European Spine Journal (2020) 29:2769–2777
https://doi.org/10.1007/s00586-020-06551-z

ORIGINAL ARTICLE

Classification of the facets of lateral atlantoaxial joints in patients with congenital atlantoaxial dislocation

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Received: 5 December 2019 / Accepted: 22 July 2020 / Published online: 30 July 2020
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Abstract

Purpose To investigate the morphological characteristics and para-positions of the facets of lateral atlantoaxial joints (FLAJs) in patients with congenital atlantoaxial dislocation (CAAD) and to propose a classification system for the FLAJs.

Methods A total of 93 cases of CAAD were included in this retrospective study. The obliquity and slippage of the FLAJs in the sagittal and coronal planes were measured and observed in the CT images of all of the cases. The obliquity and slippage of the FLAJs represented the morphological characteristics and the para-positions, respectively, and were used as classification parameters. Accordingly, a classification system for the FLAJs was established. We additionally investigated the correlation between the classifications of the FLAJs and various types of CAAD. The classifications of the FLAJs in 34 patients with irreducible AAD (IAAD) were also investigated.

Results One hundred eighty-six FLAJs in 93 patients were classified into 6 types (namely, *A*, *B*1, *B*2, *C*, *D*1, and *D*2) for obliquity and 3 types (namely, S_0, S_1, and S_2) for slippage. Among the 186 FLAJs, type B1 and type S_0 were the most common obliquity and slippage types, respectively. There were 11 combination types for obliquity and 5 combination types for slippage of bilateral FLAJ in 93 patients. Most of the patients (69.7%, 47/70) with anteroposterior AAD had accompanying slippage and anteversion of the FLAJ in the sagittal plane. Rotational AAD was found in 10 patients with asymmetrical slippage in both FLAJs in the sagittal plane. Lateral translational AAD was found in 6 patients with an S_1-type FLAJ in the coronal plane. In 5 patients with lateral angular AAD, FLAJs of types *D*1 and S_2 were observed on one side. Among the 34 patients with IAAD, 31 patients had both obliquity and slippage in the FLAJs on one or both sides.

Conclusion The morphological characteristics and para-positions of the FLAJs on both sides largely determine the types of AAD in patients with CAAD. The types of obliquity and slippage of the FLAJ are related to the reducibility of AAD.

Keywords Congenital atlantoaxial dislocation · The facets of lateral atlantoaxial joints · Obliquity · Slippage · Classification

Introduction

Congenital atlantoaxial dislocation (CAAD) is a complex malformation of the craniovertebral junction (CVJ), and it is always accompanied by *C*1 arch assimilation into the occiput, basilar invagination (BI), *C*2–*C*3 fusion, and os odontoideum. The types of CAAD reported include anteroposterior, rotational, vertical or central, lateral angular, and translational dislocation [1]. Anteroposterior and vertical dislocation are the most common types. Lateral atlantoaxial joints (LAJs) play an important role in neck movements, such as axial rotation, flexion–extension, and lateral bending. The stability of LAJs is largely determined by factors such as the characteristics of the facets and their para-positions [2]. In patients with CAAD, the obliquity of the facets of LAJs (FLAJs) is frequently observed in the sagittal plane and occasionally observed in the coronal plane [2,3]. In addition, the extent of slippage of the FLAJs has also been assessed by CT imaging [4]. The obliquity of the facets in the sagittal plane can possibly determine the anterior slippage of *C*-1 over *C*-2, which leads to anteroposterior and

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vertical dislocation of the atlantoaxial joint [2]. The slippage of the FLAJs in the coronal plane determines the telescoping of *C*-2 into *C*-1 (vertical dislocation) [2]. Currently, few morphological studies of the facets in patients with CAAD have been conducted, and a classification system based on the obliquity and slippage of the FLAJs in the sagittal plane and coronal plane has not been proposed. This retrospective study aimed to analyze the correlation between the morphological characteristics and para-positions of the FLAJs and various types of CAAD and propose a classification system for the FLAJs in patients with CAAD.

Materials and methods

Clinical data

Ethical approval was obtained before this retrospective study was initiated (number: KY2019224). Patients with CAAD treated from June 2013 to June 2019 were included in this study. The inclusion criteria were as follows: (1) AAD caused by congenital etiologies and (2) neutral position thin-slice computerized tomographic (CT) images with 3-dimensional (3D) data of the CVJ. The exclusion criteria were as follows: (1) AAD caused by infection, inflammatory disease, trauma, or a tumor; (2) a history of significant trauma; (3) a history of LAJ fractures; (4) a severely underdeveloped or absent FLAJ preventing relevant parameters from being measured; (5) a history of surgeries involving the CVJ; and (6) irreducible AAD (IAAD) caused by osseous fusion. Ultimately, 93 patients were included in the observation group in this study (11 were diagnosed with os odontoideum, and 82 were diagnosed with BI). There were 83 cases of C1 arch assimilation into the occiput, 47 cases of *C*2–*C*3 fusion, 24 cases of Chiari malformation, and 12 cases of syringomyelia. Among the patients, 33 were males, and 60 were females, with an average age of 40.5 years (range, 4–76 years). All of the patients experienced varying degrees of neurological deficits or neck pain and underwent surgical treatments in our department. The control group comprised 30 patients who underwent complete neutral-position 3D-CT examinations of the CVJ and cervical spine because of trauma, and the CT scans showed no obvious injuries to the CVJ or cervical spine. The patients in the control group and the observation group were matched by age and sex. Among the patients in the control group, 12 were males, and 18 were females, with an average age of 41.2 years (range, 5–76 years).

