

## CLINICAL ARTICLE

# Feasibility and Safety of Cervical Kinematic Magnetic Resonance Imaging in Patients with Cervical Spinal Cord Injury without Fracture and Dislocation

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**Objective:** To evaluate the feasibility and safety of cervical kinematic MRI (KMRI) in patients with cervical spinal cord injury without fracture and dislocation (CSCIWFD).

**Methods:** This was a single-institution case-only study. Patients with CSCIWFD were enrolled in our institution from February 2015 to July 2019. Cervical radiography and CT were performed first to exclude cervical tumors, and major fracture or dislocation. Then neutral static and kinematic (flexion and extension) MRI was performed for patients who met the inclusion criteria under the supervision of a spinal surgeon. Any adverse events during the KMRI examination were recorded. Patients received surgical or conservative treatment based on the imaging results and patients' own wishes. The American Spinal Injury Association impairment scale (AIS) grade and the Japanese Orthopedic Association (JOA) score were evaluated on admission, before KMRI examination, and after KMRI examination. For the surgical patients, AIS grade and JOA score were evaluated again 1 week after the operation. The JOA scores were compared among different time points using the paired *t*-test.

**Results:** A total of 16 patients (12 men and 4 women, mean age: 51.1 [30–73] years) with CSCIWFD were included in the present study. Clinical symptoms included facial trauma, neck pain, paraplegia, paresthesia, hyperalgesia, sensory loss or weakness below the injury level, and dyskinesia. On admission, AIS grades were B for 2 cases, C for 5, and D for 9. A total of 14 patients underwent neutral, flexion, and extension cervical MRI examination; 2 patients underwent neutral and flexion examination because they could not maintain the position for a prolonged duration. No patient experienced deterioration of neurological function after the examinations. The AIS grades and JOA scores evaluated post-examination were similar to those evaluated pre-examination ( $P > 0.05$ ) and significantly higher than those on admission ( $P < 0.05$ ). A total of 12 patients received surgical treatment, 11 of whom underwent anterior cervical discectomy and interbody fusion and 1 underwent posterior C3/4 fusion with lateral mass screws. The remaining 4 patients were offered conservative therapy. None of the patients experienced any complications during the perioperative period. The AIS grade did not change in most surgical patients, except that 1 patient changed from grade C to D 1 week after the operation. The JOA score 1 week after surgery was significantly higher than those on admission and around examination for the surgical patients ( $P < 0.05$ ).

**Conclusion:** Cervical KMRI is a safe and useful technique for diagnosis of CSCIWFD, which is superior to static cervical MRI for therapeutic decision-making in patients with CSCIWFD.

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## Introduction

Cervical spinal cord injury without fracture and dislocation (CSCIWFD) is a special type of cervical injury that refers to injuries from external force resulting in patients having clinical signs and symptoms but without abnormal radiographic or CT evidence<sup>1</sup>. Most patients are elderly and have radiographic abnormalities such as osteophyte, disc herniation, hypertrophy of the ligamentum flavum, or ossification of the posterior longitudinal ligament, which can cause stenotic spondylotic canal and spinal cord compression<sup>2</sup>. Traffic accidents, sports-related injuries, and falls are the common reasons for CSCIWFD<sup>3,4</sup>. CSCIWFD can be easily misdiagnosed or overlooked without positive radiographic or CT imaging diagnosis, leading to delayed treatment and rehabilitation.

MRI has played an important role in diagnosing cervical spine injuries. Hyperintensive signal changes in the cervical spinal cord, disc herniation and rupture, spinal canal stenosis, and effusion in front of the cervical vertebra can be observed in MRI scans, while often being missed on CT. However, prior studies have shown that some clinically diagnosed cases of cervical disc herniation based on physical examination could not be confirmed by static radiographies, including neutral static MRI scans<sup>5</sup>. Sometimes it is difficult to determine the injured disc or unstable segment directly by static cervical MRI in neutral position. Therefore, MRI does not appear to be useful in determining cervical stability when CT scanning or radiography demonstrates no fractures or signs of instability<sup>6</sup>.

In initial and follow-up studies, dynamic flexion and extension radiography has been used to exclude the possibility of cervical instability in cervical trauma patients without instability in static MRI or CT. For example, Yeo *et al.*<sup>7</sup> reported that four patients whose initial static CT and MRI showed no instability were diagnosed with cervical instability by dynamic radiographs several days to weeks after injury and then received surgical treatment. Anekstein *et al.*<sup>8</sup> used dynamic CT to evaluate instability due to occult ligamentous injury of the cervical spine in comatose trauma patients. It was found that the dynamic CT had better visualization of the C6/7 and C7/T1 segments with no complications directly related to the dynamic examination. Moreover, Wadhwa *et al.*<sup>9</sup> showed that flexion and extension CT scanning with reconstruction had high sensitivity (80%) and specificity (98.6%) for all radiographic abnormalities and was 100% sensitive to clinically unstable cervical spine injuries in trauma patients.

Despite their application in identification of cervical spine instability, both kinematic radiography and CT have their limitations. Previous studies have shown that patients' clinical symptoms are not completely related to the instability in kinematic radiographic imaging. Qian<sup>10</sup> reported that while instability existed in 55.9% of patients with cervical spondylotic

sympathetic symptoms, it also occurred in 21.8% of patients without sympathetic symptoms. Kinematic radiographic imaging did not demonstrate instability in 47.7% (21/44) of patients whose MRI showed anterior longitudinal ligament disruption and in 51.3% (19/37) of patients whose MRI showed total cervical disc damage<sup>11</sup>. In addition, it was difficult to observe the C7/T1 motion segment in dynamic radiography for comatose trauma patients<sup>12</sup>. Oh<sup>13</sup> found that flexion–extension radiography did not contribute additional diagnostic accuracy for the detection of ligamentous injury to the cervical spine following a normal CT. It was, therefore, recommended that flexion–extension radiography should be removed from cervical spine clearance protocols. Kinematic CT myelography of the spinal cord revealed the cerebrospinal fluid space, dynamic canal stenosis, spinal cord impingement, and bony formations such as spurs<sup>14</sup>. Kinematic CT was also recommended to evaluate the dynamic change of the upper cervical spine in patients with rheumatoid arthritis complaining of severe neck pain and symptoms due to spinal cord compression. However, the radiation exposure from CT is higher than from computed radiography, and CT is not sensitive to cervical spinal cord injury<sup>15,16</sup>. Therefore, a new method of evaluating the spinal cord injury and instability should be established.

