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Retropharyngeal Reduction Plate for Treatment of Irreducible Atlantoaxial Dislocation: A Cadaveric Test and Finite Element Analysis

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Abstract

Background: Clinical studies have shown that irreducible atlantoaxial dislocation (IAAD) can achieve reduction, decompression, fixation and fusion by transoral, posterior, and other traditional approaches. The present study aims to introduced a newly designed reduction plate through the retropharyngeal approach and evaluate its feasibility by cadaveric test and finite element analysis.

Methods: A cadaveric specimen and a 45-year-old postoperative female patient diagnosed with IAAD who underwent the traditional posterior fixation were enrolled in this scientific study. The retropharyngeal approach involved placing the reduction plate into a cadaveric specimen's cervical spine. Spiral CT thinly scanning (0.05 mm) from the base of the occipital bone to C7 vertebrae was performed and reconstructed for three-dimensional (3D) finite element analysis using Mimics software based on the Dicom data of two different fixations. Biomechanical distribution was compared between two fixations under different stress conditions, including flexion, extension, bending and rotation, respectively.

Results: There was no significant difference in maximum stress between the retropharyngeal reduction plate system and the posterior atlantoaxial pedicle screw fixation system during flexion. Under states of extension, bending and rotation, the maximum stress of the reduction plate system was significantly lower than that of the posterior atlantoaxial pedicle screw fixation system. Both of the maximum stresses between two fixations were far lower than the maximum yield strength (795-827 MPa) and ultimate strength (860-896 MPa) of the titanium alloys. There was no significantly stress concentration between retropharyngeal reduction plate system and the posterior atlantoaxial pedicle screw fixation system under different movement.

Conclusions: The cadaveric test showed that it is feasible to place the reduction plate using the retropharyngeal approach. The finite element analysis indicated that the retropharyngeal reduction plate system may provide relatively reliable fixation compared with traditional posterior fixation. A new choice of designing a surgical plan for treating atlantoaxial dislocation is presented.

Background

Numerous pathologies, such as congenital abnormalities, rheumatoid arthritis, Down's syndrome, inflammatory abnormalities, traumatic dens fracture, or metabolic diseases, affecting the craniovertebral junction (CVJ) can lead to atlantoaxial dislocation (AAD). The instability of the atlantoaxial joint can lead to a variety of symptoms, such as local pain, limb anesthesia, urination dysfunction, defecation dysfunction, and even death. Consequently, if AAD is not treated in a timely and appropriate manner, the displacement may become irreversible [1–4]. If observation of the dynamic X-ray shows that the reduction of the atlantoaxial joint failed with skeletal traction under general anesthesia, AAD is considered irreducible [5]. To date, available treatments for IAAD are posterior decompression, anterior release via transoral approach followed by posterior fixation, and transoral atlantoaxial reduction plate (TARP) internal fixation, to name a few [6–8]. However, traditional transoral ventral decompression or

anterior release followed by posterior fixation is accompanied by many inevitable disadvantages, such as a narrow and unclear surgical field, difficult operative procedures, postoperative throat discomfort, and high-risk postoperative infection [9, 10]. These disadvantages can lead to high morbidity and mortality rates. Currently, the choice of treatments for IAAD is controversial, and no consensus has been reached.

Recently, studies involving retropharyngeal release and reduction approach for the treatment of IAAD have been reported. This approach has resulted in positive clinical outcomes and less postoperative complications. In this study, we designed a new reduction plate based on the retropharyngeal approach. In order to evaluate its feasibility of placement, the cadaveric test was performed. In addition, the 3D finite element analysis was conducted to analyze its biomechanical properties [11, 12]. The purpose of this study was to evaluate our newly designed reduction plate system via cadaveric test and finite element analysis and explored its feasibility of clinical application.

Methods

Design of retropharyngeal reduction plate system.

The retropharyngeal reduction plate system consists of different sized T-type titanium plates, screws, adjustable screwdrivers, and other supporting surgical instruments (Fig. 1). The T-type plates consist of horizontal and vertical parts at specific angles with different amounts of round holes on each part, depending on the size of plates. The round holes are used for inserting screws. In addition, there are two or three specially designed oval holes in the center of the plate. There are micro-switches in the oval hole that are designed for facilitating reduction by inserting lag screws into axis with multiple angles (Fig. 2a). The atlantoaxial reduction can be achieved by providing the atlantoaxial joint with forward and downward traction by inserting lag screws through an oval hole in one stage (Video 1, Fig. 2b).

Fixing the retropharyngeal reduction plate on cadaveric specimen.

One formalin-preserved specimen was obtained from department of Anatomy, Qingdao University. A 0.5 mm spiral CT scan confirmed the integrity of the cervical spine. With the careful dissection of CVJ, C1 transverse ligament was ruptured and the IAAD model was obtained by using proper external force. Moreover, the newly designed retropharyngeal reduction plate was placed on the specimen through the retropharyngeal approach. The cadaveric specimen with the retropharyngeal reduction plate was obtained to make further finite element analysis (Fig. 3).

Finite element model of two internal fixations.