Since 2008, all of the patients with CAAD underwent cranial traction under general anesthesia in our department, and the degree of reduction in AAD was detected by intraoperative C-arm fluoroscopy. According to previous reports, the degree of reduction in AAD under intraoperative traction is an important factor for the selection of the surgical method [5,6]. Therefore, based on a report by Liao and our previous study, patients with a magnitude of AAD reduction greater than 50% were regarded as having reducible AAD, and patients with magnitude of AAD reduction less than 50% were regarded as having irreducible AAD [5,6]. The clinical data of the cases revealed that in the observation group, 59 cases were reducible, and 34 cases were irreducible.

Measurement of parameters and methods

The obliquity of the FLAJ (the sagittal inferior *C*-1 facet angle, which was measured on sagittal CT scans) in the sagittal plane was measured as the angle between the line extending posteriorly from the anterosuperior point of the hard palate and its posterior tip and the line joining the anterior and posterior points of the inferior *C*-1 facet surface (or the perpendicular line if the lines do not meet). Anteversion was recorded as a positive value, and angles sloped dorsally were recorded as negative values. The obliquity of the FLAJ (the coronal inferior *C*-1 facet angle, which was measured on coronal CT) in the coronal plane was measured as the angle between the line extending between the medial and lateral points along the inferior surface of the *C*-1 facet and the line joining the upper-most points of the foramen magnum (Fig. 1). The slippage was defined as that the FLAJ were not normally joined together, on 2D CT (sagittal and coronal CT) and 3D CT scans, and the presence of partial displacement (interarticular displacement greater than 3 mm) in the sagittal plane (anterior or posterior) or coronal plane (lateral) was considered partial slippage. Complete displacement between the joints was considered complete slippage or olisthy, and dislocation with facet locking was regarded as a locked joint. All of the parameters were independently measured and evaluated with the CT advantage workstation (ADW) by two spinal surgeons. The mean of

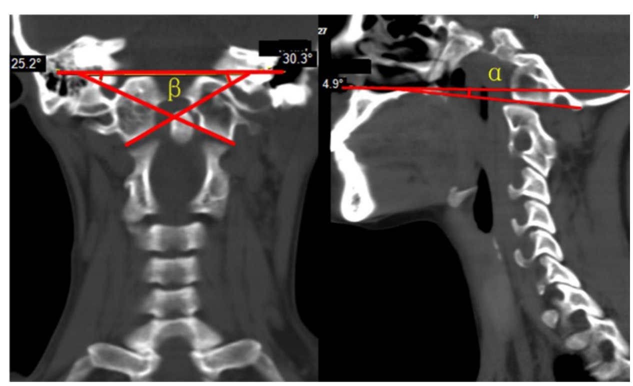

Fig. 1 Measurement of the obliquity of the FLAJ in the sagittal and coronal planes with 2D CT. β represents the obliquity in the coronal plane, and α represents the obliquity in the sagittal plane

the measurements taken by these two surgeons was recorded as the final result. CT was performed using a 64-slice or 256 spiral CT machine (Ingenia, Philips Medical Systems, The Netherlands). The parameters were as follows: the layer thickness and spacing were 0.625 mm, and the length was accurate to 0.1 mm.

Basis and methods of classification

The inferior *C*-1 facet angles in the sagittal and coronal planes were measured on the sagittal and coronal CT scans in both the control and observation groups. The degree of interarticular displacement was also recorded in the observation group. The inferior *C*-1 facet angles in the sagittal and coronal planes of the 60 sides of the FLAJs in 30 patients in the control group were compared with those in the patients in the observation group for the evaluation of obliquity, and the degree of interarticular displacement was used to evaluate slippage. The obliquity and slippage of the FLAJ indicated the morphological characteristics and the para-positions, respectively, and were used as classification parameters. Inferior *C*-1 facet angles in the sagittal plane among the patients in the observation group that were larger than the upper limit of the bilateral 95% range of the normal values in the control group indicated anteversion, and inferior *C*-1 facet angles smaller than the lower limit of the bilateral 95% range of the normal values indicated that the facet sloped dorsally. Inferior *C*-1 facet angles in the coronal plane among the patients in the observation group that were larger than the upper limit of the unilateral 95% range of the normal values in the control group indicated coronal obliquity. The classifications were as follows: patients without anteversion, facets that sloped dorsally, and coronal obliquity were categorized as type *A*. Patients with anteversion or facets that sloped dorsally and without coronal obliquity were categorized as type *B*. Furthermore, patients with anteversion and without facets that sloped dorsally and coronal obliquity were categorized as type *B*1, and patients with facets that sloped dorsally and without anteversion and coronal obliquity were categorized as type *B*2. Patients with coronal obliquity and without anteversion and facets that sloped dorsally were categorized as type *C*. Patients with coronal obliquity and anteversion or facets that sloped dorsally were categorized as type *D*. Furthermore, patients with anteversion and coronal obliquity without facets that sloped dorsally were categorized as type *D*1, and patients with facets that sloped dorsally and coronal obliquity without anteversion were categorized as type *D*2 (Fig. 2). In addition, patients without interarticular slippage were regarded as S_0, patients with accompanying partial slippage in the sagittal or coronal plane were regarded as S_1, and patients with accompanying complete slippage (olisthy) or locked facets were regarded as S_2 (Fig. 3).