Cervical kinematic MRI (KMRI) has been used to identify dynamic compression of the spinal cord in patients with cervical spondylosis and spinal canal stenosis at different positions. KMRI has shown its efficiency in evaluating motion-dependent cord compression and is helpful in decision-making for surgical treatment<sup>17</sup>. KMRI is a safe tool to evaluate the cervical spine and cervicomedullary junction in various pediatric populations, including children with skeletal dysplasia, and can be performed safely without direct neurosurgical supervision<sup>18,19</sup>. However, to the best of our knowledge, there are no reports on the safety of KMRI application in patients with CSCIWFD, leaving its feasibility unclear in this disease.

In the present study, KMRI was used to observe the dynamic changes in disc herniation and canal stenosis at the sub-axial cervical spine levels in flexion and extension. The objectives of this study were: (i) to evaluate the feasibility of KMRI in patients with CSCIWFD; (ii) to evaluate the safety of KMRI in patients with CSCIWFD; and (iii) to evaluate the clinical significance of KMRI to patients with CSCIWFD.

## Materials and Methods

### *Ethical Approval and Informed Consent*

This study was approved by the ethics committee of Yuebei People's Hospital Affiliated to Shantou University Medical College and was performed according to the ethical standards laid down in the 1964 Declaration of Helsinki and its

later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

### **Inclusion Criteria**

This was a single-institution case-only study. Data of patients with CSCIWFD were obtained from Yuebei People's Hospital Affiliated to Shantou University Medical College Medical College from February 2015 to July 2019. The inclusion criteria were defined as follows: (i) patients with CSCIWFD but without respiratory myo-paralysis; (ii) no cervical tumor, cervical vertebral fracture, or dislocation on cervical radiography or CT; (iii) no medical history of cervical spine injury or operation; and (iv) patients agreed to receive a cervical KMRI. Cervical radiography and CT were performed first to exclude cervical tumors, and major fractures or dislocation. Patients received surgical or conservative treatment based on the neutral static and kinematic imaging results and patients' own wishes. Neurological function, clinical symptoms, vital signs, and respiratory condition were evaluated by physical examination, American Spinal Injury Association (ASIA) impairment scale (AIS) grade, and Japanese Orthopedic Association (JOA) score on admission, before and after KMRI examination, and 1 week after operation for surgical patients. AIS grade and JOA score were compared among different time points.

### **MRI Technique**

Neutral static cervical MRI was first performed to confirm the spinal cord injury without fracture and dislocation. Therefore, neutral static and kinematic (flexion and extension) MRI scans were performed with a 3.0T scanner (GE Medical Systems, Milwaukee, WI, USA) under the supervision of a spinal surgeon. The image protocol included T1-weighted and/or T2-weighted sagittal fast spin echo (FSE) images that were obtained with the patient lying on a bed in neutral, flexion ( $-30^\circ$ ), and extension ( $15^\circ$ ) positions while being scanned with a 3.0T scanner (Fig. 1). The imaging protocol for T1-weighted sagittal spin echo images included a repetition time of 860 ms, echo time 8 ms, thickness 3.0 mm, and matrix  $216 \times 512$ . The imaging parameters for sagittal FSE T2 included a repetition time of 2270 ms, echo time 116 ms, thickness 3.0 mm, and matrix  $216 \times 512$ . Positioning was achieved by placing several towels under the occipital bone for flexion and under the back and cervical spine for extension. The dynamic angles of flexion or extension were reduced if the patient felt any discomfort.

### **Surgery Procedure**

Anterior cervical discectomy and fusion (ACDF) was performed as follows. Step 1: The patient was kept in the supine position with the neck slightly extended. A 1–2-inch incision was made on the right of the neck according to injury segments. Step 2: The platysma was split in line with the skin incision to enter the plane between the sternocleidomastoid muscle and the strap muscles, and the plane between the trachea/esophagus and the carotid sheath. After removing the

pre-vertebral fascia, the discs were exposed and confirmed in C-arm CT. Step 3: The disc and cartilage endplates were removed. Disc injury was recorded and cervical spinal canal decompression was performed in this step. Step 4: A properly size cage was inserted into the evacuated disc space and a right length titanium plate was fixed to the upper and lower vertebrae. Step 5: The wound was washed with physiological saline, the bleeding was stopped, and the incision was closed.

Posterior lateral mass screw fixation was performed as follows. Step 1: The patient was kept in prone position with the neck slightly flexed. A 6–7-cm incision was made on the back of the neck according to injury segments. Step 2: Muscles were removed to expose the facet joint at the level that needed fusion. Step 3: Lateral mass screws were implanted and fixed with the rods. Step 4: The wound was washed with physiological saline, the bleeding was stopped, and the incision was closed.