A 45-year-old postoperative female patient diagnosed with IAAD was selected and regarded as a reference for further finite element study. The female patient underwent the operation for atlantoaxial reduction using traditional posterior atlantoaxial pedicle screw fixation. To further verify the different stress distribution between the retropharyngeal reduction plate system and the posterior atlantoaxial pedicle screw fixation system, we respectively established the finite element model of two different

internal fixations. We divided the two different fixations into two groups for a clear presentation. The A group was the cadaveric specimen with the retropharyngeal reduction plate. The B group included the 45-year-old postoperative female patient with the posterior atlantoaxial pedicle screw fixation. Spiral CT scanning was performed from the base of the occipital bone to the C7 vertebrae using 0.5-mm thick slices. In total, 746 scanning images were collected and stored in digital imaging and communications in medicine (DICOM) format for the reconstruction of a 3D bone structure using Mimics 12.0 software (Materialise, Leuven, Belgium). In order to further facilitate finite element analysis, two geometric solid models were obtained after sanding, filling, and denoising (Fig. 4).

3D finite element analysis of two treatments for IAAD.

The 3D finite element analysis was achieved by using HyperWorks™ software (Altair Engineering Inc., Troy, MI, USA). Based on the parameters of Young modulus and Poisson's ratio in Table 1, the scientific assignment of elements was obtained [13]. The coupling points were loaded by using Hypermesh software (Altair Engineering Inc., Troy, MI, USA), facilitating the simulation of different motions of cervical vertebra including flexion, extension, bending and rotation. To achieve the simulation of stress to the cervical vertebra from the head due to gravity, 45 N of vertical downward pressure was imposed on the surface of the occipital condyle [12]. Approximately 1.5 N m torque was imposed on the models from different directions to simulate a force to the of cervical vertebrae under normal physiologic conditions. We respectively measured and calculated the stress of two internal fixations under different movements.

Table 1
Property of the Materials for the Finite Element Model

Element	Modulus of Elasticity (MPa)	Poisson Ratio
Vertebra		
Cancellous Bone	100	0.2
Cortical bone	12000	0.3
Endplate	24	0.4
Spinous process	3500	0.25
Intervertebral Disc		
Nucleus Pulposus	1	0.49
Fiber loop	6	0.45

Results

Validation of the placement of the retropharyngeal reduction plate through the retropharyngeal approach.

The suitable retropharyngeal reduction plate was located at the body of the atlas through inserting screws after exposing the atlantoaxial joint employing the retropharyngeal approach. Screws with diameters of 2.0 mm were inserted approximately in depth through the center oval hole, consisting of special micro-switches, with the assistance of screwdrivers. After the insertion of the lag screw, the atlantoaxial reduction was achieved by providing the atlantoaxial joint with forward and downward traction through the oval hole in one stage. In total, another two screws were located at the surface of the axis for helping improve the fixation strength. Spiral CT showed that the reduction plate had a reliable fixation with the accurate screw insertion (Fig. 5).

Comparison of Von mises stress between two internal fixations.

There was no apparent difference in maximum stress between the A group and B group during flexion. The maximum stress of the A group was lower than that of the B group under other movements, including extension, bending and rotation (Fig. 6).

Stress distribution of two internal fixations.

Redness represents the maximum element stress, whereas blueness represents the minimum element stress. Under identical loading conditions, the stress distribution of the two internal fixations was not significantly different after the simulation experiments for movements such as flexion, extension, bending, and rotation. There was no significant stress concentration in the two internal fixations under different movements.

In the posterior pedicle screw fixation system, the junctions of the screw, bone, and rod bore relatively less stress in flexion, extension and bending, respectively. But there was a small redness area which means relative high stress at the right junction of screw under rotation (Fig. 7). In our newly designed retropharyngeal reduction plate system, the stress was distributed evenly on the plate, and the junction of the screw and plate bore less stress in the same motion states (Fig. 8). The stress tolerance of the two internal fixations are consistent in flexion, extension, bending, and rotation. In addition, the mean stress of the two internal fixations was far below the maximum yield strength (795–827 MPa) and ultimate strength (860–896 MPa) of titanium alloy [14].

Discussion

Atlantoaxial dislocation (AAD) can result from several causes, including congenital abnormalities, trauma, inflammatory, or iatrogenic injury [15]. Recently, the treatment of IAAD has been reported by many researchers, where the traditional treatment procedure is posterior pedicle internal fixation after anterior transoral release [8]. Lv et al. [16] demonstrated rotating rod techniques to spare occipital-C1 motion of patients, which resulted in neurologic symptoms and congenital odontoid aplasia. Liu et al. [13] applied a cable-dragged reduction/cantilever beam internal fixation technique for the treatment of old irreducible atlantoaxial subluxation. Nonetheless several approaches of posterior cervical fusion could inevitably lead to the loss of atlantoaxial joint mobility. Wang et al. [17] demonstrated that the one-stage anterior

transoral release and posterior internal fixation were safe and reliable for treating IAAD. Ren et al. [18] demonstrated the efficacy of anterior submandibular retropharyngeal release and posterior reduction and fixation as the optimal treatment for patients with IAAD. In their study, all patients achieved satisfactory clinical outcomes without apparent complications including, pharyngeal or chest infection, deep vein thrombosis, or dyspnea postoperatively. Yin et al. demonstrated a case series of 31 patients undergoing anterior release with TARP internal fixation for treating IAAD [8]. In their study, they determined that the majority of IAAD cases could become reducible after anterior release without odontoid resection. Thus, the clinical outcome of traditional treatments for IAAD was relatively satisfactory [18–20].