Statistical analysis

The data were analyzed using SPSS 19.0 software (SPSS, Inc., Chicago, IL, USA). The age and sex of the patients in the two groups were compared by independent-samples *t* tests and chi-square tests, respectively. The means ± standard deviations (SDs) of the sagittal inferior *C*-1 facet angles and the coronal inferior C-1 facet angles are presented for each type. A *P* value of less than 0.05 was considered to be statistically significant.

Results

There were no significant differences in age or sex between the control and observation groups ($p > 0.05$). In the control group, the sagittal and coronal inferior *C*-1 facet angles were 24.7° ± 4.3° and 3.0° ± 5.7°, respectively. The bilateral 95% range of the normal values of the inferior *C*-1 facet angle in the sagittal plane ranged from − 8.2° to 14.2° in the control group (an angle less than − 8.2° indicated the facet sloped dorsally, and an angle larger than 14.2° indicated anteversion in the observation group). The upper limit of the unilateral 95% range of the normal values of the inferior *C*-1 facet

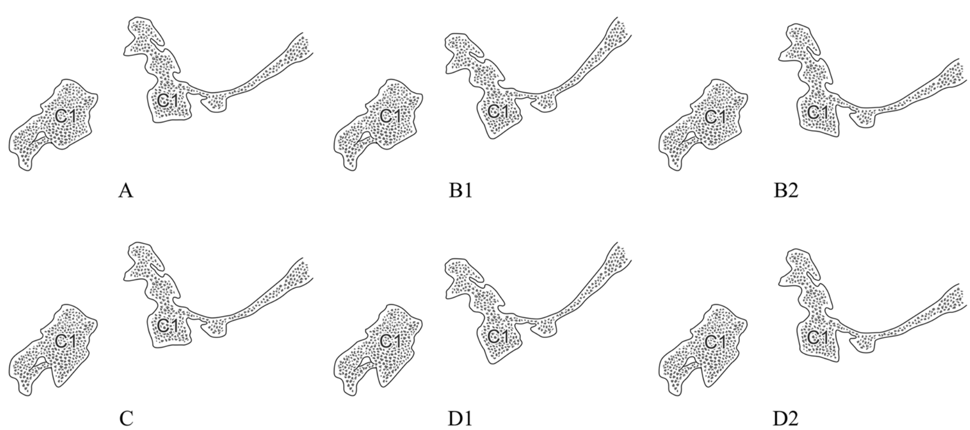

Fig. 2 A schematic drawing illustrating the 6 types of obliquity (the coronal and sagittal views of the inferior *C*-1 facet of the FLAJ) of the FLAJ

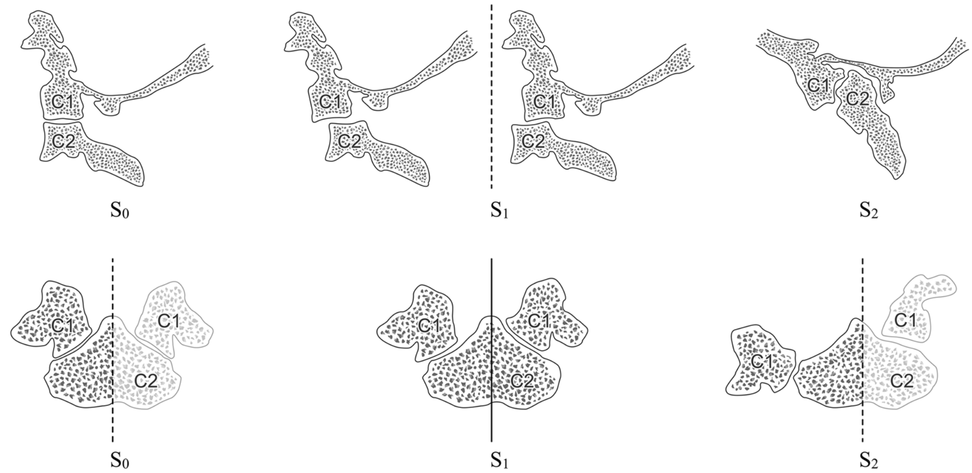

Fig. 3 A schematic drawing illustrating the 3 types of slippage (the para-positions of the FLAJ in the sagittal and coronal planes) of the FLAJ

angle in the coronal plane was 31.8° in the control group (an angle larger than 31.8° indicated coronal obliquity in the observation group).

