CLINICAL ARTICLE

Retropharyngeal Reduction Plate for Atlantoaxial Dislocation: A Cadaveric Test and Morphometric Trajectory Analysis

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Objective: To evaluate the placement feasibility and safety of the newly designed retropharyngeal reduction plate by cadaveric test and to perform morphometric trajectory analysis.

Methods: The five cadaveric specimens with intact atlantoaxial joint were enrolled in this study. They were used for simulating the placement process and evaluating the placement feasibility of the retropharyngeal reduction plate. The atlantoaxial dislocation (AAD) of five cadaveric specimens were obtained by proper external force after dissecting ligaments. The retropharyngeal reduction plate was placed on atlantoaxial joint of cadaveric specimens. The X-ray and three-dimensional (3D) spiral CT were used for evaluating the placement safety of retropharyngeal reduction plate. The DICOM data was obtained after 3D spiral CT scanning for the morphometric trajectory analysis.

Results: The reduction plates were successfully placed on the atlantoaxial joint of five cadaveric specimens through the retropharyngeal approach, respectively. The X-ray and 3D spiral CT showed the accurate screw implantation and satisfying plate placement. The length of the left/right atlas screw trajectory (L/RAT) was, respectively, 1.73 ± 0.01 cm (LAT) and 1.71 ± 0.02 cm (RAT). The length of odontoid screw trajectory (OST) was 1.38 ± 0.02 cm. The length of the left/right axis screw trajectory (L/RAXT) was, respectively, 1.67 ± 0.02 cm (LAXT) and 1.67 ± 0.01 cm (RAXT). There was no statistical significance between left side and right side in terms of AT and AXT ($P > 0.05$). The angles of atlas screw trajectory angle (ASTA), axis screw trajectory angle (AXSTA), and odontoid screw trajectory angle (OSTA) were $38.04° \pm 2.03°$, $56.92° \pm 2.66°$, and $34.78° \pm 2.87°$, respectively.

Conclusion: The cadaveric test showed that the retropharyngeal reduction plate is feasible to place on the atlantoaxial joint, which is also a safe treatment choice for atlantoaxial dislocation. The meticulous preoperative planning of screw trajectory based on individual differences was also vital to using this technique.

Key words: Atlantoaxial dislocation; Cadaveric study; Craniovertebral junction; Morphometric trajectory analysis; Retropharyngeal approach

Introduction

The lateral atlantoaxial joint is composed of three independent joints, two of which consist of the joint surface between atlas lateral mass and axis. The third is composed of anterior articular surface of the axis odontoid process and the articular surface behind the anterior arch of the atlas[1]. The atlantoaxial joint capsule is thin and loose, which needs the extra ligaments to maintain stability including the apical

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dental ligament, alar ligament, cruciform ligament of atlas, and transverse ligament of atlas[2]. The atlantoaxial joint is an axial joint with only one motion axis, and the left and right turning movement depend on the rotation around the vertical axis together between atlas and cranium. Behind the atlantoaxial joint is the high spinal cord and vital center; therefore, serious consequences occur if the spinal cord is compressed by atlantoaxial dislocation (AAD)[3–5]. Numerous pathologies, such as congenital abnormalities, rheumatoid arthritis, Down syndrome, inflammatory abnormalities, traumatic dens fracture, or metabolic diseases, can lead to atlantoaxial dislocation by affecting the craniovertebral junction. A variety of symptoms, such as local pain, limb anesthesia, urination dysfunction, defecation dysfunction, and even death, could be caused by the instability of the atlantoaxial joint in different situations[6].

