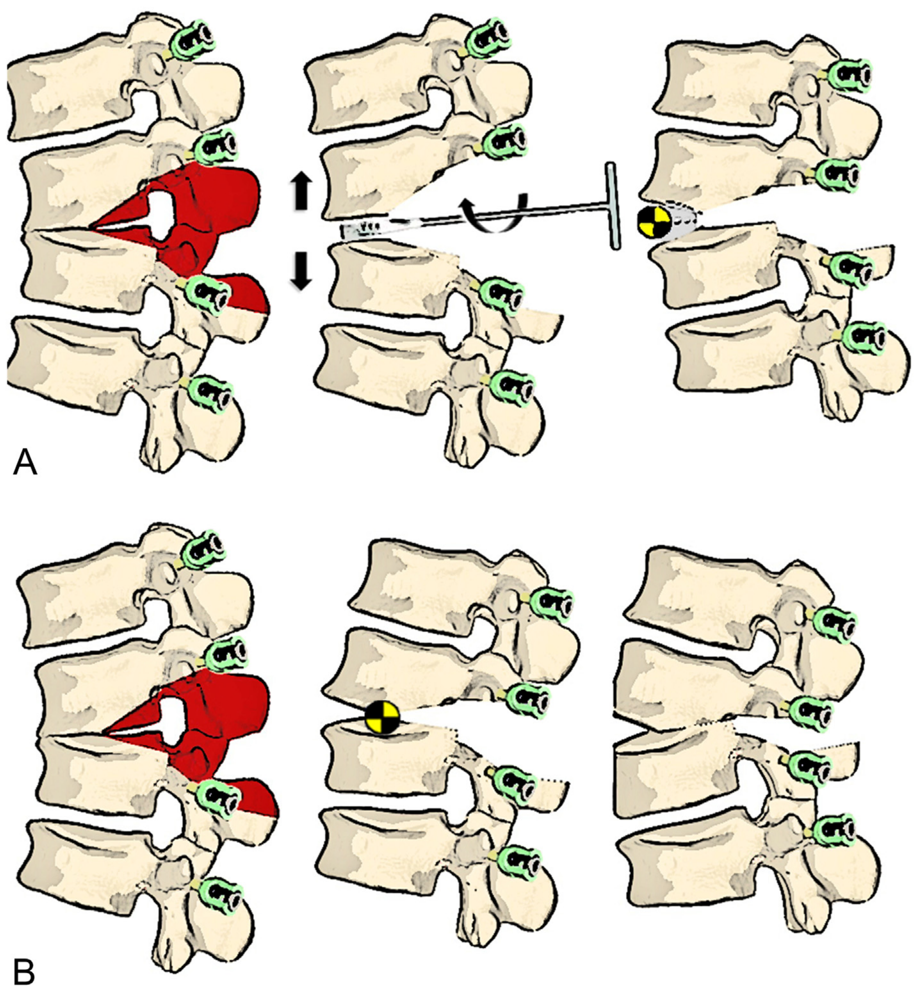

Fig. 10. Schematic of the type II + TIO with preservation of partial ventral endplates (**A**) with or (**B**) without cage insertion, and the COR is marked. When inserting a cage, a disc spacer could be utilized to restore the height of the intervertebral disc space.

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Chinses PLA General Hospital, and all participants provided written informed consent. All procedures were performed in accordance with relevant guidelines.

Authors' contributions

All authors have read and approved the final manuscript. YW was involved in the study design, data collection, and drafting and revising of the manuscript. YH and GZ were involved in the study design, analysis and interpretation of the data, and drafting and revising of the manuscript. XZ, KM, ZW, TW and DQ were involved in the data collection. WH and CX were involved in the analysis and interpretation of the data. YZ was involved in the study design, data collection, analysis and interpretation of the data. YW was involved in the study design, drafting and revising of the manuscript and has given final approval.

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Availability of data and materials

The datasets used or analysed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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