ACTUAL CONCEPTS OF CLASSIFICATION, DIAGNOSIS AND TREATMENT OF ATLANTO-OCCIPITAL DISLOCATIONS IN ADULTS

Non-systematic literature review

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Objective. To review the literature on atlanto-occipital dislocation (AOD) in adults to determine the optimal classification, diagnostic method and treatment.
Material and Methods. A search was conducted in the PubMed database for the period from 1966 to 2020. The initial search revealed 564 abstracts of articles. A total of 95 studies were selected for a detailed study of the full text, of which 47 studies describing data from 130 patients were included in this review.
Results. The paper describes all the available AOD classifications, and discusses their advantages and disadvantages. The clinical picture, features of the diagnosis in published observations of AOD in adults, as well as the applied treatment methods and their results are presented.
Conclusion. Atlanto-occipital dislocation is one of the most severe types of injuries of the cervical spine in adults, which is accompanied by damage to the medulla oblongata and gross neurological deficit in 70 % of cases. The sensitivity of radiography for the diagnosis of AOD was 56.3 %. In 18.5 % of patients, its use led to untimely diagnosis and could cause subsequent deterioration. The CT sensitivity was 96.8 %. The most accurate method of AOD verification was to determine the atlanto-occipital interval (100 % sensitivity and specificity). The optimal method of treating victims with AOD is surgical one.
Key Words: atlanto-occipital dislocation, injuries of the cervical spine, radiography, MRI, CT.
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Atlanto-occipital dislocation is the most severe and hazardous type of injury to the craniovertebral region. It is found in 10% of those who died with injuries to the cervical spine and in every third accident victim [1–3]. In most cases this injury is unstable, requiring external or internal immobilization. Procrastination during surgical treatment can cause the onset and increase of severe neurologic impairment, up to a fatal outcome [4, 5]. While improving the safety of transporting patients from the scene of a traffic collision and improving the care quality in the intensive care unit resulted in an increase in the survival rate of such patients. This is evidenced by the annual increase in the number of articles concerning individuals with atlanto-occipital dislocation (Fig. 1).

At present, only one advisory protocol for the treatment of atlanto-occipital dislocations has been published, following on from a systematic literature review [6]. These recommendations were based on the experience of treating both adults and children. However, it is a well-known that atlanto-occipital dislocations in children develop 3 times more frequently than in adults. This is explained by the more horizontal orientation of the articular surfaces of the atlanto-occipital joint, the greater elasticity of the ligamentous apparatus and the greater relative weight of the head in children [7]. Moreover, the recovery potential of the ligamentous apparatus and neural structures in childhood is quite high. This can produce better results of conservative treatment with the use of external immobilization.

The objective is to review the literature on atlanto-occipital dislocation (AOD) in adults to determine the optimal classification, diagnostic method and treatment.

Material and Methods

The article is a non-systematic review. A search was conducted in the PubMed database for the period from 1966 to 2020. The search query included the following keywords: occipitocervical OR occipitoatlantal OR atlanto-occipital AND dislocation OR instability OR dissociation. The following word combinations were used to search for Russian-language articles in eLibrary.ru: atlantooccipital, occipitocervical, atlanto-occipital and dislocation, displacement, dissociation, disruption.

The inclusion criteria in the review are as follows: 1) availability of full-text articles in Russian or English; 2) patients older than 15; 3) technique description of external or internal immobilization; 4) description of the treatment outcome. All articles do not meet these criteria are excluded from the review. We also did not examine the data of patients who died in the first three days after the injury, and excluded one article describing dislocation fractures associated with ankylosing spondylitis.

The search revealed 564 abstracts of articles. A total of 95 studies were selected for a detailed study of the full text, of which 47 studies describing data from 130 patients were included in this review.

Statistical analysis was done in Microsoft Excel (Office 2016 for Mac) using descriptive statistics methods.

Results

Classifications of atlanto-occipital dislocations

The first classification was proposed by Traynelis et al. in 1986 [8]. It separated atlanto-occipital dislocations depending on the displacement direction (Fig. 2): anterior (type I), vertical (type II) and posterior (type III). This classification shows only the displacement in the atlanto-occipital joint at the time of the study. Given the high instability of the injury, all three types can develop in one patient, depending on the head setup. Thus, this classification has no great clinical significance [5].

The Harborview Medical Center classification [9] is based on an integrity assessment of C0–C1 ligament complex (Fig. 3), defining 3 stages of atlanto-occipital dislocation. The first stage is minimal injury to the ligamentous apparatus, which is found only in MRI findings. Moreover, dislocation in the joints is minimal or not observed. Traction X-ray demonstrates the joint space extension C0–C1 no more than 2 mm. The second stage is followed by injury to the pterygoid ligaments. In this case, dislocation might not be observed, and the traction test demonstrates the joint space extension by 3 mm or more. The third stage is characterized by complete destruction of the entire ligamentous apparatus of the atlanto-occipital segment with displacement in any direction. If there is no displacement, then, according to static radiography, the joint space is expanded by 3 mm or more.