Consequently, if atlantoaxial dislocation is not treated in a timely and appropriate manner, the displacement may become irreversible leading to hard reduction by posterior fixation[7]. Greenberg was the first to classify atlantoaxial dislocation into reversible or irreversible types in 1968[8]. In China, Yin *et al*[9]. indicated that the atlantoaxial dislocation could be divided into three types including easily reversible type, reversible type with difficulty, and irreversible type in 2003. To our best knowledge, no consensus has been reached about the diagnostic criteria of irreducible atlantoaxial dislocation (IAAD). Our previous studies confirmed that sagittal atlantoaxial joint inclination (SAAJI) and reduction index (RI) were the important imaging indicators to determine the reversibility of irreducible atlantoaxial dislocation. We also found that the reduction and fixation can be achieved by the posterior approach alone if the RI value is >27.9% and SAAJI value is <32.5[10]. At present, it is generally accepted that the reduction of the atlantoaxial joint failed with skeletal traction under general anesthesia by the observation of the X-ray, atlantoaxial dislocation is considered irreducible[11].

To date, the main treatments for atlantoaxial dislocation are the transoral release and instrumentation, transoral release followed by posterior fixation, posterior decompression, and fixation[12]. Also, for patients with irreducible atlantoaxial dislocation, the anterior release is considered essential to achieve the reduction. However, traditional transoral approach 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[13]. Besides, the transoral approach is not suitable for irreducible atlantoaxial dislocation patients with limited opening range of oral cavity or oral disease. However, the anterior release followed by posterior instrumentation also has some disadvantages, such as excessive muscle damage and postoperative cervical axial pain. These disadvantages will increase the high morbidity and mortality rates. Currently, the choice of treatments for atlantoaxial dislocation is controversial, and no consensus has been reached.

In 1966, Stevenson *et al.* firstly reported the retropharyngeal approach for the treatment of clivus chordoma[14]. Recently, studies involving retropharyngeal release and reduction approach for the treatment of anterior high cervical spine cases have been reported. Kiyoshi *et al.* reported the treatment of high-positioned chordoma using retropharyngeal approach[15]. Vender *et al*[16]. achieved successful fusion and instrumentation in seven patients with different high cervical diseases. They found that this approach not only eliminated the need for an additional posterior procedure but also maintained the mobility of occipital–C1. The retropharyngeal approach can provide surgeons with good and safe access in the region of the upper cervical spine and broad bilateral exposure. In addition, the arthrodesis and instrumentation can be achieved at the same time in one stage, which means the second posterior stage is no longer necessary. Some severe complications of oropharyngeal cavity could also be avoided, like infection, dysphagia, velopharyngeal dysfunction, and dental malocclusion.

Based on the many cases of atlantoaxial dislocation, this new reduction plate system was designed through the retropharyngeal approach. In order to evaluate its feasibility of placement, the cadaveric study was performed to simulate the placement process of reduction plate system. In addition, morphometric trajectory analysis of screws can help surgeons understand the important surrounding structure of atlantoaxial joint to perform this technique safely and effectively[17–19]. The anatomic relationships between the retropharyngeal reduction plate and vertebral artery, spinal cord, and other vital surrounding structures were studied by cadaveric study. The CT-based morphometric measurements, such as screw insertion length, of reduction plate's screw placement were also performed to help surgeons understand this technique.

The aim of the present study was to: (i) help surgeons to further understand the complex anatomy of atlantoaxial joint; (ii) allow surgeons to evaluate the placement feasibility of retropharyngeal reduction plate; and (iii) provide surgeons with basic parameters of screw direction and internal depth for placing reduction plate in the future.

Materials and 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. The T-type plates consist of horizontal and vertical parts at specific angles (30°–35°) with different amounts of round holes (diameter: 4.5–5.0 mm) on each part, depending on the size of the plates. The length and width of the plate are ~25–55 and 20–25 mm. The round holes are used for inserting screws. In addition, there are two or three specially designed oval holes (diameter: 5.0–5.5 mm) 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. The atlantoaxial reduction can be achieved by providing the atlantoaxial joint with forward and downward traction by inserting screws in one stage (Figs 1,2).