### **American Spinal Injury Association Impairment Scale Grade**

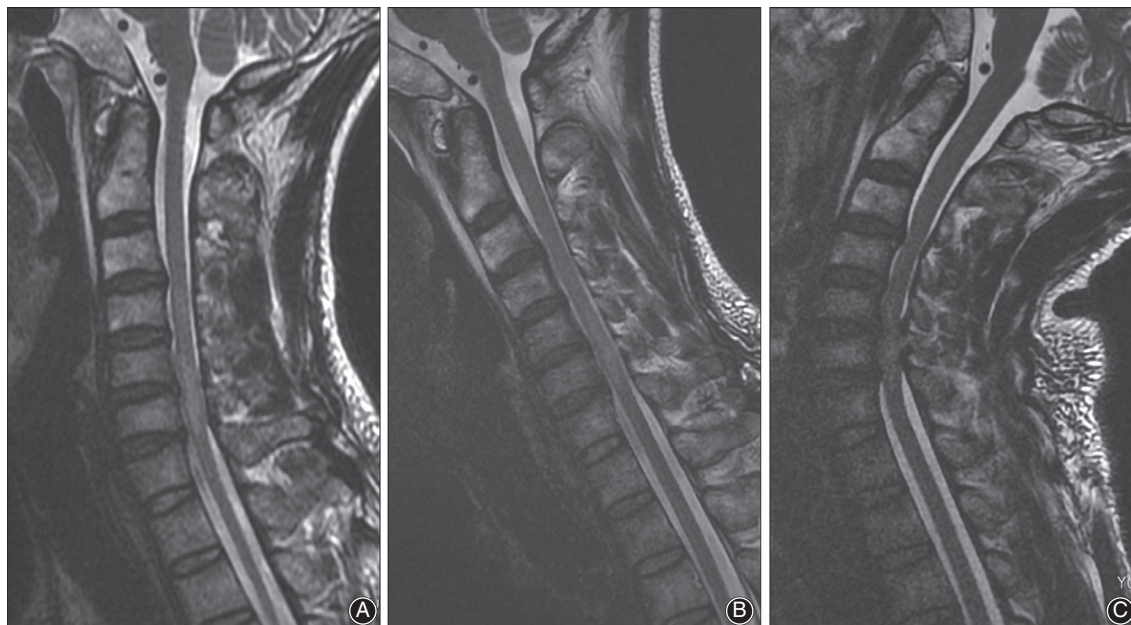
The AIS grade was used to evaluate the neurological function (sensory and motor) affected by spinal cord injury. The scale includes five classification levels, ranging from complete loss of neural function in the affected area to completely normal<sup>20</sup>. Grade A: The impairment is complete. There is no motor or sensory function left below the level of injury. Grade B: The impairment is incomplete. Sensory function, but not motor function, is preserved below the neurological level (the first normal level above the level of injury) and some sensation is preserved in the sacral segments S4 and S5. Grade C: The impairment is incomplete. Motor function is preserved below the neurological level, but more than half of the key muscles below the neurological level have a muscle grade less than 3 (i.e. they are not strong enough to move against gravity). Grade D: The impairment is incomplete. Motor function is preserved below the neurological level, and at least half of the key muscles below the neurological level have a muscle grade of 3 or more (i.e. the joints can be moved against gravity). Grade E: The patient's functions are normal. All motor and sensory functions are unhindered.

### **Japanese Orthopedic Association Score**

The JOA score was used to evaluate the severity of clinical symptoms. The score ranges from 0 to 17. The JOA score includes motor function (from 0 to 8, upper extremity: 0 to 4, lower extremity: 0 to 4), sensory function (from 0 to 6, upper extremity: 0 to 2, lower extremity: 0 to 2, trunk: 0–2), and bladder function (from 0 to 3). The lower the score, the more severe the deficits<sup>21</sup>.

### **Statistical Analysis**

All obtained data were statistically analyzed using SPSS 19.0 (SPSS, Chicago, IL, USA). The JOA scores were compared among different time points using the paired *t*-test. All significance levels were set at  $P < 0.05$ .



**Fig. 1** Cervical kinematic MRI of spinal cord injury in a 44-year-old male patient without fracture and dislocation. Neutral position MRI (A) demonstrated abnormal signals in the spinal cord and canal stenosis from C4 to C5/6; flexion position MRI (B) showed that the abnormal signal became inapparent with the degree of canal stenosis reduced; extension position MRI (C) revealed that the canal stenosis became obvious at C4/5 and C5/6.

## Results

### General Information

Sixteen patients (12 men and 4 women) with CSCIWFD were included (Table 1). The mean age of the patients was 51.1 (range: 30–73) years. Injury causes included fall (11/16, 68.75%), motor vehicle accident (4/16, 25.00%), and heavy pound injury (1/16, 6.25%). The time period from injury to admission ranged from 2 to 72 h ( $19.94 \pm 20.12$  h). Clinical symptoms included facial trauma, neck pain, paraplegia, paresthesia, hyperalgesia, sensory loss below the injury level, and dyskinesia.

### Feasibility and Safety of Cervical Kinematic MRI

All the patients received KMRI examination under the supervision of a spinal surgeon. A total of 14 patients underwent neutral, flexion, and extension examination; 2 patients underwent neutral and flexion examination as they could not maintain the position for a prolonged duration. Clear MRI images were obtained for all patients to make therapeutic decisions. No patient experienced deterioration of neurological function after the examinations.

### Therapeutic Management

All patients underwent surgery and were managed by the same group of doctors (Table 3). Twelve patients received surgical treatment as per the neutral static and kinematic imaging results. The period of operation was

$2.25 \pm 0.62$  days (range: 1–3 days) after admission. Single-level ACDF was performed in 7 patients, with 3 at the C3/4 level, 1 at the C4/5 level, 2 at the C5/6 level, and 1 at the C6/7 level. Double-level ACDF was performed in 3 patients, with 2 at the C4/5 and C5/6 levels and 1 at the C5/6 and C6/7 levels. Triple-level ACDF was performed in 1 patient at the C3/4, C5/6, and C6/7 levels. Disc damage and instability of the injured segments were confirmed during the operations. One patient underwent posterior C3/4 fusion with lateral mass screws. The mean operative time was  $89.25 \pm 22.99$  min (range: 60–30 min) and the mean blood loss was  $42.50 \pm 23.69$  mL (range: 20–100 mL). No surgical complication occurred in this group of patients during the perioperative period.

The remaining 4 patients, 1 of whom had no obvious cervical cord compression and minimal signal changes on MRI and 3 of whom were unwilling to undergo surgery, were offered conservative therapy. There were no complications in this group of patients during the perioperative period.

### American Spinal Injury Association Impairment Scale Grade

The AIS grades were B for 2 patients, C for 5 patients, and D for 9 patients on admission (Table 3). The AIS grades before and after KMRI examination were the same as those on admission. One patient changed from grade C to D 1 week after the operation, whereas the other surgical patients had no change in their AIS grades.