The 186 FLAJ in the observation group were classified into 6 types for obliquity (Fig. 4a–f) and 3 types for slippage (Fig. 5a–c). Among them, there were 60 FLAJs of type *A* (32.3%), 16 of which were type S_1; 83 FLAJs of type *B*1 (44.6%), 51 of which were type S_1 and 3 of which were type S_2; 10 FLAJs of type B2 (5.4%), 2 of which were type S_1; 3 FLAJs of type *C* (1.6%), 2 of which were type S_1; 29 FLAJs of type *D*1 (15.6%), 16 of which were type S_1 and 7 of which were type S_2; and 1 FLAJ of type D2 (0.5%). Most of the joints of types *B*1 and *D*1 exhibited partial slippage, and the 10 sides of the joints with complete slippage or olisthy were of these two types (Table 1). There were 11 combinations of bilateral FLAJs for obliquity among the 93 patients, among which *A*–*A* and *B*1–*B*1 were the most common. Only 8% (2/25) of the patients had IAAD of type *A*–*A*, but 43.8% (14/32) of the patients had IAAD of type *B*1–*B*1. As many as 77.3% (17/22) of the patients who had unilateral or bilateral type *D*1 (*A*–*D*1/*D*1–*A*, *B*1–*D*1/*D*1–B1 and *D*1–*D*1) were classified as having IAAD (Table 2). Regarding slippage, there were 5 combinations of bilateral FLAJs, among which S_1–S_1 was the most common type, with 31 cases, and S_2–S_2 was the least common type, with2 cases. More severe slippage of the bilateral FLAJs was associated with a higher percentage of IAAD in the patients in our study (Table 3). Rotational AAD was found in 10 patients with asymmetrical slippage of the bilateral facets in the sagittal plane. Lateral translational AAD was found in 6 patients with partial slippage of the facets in the coronal plane. In 5 patients with lateral angular AAD, one side of the FLAJ was of type *D*1 and S_2. Among the 34 patients with IAAD, only 1 patient did not exhibit slippage of the FLAJ, 2 patients did not exhibit obliquity in the coronal and sagittal planes of the FLAJs on both sides, and the other 31 patients exhibited both obliquity and slippage in the FLAJs on one or both sides.

Discussion

The FLAJ has often been classified as planar in normal people [2]. The characteristics of the facets and para-positions of the LAJs in patients with *C*1 arch assimilation into the occiput or CAAD have been shown to differ from those in a normal population [7]. Changes in the facets and para-positions of the LAJs, as well as the secondary abnormalities of ligament structures, have been found to be important factors of the occurrence and development of different types of AAD [2,8]. 3D-CT can accurately show morphological features and para-positions of the FLAJ [8]. Yin et al. [4] compared and analyzed 3D-CT images of the CVJ between patients with occipitalization of the atlas and normal people, and they found that most of these patients with anteroposterior AAD had accompanying anteversion and slippage of the FLAJ in the sagittal plane. They concluded that anteversion and slippage of the facets in the sagittal plane are the pathological, anatomical bases of AAD [4]. This point was also confirmed by Salunke et al. [1,2], the authors showed that due to sagittal anteversion of the facets, under the gravitational force from the head, *C*1 slips forward and downward toward *C*2, leading to anteroposterior and vertical AAD. Most of the patients with anteroposterior AAD in our study also exhibited slippage and anteversion of the FLAJ in the sagittal plane. However 5 patients with anteroposterior AAD did not exhibit anteversion or slippage in the FLAJs on either side, and 12 patients with anteroposterior AAD did not exhibit slippage in the FLAJs on either side in our study. A backward tilt of the odontoid in the sagittal plane was the main reason for anteroposterior AAD, as reported by Xia et al. [9]. There were 6 patients (3 patients with unilateral slippage and 3 patients with bilateral slippage) with slippage and without anteversion of the FLAJ in the sagittal plane, including 5 cases of BI and 1 case of os odontoideum. These patients had accompanying atlanto-occipital fusion or *C*2–3 fusion, which leads to concentrated stress, slippage of the