Fixing the Retropharyngeal Reduction Plate on Cadaveric Specimen

Five formalin-preserved cadaveric specimens were obtained from the Department of Anatomy, Qingdao University. The exposure of ventral part of atlantoaxial joint was obtained after the dissection through retropharyngeal approach. With the careful dissection of craniovertebral junction, the ligaments among atlantoaxial joint, such as C_1 transverse ligaments, were ruptured and the atlantoaxial dislocation model was obtained by using proper external force after dissecting ligaments, respectively. The atlas screw canals were achieved through the top holes of reduction plate by hand drill. The atlas screws were inserted through the top holes to fix the plate onto atlas. Then the hand drill was used to build the odontoid screw canal through the special oval hole of reduction plate. The odontoid screw was slowly inserted into middle of odontoid through oval hole to provide the plate with forward and downward traction. The reduction plate was able to force the dislocated atlas to restore to the normal position. Moreover, the newly designed retropharyngeal reduction plates were placed firmly on the specimens after the placement of axis screws through the bottom hole of plate, respectively (Fig. 3).

Fig. 1 The different size T-type (holes: 6, 7 and 8; length: 25–55 mm; width: 20–25 mm) titanium plates and screws (length: 16–18 mm; diameter: 4.0–4.5 mm)

X-Ray and CT Scanning

The X-ray and spiral CT scanning of specimens after the placement of reduction plates were performed from the base of the occipital bone to the C_7 vertebrae using 0.5-mm thick slices, respectively. The scanning images were collected and stored in DICOM format for the 3D reconstruction and further morphometric trajectory analysis, respectively.

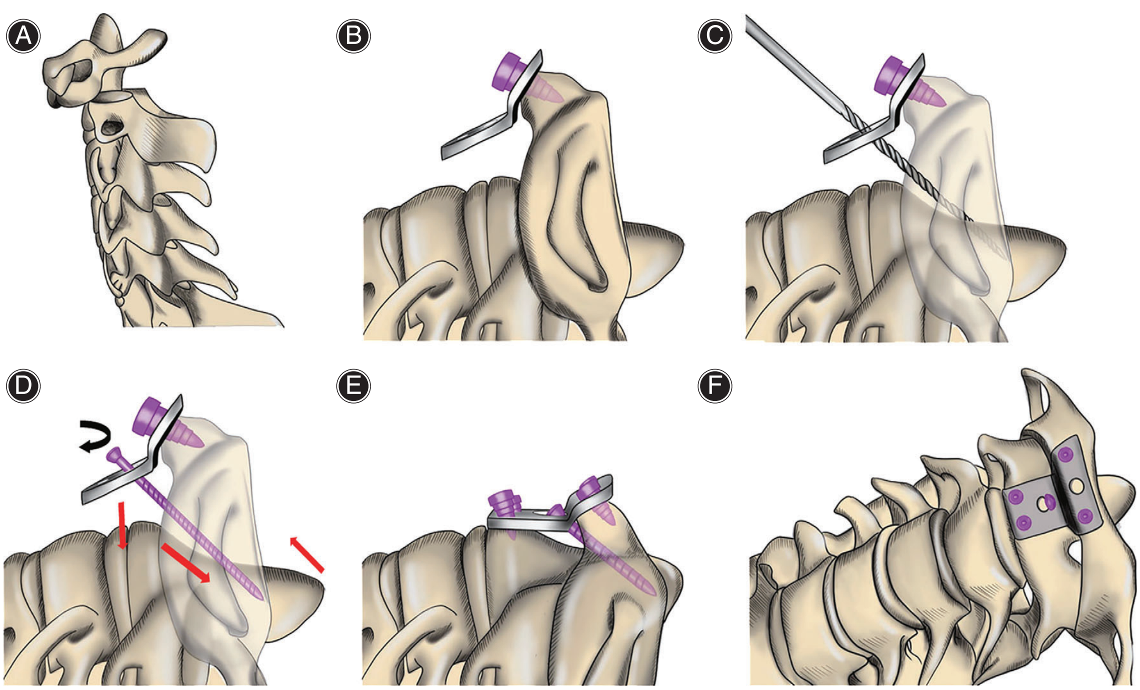

Fig. 2 The demonstration of placing the retropharyngeal reduction plate. (A) The irreducible atlantoaxial dislocation. (B) Fixing the retropharyngeal reduction plate on the C_1 vertebral body by inserting screws through upper round holes. (C) The lag screw path is acquired through C_2 vertebral body by using hand drill. (D) Inserting lag screw through the special oval hole to achieve the atlantoaxial reduction. (E) Fixing the retropharyngeal reduction plate by inserting screws to C_2 vertebral body. (F) The atlantoaxial reduction is achieved by placing the retropharyngeal reduction plate