TABLE 1. Clinical summary of 16 patients who suffered from cervical spinal cord injury without fracture and dislocation

Case number	Sex/Age	Trauma mechanism	Neutral/flexion/extension MRI	Injury level	JOA score		AIS grade		Treatment				
					On admission	Before KMRI	After KMRI	1 week after operation	On admission	Before KMRI	After KMRI	1 week after operation	
1	Female/62	Fall	Neu/fle/ ext	C4/5	8	9	9	D	D	D	D	D	Conservative therapy
2	Male/45	Motor vehicle accident	Neu/fle/ ext	C4/5,	C5/6	4	4	7	C	C	C	C	C
3	Female/55	Fall	Neu/fle	C4/5,	C5/6	9	10	11	D	D	D	D	D
4	Male/46	Heavy pound injury	Neu/fle/ ext	C6/7	12	13	13	D	D	D	D	D	ACDF (C6/7)
5	Male/53	Fall	Neu/fle/ ext	C4/5	5	5	5	C	C	C	C	C	ACDF (C4/5)
6	Male/61	Motor vehicle accident	Neu/fle/ ext	C4/5	11	11	11	D	D	D	D	D	Conservative therapy
7	Female/30	Motor vehicle accident	Neu/fle/ ext	Unclear	13	13	13	D	D	D	D	D	Conservative therapy
8	Male/57	Fall	Neu/fle	C5/6	8	9	9	D	D	D	D	D	ACDF (C5/6)
9	Male/49	Fall	Neu/fle/ ext	C5/6	7	7	7	D	D	D	D	D	Conservative therapy
10	Male/73	Fall	Neu/fle/ ext	C5/6	1	1	1	B	B	B	B	B	ACDF (C5/6)
11	Female/48	Motor vehicle accident	Neu/fle/ ext	C3/4	9	10	10	D	D	D	D	D	ACDF (C3/4)
12	Male/50	Fall	Neu/fle/ ext	C3/4	5	5	5	C	C	C	C	C	ACDF (C3/4)
13	Male/43	Fall	Neu/fle/ ext	C3/4,	C4/5	4	4	6	C	C	C	C	C
14	Male/54	Fall	Neu/fle/ ext	3/4	5	5	5	C	C	C	C	C	Posterior C3/4 (lateral mass screw fixation)
15	Male/51	Fall	Neu/fle/ ext	C3/4,	C5/6, C6/7	0	1	3	B	B	B	B	B

ACDF (C3/4, C5/6, C6/7)	16	Male/40	Fall	Neu/fle/ext	C3/4	9	6.88 ± 3.70*	9	7.25 ± 3.82	9	7.25 ± 3.82	12	8.25 ± 3.82	D	D	D	D	ACDF (C3/4)
ACDF, Anterior cervical discectomy and fusion; AIS, American Spinal Injury Association impairment scale; JOA, Japanese Orthopedic Association; KMRI, kinematic MRI imaging; * JOA score on admission was significantly lower than those recorded before KMRI, after KMRI, and 1 week after operation ( $P < 0.05$ ).																		

### Japanese Orthopedic Association Score

The JOA scores recorded before KMRI, after KMRI, and 1 week after the operation generally increased compared with those recorded on admission (Table 3). The mean JOA scores before and after KMRI examination were both  $7.25 \pm 3.82$ , which were 5.38% higher than on admission ( $6.88 \pm 3.70$ ,  $P = 0.009$ ). The mean JOA score 1 week after the operation was  $8.25 \pm 1.07$ , which was 13.79% higher than before and after KMRI ( $P = 0.000$ ).

### Typical Cases

#### Case 4

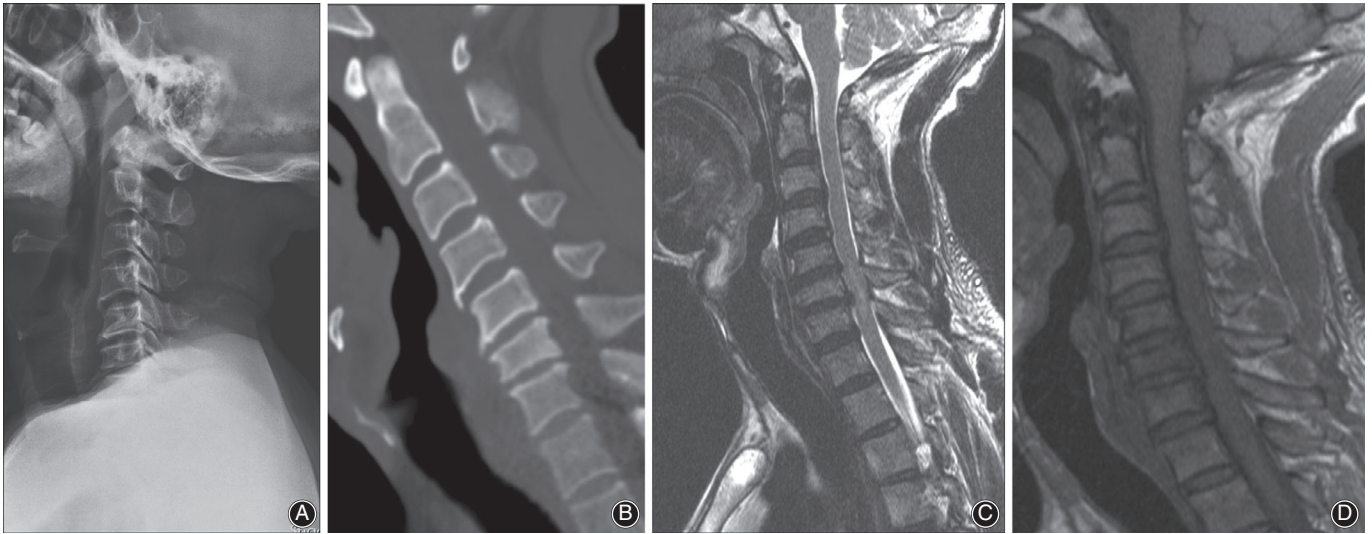
A 45-year-old male patient was injured by a falling tree with and complained of neck pain, acroanesthesia, and incomplete paralysis of extremities for 1 day before admission. The AIS grade was D, and the JOA score was 10. Reduced cervical physiological lordosis and hyperostosis but no instability, fracture, and dislocation were observed in radiography and CT scans. Cervical neutral MRI showed that abnormal signals in the spinal cord appeared from the C5/6 disc to the C7 vertebral body level (Fig. 2). Flexion MRI showed that the abnormal signal became obvious with the degree of disc protrusion and canal stenosis reduced in T2 imaging and instability at C6/7, and C6 vertebral slipping forward approximately 3.0 mm in T1 imaging (Fig. 3). Extension MRI showed C3/4, C4/5, C5/6, C6/7, and C7/T1 disc protrusion and canal stenosis in T2 imaging, and the spondylolisthesis of C6 was reduced in T1 imaging (Fig. 4). Hence, ACDF was performed on the patient at the level of the C6/7 disc, and C6/7 disc disruption was observed during the operation. The AIS grade was D and the JOA score was 14 4 days after the operation. The repeated MRI showed that abnormal signals mainly appeared at the C6/7 level in the spinal cord and canal stenosis was reduced 4 days after the operation (Fig. 5C). Eight months later, MRI showed chronic injury in the spinal cord (Fig. 5D). The AIS grade was D and the JOA score was 16.

