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Comparison of Hybrid Constructs with 2-Level Artificial Disc Replacement and 2-Level Anterior Cervical Discectomy and Fusion for Surgical Reconstruction of the Cervical Spine: A Kinematic Study in Whole Cadavers

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Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: Multi-level cervical degeneration of the spine is a common clinical pathology that is often repaired by anterior cervical discectomy and fusion (ACDF).
The aim of this study was to investigate the kinematics of the cervical spine after hybrid surgery compared with 2-level ACDF.

Material/Methods: Five freshly frozen, unembalmed whole human cadavers were used including 3 males and 2 females with a mean age of 51±8 years. After evaluating the intact spine for range of motion (ROM), sagittal alignment and instantaneous center of rotation (ICR), each cadaver underwent 4 consecutive surgeries: 2-level artificial disc replacement (ADR) from C4 to C6 (ADR surgery); 2-level ACDF from C4 to C6 (ACDF surgery); hybrid C4-5 ACDF and C5-6 ADR (ACDF+ADR surgery); and hybrid C4-5 ADR and C5-6 ACDF (ADR+ACDF surgery). The ROM and ICR of adjacent intact segments (C3-4; C6-7), and whole sagittal alignment were revaluated.

Results: Two-level ACDF resulted in increased ROM at C3-4 and C6-7 compared with intact spine. ROM was significantly different to intact spine using ACDF surgery at C3-C4 and C6-C7 and ROM was increased with ACDF+ADR surgery at C6-C7 (all $P<0.05$). No improvement in sagittal alignment was observed with any approach. The localization of the ICR shifted upwards and anteriorly at C3-C4 after reconstruction. ICR changes at C3-C4 were greatest for ADR+ACDF surgery and were significantly different to ACDF surgery ($P<0.05$), but not between ADR surgery and ACDF+ADR surgery. At C6-C7, the ICR was more posterior and superior than in the intact condition. The greatest change in ICR was observed in ACDF surgery at the C6-C7 level, significantly different from the other groups ($P<0.05$).

Conclusions: For 2-level reconstruction, hybrid surgery and ADR did not alter ROM and minimally changed ICR at the adjacent-level. The type of surgery had a significant impact on the ICR location. This suggests that hybrid surgery may be a viable option for 2-level cervical surgery.

MeSH Keywords: Cervical Spine • Hybrid Surgery • Instantaneous Center of Rotation • Kinematics • Radiography

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Background

Anterior cervical discectomy and fusion (ACDF) is the most accepted procedure for treatment of intervertebral disc disease [1], with proven radiological fusion rates of 90–100% [2]. However, altered kinematics can occur after fusion, sometimes leading to accelerated adjacent-segment degeneration [2]. To avoid the disadvantages of fusion, artificial disc replacement (ADR) has been designed. The results of ADR are excellent in terms of motion preservation of the implanted functional spine unit, reducing adjacent-segment degeneration [3]. However, ADR is associated with a longer surgical procedure, more important blood losses and higher risk of complications including the loss of disc space height and functional spinal unit (FSU) misalignment, the loss of lordosis and the appearance of segmental kyphosis at the treated level [1,4,5]. In addition, most of these previous studies have focused on single-level ADR rather than 2-level ADR.

The evidence and indication for multilevel arthroplasty remains controversial in patients with multilevel spondylotic disease of the cervical spine. Recently, hybrid surgery has been proposed as a treatment option for multilevel cervical disc disease, allowing the severely spondylotic segment to be fused and the more mobile level to be treated by ADR [6–8]. This approach combines ACDF and ADR with the goal of maintaining cervical motion and avoiding the potential for increasing the drawbacks of ADR such as increased surgery time and blood loss that might be amplified when used on multiple levels. In addition, it can be used to manage adjacent-level disease in patients with prior fusion surgery.

The existing literature consists of a few studies looking independently at ACDF *vs.* hybrid surgery generally using isolated spines [7–14]. The purpose of the present study was to evaluate hybrid surgery using a whole human cadaver model and to compare this approach with the intact spine and multilevel ADR. We also investigated different types of hybrid surgery reconstruction.