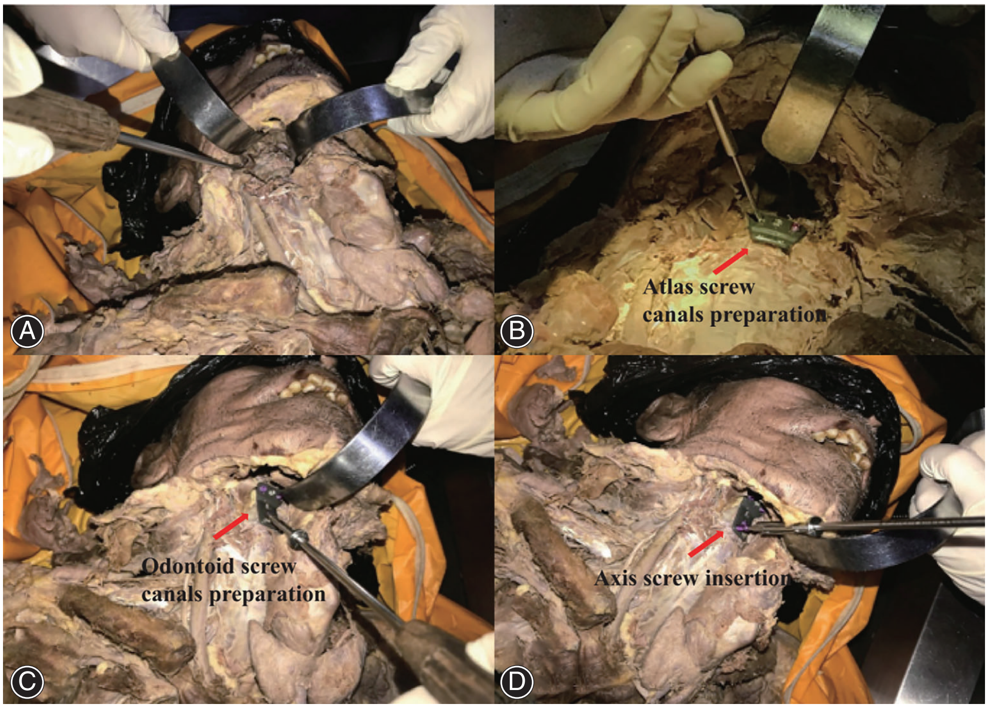

Fig. 3 The diagrams of placing the retropharyngeal reduction plate on the cadaveric specimen. (A) Exposing the dislocated atlantoaxial joint. (B) Establishing the atlas screw canals for fixing the retropharyngeal reduction plate on the atlantoaxial joint by inserting screws to C_1 vertebral body through upper round holes. (C) Establishing the odontoid screw canals for achieving the atlantoaxial reduction by providing dislocated 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 C_2 vertebral body through bottom round holes to improve the strength of fixation

Morphometric Trajectory Analysis

The morphometric trajectory analysis was achieved by using Xiaosai DICOM Viewer (V1.1.9, China). The several screw length parameters of screw were measured and collected, such as the length of left/right atlas screw trajectory (L/RAT), odontoid screw trajectory (OST), and left/right axis screw trajectory (L/RAXT). We also measured and collected the insertion angle of screw including atlas screw trajectory angle (ASTA), odontoid screw trajectory angle (OTA), and axis screw trajectory angle (AXSTA) (Figs 4,5).

Length of Left/Right Atlas Screw Trajectory

The length of left/right atlas screw trajectory (L/RAT) was the screw insertion part of atlas. It is able to be measured in CT scanning images and help the surgeon understand the appropriate screw insertion length to avoid the neurovascular injury.