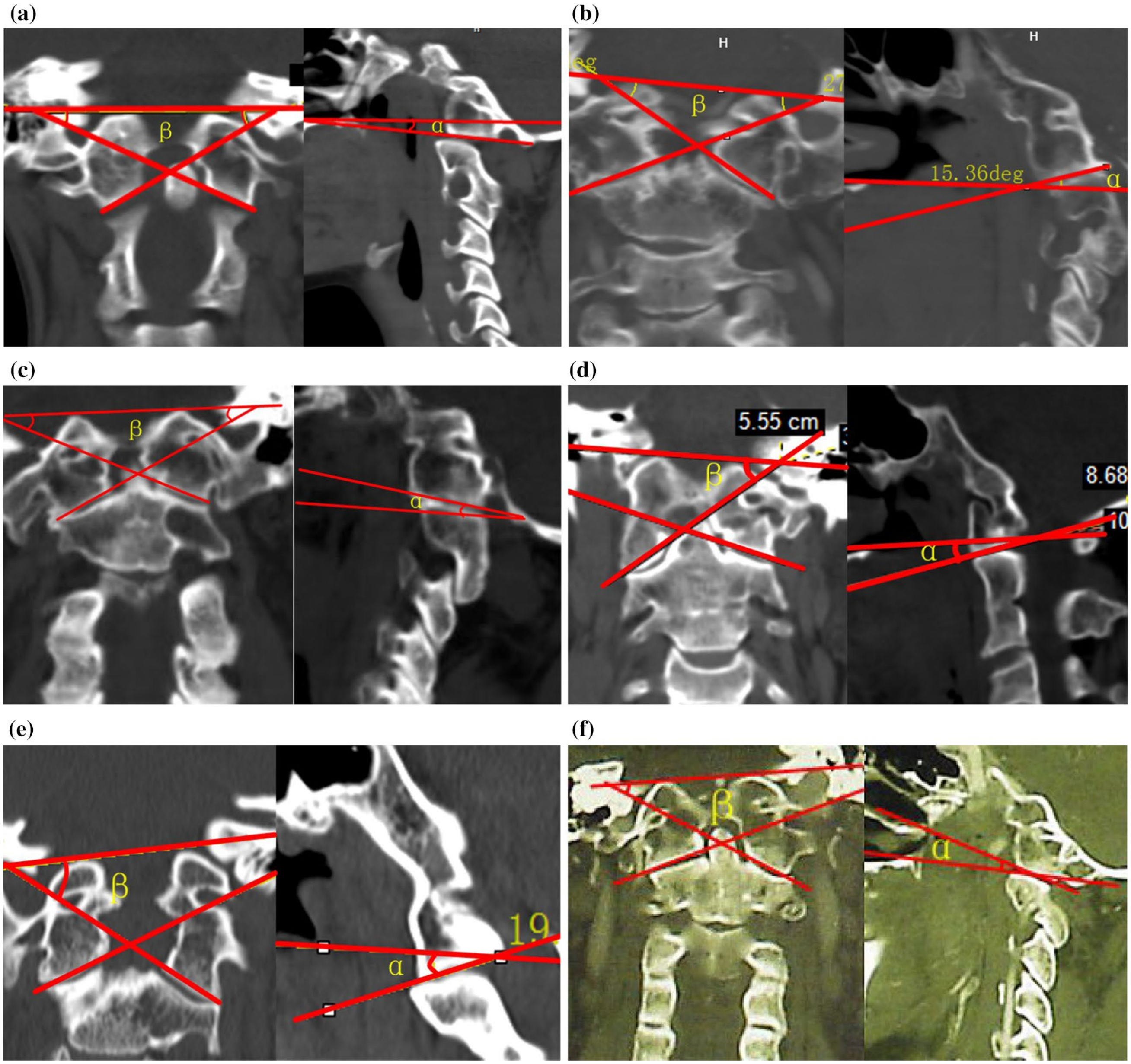

Fig. 4 Six types of obliquity of the FLAJ assessed by 2D CT. **a** represents type *A*, and the coronal and sagittal inferior *C*-1 facet angles of the right FLAJ were 30.3° and − 4.9°, respectively. **b** represents type B_1, and the coronal and sagittal inferior *C*-1 facet angles of the left FLAJ were 27.2° and 15.4°, respectively. **c** represents type B_2, and the coronal and sagittal inferior *C*-1 facet angles of the right FLAJ were 25.4° and − 11.6°, respectively. **d** represents type *C*, and the coronal and sagittal inferior *C*-1 facet angles of the right FLAJ were 39.5° and 10.7°, respectively. **e** represents type D_1, and the coronal and sagittal inferior *C*-1 facet angles of the left FLAJ were 43.6° and 19.4°, respectively. **f** represents type D_2, and the coronal and sagittal inferior *C*-1 facet angles of the left FLAJ were 35.1° and − 14.1°, respectively

FLAJ, and subsequently, anteroposterior AAD. Therefore, there may not be an inevitable relationship relationships between anteroposterior AAD and anteversion and slippage of the FLAJ in the sagittal plane. Unilateral or bilateral dorsally sloped FLAJs in the sagittal plane were only found in 6 patients with vertical AAD. Ten patients with rotational AAD showed bilateral slippage of the FLAJ in the same direction and in different degrees or in the reverse direction in the sagittal plane. Lateral translational AAD was essentially defined as partial slippage (S_1) of the FLAJ in the coronal plane with or without slight obliquity of the facets.