However, the complications of these approaches are still inevitable and have also been reported by other researchers; for example, complications including cerebrospinal fluid leakage, infection, and abscess formation. In addition, some patients with no posterior arch of the atlas were not suitable for posterior cervical fusion [21]. Additionally, posterior cervical fixation and fusion require occipitocervical fusion that can lead to the loss of occipitocervical joint function. In order to solve such problems, the retropharyngeal approach was described and was regarded as an alternative treatment for IAAD in recent years [22]. Given the advancements in surgical equipment, a clear surgical field can be achieved, with the assistance of a cold light source headset lamp, through the retropharyngeal approach [23].

The retropharyngeal approach is an effective method for cervical discectomy and fusion, and its efficacy was reported by other surgeons. Cai et al. [2] indicated that their anterior atlantoaxial trans-articular locking plate system using the retropharyngeal approach provided biomechanical stability for those patients with atlantoaxial instability. Inspired by TRAP, we designed our retropharyngeal reduction plate system. Our findings indicated that our retropharyngeal reduction plate system might provide a new option for the treatment of IAAD with a low incidence of complications. Compared to the traditional treatment procedure for IAAD, one-stage effective reduction was achieved using our plate system by providing the atlantoaxial joint with forward and downward traction. In some cases, patient's anterior C1 arch may be structurally weak and lateral mass screws can be an alternative choice to fix plate through upper round holes. The risk of infection is low because the transoral release is no longer needed. Meanwhile, our retropharyngeal reduction plate was performed in a fresh cadaveric atlantoaxial joint specimen to verify its feasibility.

In 1972, the finite element analysis was used by Brekelmans et al. [24] for the first time for biomechanical analysis in orthopedics. Recently, the finite element analysis can successfully analyze the inner stress and strain, which is hard to achieve by traditional experimental methods [25, 26]. The finite element analysis can not only provide surgeons with vital clinical data for further instruction in making individual operation plans, but also simulates the operation to better predict clinical outcomes. The publicity and presentation of retropharyngeal approach for IAAD is our ultimate purpose of this paper by introducing our newly designed reduction plate. Cadaver experiment showed that the newly designed reduction plate could be suitable to achieve placement on atlantoaxial joint through retropharyngeal approach. We compared the maximum stress of two different internal fixations using the 3D finite element analysis to make further verification of their biomechanical properties. The mean stress of two internal fixations was

far below the maximum yield strength (795–827 MPa) and ultimate strength (860–896 MPa) of titanium alloy [14]. Our finite element analysis also indicated that the stress was distributed evenly in the retropharyngeal reduction plate system.

In our study, the data and clinical outcomes cannot reflect upper cervical vertebra movements comprehensively because some data would be lost during modeling by using 3D finite element analysis. In addition, further verification of our retropharyngeal reduction plate system's biomechanical properties is still needed because of limited cases allotted.

Conclusions

The concept retropharyngeal reduction plate system may offer an effective new choice for treating IAAD. Aiming to reduce the postoperative complications, the retropharyngeal approach may be the alternative surgical plan for IAAD comparing with the transoral and posterior approach in the future.

Abbreviations

IAAD: irreducible atlantoaxial dislocation; 3D: three-dimensional; CVJ: craniovertebral junction; AAD: atlantoaxial dislocation; TARP: transoral atlantoaxial reduction plate

Declarations

Acknowledgements

Not applicable.

Availability of data and material

The data used and analyzed during the current study are available in anonymized form from the corresponding author on reasonable request.

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Authors' contributions

YK and ZM carried out the finite element analysis and drafted the manuscript. YM, XY and JD participated in the study design. JY, HQ, TS, JW, YY, TS, CS and YQ took part in the cadaveric test. ZZ and YK constructed the finite element models, performed the biomechanical analysis. All of the authors read and approved the final manuscript.

Ethics approval and consent to participate

This study was conducted with approval from the Ethics Committee of the affiliated hospital of Qingdao University. Written informed consent was obtained from participant.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Additional Files

Video 1. The three-dimensional animation shows the specific procedures of treating irreducible atlantoaxial dislocation using the retropharyngeal reduction plate system.

Figures



Figure 1

The different size T-type titanium plates, screws and the adjustable screwdriver.