Horn et al. [5] proposed a simplified classification of atlanto-occipital dislocations, defining 2 types according to CT and MRI findings. Type I injuries are followed by the absence of pathology according to CT findings (Power ratio, X-lines, etc.), with signs of injured articular capsules C0–C1 and posterior ligamentous apparatus according to MRI data. Type II is unstable. It is accompanied by at least one of the criteria of atlanto-occipital dislocations according to CT data and injury of pterygoid ligaments and tectorial membranes according to MRI.

Currently, none of the classifications of atlanto-occipital dislocations has been studied for reliability and repeatability. Nevertheless, the simplest and most rational scheme is Horn et al. According to this arrangement it is possible to draw conclusions regarding the injury stability and further treatment policy. The Harborview classification details well injuries. However, it requires a traction test, which complicates its use.

Clinical picture of atlanto-occipital dislocations

The main cause of atlanto-occipital dislocations in adults appeared to be high-impact trauma, which resulted in both severe concomitant injury and major neurologic impairment in most of the patients. In 20 out of 130 patients, the injury cause is not specified. Out of the remaining 110 patients, the majority (59.1 %) were injured in a traffic collision (the driver or passenger in the front seat); one in five (18.2 %) was driving a motorcycle or all-terrain vehicle; 7.3 % were pedestrians in a traffic collision, and 11.8 % were injured in fall from height (catatrauma) (Table 1).

The neurological status at the time of admission was indicated in 111 patients; 7 of them were in a coma (Table 1). There were no signs of neurologic impairment in 37.5 % (39 individuals) of the remaining 104 patients, 14.4% of patients had quadriplegia (or ASIA A

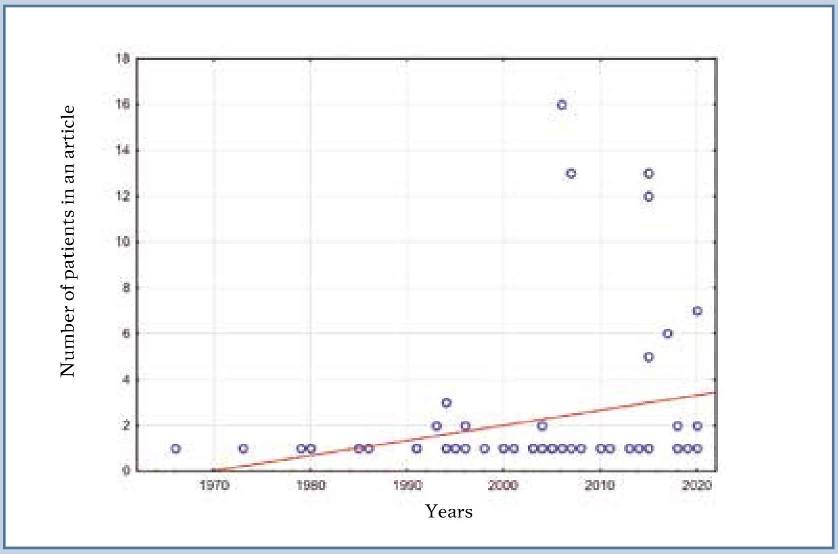

Fig 1
A scatter chart showing an increase in the number of published observations on survived adult patients with atlanto-occipital dislocation

or B), and 37.5 % had quadriparesis (or ASIA C and D). Hemiparesis or hemiplegia were less common – 5 (4.8 %) patients, paraparesis – 2 (1.9 %), monoparesis – 1 (0.95 %), triplegia – 1 (0.95 %). The severity of spinal cord injury in five cases was not specified; isolated injury to cranial nerves was observed in two cases.

Cranial nerve paresis was diagnosed in 17 patients (Table 1). The most common was paresis of the VI pair of cranial nerves. In 10 patients, insufficiency of one pair of cranial nerves was detected, in 2 – two pairs, in 1 – three pairs and in 4 – four pairs.