The *C*1 facet with occiput on one side subluxes completely lateral to the *C*2 facet (S_2 in the coronal plane) were considered to indicate lateral angular AAD [2]. Asymmetry

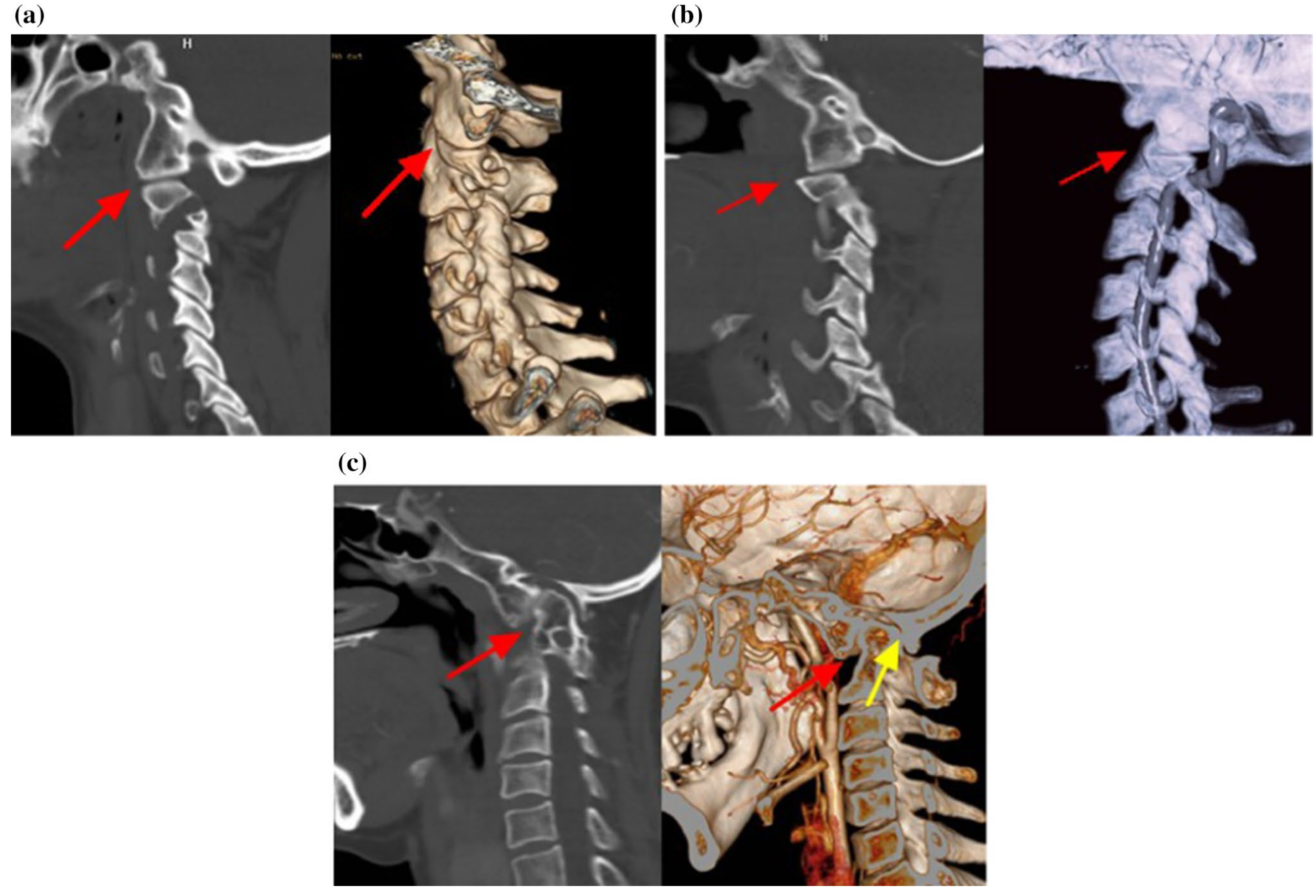

Fig. 5 Three types of slippage of the FLAJ assessed by 2D and 3D CT; the red arrows indicate the slippage of the FLAJ. **a** Represents type S_0, without slippage of the FLAJ. **b** Represents type S_1, with partial slippage of the FLAJ. **c** represents type S_2, with complete slippage of the FLAJ (the yellow arrow indicates the superior facet of *C*2 LAJ and the posterior arch of atlas formed the support joint)