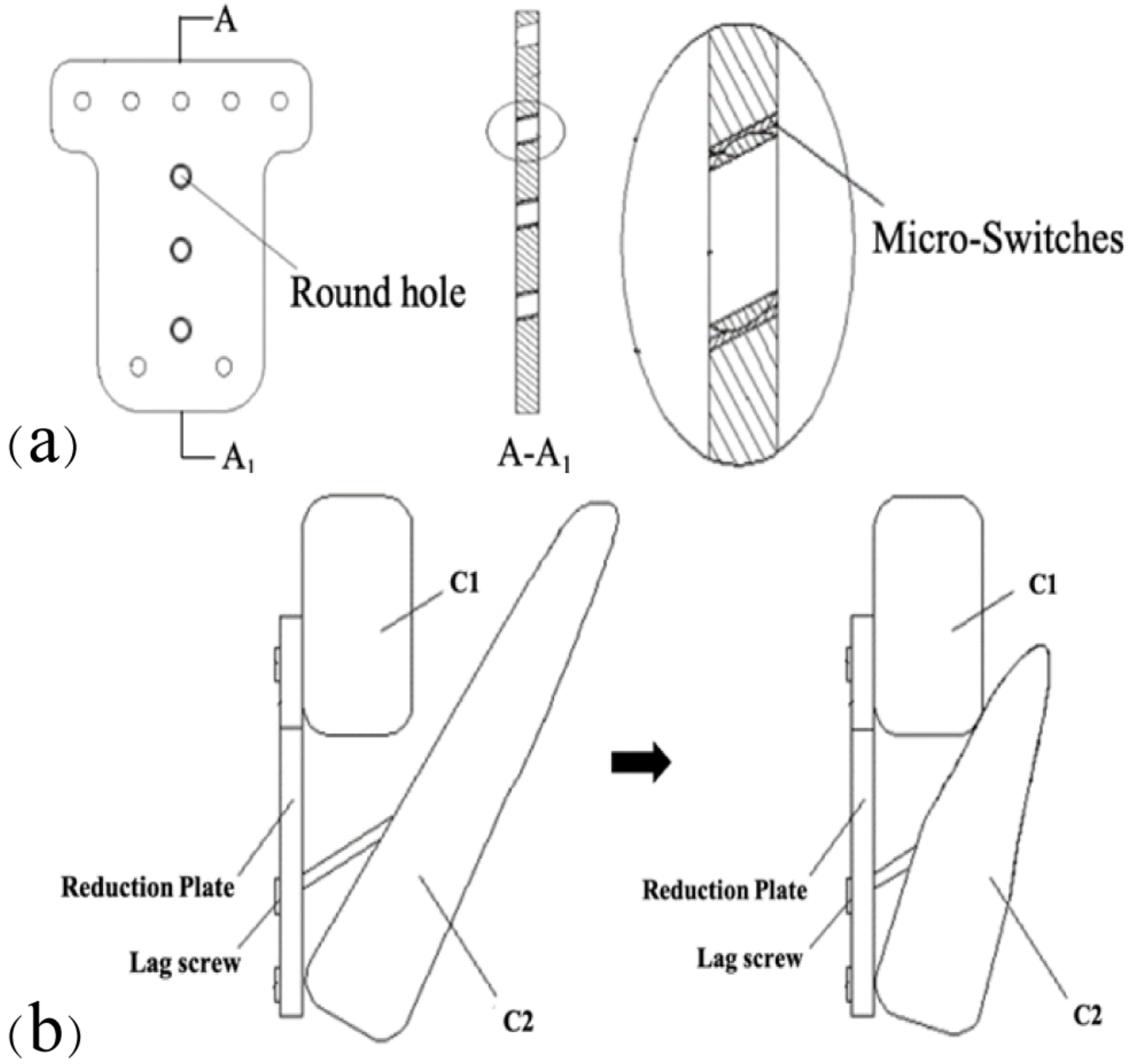


Figure 2

Design of the retropharyngeal reduction plate system. a) The schematic form of special round hole; b) The schematic form of reduction process of the retropharyngeal reduction plate.