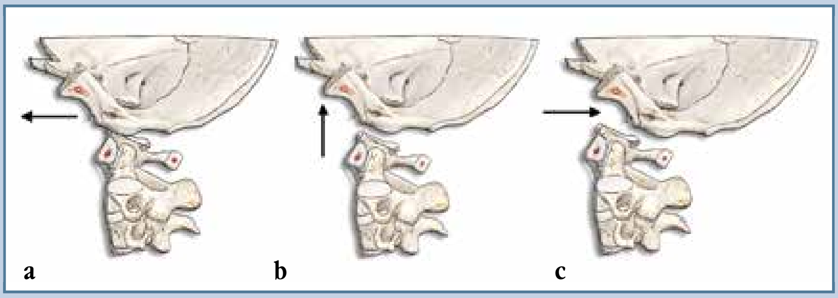

Fig 2
Classification of atlanto-occipital dislocations proposed by Traynelis et al. [8]: **a** – type I; **b** – type II; **c** – type III

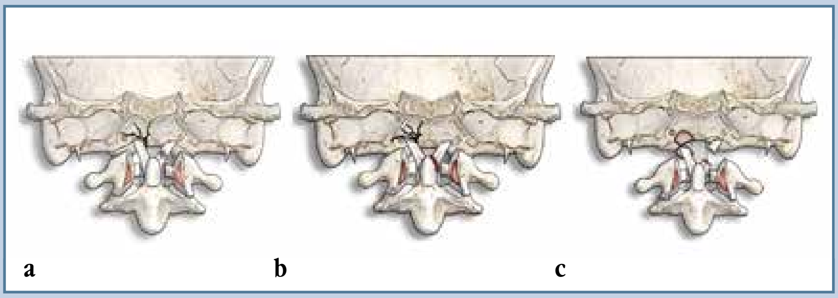

Fig 3
Classification of atlanto-occipital dislocations by Harborview [9]: **a** – 1st stage; **b** – 2nd stage; **c** – 3rd stage

Diagnosis of atlanto-occipital dislocations

The sequence of diagnostic tests for atlanto-occipital dislocations. Among the published studies, a description of the sequence of diagnostic tests and their results is indicated for 81 patients in 44 papers. Radiography as the primary imaging method was applied in 2/3 of patients (54 people); in 1/3 (27 observations) CT scan was used. In accordance with the available guidelines based on a single systematic review [6], lateral radiography can be used to diagnose atlanto-occipital dislocations. Nonetheless, the authors point out that the sensitivity of this diagnostic technique for adults and children is 50.5 %. In this review (Table 1) it was discovered that the radiography procedure was ineffective in 27 out of 48 adult patients, for whom its sensitivity was 56.3 %. The low sensitivity of this method is due to the difficulties of qualitative visualization of the atlanto-occipital joints owing to the parallax effect and the shadow of the mastoid process superimposed on this area. Out of these 27 patients, 5 (18.5 %) had untimely diagnosis and, accordingly, lack of high-quality neck immobilization could be the causes of severe neurologic impairment [9–13]. Soft tissue oedema on lateral radiographs was found in 30 (55.5 %) adult patients, which is less than in the mixed group of adults and children (69.0 %) [6].

CT imaging of the cervical spine was performed in 93 cases. Only in three of them [11, 13], MRI was necessary to verify the atlanto-occipital dislocation. CT sensitivity for adults was 96.8 %, which is significantly higher than for a mixed group of adults and children (63.0 %) [6].

MRI was performed in more than 30 patients. It was done to clarify the injury extent, and in only three people it was the only diagnostic technique for atlanto-occipital dislocation. In these observations, with minimal dislocation in the joints, injury to articular capsules, tectorial membranes and hemorrhage into paravertebral soft tissues were detected.

Verification techniques of atlanto-occipital dislocations on radiographs and CT reconstructions. One of the first ways to identify atlanto-occipital dislocations on radiographs was the Powers ratio method [10]. Two distances are measured: 1) between the anterior edge of the foramen magnum (point B) and the middle of the anterior cortical layer of the C1 posterior half-arch (point C); 2) between the middle of the posterior cortical layer of the C1 anterior half-arch (point A) and the posterior edge of the foramen magnum (point O). The presence of atlanto-occipital dislocations is verified when the BC/OA ratio is more than 1 (Fig. 4a).

The Wholey line (basion-dens interval) [14] involves determining the distance between point B and the apex of odontoid process (D) (Fig. 4b). In health, the basion-dens interval does not exceed 12 mm.

The Harris method [15] consists in simultaneous use of basion-dens interval and basion-axial interval, which is determined as a perpendicular from point B to the line of the posterior contour of C2 vertebral body (Fig. 4c). In health, the basion-axial interval is from 4 to 12 mm.

The X-line method [14] consists in constructing two lines: 1) between point B and the spinolaminar junction of C2 vertebra; 2) between point O and the posterior edge of C2 vertebral body (Fig. 4d). In health, the first line should not intersect with the odontoid process of C2 vertebra, and the second should not intersect with C1.