Table 1 Classification of FLAJ and corresponding oblique angle

Types (sides)	The coronal inferior *C*-1 facet angle (°)	The sagittal inferior *C*-1 facet angle (°)	Slippage		
			S_0	S_1	S_2
A (60)	25.3 ± 3.8	3.5 ± 5.9	44	16	0
*B*1 (83)	25.6 ± 3.8	21.9 ± 7.9	29	51	3
*B*2 (10)	24.4 ± 5.5	− 14.0 ± 3.4	8	2	0
C (3)	40.6 ± 4.8	9.1 ± 3.0	1	2	0
*D*1 (29)	44.7 ± 10.8	36.1 ± 15.7	6	16	7
*D*2 (1)	37.6	− 20.7	1	0	0

of the serious obliquity of on two sides of the FLAJ in the coronal plane leads to differential movement on one side under the gravitational force of the head, which can cause progressive lateral tilt, slippage of the FLAJ, and eventually, the occurrence of lateral angular AAD [2]. Five patients in our study had lateral angular AAD, and all of them had accompanying unilateral or bilateral severe obliquity of the FLAJs both in the coronal and sagittal planes with complete slippage or olisthy on one side of the joint in the coronal plane. Therefore, anteroposterior, vertical, and lateral angular AAD occurred at the same time. In the patients with CAAD, most of the slippage of the FLAJ was secondary to (or was accompanied by) obliquity in the joints. Generally, the more severe the obliquity of the FLAJ is, the more severe the slippage [2,4]. When complete slippage of the FLAJ occurred, there was no support between the articular surfaces of *C*1 and *C*2, and accordingly, the superior facet of the *C*2 LAJ and the posterior arch of the atlas formed the support joint. These patients were usually younger; therefore, it cannot be ruled out that slippage is congenital rather than a result of progressive aggravation due to the gravitational force of the head associated with the obliquity of the FLAJ.

The obliquity of the facets in the coronal or sagittal plane and slippage may largely affect the choice of surgery and surgical procedure [1,3]. On the one hand, the obliquity and slippage of the FLAJ are related to the reducibility of AAD, which is important for guiding the selection of surgical methods or surgical approaches [1–3,10]. IAAD appears to be a dynamic process, and cases of dislocation become

Table 2 Data of 93 cases with CAAD and corresponding obliquity combination forms of the bilateral FLAJ

Types (cases)	Diseases (BI/Os)	Agender (M/F)	Age (years)	Types of AAD				IAAD (cases)
				AP	V	AP + V	AP + V + LA	
A–A (25)	21/4	12/13	41.3 ± 16.4	4(Os)	15	6	0	2
*A–B*1 or *B*1–*A* (6)	6/0	1/5	42.0 ± 14.5	0	1	5	0	0
*B*1–*B*1 (32)	29/3	11/21	42.4 ± 15.4	3 (Os)	1	28	0	14
*B*1–*B*2 (1)	1/0	0/1	48	0	1	0	0	0
B2-B2(4)	4/0	3/1	42.3 ± 2.5	0	4	0	0	0
A–C (1)	1/0	1/0	58	0	0	1	0	0
*A–D*1 or *D*1–*A* (3)	3/0	0/3	36.7 ± 4.5	0	0	2	1	2
*B*2–*D*2 (1)	1/0	0/1	46	0	1	0	0	0
C–C (1)	1/0	1/0	36	0	0	1	0	1
*B*1–*D*1 or *D*1–*B*1 (12)	10/2	3/9	36.4 ± 19.2	2 (Os)	0	8	2	10
*D*1–*D*1 (7)	5/2	1/6	31.9 ± 21.9	1 (Os)	0	4	2 (one with Os)	5

BI Basilar invagination, *Os* odontoideum, *M* Male, *F* Female, *AP* Anteroposterior dislocation, *V* Vertical dislocation, *LA* Lateral angular dislocation

Table 3 Slippage combination forms of the bilateral FLAJ and corresponding types of AAD

Types (cases)	Diseases (BI/Os)	Agender (M/F)	Age (years)	Types of AAD				IAAD (cases)
				AP	V	AP + V	AP + V + LA	
S_0–S_0 (31)	27/4	14/17	41.1 ± 14.7	4 (Os)	17	10	0	1
S_1–S_0 or S_0–S_1 (27)	26/1	8/19	41.9 ± 15.2	1 (Os)	4	22	0	5
S_1–S_1 (27)	22/5	10/17	40.9 ± 16.5	6 (five with Os)	2	19	0	20
S_1–S_2 or S_2–S_1 (6)	5/1	1/5	32.0 ± 23.8	0	0	1	5 (one with Os)	6
S_2–S_2 (2)	2/0	0/2	34.0 ± 12.7	0	0	2	0	2