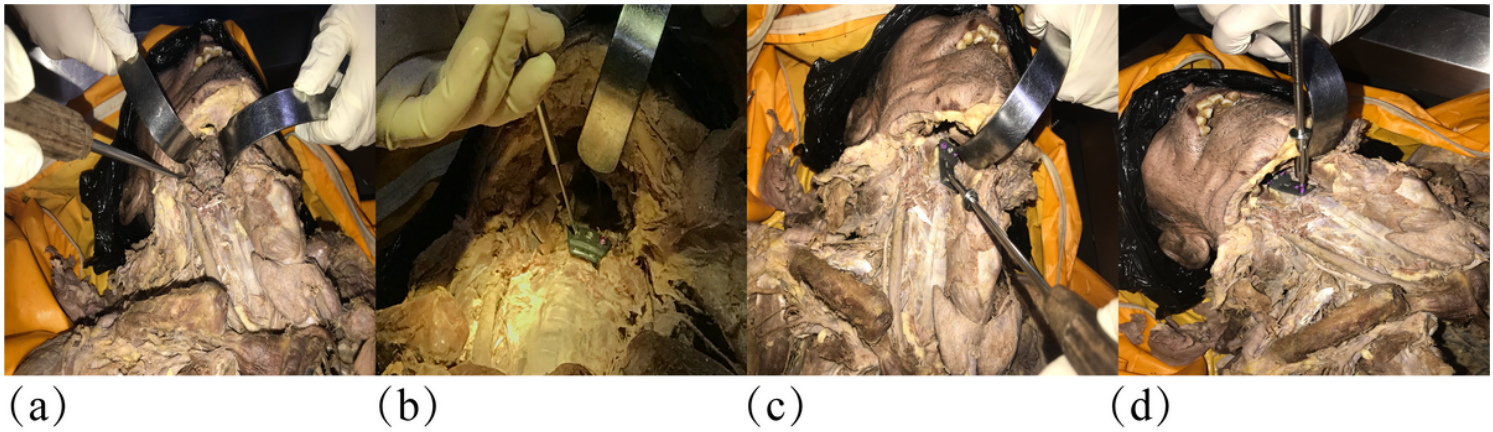


Figure 3

The diagrams of placing the retropharyngeal reduction plate on the cadaveric specimen. a) Exposing the dislocated atlantoaxial joint. b) Fixing the retropharyngeal reduction plate on the atlantoaxial joint by inserting screws to C1 vertebral body through upper round holes. c) Achieving the atlantoaxial reduction by providing atlantoaxial joint with forward and downward traction through the special oval hole while inserting the lag screw. d) Fixing the retropharyngeal reduction plate by inserting screws to C2 vertebral body through bottom round holes helping in improving the strength of fixation.

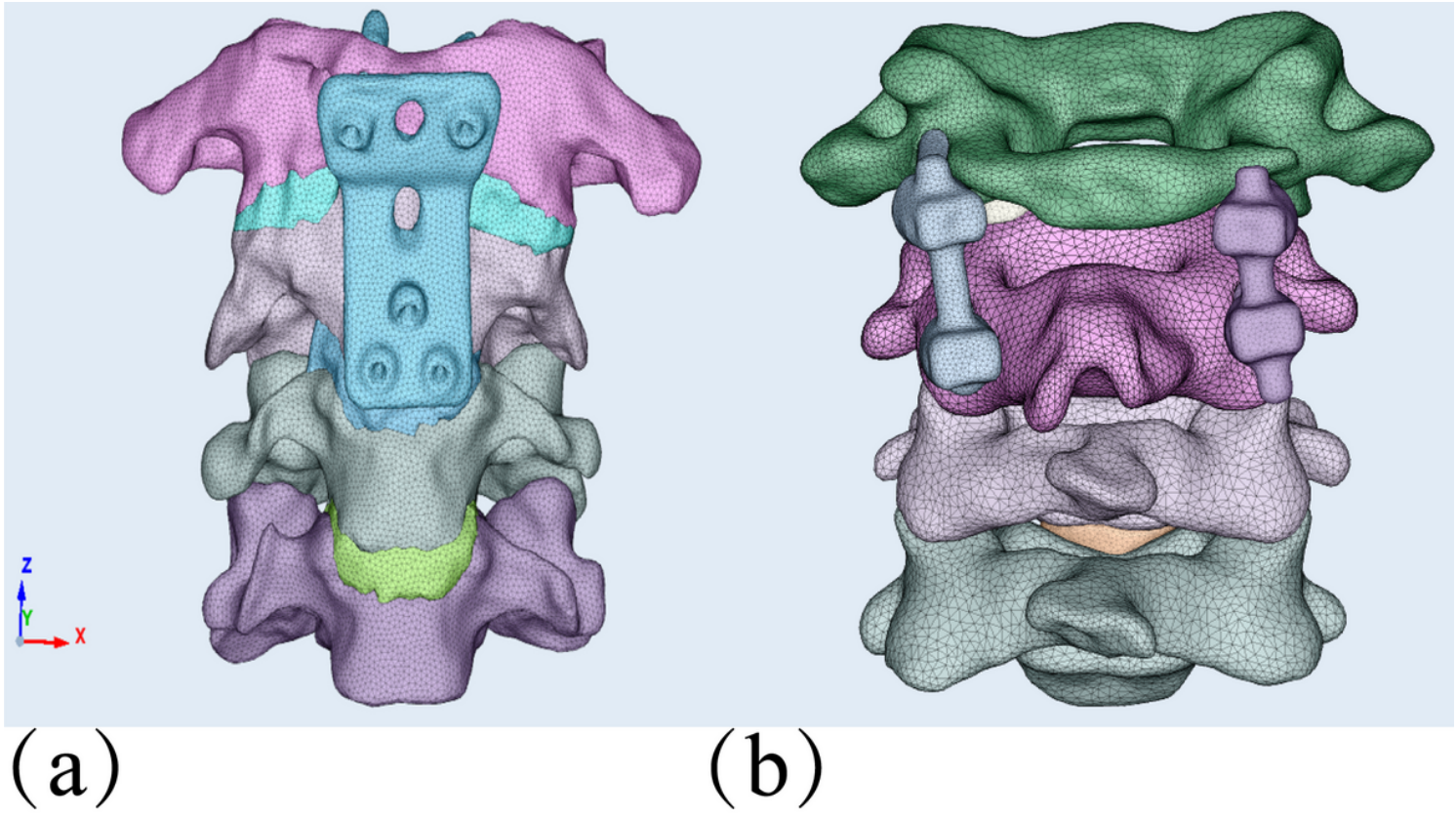


Figure 4

The 3D finite element model of two different fixations. a) The retropharyngeal reduction plate; b) The posterior atlantoaxial pedicle screw.