CCI (condyle-C1 interval, or atlanto-occipital interval) or Pang method [16, 17] is applied exclusively under CT reconstructions of atlanto-occipital joints. Four measurements of joint space are performed on sagittal reconstructions; and four measurements are performed on frontal reconstructions (Fig. 4e). After that, the average value is estimated, which normally should not exceed 1.5 mm. An alternative to the Pang method is the definition of revised CCI (Fig. 4f). It is a measurement in the sagittal projection between the most prominent part of condylus and the corresponding depression in the articular surface of the atlas. In health, this distance does not exceed 2 mm. The sum of the right and left CCI or revised CCI is called the condylar sum, which, according to some data [17], should not exceed 3 mm, and according to others [18] – 5 mm.

Analyzing the sensitivity and specificity of the above techniques (Table 2) it should be mentioned that the highest values were obtained using CT data [11] for different CCI variations. A significant disadvantage of the X-line, basion-dens interval, and basion-axial interval techniques was the dependence of the stability of the atlanto-axial complex. In case of dislocation in C1–C2 segment, they will also increase. According to a number of studies with class I evidence [17, 19, 20], only the Pang method had 100 % sensitivity and specificity for the diagnosis of atlanto-occipital dislocations. An essential indicator is also the same interpretation of the diagnostic method of atlanto-occipital dislocations. For example, the level of interrater agreement was evaluated in the paper by Dahdaleh et al. [18]. The response level was absolute only for CCI. For the basion-dens interval, basion-axial interval, X-lines and Powers ratio, the weighted kappa was significantly lower: 0.57; 0.25; 0.25 and 0.20, respectively.

Treatment of atlanto-occipital dislocations

The main treatment methods for atlanto-occipital dislocations and their outcomes are given in Table 3.

Out of 130 patients, 103 (79.2 %) were eventually operated; external immobilization was the only treatment method for 27 (20.8 %) patients. The mortality rate was 13.1 %; 16 of them died in the first 3–90 days at the hospital and 1 – on the 150th day after the injury. For 50 patients, the average duration of follow-up was 20.4 months (3–114). For the remaining 63, the outcomes are given without specifying the exact dates. Out of 113 patients who survived, the final examination revealed improvement in 80.5 %, deterioration in 3.6 %, and the condition remained unchanged in 15.9 %.

In two cases, primary immobilization of the cervical spine was not conducted [12, 21, 22], which caused the development of neurologic impairment in one case.

Traction as the primary treatment method was used in 9 (6.9 %) patients [13, 23–27]. Deterioration in the neurological status was noted in 30 % of patients; in one case, this resulted in a fatal outcome. Two patients died; six in the interim period of injury required surgical treatment. Orthotic device immobilization alone was initially used in 12 patients [5, 28–36]; in 3 patients, immobilization was performed as the first stage before surgical treatment. Out of 12 patients, 5 died in the first 90 days; 4 were improved without surgery; the condition of 3, despite the surgical treatment, remained unchanged.

The halo device as a frontline treatment method was applied in 23 patients [9–11, 25, 35–42]. The increase in neurologic impairment was observed in only two patients. The operation was finally required in nine cases. Out of the remaining 14 patients, three died, 11 improved.

The majority (86 people, 66.2 %) of patients underwent surgery [5, 9, 11, 13, 25, 35, 39, 4–62]. The main surgical technique was occipitospondylodesis. Transarticular fixation of C0-C1 has been reported in two studies [49, 50]. A short occipitocervical fixation up to C1 vertebra was performed only in one case [21]. In the remaining patients, occipitospondylodesis ended at the C2 level (26 patients), at the C3 level (26 patients), at the C4 level (15 patients) or below C4 level (8 patients). In the remaining cases, the level of occipitospondylodesis was not identified. Only one patient had an increased neurologic impairment after surgery. There were no improvements in 12 patients; 5 individuals died in the first 90 days. The condition of the remaining 68 patients improved.

Conclusion

Atlanto-occipital dislocation is one of the most severe types of injuries of the cervical spine in adults. In 70 % of cases, it is followed by damage to medulla oblongata and a major neurologic impairment. A literature analysis has shown that the absolute majority (84.6 %) of patients with atlanto-occipital dislocations are victims of various traffic crashes involving cars and motor vehicles. Such patients, as a rule, have severe concomitant injury, including traumatic brain injury. The latter can considerably complicate the diagnosis of atlanto-occipital dislocations. Despite its simplicity, X-ray examinations did not reveal atlanto-occipital dislocations in 43.7 % of patients. In 18.5 % of patients, the use of this diagnostic technique resulted in untimely diagnosis and could cause subsequent deterioration. Prevertebral soft-tissue swelling was observed in 55.5 % of patients with atlanto-occipital dislocations. Its presence in the absence of displacement in atlanto-occipital joints is an indication for MRI. CT is the best diagnostic method; in 96.8 % of patients, atlanto-occipital dislocations were found with its help in a timely manner. The optimal method for verifying atlanto-occipital dislocations is CCI and the calculation of the condylar sum, which have not only 100 % sensitivity and specificity, but also the highest level of interrater agreement. If CT or MRI are impossible to be performed, then it is feasible to use radiography with the calculation of basion-axial and basion-dens intervals.