#### Case 10

A 73-year-old male patient was injured by falling down the stairs and had complains of neck pain, acroanesthesia, and complete paralysis of extremities for 1 day prior to admission. The AIS grade was B, and the JOA score was 1. Neutral static MRI revealed multilevel disc herniation and canal stenosis from the C3/4 to C6/7 level without instability (Fig. 6). In similar cases, laminoplasty would usually be performed in our hospital. However, flexion MRI showed instability at the C5/6 level with C5 vertebra slipping forward approximately 2.2 mm and canal stenosis was relieved at other levels (Fig. 7). Finally, single-level anterior cervical discectomy and interbody fusion (ACDF) was performed at C5/6.

#### Case 14

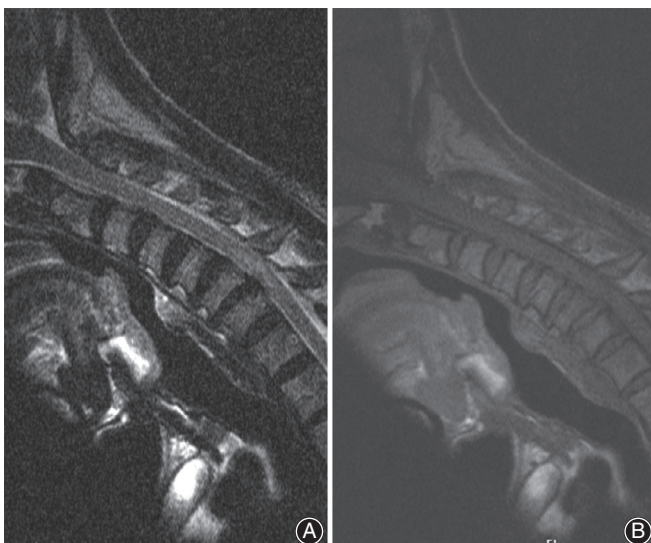
A 54-year-old male patient was injured in a fall and had complaints of neck pain, acroanesthesia, and incomplete



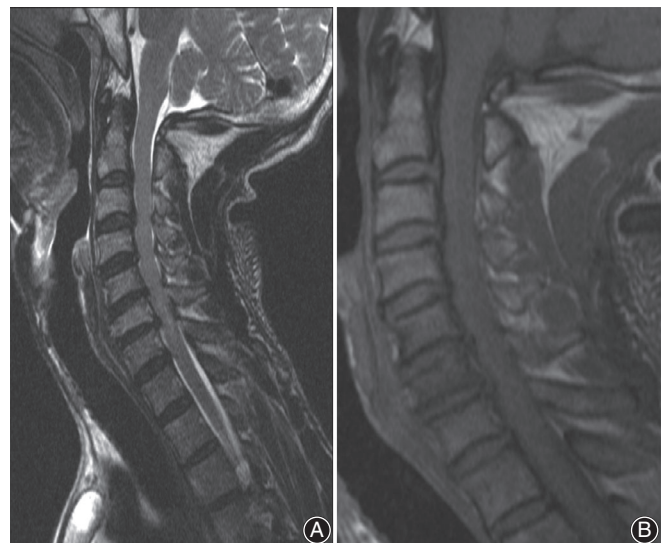
**Fig. 2** Lateral radiography (A) and CT (B) before operation demonstrated no instability, fracture, or dislocation in a 45-year-old male patient injured by a falling tree. Cervical neutral sagittal T2 imaging (C) showed abnormal signals in the spinal cord that appeared from the C5/6 disc to the C7 vertebral body level. Cervical neutral sagittal T1 imaging (D) revealed the disc herniation at C5/6 and C6/7.

paralysis of extremities for 10 hours prior to admission. The AIS grade was C, and the JOA score was 5. A cervical congenital vertebral segmentation fusion defect at C2 and C3 was observed in lateral radiograph and sagittal CT imaging. Abnormal signals appeared at the C3/4 level in the spinal cord on preoperative neutral cervical MRI (Fig. 8). KMRI was performed for further imaging evaluation. Cervical