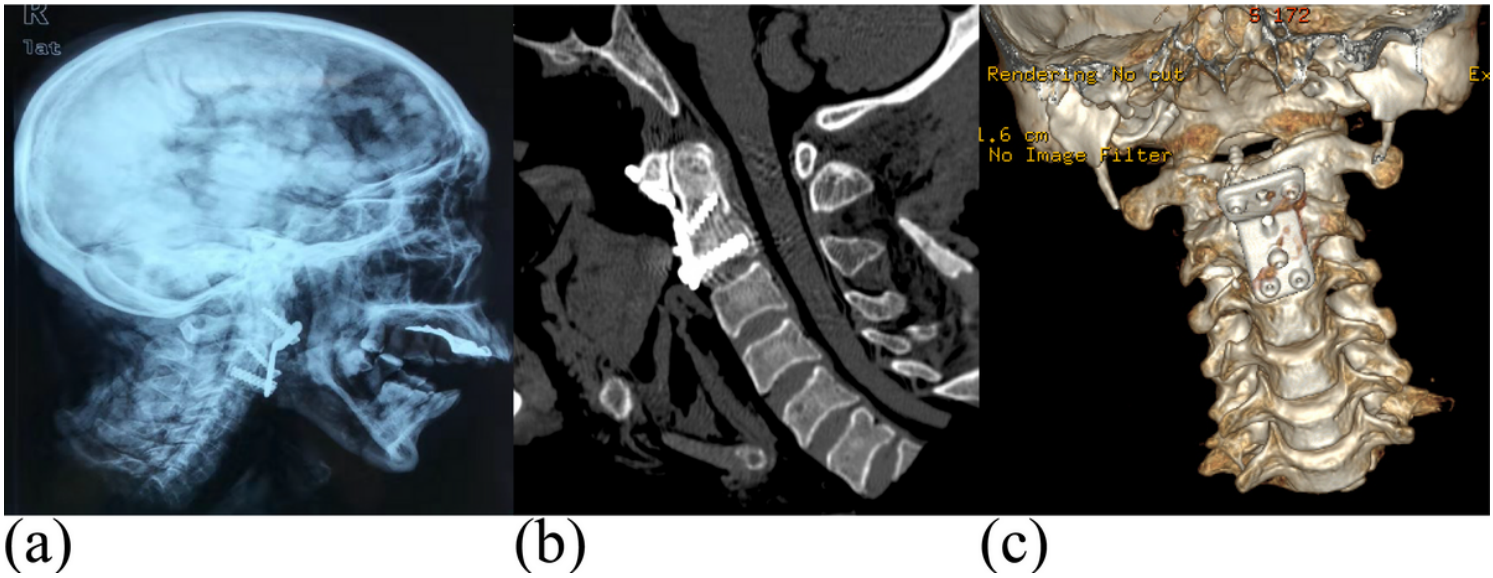


Figure 5

a) Lateral radiograph of cadaveric specimen after placing the retropharyngeal reduction plate. b, c) The screws of C1 and C2 vertebra body are in suitable depth.