Material and Methods

Cadavers

The present study used 3 fresh whole human cadavers without embalming fluids. The cadavers were 2 females and 3 males, aged 40-60 years at time of death. According to the certificates, there was no advanced surgery or destructive disease history. The cadavers were fresh frozen within 6 hours after death. They were obtained from the Beijing Society for Anatomical Sciences (Beijing, China). Standard anteroposterior and lateral plain films were taken to exclude the following conditions: prior surgery, destructive disease, and congenital cervical vertebral fusion. Before testing, the cadavers were completely thawed to room temperature to ensure the cervical spine was back to its natural state. Each cadaver was preconditioned with 3 cycles of full flexion and extension and the experiments began immediately.

Figure 1. The cadaver was fixed on a chair, and a C-arm fluoroscope was positioned to obtain lateral cervical radiographs.

A traditional anterior approach to the cervical spine was made. Four metal markers of 1 mm in diameter were implanted on 3 corners of the vertebral bodies being evaluated. The cadavers were secured in the upright and seated position on a chair using 1 strap across the pelvis and another across the chest. The head of the cadaver was controlled with a skull traction caliper. A goniometer was attached to the lateral side of the head to record the range of motion (ROM). A gradienter was affixed to the front of the head to ensure that motion occurred in the sagittal plane during the testing process. The traction caliper was connected to a tensiometer to provide consistent moment of force (20 N) during the full range of flexion and extension, 20N was selected to be similar to 5lb force (22N) used in previous study [15].

A single C-arm fluoroscope was positioned to obtain lateral cervical radiographs centered on C4. Each cadaver was preconditioned with 3 cycles of full flexion and extension. On the sixth cycle, lateral images were obtained with the neck in neutral position, full flexion, and full extension (Figure 1). Data were obtained 3 times.

Interventions

The intact cadaver was first tested, and the 3 surgical approaches were then performed and evaluated in the following order in

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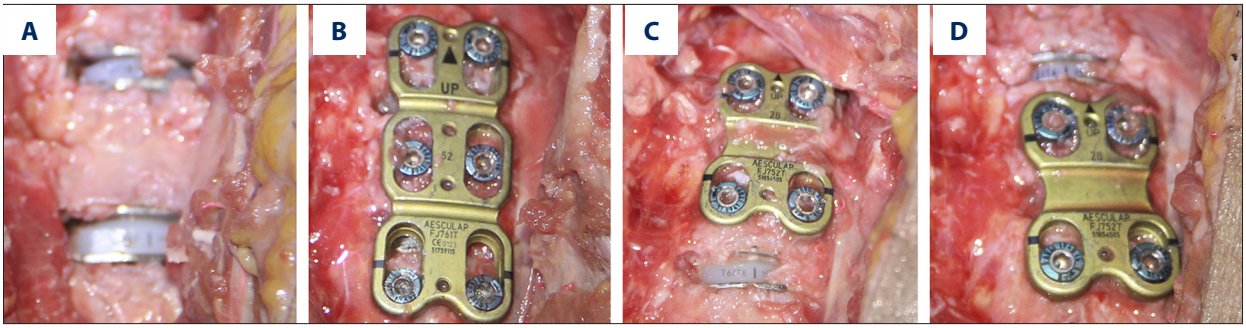

Figure 2. Anterior view of the 3 intervention specimens (C4-C6): (**A**) two-level artificial disc replacement (ADR); (**B**) two-level anterior cervical discectomy and fusion (ACDF); (**C**) C4-C5 ACDF and C5-C6 ADR; and (**D**) C4-C5 ADR and C5-C6 ACDF.

each cadaver: 2-level ADR from C4 to C6 (ADR surgery); 2-level ACDF from C4 to C6 (ACDF surgery); hybrid C4-5 ACDF and C5-6 ADR (ACDF+ADR surgery); and hybrid C4-5 ADR and C5-6 ACDF (ADR+ACDF surgery) (Figure 2). The artificial discs used were Mobi-C cervical discs (LDR medical, France). Nonlimiting cervical vertebral fixation was by screw through the plate with respect to the angle of the plate or the presence of micro-locations to achieve dynamic compression. The disc arthroplasty plate was an Aesculap plate (Aesculap Implant Systems, Inc., USA).