Table 1

Features of the clinical picture and diagnostic algorithm in patients with atlanto-occipital dislocations (literature data)

Study	Cause of AOD	Neurologic impairment at admission to hospital	Examination procedure sequence	AOD is not found within initial examination	Increase in neurologic impairment
Gabrielsen, Maxwell [26]	TC	CN IV	Rg	+	–
Page et al. [28]	TC	Quadriplegia, CN X, XII	Rg	–	–
Powers et al. [10], case 4	TC	Hemiparesis, CN VII	Rg	–	–
Dublin et al. [23], case 3	TC	Quadriplegia, CN VI	Rg	–	–
Woodring et al. [21], case 2	TC	Monoparesis	Rg	+	+
Watridge et al. [12]	TC	Paraparesis	Rg, CT	+	–
Ramsay et al. [22]	Motorcycle	Coma	Rg	+	N/D
Belzberg et al. [27]	TC	Quadriparesis, CN VI, IX, X	Rg	+	–
Montane et al. [24], case 1	TC	Quadriparesis	Rg	–	–
Lee et al. [43], case 1	N/D	No	Rg	–	–
Dickman et al. [13]					
case 3	Motorcycle	Quadriparesis, CN VI	Rg, CT	+	+
case 4	Pedestrian	Quadriparesis, CN VI	Rg, CT, MRI	+	+
Ahuja et al. [25] cases 1, 2, 3, 6	TC	N/D	Rg (all), CT (n = 2)	N/D	Case 1
Palmer et al. [44]	TC	Quadriparesis, CN VI	Rg, CT, MRI	+	–
Guigui et al. [45]	TC	No	Rg, CT	–	–
Ferrera et al. [37], case 1	TC	N/D	N/D	–	–
Przybylski et al. [11]					
case 4	N/D	Quadriplegia	Rg, CT	+	N/D
case 5	N/D	No	Rg, CT	+	+
Takayasu et al. [30]	Motorcycle	Quadriplegia	N/D	+	–
Chattar-Cora et al. [46]					
case 1	N/D	Hemiplegia, CN VI	Rg	–	–
case 2	N/D	Hemiparesis, CN VI	Rg	–	–
case 3	Motorcycle	Coma	Rg, CT, MRI	–	–
Junge et al. [47], case 1	TC	Quadriparesis	Rg, CT, MRI	–	–
Govender et al. [41]					
case 1	N/D	Hemiparesis	Rg	+	–
case 2	N/D	CN VI, IX, X, XII	Rg, CT, MRI	+	–
case 3	N/D	Quadriparesis, CN VI	Rg, CT, MRI	–	–
case 4	N/D	No	Rg, CT, MRI	–	–
Labler et al. [48]					
case 3	Motorcycle	Quadriplegia, CN VI, IX	Rg, CT, MRI	+	–
case 4	Other	Paraparesis	Rg, CT, MRI	–	–
Punjaisee [32]	Motorcycle	Quadriparesis	Rg	–	–
Gregg et al. [51]	TC	Quadriplegia	CT	–	–
Payer et al. [33]	Motorcycle	Quadriparesis	CT, MRI	–	–
Feiz-Erfan et al. [49]	TC	No	Rg, CT, MRI	+	–
Gonzalez et al. [50], case 2	TC	No	Rg, CT, MRI	+	–
Seibert et al. [52]	TC	No	Rg, CT, MRI	–	–
Hamai et al. [53]	Motorcycle	Quadriparesis	Rg, CT, MRI	–	–
McKenna et al. [54]	TC	No	CT, MRI	–	–
Bellabara et al. [9], cases 2–17	TC – 10, Pedestrian – 3, catatrauma – 3	ASIA A – 2, ASIA C – 8, ASIA D – 4, no – 2, CN V, VI, VII, XII (2 cases)	Rg (n = 14), CT (all), MRI (N/D)	13 patients	5 cases