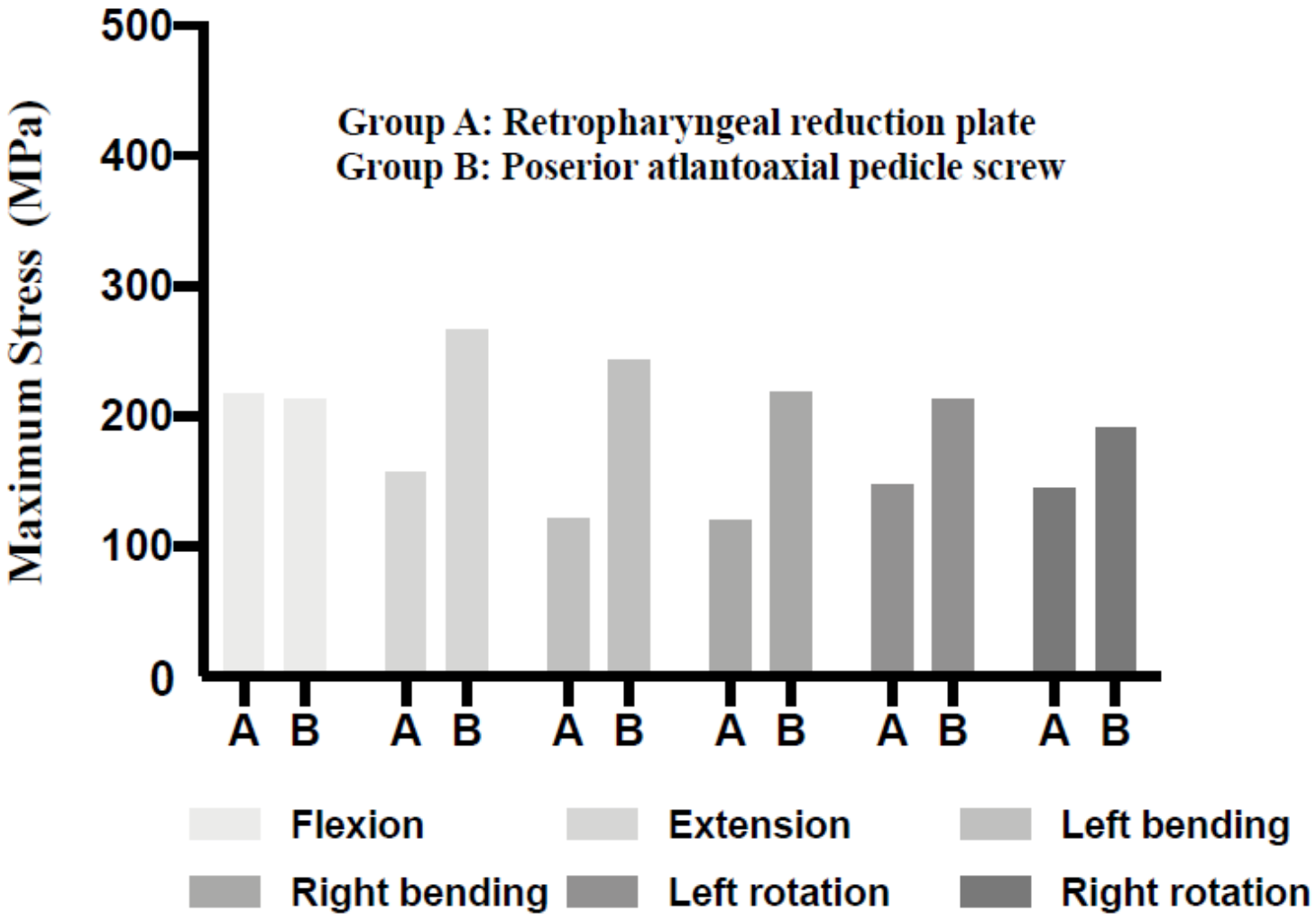


Figure 6

The maximum stress of two different internal fixations under different movements.