Experimental procedure

The theory for our determination of the instantaneous center of rotation (ICR) was based on general kinematic concepts [16–18]. The radiographic images of the underlying cervical vertebra were superimposed. Two lines were drawn to connect the identical points of the above vertebra on the flexed and extended positions. The point of intersection of the perpendicular bisectors of the 2 lines indicated the location of the ICR. In the present study, the segmental extension and flexion images were automatically superposed according to the metal landmarks using the point-registration tool of the Mimics software (Materialise, Leuven, Belgium). The 2 corresponding metal points on the superior vertebra were connected by lines, and the ICR was determined as the intersection of the perpendicular bisectors of these 2 lines (Figure 3).

The ICR of each FSU was obtained at C3-4 and C6-7. The ICR was calculated only if the segmental motion was greater than 5° in the sagittal plane [19]. For all specimens, the ICR at adjacent (C3-4 and C6-7) motion segments were represented on a lateral image of the intact spine in the neutral position. The distance between the ICR of intact spine and the ICR of each reconstruction was measured. The real length was recorded for comparisons.

Sagittal alignment between C2 and C7 was measured on the neutral-position lateral image using the Cobb method, which were measured from lines drawn parallel to the inferior aspects of the C2 and C7 vertebral bodies[20,21]. Negative and

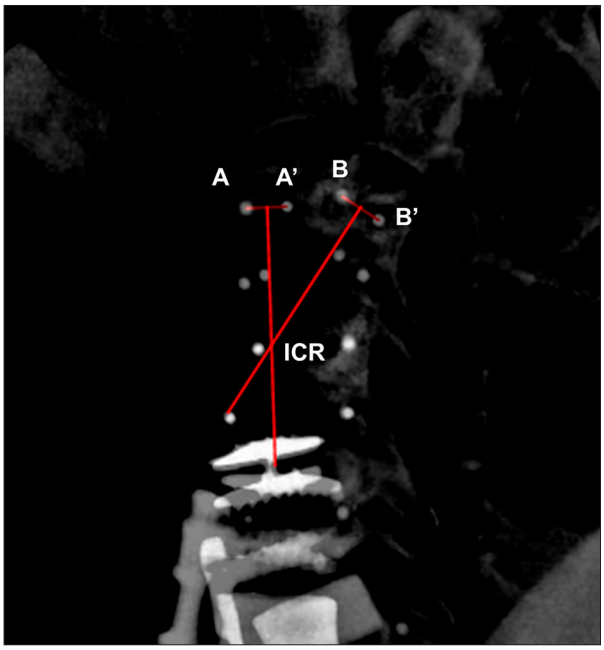

Figure 3. Measurement of instantaneous center of rotation (ICR) on flexion-extension plain lateral radiographs by superposing the underlying cervical vertebra according to the method of perpendicular bisectors and establishment of coordinate. Two corresponding metal points on the superior vertebra (A and A' and B and B') were connected by lines, and the ICR was determined as the intersection of the perpendicular bisectors of these two lines.

positive lordotic angles indicated cervical kyphosis and lordosis, respectively. The ROM was assessed by drawing 2 lines that were tangential to the superior and inferior to the endplates of the functional spinal unit. The angle between the 2 lines was measured. The ROM of functional spinal unit was represented as the summation of angles on the flexion and extension position. The ROM at cranial (C3-4) and caudal levels of the cervical spine (C6-7) were calculated.

Three orthopedists independently analyzed all radiographs. The mean value was used for analysis.

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Statistical analyses

Data are presented as mean ± standard deviation (SD). Inter- and intraobserver reliabilities of each measurement procedure were assessed by intraclass correlation coefficients (ICCs). Continuous variables were analyzed using ANOVA with the Tukey's post hoc test. P-values <0.05 were considered to be statistically significant. SPSS 13.0 (SPSS Inc., Chicago, IL, USA) was used for data analysis.