aggravated over time in patients with CAAD. The more severe the obliquity and slippage of the FLAJ are in the coronal and sagittal planes, the more difficult the reduction [1,2]. Salunke et al. [2] believed that the inferior *C*-1 facet angle of the FLAJ in the sagittal plane was greater than 150° (less than 30° in our study), which indicated that it can be easily realigned through a posterior approach and that satisfactory reduction can be achieved. Yuan et al. [10] analyzed the correlation between the obliquity angle (which is composed of the angle bisector of the upper and lower facets of the LAJ in the sagittal plane and the horizontal line) of the FLAJ in the sagittal plane and the reducibility of IAAD. The results showed that if the oblique angle is less than 32.5°, satisfactory reduction can be achieved through a single posterior operation; otherwise, the anterior–posterior approach is required. Cranial traction under general anesthesia has been shown to be an effective technique for evaluating the reducibility of AAD, and the appropriate surgical treatments have been determined accordingly [5,6,11]. According to Liao's report and our previous study, if ADD reduction by more than 50% is achieved after skull traction under general anesthesia, good reduction can be achieved through simple distraction by a posterior approach, otherwise, anterior or posterior release of the LAJ is required [5,6]. In our study, 31 out of 34 patients with IAAD (cases in which AAD reduction was less than 50% were regarded as IAAD cases) had varying degrees (S_1 or S_2) of obliquity and slippage of the FLAJ. Among these patients, 8 had type S_2 (complete slippage or locked facets) FLAJs on one or both sides that were irreducible. Therefore, we hold the opinion that the obliquity and slippage of the FLAJ is an important reference index that can be used to evaluate the reducibility of AAD before operations. Fusion of the LAJ is a definite imaging feature of IAAD. Most patients with osseous fusion of the LAJ had a clear or unclear history of trauma, which interferes with the measurement of relevant parameters to some extent; therefore, patients with osseous fusion of the LAJ were excluded from our study.

On the other hand, the obliquity and slippage of the FLAJ in the coronal and sagittal planes also affects the operation, especially regarding the support or fusion technology used for the LAJ [1,12]. This technique, which was first reported by Goel in 2004, has been widely used in patients with different atlantoaxial diseases [13]. It may be necessary to use an osteotome that can be introduced within the joint and then rotated to achieve distraction and reduction and use a power drill or an ultrasonic scaler to shape the joint surfaces to obtain stable support in patients with obliquity and slippage of the FLAJ in the sagittal plane [2,14,15]. Patients with congenital lateral angular AAD are usually younger, and they often have accompanying torticollis and spastic paralysis. It is extremely difficult to operate on this type of patient due to the abnormal anatomy of the CVJ. A lack of understanding of the anatomical structure often leads to the failure of the operation. These patients with severe obliquity and slippage on the FLAJ on one side in the coronal plane require vertical coronal distraction of the joint, drilling, and implantation of two spacers of unequal height into the LAJ bilaterally to correct the neck tilt [3].

Various methods of measuring the oblique angles of the FLAJ in the coronal and sagittal planes in patients with CAAD have been reported previously [2,9,16]. Although the measurement methods differ to some extent, all of them address the characteristic changes in the angles that occur in these pathological states. In our study, we used the measurement method proposed by Salunke et al. [3], and we considered the angle between the line extending posteriorly from the anterosuperior point of the hard palate and its posterior tip and the line joining the anterior and posterior points of the inferior *C*-1 facet surface, which was the sagittal inferior *C*-1 facet. For the coronal inferior *C*-1 facet angle, we measured the angle between the lines extending between the medial and lateral points along the inferior surface of the *C*-1 facet and the line joining the upper-most points of the foramen magnum. We believe that the upper-most points of the foramen magnum can be located more easily than can the medial-most points of the foramen magnum, as proposed by Salunke. Most patients with CAAD have *C*1 arch assimilation into the occiput, and the relationship of the *C*-1 inferior facet with the occipital condyle and the hard palate remains constant, which is the reason that the inferior facet of *C*-1 rather than the superior facet of *C*-2 should be utilized [3].

This study has some limitations. First, this study was a retrospective, small-sample, single-center study. Another limitation of the current study was that the classification system of the slippage of the FLAJ was based on the degree of slippage, and the direction of slippage (anterior or posterior direction in the sagittal plane or lateral direction in the coronal plane) was not analyzed in our study. The inclusion of the direction of slippage in the classification system will make the classification of the FLAJs more complicated and it will not be easily useful. Therefore, it is suggested that the direction of slippage is considered when the classification system is used.

Conclusion

For most patients with CAAD, anteversion and slippage of the FLAJ in the sagittal plane are the anatomical bases of anteroposterior AAD, while the obliquity and slippage of the FLAJ in the coronal plane are the bases of lateral angular AAD. Both of these factors are vital factors of the upward movement of the odontoid or aggravation of vertical AAD. Rotational AAD is often characterized by asymmetrical slippage in the sagittal plane of the FLAJ, and lateral translational AAD is always characterized by partial slippage in the coronal plane of the FLAJ. Therefore, the morphological characteristics and para-positions of the FLAJs on both sides largely determine the deformities of the CVJ and the types of AAD, which accordingly lead to the polymorphism of atlantoaxial malformations in patients with CAAD. In addition, the obliquity and slippage of the FLAJ are related to the reducibility of AAD. Complete slippage or joint locking of the FLAJ suggests IAAD. Consequently, our classification system of the FLAJ is important for guiding the selection of surgical methods for patients with CAAD.

Funding The funding was provided by The Affiliated Hospital of Southwest Medical University. Grant No. (2019-ZRQN-055).

Compliance with ethical standards

Conflict of interest We have no potential conflict of interest.

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