End of Table 1

Study	Cause of AOD	Neurologic impairment at admission to hospital	Examination procedure	AOD is not found within initial examination	Increase in neurologic impairment
Gautschi et al. [34]	Motorcycle	Quadriplegia, CN IX, X, XI, XII	Rg, CT, MRI	–	–
Horn et al. [5], cases 7–9, 12–15, 20, 21, 24–27	N/D	Coma – 3, spinal injury – 4, TBI + spinal injury – 1, no – 5	N/D	N/D	N/D
Kleweno et al. [38]	TC	Quadriplegia	Rg, CT, MRI	–	–
Sweet et al. [55]	TC	Quadriparesis, CN VI	CT, MRI	–	–
Ehlinger et al. [56]	All-terrain vehicle	Hemiplegia	CT, MRI	–	–
Chaudhary et al. [39]	TC	Triplegia	CT, MRI	–	–
Skala-Rosenbaum et al. [57]	Catatrauma	No	CT, MRI	–	–
Desai et al. [58]	Pedestrian	Quadriplegia	CT, MRI	–	–
Kato et al. [40]	TC	Quadriplegia	CT, MRI	–	–
Anania et al. [60]	Catatrauma	No	CT, MRI	–	–
Mendenhall et al. [35], cases 1–31	TC – 17, motorcycle – 8, all-terrain vehicle – 3, pedestrian – 2, catatrauma – 1	No – 11, ASIA D – 5, ASIA C – 10, ASIA B – 1, ASIA A – 1, Brown-Sequard Syndrome, N/D – 2	Rg (N/D), CT (all), MRI (N/D)	N/D	N/D
Menon et al. [59], cases 1–5	TC	Coma – 3, N/D – 2	Rg (N/D), CT (all), MRI (N/D)	N/D	N/D
Clifton et al. [63]					
case 1	Pedestrian	Quadriparesis	CT, MRI	–	–
case 2	TC	Quadriplegia	CT, MRI	–	–
Tavolaro et al. [61]	Fall from height	No	CT, MRI	–	–
Tobert et al. [62]	TC	No	CT, MRI	–	–
Rief et al. [64]	TC	Coma	CT, MRI	–	–
Park et al. [36], case 2	Catatrauma	Coma	CT, MRI	–	–
Chang et al. [42], cases 1, 2, 4, 5, 8–12, 14	Catatrauma – 6, TC – 3, fall from height – 1	Quadriplegia – 1, coma – 1, no – 8	N/D	N/D	N/D

AOD – atlanto-occipital dislocation; TC – traffic collision; All-terrain vehicle – injury that occurs on all-terrain vehicle; Motorcycle – motorcycle injury; N/D – no data available ; CN – pair of cranial nerves; TBI – unspecified traumatic brain injury; ASIA – American Spinal Injury Association Impairment Scale, spinal cord injury scale; Rg – radiography.

Surgical treatment is the optimal choice for patients with atlanto-occipital dislocations. The absence of immobilization of the cervical spine or the use of skeletal traction is associated with a high probability of deterioration of the patient's condition. The use of external immobilization with a halo device or a rigid orthotic device can produce a good result. Nevertheless, it is advisable only as the first stage of treatment, until the patient's condition stabilizes, after which surgery is required.

The study had no sponsors. The authors declare that they have no conflict of interest.

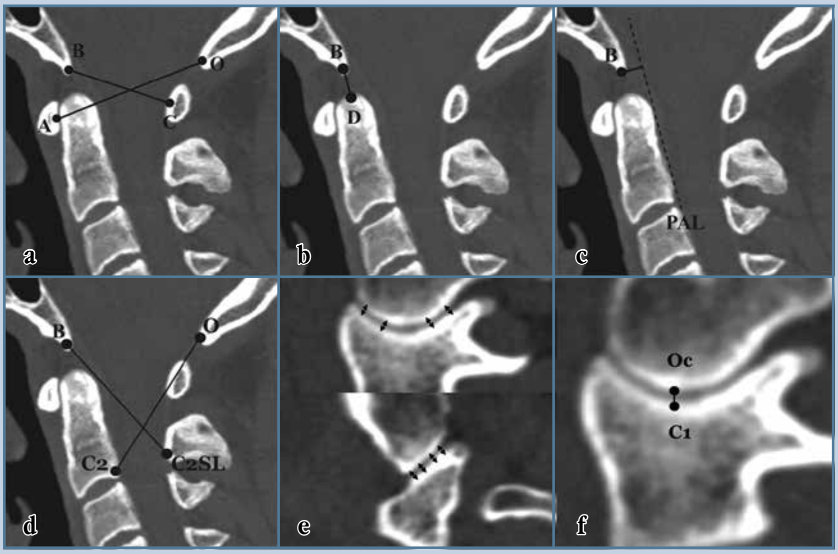

Fig 4
Display of various verification methods of atlanto-occipital dislocations: **a** – Powers ratio; **b** – Wholey line; **c** – Harris method; **d** – X-line method; **e** –CCI; **f** – revised CCI