Results

Range of motion

The inter-orthopedist reliability was evaluated using the ICC, and demonstrated a good inter-observer reliability (ICC=0.82, 95%CI: 0.73–0.91). Analysis of kinematics demonstrated that there was no significant difference between the intact spine and 2-level ADR, according to ROM. Two-level ACDF resulted in a significant increase in ROM at C3-4 and C6-7 compared with the intact spine. Compared with the intact spine, the ROM at C3-C4 was significantly different using ACDF surgery. Compared with the intact spine, ROM at C6-C7 was significantly different after both ACDF surgery and ACDF+ADR surgery. In ACDF+ADR surgery, ROM was increased at C3-4 and C6-7 compared with intact spine; however, significant changes were noted only at lower levels (C6-C7) (P<0.05). In ADR+ACDF surgery, ROM in flexion and extension were increased at C3-4 and C6-7, but the differences were not significant compared with the intact spine (Figure 4A).

Sagittal alignment

Compared with the intact spine, there was no significant increase in sagittal alignment in any surgeries, although there was an increasing trend after operation (Figure 4B).

Instantaneous center of rotation

The localization of the ICR shifted upwards and anteriorly at C3-C4 after reconstruction compared with intact spine. However, the change differed depending upon the surgical intervention. Significant changes of ICR at C3-C4 were observed between ACDF surgery and ADR+ACDF surgery (P<0.05), but there were no significant differences in changes in ICR at C3-C4 between ADR surgery and ACDF+ADR surgery. The changes in ICR at C3-C4 for ADR+ACDF surgery showed the greatest change. At the C6-C7 level, the ICR was more posterior and superior than in the intact condition. The greatest change in ICR was observed in ACDF surgery at the C6-C7 level, which was significantly different from all other surgery groups. Moreover, the ICR at the C6-C7 level for ACDF+ADR surgery was found to be no different from that of ADR surgery and ADR+ACDF surgery (Figure 4C).

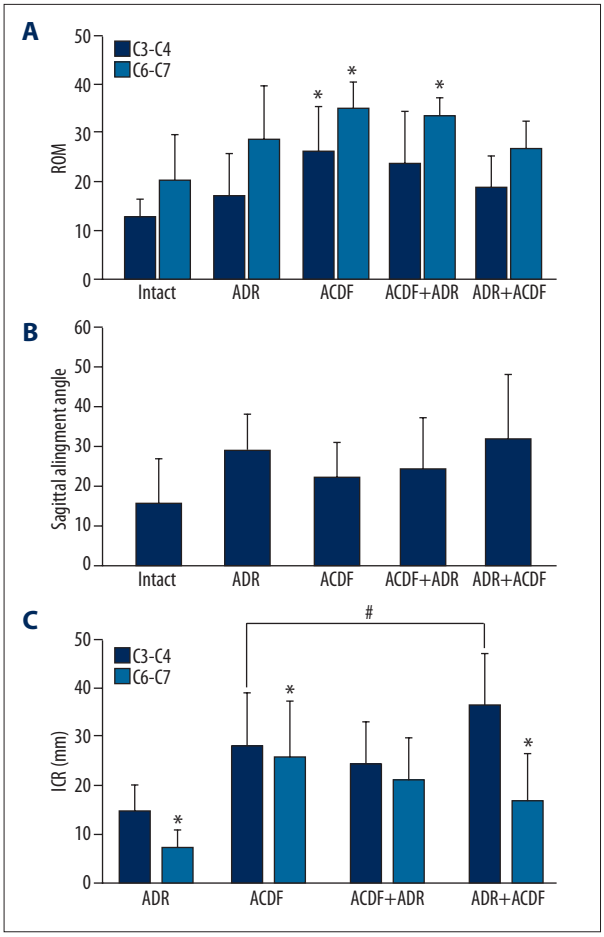

Figure 4. Cervical spine measurements for the intact spine, artificial disc replacement from C4 to C6 (ADR), two-level anterior cervical discectomy and fusion from C4 to C6 (ACDF), and hybrid surgeries of C4-5 ACDF and C5-6 ARD (ACDF+ADR), and C4-5 ARD and C5-6 ACDF (ADR+ACDF) (**A**) Range of motion (ROM) for adjacent motion segments compared with intact spine (3 cycles/cadaver). * P<0.05 *vs.* the intact spine. (**B**) Sagittal alignment for adjacent motion segments compared with intact spine (3 cycles/cadaver): (**C**) Translational distance of instantaneous center of rotation (ICR) in each specimen (3 cycles/cadaver). # P<0.05 for ICR at C3-C4 between ACDF surgery and ADR+ACDF surgery. * P<0.05 for ICR at C6-C7 between ACDF+ADR surgery *vs.* the other 3 surgeries.