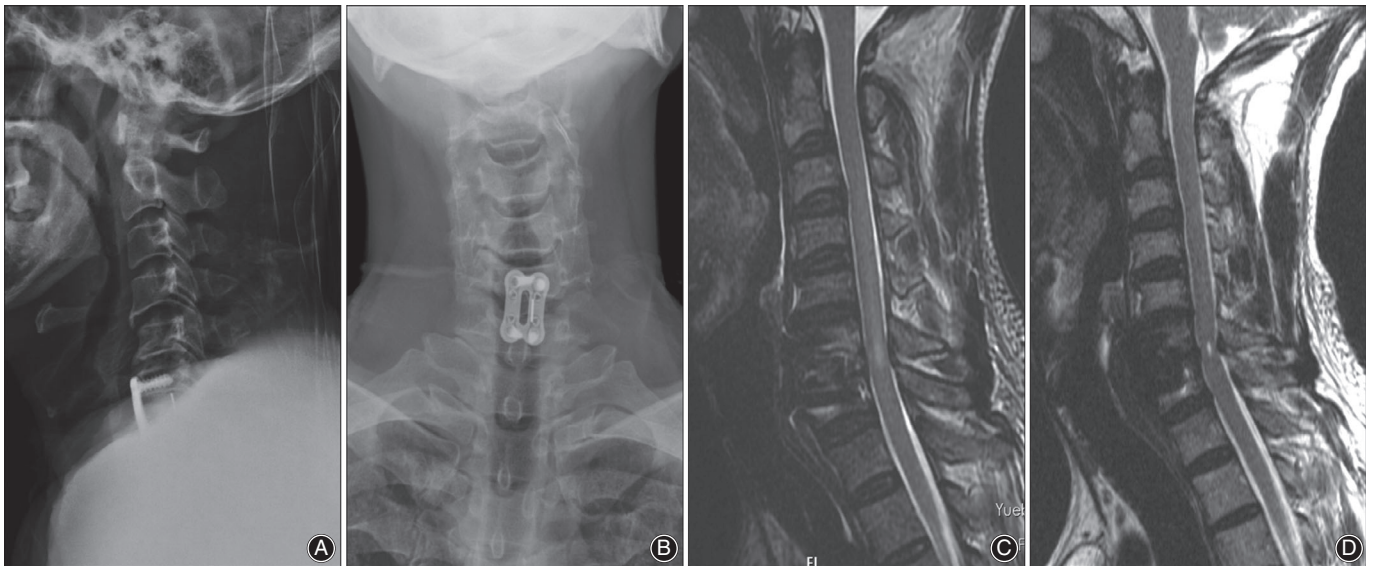
flexion T1 imaging showed that there was no instability at the C3/4 level. However, extension MRI showed instability at the C3/4 level with C2 and C3 vertebrae slipping backward approximately 2.9 mm (Fig. 9). Finally, posterior fusion with lateral mass screws was performed at C3/4 (Fig. 10). The AIS grade was D and the JOA score was 9 1 week after the operation.



**Fig. 3** Flexion cervical sagittal T2 imaging (A) showed that the abnormal signal became obvious with a reduced degree of disc protrusion and canal stenosis in the 45-year-old male patient. Instability at C6/7 was observed in flexion cervical sagittal T1 imaging (B).



**Fig. 4** Extension cervical sagittal T2 imaging (A) showed C3/4, C4/5, C5/6, C6/7, and C7/T1 disc protrusion and canal stenosis in the 45-year-old male patient. Extension cervical sagittal T1 imaging (B) revealed that the spondylolisthesis of C6 was reduced.

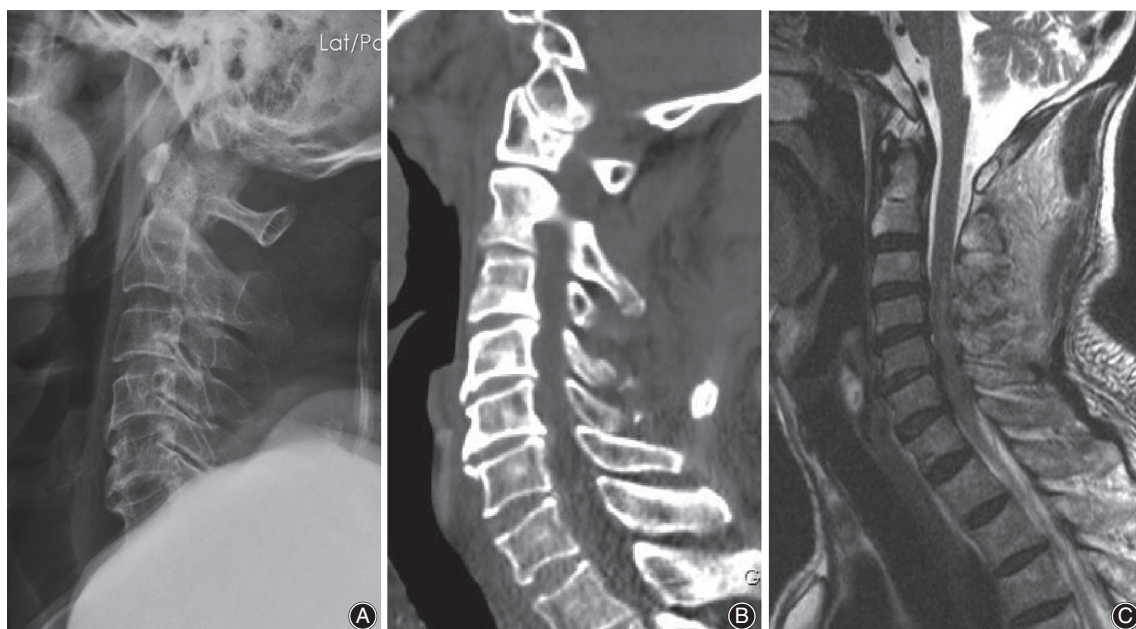


**Fig. 5** Lateral–frontal radiography (A, B) 4 days after operation of the 45-year-old male patient. Repeated MRI (C) showed that abnormal signals mainly appeared at the C6/7 level in the spinal cord, and the herniation and canal stenosis at C6/7 was reduced 4 days after the operation. Eight months later, MRI showed chronic injury in the spinal cord (D).