Table2
Sensitivity/specificity of various validation methods of atlanto-occipital dislocations (literature data)

Study	Evidence level	Data	Powers ratio	BDI	BAI - BDI	X-lines	CCI	Revised CCI	Condylar sum
Lee et al. [14]	II	Rg	33/n.d.	50/n.d.	–	75/n.d.	–	–	–
Harris et al. [15]	II	Rg	60/n.d.	–	100/n.d.	15/n.d.	–	–	–
Przybylski et al. [11]	III	Rg	60/n.d.	–	60/n.d.	80/n.d.	–	–	–
Dziurzynski et al. [20]	I	Rg	46/97	73/94	68/94	60/91	–	100/89	–
		CT	74/99	100/95	96/98	71/87	–	92/95	–
Gire et al. [19]	I	CT	26/94	72/92	–	54/38	–	100/84	100/92
Martinez-del-Campo et al. [17]	I	CT	54.5/100	45.5/100	–	40.9/93.2	100/100	–	100/100
Dahdaleh et al. [18]	I	CT	50/100	75/100	–	67/50	–	100/94	–

AOD – atlanto-occipital dislocation; BAI – basion-axial interval; BDI – basion-dens interval; CCI – condyle-C1 interval, atlanto-occipital interval; Condylar sum – condylar sum; Rg – radiography; n.d. – no data available.

Table 3
Treatment methods of atlanto-occipital dislocations and their outcomes in adults (literature data)

Study	Frontline treatment	Deterioration after frontline treatment	Postponed surgical treatment, term	Final outcome	Neurologic impairment at the time of outcome assessment
Gabrielsen, Maxwell [26]	Skeletal traction, then orthotic device	–	Yes, 12 months	Without changes	CN VI
Page et al. [28]	Skeletal traction, then orthotic device	–	Yes, 5 months	Improvement	Hemiparesis, CN X
Powers et al. [10], case 4	Halo device	–	–	Improvement	Hemiparesis
Dublin et al. [23], case 3	Skeletal traction	–	–	Death on the 14th day	–
Woodring et al. [21], case 2	Skeletal traction	–	Yes, 1 month	Deterioration	Quadriplegia
Watridge et al. [12]	No	–	Yes, 6 weeks	Improvement	No
Ramsay et al. [22]	No, after deterioration – skeletal traction	Yes	–	Deterioration	Hemiplegia
Belzberg et al. [27]	Skeletal traction, then halo device	–	Yes, 1 month	Improvement	Monoparesis, CN VI
Lee et al. [43], case 1	Surgery	–	–	Improvement	No
Montane et al. [24], case 1	Skeletal traction	–	Yes, N/D	Improvement	No
Dickman et al. [13] case 3 case 4	 Skeletal traction Surgery	 Yes –	 Yes, 1 month –	 Deterioration Improvement	 Quadriparesis Hemiparesis
Ahuja et al. [25] case 1 case 2 case 3 case 6	 Skeletal traction Halo device Surgery Surgery	 Yes – – –	 – – – –	 Death on the 30th day Improvement Improvement Improvement	 – N/D N/D N/D
Palmer et al. [44]	Surgery	–	–	Improvement	Quadriparesis
Guigui et al. [45]	Surgery	–	–	Improvement	No
Ferrera et al. [37], case 1	Halo device	–	Yes, 6 months	Without changes	Apallic syndrome
Przybylski et al. [11] case 4 case 5	 Halo device Surgery	 – Yes	 Yes, 5 months –	 Without changes Deterioration	 Quadriplegia CN X
Takayasu et al. [30]	Skeletal traction	Yes	Yes, 5 months	Improvement	No
Chattar-Cora et al. [46] case 1 case 2 case 3	 Surgery Halo device, then surgery on the 7th day Skeletal traction, then halo device, then surgery on the 5th day	 – – –	 – – –	 Improvement Improvement	 CN VI CN VI –
Junge et al. [47]	Surgery	–	–	Improvement	Monoparesis
Govender et al. [41] case 1 case 2 case 3 case 4	 Surgery Surgery Surgery Halo device	 – – – –	 – – – –	 Improvement Improvement Improvement Improvement	 No No Paraparesis No
Labler et al. [48] case 3 case 4	 Surgery Surgery	 – –	 – –	 Improvement Improvement Improvement	 Paraparesis, CN VI No
Punjaisee [32]	Orthotic device	–	Yes, 12 months	Improvement	Quadriparesis
Feiz-Erfan et al. [49]	Surgery	–	–	Improvement	No
Gonzalez et al. [50], случай 2	Halo device, then surgery	–	–	Improvement	No
Gregg et al. [51]	Halo device, then surgery	–	–	Without changes	Quadriparesis