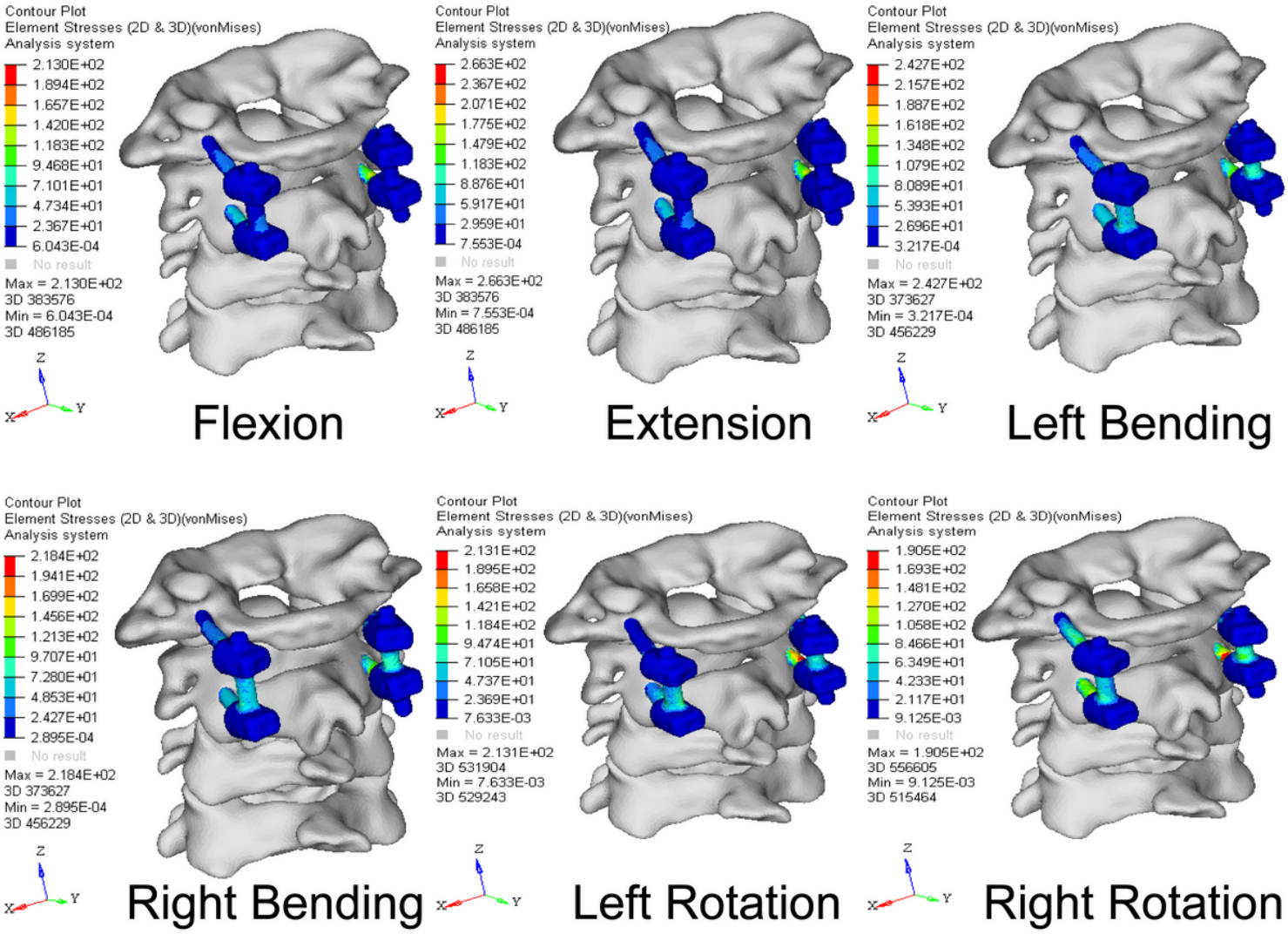


Figure 7

The stress distribution of traditional posterior pedicle screw fixation under the movements including flexion, extension, bending and rotation, respectively. All units are in MPa.

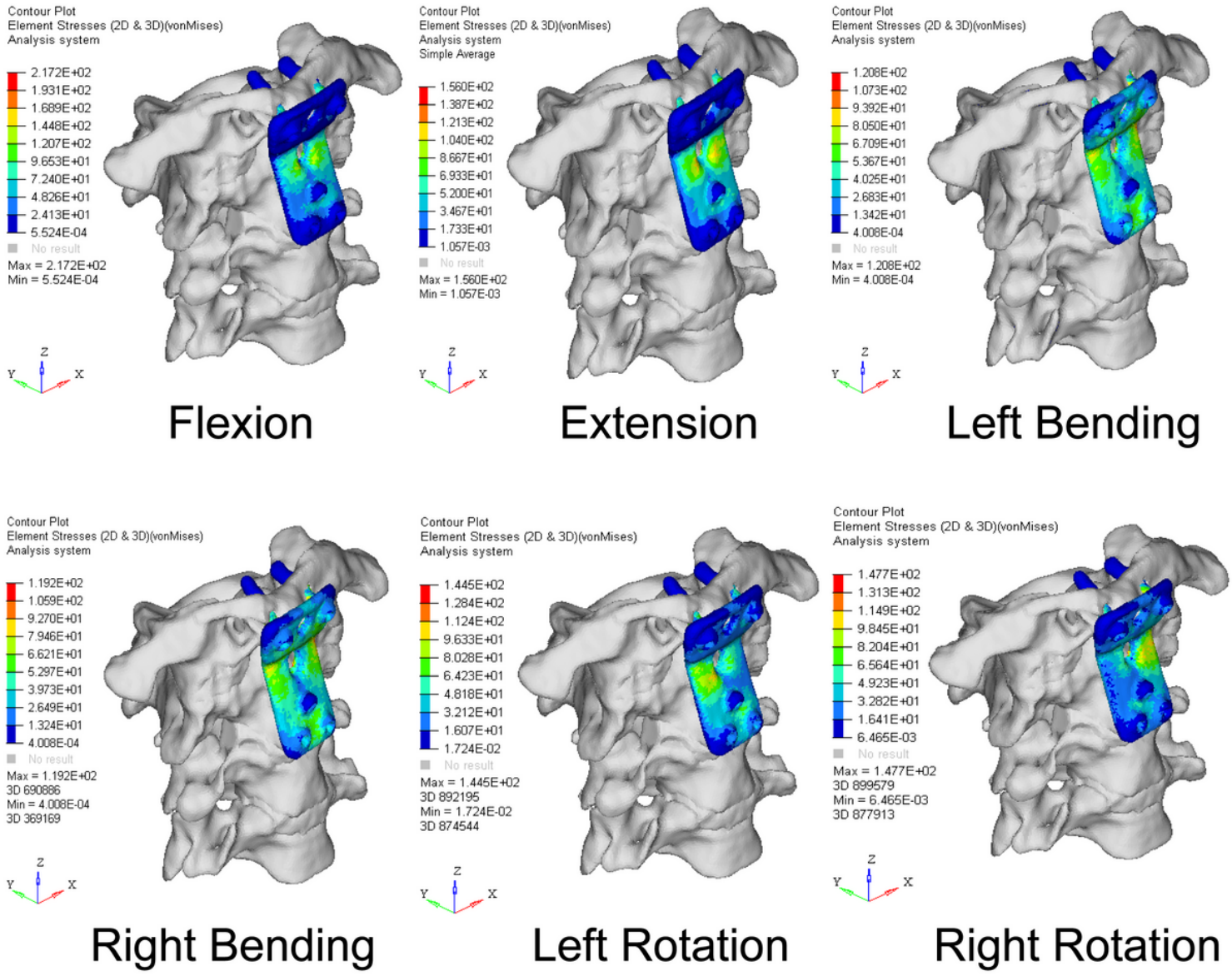


Figure 8

The stress distribution of retropharyngeal reduction plate under the movements including flexion, extension, bending and rotation, respectively. All units are in MPa.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Video1.mp4