Discussion

The ideal reconstruction method for cervical spondylotic myelopathy has been sought for decades. To address accelerated adjacent-segment degeneration associated with ACDF, total

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ADR has been developed to preserve motions at the treated level. Although total ADR is recognized as an attractive treatment option for single-level cervical disc disease, there is still no consensus regarding treatment options for multilevel disease [4,22,23]. In addition to ACDF and total ADR, the use of both methods has been reported. Outcomes after hybrid surgery are still under investigation, especially with regard to the effect on cervical kinematics at adjacent disc levels [24]. There is some suggestion that ADR located close to 2-level fusion may be a more challenging biomechanical environment compared to ADR alone [13].

In this line, the results of the present study showed that 2-level ACDF resulted in increased ROM at C3-4 and C6-7 compared with intact spine. There was no significant difference between 2-level ADR and intact spine. Using ACDF+ADR surgery, significant changes were noted at lower levels only. There was no significant difference in ADR+ACDF surgery for flexion and extension ROM at C3-4 and C6-7. No improvement in the sagittal alignment was observed in any surgical approach. ICR was different between ACDF surgery and ADR+ACDF surgery at C3-C4, but not between ADR surgery and ACDF+ADR surgery. At C6-C7, the ICR were localized more posterior and superior than in the intact condition in ACDF surgery and ACDF+ADR surgery approaches.

We observed that adjacent level ROM was preserved after cervical disc arthroplasty, but was significantly increased with ACDF, similar to studies that have reported earlier [11]. A study of 12 fresh human cadaveric spines from C2 to T2 focused on the contribution of adjacent segments to ROM. The specimens were loaded with pure moments loading of 2 Nm. The study found that hybrid surgery preserved the contribution at adjacent levels. However, only 1 type of hybrid surgery was investigated [9]. Lee et al. [12], in a biomechanical study of 2 approaches of hybrid surgery using 3 cadaveric cervical spines, showed that the location of the single-level fusion, above or below the arthroplasty, did not significantly affect the ROM and could reduce hypermobility in adjacent-level. Cho et al.[10] used cadaveric spine specimens to explore biomechanics under a compressive load after 2 types of hybrid surgery; results demonstrated no significant change in ROM at adjacent levels or in the entire cervical spine when comparing both types of surgery with the intact spine. In the present study performed in whole cadavers, there was a significant difference between the 2 hybrid surgery methods. Although ACDF+ADR surgery (C4-C5 arthroplasty and C5-C6 ACDF) demonstrated increased ROM at adjacent levels compared with the intact spine, the changes were not statistically significant. However, increases in ROM in the lower segments were significantly greater in ACDF+ADR surgery. This was adjacent to the ADR not the ACDF in ACDF+ADR surgery, and may be due to physiological and anatomical structure of C6-C7 that commits more under physiological conditions to the entire ROM of the cervical spine. Our study suggests that the type of hybrid surgery may affect the kinematic behavior of adjacent segments, suggesting that the decrease or increase in ROM at the operative levels requires compensation at adjacent levels.

Further assessment of the sagittal alignment revealed an increasing trend in all cadavers after implant insertion, but the changes were not significant. However, the relationship between spine curvature and clinical outcomes remains controversial. Some studies have demonstrated that sagittal alignment in the cervical spine may change after arthroplasty [25,26]. Kyphotic changes should be avoided to reduce axial neck pain and to prevent stresses at adjacent levels.

As a kinematic parameter, ROM describes the quantity of motion only. However, preservation of physiological motion requires not only maintaining the quantity of motion, but also restoring the quality of motion. In the present study, we used a kinematic parameter for the qualitative evaluation of cervical spine kinematics, ICR, to analyze the motion changes after reconstruction. ICR is a more sensitive parameter in the detection of abnormal mobility of the cervical spine resulting from a cervical disorder [27]. It can reveal abnormal patterns of motion within individual segments despite a normal ROM. This is of concern because some research has suggested that multi-level arthroplasty can increase buckling of the spine [14]. In our study, after ADR, the location of the ICR shifted upwards and anteriorly at the C3-4 level, and more posteriorly and superiorly at the C6-7 level, compared with the intact spine. For ACDF and ADR, arthrodesis resulted in exaggerated shift of the ICR. These changes may result in accelerated adjacent-segment degeneration, and this trend was preserved after ADR. Furthermore, the type of hybrid surgery was found to have a significant impact on the location of the ICR. The rigidity of the fused segment may logically cause abnormal kinematics at adjacent levels.