Continuation of table 3

Study	Frontline treatment	Deterioration after frontline treatment	Postponed surgical treatment, term	Final outcome	Neurologic impairment at the time of outcome assessment
Payer et al. [33]	Orthotic device	–	Yes, 3 weeks	Improvement	No
Seibert et al. [52]	Surgery	–	–	Improvement	No
Bellabarba et al. [9]					
cases 2, 6, 7, 10, 16	Surgery	–	–	Improvement	No
cases 3, 5, 8, 11, 13, 14	Surgery	–	–	Improvement	ASIA D or ASIA C
case 9	Surgery	–	–	Improvement	No
case 15	Halo device	–	Yes, 2 weeks	Without changes	ASIA C
cases 4, 12	Surgery	–	–	Without changes	ASIA A
case 17	Surgery	–	–	Improvement	No
Hamai et al. [53]	Halo device then surgery	–	–	Improvement	Quadriparesis
McKenna et al. [54]	Surgery	–	–	Improvement	No
Gautschi et al. [34]	Orthotic device	–	Yes, 7 weeks	Without changes	Quadriplegia, CN IX, X, XI, XII
Kleweno et al. [38]	Halo device	–	Yes, 24 days	Improvement	Quadriplegia
Sweet et al. [55]	Surgery	–	–	Improvement	Quadriplegia
Horn et al. [5]					
cases 8, 12, 14, 15	Surgery	–	–	Improvement	No
case 7	Surgery	–	–	Improvement	No
case 9	Surgery	–	–	Improvement	Quadriparesis
case 13	Surgery	–	–	Without changes	Quadriplegia
cases 20, 21	Orthotic device	–	–	Improvement	No
cases 24, 25, 26	Surgery	–	–	Death on 6-42 day after surgery	–
case 27	Surgery	–	–	Death on the 3rd day after surgery	–
Ehlinger et al. [56]	Surgery	–	–	Improvement	No
Chaudhary et al. [39]	Surgery	–	–	Improvement	Monoparesis
Skala-Rosenbaum et al. [57]	Surgery	–	–	Improvement	No
Desai et al. [58]	Surgery	–	–	Death on the 30th day	–
Kato et al. [40]	Halo device	Yes	Yes, 10 days	Death on the 150th day	–
Mendenhall et al. [35]					
case 1	Surgery	–	–		ASIA D
cases 2, 6, 12, 23	Surgery	–	–	Improvement	ASIA E or ASIA D
cases 3–5, 8, 9, 11, 16,	Surgery	–	–	Improvement	No
cases 7, 13, 14, 21	Surgery	–	–	Improvement	ASIA D
cases 10, 15, 18, 19	Surgery	–	–	Without changes	ASIA C
cases 17, 20	Halo device	–	–	Without changes	No
case 22	Surgery	–	–	Improvement	No
cases 24, 31	Halo device	–	–	Improvement	–
case 26	Halo device	–	–	Death on the 90th day	–
cases 25 и 27	Orthotic device	–	–	Death on the 90th day	–
case 28	Orthotic device	–	–	Death on the 90th day	–
case 29	Orthotic device	–	–	Death on the 90th day	–
case 30	Orthotic device	–	–	Death on the 90th day	–
				Death on the 90th day	
Menon et al. [59]					
cases 1, 2, 4	Surgery	–	–	Improvement	N/D
cases 3, 5	Surgery	–	–	Improvement	N/D
Anania et al. [60]	Surgery	–	–	Improvement	No
Clifton et al. [63]					
case 1	Halo device	Yes	Yes, N/D	Improvement	No
case 2	Halo device	–	Yes, 22 days	Improvement	Quadriparesis
Tavolaro et al. [61]	Surgery	–	–	Improvement	No

End of Table 3

Study	Frontline treatment	Deterioration after frontline treatment	Postponed surgical treatment, term	Final outcome	Neurologic impairment at the time of outcome assessment
Tobert et al. [62]	Surgery	–	–	Improvement	No
Rief et al. [64]	Halo device	–	–	Improvement	Quadriparesis, CN IX
Chang et al. [42]					
case 1	Surgery	–	–	Improvement	No
case 2	Surgery	–	–	Improvement	No
cases 4, 5, 9, 12, 14	Halo device	–	–	Improvement	No
case 8	Orthotic device	–	–	Without changes	Quadriplegia
cases 10, 11	Orthotic device	–	–	Improvement	No
Park et al. [36], case 2	Orthotic device	–	Yes, 26 days	Without changes	Quadriplegia

AOD – atlanto-occipital dislocation; N/D – no data available; CN – pair of cranial nerves.

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