### Discussion

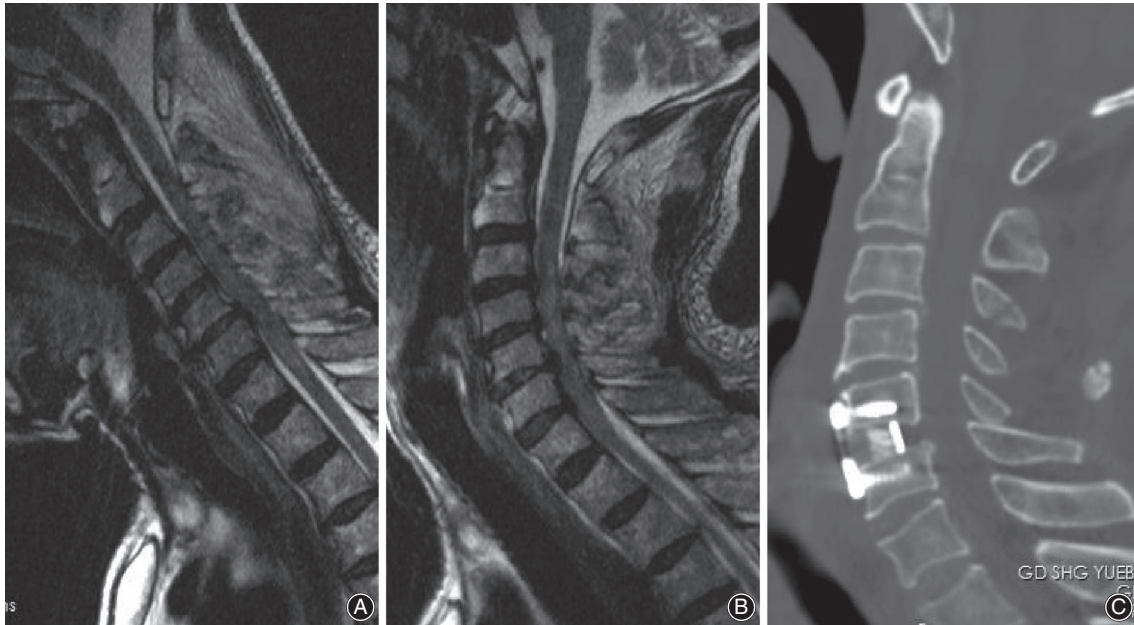
MRI is superior at identifying spinal cord injury and should be performed as soon as possible for patients with CSCIWFD, which will help to clarify the cervical spinal cord injury level and severity of canal stenosis and instability.

In our study, high signal change in T2 imaging was observed in all patients that underwent surgery, except in a 30-year-old patient who preferred conservative therapy. Treatments were made based on the examination information. Cervical surgical treatment can relieve compression to the cervical



**Fig. 6** Lateral radiography (A) and CT (B) before operation demonstrated no instability, fracture, or dislocation in a 73-year-old male patient injured by falling down the stairs. Cervical neutral sagittal T2 imaging (C) showed abnormal signals in the spinal cord from C3 to C6/7 level and revealed multilevel disc herniation and canal stenosis from C3/4 to C6/7 level without instability.

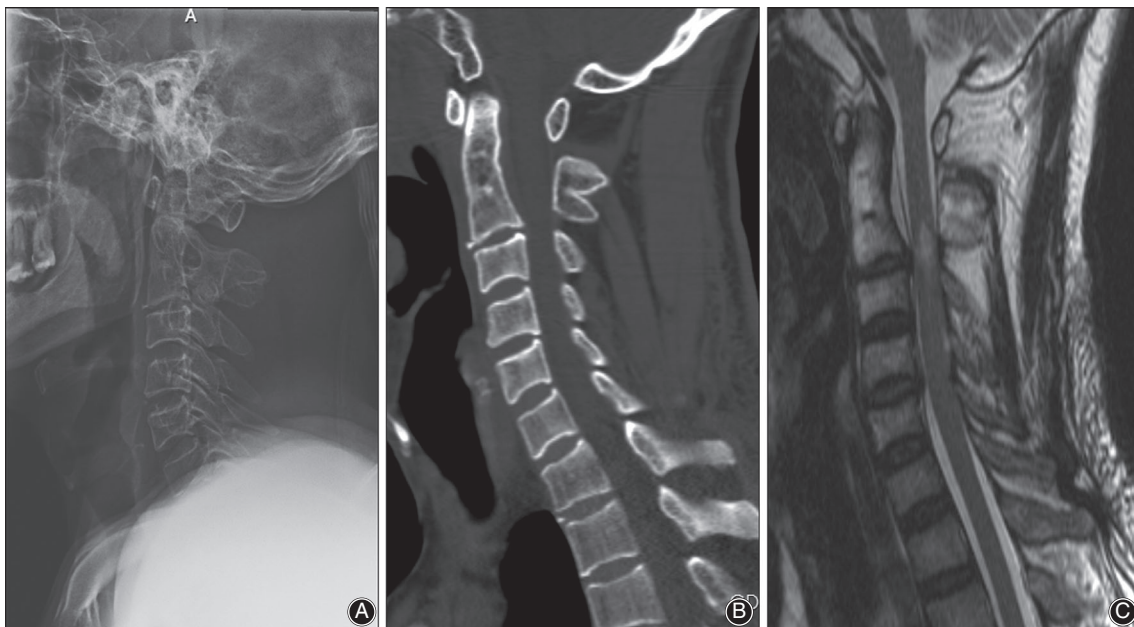




**Fig. 7** Cervical flexion T2 imaging (A) showed instability at the C5/6 level with C5 vertebra slipping forward approximately 2.2 mm and canal stenosis was relieved at other levels in the 73-year-old male patient. Cervical extension sagittal T2 imaging (B) showed the disc protrusion and canal stenosis from C3/4 to C7/T1. Sagittal CT (C) showed the plate, screws, and cage after the operation.

spinal cord and rebuild stability of the cervical spine. Some studies have shown that early decompression could lead to better neurological improvements even in the elderly<sup>22,23</sup>. However, some previous studies have proved that static MRI

showed no statistical correlation with intraoperative findings in patients with lower cervical trauma<sup>24</sup>. Neutral static cervical MRI has a limitation in demonstrating the dynamic changes of the longitudinal ligament and intervertebral disc,



**Fig. 8** Lateral radiograph (A) and sagittal CT reconstruction (B) showed congenital vertebral segmentation fusion defect at C2 and C3 in a 54-year-old male patient injured in a fall. Cervical neutral sagittal T2 imaging (C) demonstrated the abnormal signal in the spinal cord at the C3/4 level.



**Fig. 9** Cervical flexion T1 imaging (A) showed no instability at the C3/4 level in the 54-year-old male patient. Cervical extension T1 imaging (B) showed instability at the C3/4 level with C2 and C3 vertebrae slipping backward approximately 2.9 mm.