Length of Odontoid Screw trajectory

The length of odontoid screw trajectory (OST) was the measurement of odontoid screw insertion part. The dorsal part of odontoid cortical bone normally is not able to be broken through by the screw. It also can be measured in CT scanning images.

Length of Left/Right Axis Screw Trajectory

The length of left/right axis screw trajectory (L/RAXT) was also the screw insertion part of axis. The bone sequence of CT scanning image is able to measure the length of trajectory. The axis screw is normally inserted into the root of odontoid process vertically.

Atlas Screw Trajectory Angle

The atlas screw trajectory angle (ASTA) was the screw insertion angle of atlas and was able to be measured in sagittal CT scanning image. It was the tilt angle of screw insertion from head to tail.

Odontoid Screw Trajectory Angle

The odontoid screw trajectory angle (OSTA) was the tilt angle of odontoid screw insertion from head to tail. It was able to help surgeons understand the appropriate odontoid screw insertion angle. Appropriate OSTA was the key to achieving reduction of atlas because the insertion process of odontoid screw was able to provide the plate with forward and downward traction.

Axis Screw Trajectory Angle

The axis screw trajectory angle (AXSTA) was the screw insertion angle of axis. The AXSTA was also the tilt angle of axis screw insertion from head to tail. But the relatively small AXSTA was not suitable to fix the reduction plate firmly.

Statistical Analysis

The results related to the screws of retropharyngeal reduction plate are presented as the means ± standard deviations. All data have been tested for normal distribution before independent samples *t*-tests. Non-parametric test was used