The degree and area of degeneration requiring clinical treatment vary. In this complex scenario, we consider hybrid surgery to be an option. For the severely spondylotic segment, ACDF could be the best for the less mobile segment and avoid unnecessary extra-motion in the treated levels after ADR. While the more mobile level with minor degeneration could be treated with ADR. In general, hybrid surgery can provide the suitable treatment according to the individual condition of affected level. Although hybrid surgery only partially restored the native kinematics of the cervical spine, this construct generated better biomechanical conditions than arthrodesis at adjacent levels. A recent pilot study in 3 patients suggests that outcomes of hybrid surgery are comparable to ACDF and arthroplasty [7], these parameters included duration of surgery, time of returning to work, cervical range of motion and functional

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scores. Another study compared hybrid surgery with ACDF in respective 20 patients. The hybrid surgery demonstrated excellent results in angular range of motion for C2–C7, the neck disability index and pain intensity, adjacent segments ROM before and after operation. Their conclusion noted that hybrid surgery was superior to ACDF [8]. These studies support the results of the present study.

The main strength of the present study was the use of fresh whole cadavers. Numerous cervical biomechanical studies have used cadaveric cervical spines, and the impact of the surrounding tissues was lost. In addition, the specimen can only be tested under uniform load-controlled condition. In the present study, a whole-cadaver model, with intact muscles and ligaments, was used. Although whole cadavers are not entirely representative of the real-life condition, the physiologic conditions they provide for the study of kinematics may be closer to those of live humans than those of detached specimens [15,28]. Through motion and weight of the head, the models underwent individual intervention to simulate behavior of the cervical spine. Thus, the data from the present study provide a better reference for clinical practice.

Limitations of the study include a small sample size, experimentation on cadavers, and the use of specimens without dynamic motion. With just 3 samples the statistical significance of the study will be greatly reduced; larger samples may reveal more subtle differences than could be evaluated here. The small number of samples also meant that the surgeries had to be performed consecutively in the same samples; this has obvious disadvantages involving repeated procedures in the same area. While it would be difficult to have a larger sample number in future studies, undertaking the different surgical approaches in different orders for each sample might help reduce the effects of this particular problem. While the cadavers had surrounding tissues the fact that these were not undergoing biological processes and the muscles, for example, were not contracting and relaxing means that the full range of effects from the surrounding tissues also cannot be evaluated in this model. Because the complexity of live humans cannot be simulated in the laboratory, clinical research is necessary to evaluate the kinematic changes described here. The accuracy of determination of ICR on radiographs can be affected by the measurement method, radiographic technique, and intra- and interobserver variations [29]. However, to eliminate measurement error, we placed metal markers and used the Mimics software to superimpose the plain radiographs automatically. We failed to measure ROM decreases at C4-5 and C5-6 in 2-level ACDF conditions, as compared to other surgeries. This would have tested whether motion was completely eliminated at the theoretically fused levels. We also did not undertake measurements of the full range of biomechanics that may influence the movement of the cervical spine, other measurements such as ligament strain could well influence the results presented here. These results are also reliant upon the plates and devices used and their dynamics, the results may differ when different devices are selected. Nevertheless, despite these shortcomings, many of which are inevitable in a cadaver model, the results presented here can help understand the kinematic properties of the optimal method for cervical spine surgical reconstruction.

Conclusions

In conclusion, hybrid surgery and ADR did not alter ROM at the adjacent-level in the cervical spine in this cadaver model, although further research is required to address the limitations of this study. Changes in ICR were minimal at the adjacent-level after hybrid surgery and ADR. The type of hybrid surgery was found to have a significant impact on the location of the ICR. These results suggest that this type of hybrid surgery may be suitable for treatment of multilevel spondylotic disease of the cervical spine.

Conflict of interest

None.

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