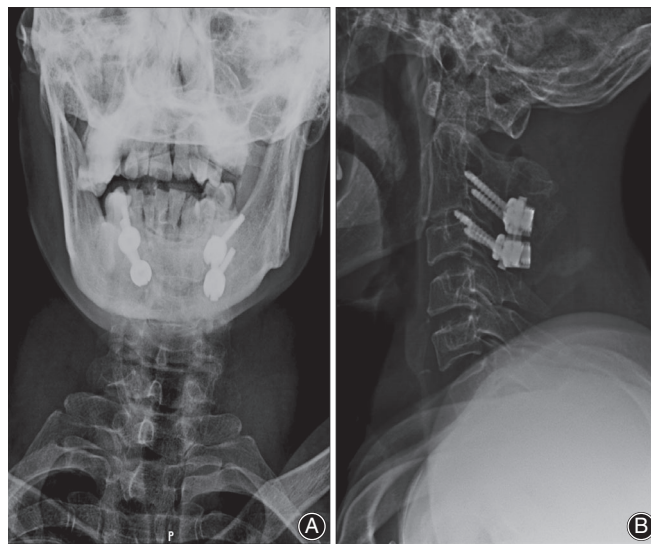
which are also considered contributors to spinal cord compression in the cervical spine flexion–extension motion.

Evidence has suggested that KMRI could elucidate spinal-cord compression with higher sensitivity, resulting in improved diagnostic accuracy of cervical spondylotic myelopathy that may impact surgical decisions for these patients<sup>25,26</sup>. Many studies have used kinematic MRI to evaluate dynamic changes in different parameters from flexion–extension in volunteers and symptomatic patients. The area in cross-sectional view of the cervical cord is larger in extension than in neutral and flexion at all cervical levels<sup>27</sup>. The spinal canal diameter tended to decrease from flexion to extension from C3/4 to C6/7, while no significant differences were seen at the C2/3 and C7/T1 levels. The anterior space available for the cord was narrowest at C4/5 and C5/6<sup>28</sup>. The study showed that KMRI was more specific and sensitive than neutral MRI with respect to patients' symptoms than objective findings on imaging that demonstrate pathology and biomechanics. A significant increase in the degree of cervical disc herniation was found by examining extension views, as it could improve detection of disc herniation by 5.78–19.46% in the kinematic position<sup>29,30</sup>.

Kinematic MRI is useful in evaluating cervical instability and has high sensitivity to detect spinal cord instability in some patients with CSCIWFD who present no instability in static MRI. Fuentes *et al.*<sup>31</sup> reported that KMRI was performed in 6 of 95 patients with spinal cord trauma suspected of having cervical instability to confirm their cervical stability. KMRI showed that extension instability existed in 4 patients and flexion–extension instability in 1 patient. The remainder of the instability in patients was associated with

herniation of a cervical disc resulting from severe cervical sprain. In our study, no instability was observed at the injured discs in neutral position, although high signal changes appeared during T2 imaging at the corresponding level. However, segmental instabilities at the injured level were observed with upper vertebra slipping forward in flexion position in 5 patients (31.25%), who were confirmed to have disc damage and instability during the ACDF procedure. The instability rate was significantly higher than that reported by Fuentes *et al.* (6.32%, 6/95). In the study by Fuentes *et al.*, KMRI was only performed on the condition that patients were suspected of having cervical instability; therefore, some patients with stability could have been missed. In our study, most therapeutic strategies (10/12) were undertaken based on the neutral static MRI imaging, while those of 2 patients depended on additional information from KMRI. Thus, KMRI proved useful when it was difficult to make a treatment decision.

To the best of our knowledge, this is the first feasibility and safety evaluation of KMRI in patients with CSCIWFD. There are few studies on the application of KMRI in patients with cervical spine injury. There are several reasons for the lack of application of KMRI examination in patients with CSCIWFD: (i) flexion–extension positioning may lead to secondary spinal cord injury because of the cervical spine instability caused by disc and/or ligament injury; (ii) patients are likely to find it difficult to maintain the same position for long to undergo the examination in both neutral and kinematic positions; and (iii) patients with high-level cervical spinal cord injury often show concomitant complications, such as phrenic nerve palsy leading to weakness of cough and expectoration. During the long period of examination, respiratory tract obstruction may occur. In our study, several



**Fig. 10** Frontal (A) and lateral (B) radiographs showed lateral mass screws in the 54-year-old male patient after operation.

measures were adopted to deal with the possible risks. First, neurological function, clinical symptoms, vital signs, and respiratory condition were evaluated by physical examination, AIS grade, and JOA score for all CSCIWFD cases. Only patients without respiratory myo-paralysis were enrolled. In this study, 5 patients had an AIS grade of C, 9 had a grade of D on admission, while the remaining 2 patients showed AIS grade of B but without respiratory myoparalysis. Second, a spinal surgeon accompanied the patients to undergo the neutral and kinematic MRI examinations and helped to place and maintain the position of patients. The KMRI was terminated if patients experienced any discomfort during the examination. In our study, all 16 patients with CSCIWFD successfully underwent cervical neutral and kinematic MRI examination without any discomfort and aggravation of neurological function after examination. Finally, only flexion or extension sagittal imaging was performed to reduce the examination time for some patients who could not keep the position for a long examination time. Fourteen patients underwent MRI in three different positions. Neutral and flexion MRI were performed in 2 patients who could not maintain the position for a long time.

Our study has some limitations. First, the study was limited by a small sample size and, thus, might not be representative of all CSCIWFD cases. More patients should be enrolled in future studies to validate the results of this study. Second, most of the enrolled patients suffered from mild spinal cord injury with AIS grade C or D. The results, therefore,

might differ from those in severe CSCIWFD cases. Cervical KMRI could be performed for patients with severe CSCIWFD under neuroelectrophysiological and electrophysiological monitoring. Finally, this was a single-institution study with a retrospective design. A prospective multicenter study would be useful for the evaluation of dynamic changes in the cervical spine and the spinal cord.

### Conclusion

To the best of our knowledge, this is the first study of the feasibility and safety of cervical KMRI in patients with CSCIWFD. Based on our results and the current literature, kinematic MRI can be applied to patients with CSCIWFD and represents a safe technique. Kinematic MRI can provide more details than static MRI and was also more useful for making therapeutic decisions in patients with CSCIWFD. However, further studies should be carried out to verify the safety and effectiveness of this technique.

### Conflict of interest

None.

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