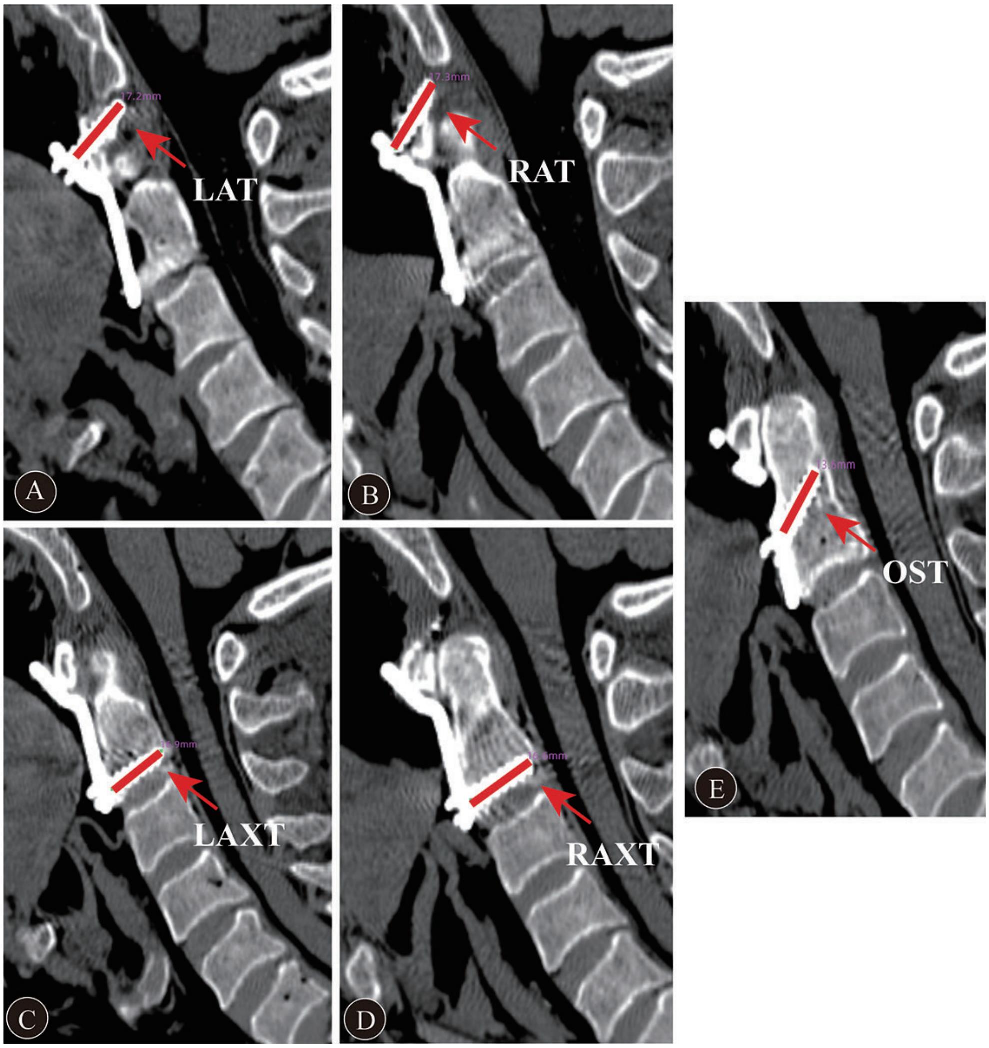

Fig. 4 The length measurements of (A) the left atlas screw trajectory (LAT), (B) the right atlas screw trajectory (RAT), (C) the left axis screw trajectory (LAXT), (D) the right axis screw trajectory (RAXT), and (E) the odontoid screw trajectory (OST)

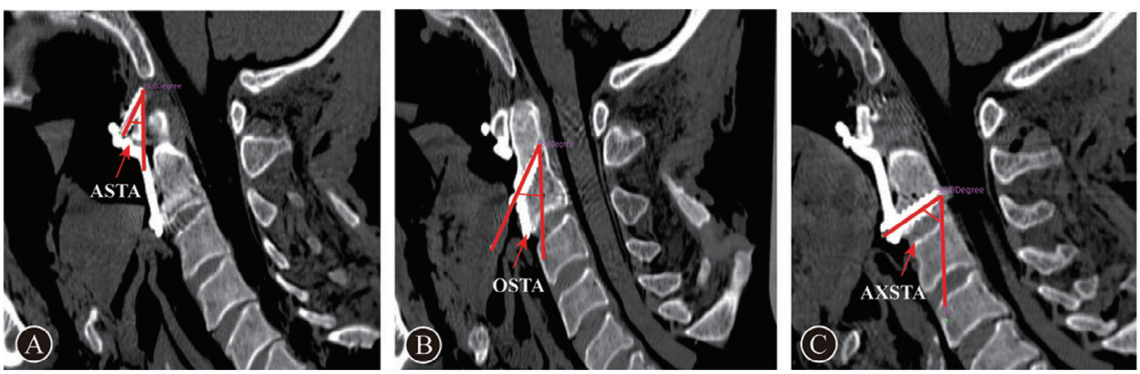

Fig. 5 The angle measurements of (A) the atlas screw trajectory angle (ASTA), (B) the odontoid screw trajectory angle (OSTA), and (C) the axis screw trajectory angle (AXSTA)

for data that did not satisfy the normal distribution. Independent sample *t*-tests were used to analyze between left side and right side in terms of AST and AXST. SPSS 23.0 software (IBM Corporation, Armonk, NY, USA) was used for all analyses, and the significance was defined as $P < 0.05$.

Results

Placement of the Retropharyngeal Reduction Plate

The suitable retropharyngeal reduction plates were successfully located at the body of the atlas through inserting screws after exposing the atlantoaxial joint through 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. The X-ray and spiral CT showed that the reduction plate had a reliable fixation with the accurate screw insertion (Fig. 6).

Morphometric Trajectory Analysis of Screws

Among five patients, the measurements of retropharyngeal reduction plate screws are displayed in Table 1. The mean length of AT and AXT were 1.73 ± 0.01 cm and 1.67 ± 0.02 cm on the left side, and 1.71 ± 0.02 cm and 1.67 ± 0.01 cm on the right side. There was no statistical significance between left side and right side in terms of AST and AXST ($P > 0.05$). In addition, the mean length of OST was 1.38 ± 0.02 cm. The mean angle of ASTA, AXSTA, and OSTA were 38.04° ± 2.03°, 56.92° ± 2.66°, and 34.78° ± 2.87°, respectively.

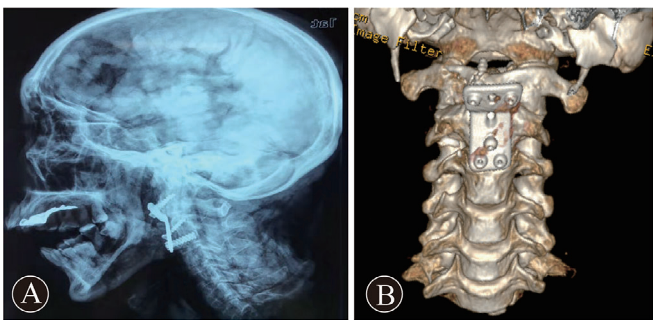

Fig. 6 (A) The lateral radiograph of skull and cervical spine after placing the retropharyngeal reduction plate on the cadaveric specimen. (B) The 3D reconstruction of CT showing reduction was achieved after inserting screws into C_1 and C_2 vertebra body in suitable depth

Discussion

Comparison Between Retropharyngeal Reduction Plate and Different Fixations

Recently, the different fixations of AAD have been reported by many researchers[20]. Liu *et al*[21]. applied a cable-dragged reduction/cantilever beam internal fixation technique for the treatment of irreducible atlantoaxial subluxation. Nonetheless, several approaches of posterior cervical fusion could inevitably lead to the loss of atlantoaxial joint mobility. As to the posterior cervical instrumentation and fusion, it is not only able to cause the loss of occipitocervical joint function but also is unsuitable for patients without the posterior arch of the atlas. However, the retropharyngeal reduction plate is suitable for such patients and can achieve the reduction and fixation without affecting the atlantoaxial joint mobility. Wang *et al*[22]. demonstrated that the one-stage anterior transoral release and posterior internal fixation were safe and reliable for treating IAAD. In addition, Yin *et al*[23]. demonstrated a case series of patients undergoing anterior release with transoral atlantoaxial reduction plate (TARP) internal fixation for treating IAAD. They indicated 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. Notably, the complications of different approaches are still inevitable, which was reported by other researchers, such as cerebrospinal fluid leakage, infection, and abscess formation[24]. As for the transoral approach, the contamination by nasopharyngeal flora has the high risk of causing postoperative infection, and high demand of

TABLE 1 The morphometric trajectory parameters of the screws of the retropharyngeal reduction plate

	AST (cm)		AXST (cm)					
Number	Left	Right	Left	Right	OST (cm)	ASTA (°)	AXSTA (°)	OSTA (°)
1	1.72	1.73	1.69	1.66	1.36	35.0	58.8	36.0
2	1.73	1.69	1.67	1.69	1.41	37.2	60.2	38.3
3	1.75	1.72	1.66	1.65	1.38	40.1	56.5	30.7
4	1.74	1.68	1.63	1.67	1.35	39.5	55.7	35.5
5	1.73	1.72	1.69	1.68	1.39	38.4	53.4	33.4
Mean ± SD	1.73 ± 0.01	1.71 ± 0.02	1.67 ± 0.02	1.67 ± 0.01	1.38 ± 0.02	38.04 ± 2.03	56.92 ± 2.66	34.78 ± 2.87

AST, atlas screw trajectory; AXST, axis screw trajectory; OST, odontoid screw trajectory; ASTA, atlas screw trajectory angle; AXSTA, axis screw trajectory angle; OSTA, odontoid screw trajectory angle.

pre/postoperative oral nursing care. The postoperative nasal feeding and tracheostoma also significantly reduce the quality of a patient's life[25]. Moreover, the anterior release is necessary for further easier reduction and fixation by posterior instrumentation and fusion to some patients with IAAD. As to the combined approach, excessive muscle damage and high-risk intraoperative postural adjustment also required the surgeons to weigh the pros and cons. So, one of the advantages of retropharyngeal reduction plate was designed to be placed through retropharyngeal approach, with the preponderance of avoiding the transoral complications. It can also achieve the release and reduction in one stage, with the advantages of reducing the excessive damage caused by combined fixation.

Advantages of Retropharyngeal Reduction Plate

The retropharyngeal approach could be regarded as an alternative treatment for some specific patients with IAAD in recent years[26]. Given the advancements in surgical equipment, a clear surgical field is able to be obtained, with the assistance of a cold light source headset lamp, through the retropharyngeal approach[27]. The retropharyngeal approach is an effective method for cervical discectomy and fusion, and its efficacy was reported by other surgeons. This approach effectively averts the transoral and tracheotomy complications and reduces the length of hospital stay. Lu *et al*[28]. evaluated the clinical feasibility of the endoscopically assisted anterior release through retropharyngeal approach and posterior cervical fusion for IAAD. They found that the neurologic function of all patients increased significantly without the obvious complications by using this novel surgical technique through retropharyngeal approach. The deep understanding of the anatomical structure helps surgeons avoid the injury of important surrounding structure including submandibular gland, hypoglossal nerve, and superior laryngeal nerve. The retropharyngeal reduction plate system was inspired by the transoral atlantoaxial reduction plate (TRAP). Our findings indicated that retropharyngeal reduction plate system might provide a new option for the treatment of IAAD with a low incidence of postoperative complications. In our former study, we demonstrated the efficacy of anterior submandibular retropharyngeal release and posterior reduction and fixation as the optimal treatment for patients with IAAD[29]. This approach requires intraoperative traction, and the patient was placed in supine position with his head moderately tilted back. The length of incision was -10 cm along the lower edge of the right jaw at 2–2.5 cm. The mandibular branch of facial nerve was located on the deep surface of platysma muscle. The incision was parallel and 2 cm lower than the mandibular margin to provide the damage of mandibular branch of facial nerve. The platysma muscle was transected parallel to the skin incision. After retracting the platysma muscle, the inferior submandibular gland was revealed, which is the marker for the next fascia layer, with bulging forward beneath the transparent fascia layer. Each layer of superficial fascia should be fully dissociated and separated in order to reveal the next layer clearly for protecting the important anatomical structures of each layer. The longus cervicalis and longus cephalus are severed to expose the bilateral atlantoaxial capsule. The bone and tissue proliferation were removed by using curette and high-speed drills. With the help of skull traction, the partial atlantoaxial reduction was achieved by gently prying the atlantoaxial joint with periosteal stripper for further reduction and fixation through posterior approach. The results showed that all patients achieved satisfactory clinical outcomes without apparent complications including pharyngeal or chest infection, deep vein thrombosis, or dyspnea postoperatively. The risk of infection is low because the transoral release is no longer necessary. Moreover, the reduction is able to be achieved after the dissection of tissue adhesions and redundant hyper-osteogeny tissue with the assistance of skull traction. Compared to the traditional treatment procedure, one-stage effective reduction was able to be achieved using the retropharyngeal reduction 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. Meanwhile, the morphometric trajectory analysis showed that the screws were able to be firmly inserted into the atlas and axis without the injury of spinal cord, nerve, and vertebral artery.

Limitations

There are still several limitations in this study. Firstly, the further verification of the retropharyngeal reduction plate's biomechanical properties is still needed. Secondly, the clinical research is also necessary for its further clinical application. Last but not least, the biomechanical analysis between retropharyngeal reduction plate and other internal fixations is required to evaluate its clinical adaptability.

Conclusion

Aiming to reduce postoperative complications, the retropharyngeal approach may be the alternative surgical approach for IAAD comparing with the transoral or combined approach in the future. This newly designed retropharyngeal reduction plate may offer an effective choice for the treatment of IAAD. The meticulous evaluation of the screw trajectory before surgery is necessary for surgeons to apply this technique safely.

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