Review article

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The classifications of subaxial cervical spine traumatic injuries. Part 6. Ben L. Allen biomechanical classification

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Traumatic injuries of subaxial cervical spine are characterized by a wide range of possible pathomorphological changes that depend not only on the direction and intensity of the traumatic force impact, but also on the initial position of cervical spine at the moment of exposure.

One of the most detailed classifications of cervical spine traumatic injuries, in which the integrated approach to assessing the type of injury considering the mechanism of injury is used, is the system developed by Ben L. Allen and published with co-authors in 1982. It is also known as the Allen-Ferguson classification and despite long history of existence, still has not lost its relevance.

In the classification when characterizing the type of traumatic injury, not only visually detected signs, but also inevitably accompanying changes are given.

In total, 6 types of damage were classified: compression-flexion, vertical compression, distraction-flexion, compression-extension, distraction-extension and lateral-flexion, which were divided into stages depending on the severity of pathomorphological changes. The authors of the classification note a pronounced correlation between the nature of damage to anatomical structures and neurological disorders in all patterns of damage.

When writing this review, a detailed analysis of the original publication was carried out, highlighting the basic biomechanical aspects that underlie the classification and still have not lost their relevance . It is noted that the schematic images of damages found in modern literature often do not correspond to the description proposed by Ben L. Allen et al., Therefore, when preparing the illustrative material, we relied solely on the data of the original article.

Along with the description of morphology, for each type and stage of injury, modern data on possible methods of treatment, both conservative and surgical are given.

The complex analysis suggests that the classification developed by Ben L. Allen is a convenient tool for assessing pathomorphological changes and allows choosing the optimal method of treating the patients in each specific clinical situation.

Key words: *traumatic injury; Allen-Ferguson classification; cervical spine; subaxial level; morphology; biomechanics*

Introduction

Traumatic subaxial injuries of the cervical spine (CS) are characterized by a wide range of possible pathomorphological changes, which are determined by a complex anatomical structure and high mobility, therefore the degree and nature of damage to certain structures depend not only on the direction and intensity of the traumatic force impact but also on the initial position of CS at the time of exposure (flexion, extension or neutral position).

Many years of clinical experience and an extensive evidence base, reflected in numerous publications, indicate the presence of a large number of methods for both surgical and conservative treatment of various types of CS injuries. It is clear that the most effective of all those available in the clinical situation is a method that takes into account all traumatic changes, and not just the most severe of those available. Despite significant advance in the field of neuroimaging in recent decades, traumatic injuries to certain anatomical structures that are critical to determining therapeutic strategy are difficult to objectify. For example, the rupture of the capsule of facet joints is evident in complete anterior dislocation, but in fact this statement is based on the assessment of the ratio of facets, rather than on the assessment of the condition of the joints capsule.

One of the most detailed classifications of traumatic subaxial CS injuries, in which an integrated approach to assessing the type of injury considering the mechanism of injury is used is the system developed by B.L. Allen and published by him jointly with co-authors in 1982 [1]. The characteristics of the type of traumatic injury include not only the signs that are visually detected, but also inevitable accompanying changes. When analyzing this system, it was noted that the types and stages of injuries identified by the author are the result of not only empirical observations, but also a detailed study of the consequences of the influence of a traumatic force, taking into account a large number of factors (intensity, direction, presence of additional force vectors, etc.). A comprehensive description of all the changes that accompany a particular type of injury is given, but the illustrations are presented only by radiographs. When writing this review, it is noted that some schematic images that occur in the literature and characterize different types of injury according to the classification of B.L. Allen, do not correspond to some of those described in the original work, so in preparing the illustrative material, we relied only on the data of the original article.

This classification is still relevant. Thus, as of July 2021, according to the results of the analysis of the site database https://scite.ai, the publication of B.L. Allen et al. is the most frequently cited of all the proposed classifications of traumatic subaxial CS injuries - in 412 publications, while the AOSpine subaxial cervical spine injury classification system is mentioned in 145. In addition, a fairly stable use of the classification B.L. Allen in R&D: in 2015–2020 it was cited 118 times, in 2010–2014 - 122 times.

General characteristics of the classification

The classification was developed by B.L. Allen (also known as Allen – Ferguson classification) based on the results of retrospective analysis of radiographs of 165 patients with closed indirect fractures and dislocations of the CS at the subaxial level. Subsequently, to reduce the misdiagnosing, all used radiographs were re-analyzed by co-authors. In addition, the neurological status of the patients was taken into account. Given that the study was retrospective, the authors were able to identify the following types of neurological disorders: radiculopathy, centromedullary syndrome, partial spinal cord injury (SC) and complete injury. The authors have demonstrated that there are at least six patterns of indirect traumatic subaxial CS injuries, with each pattern being divided into stages according to the severity of the osteoligamentous injury. In addition, a significant correlation was found between the nature of the injury of anatomical structures and neurological disorders in all patterns of damage.

When analyzing the circumstances of the injury, it is proposed to distinguish between general and specific mechanisms. The general mechanisms included a motor vehicle accident, a motorcycle accident, diving into shallow water, a direct blow, a falling, etc., but they could not fully characterize the mechanism of injury. Specific mechanisms were identified in the presence of reliable information about the position of the head and neck during the injury, the place and direction of force application, as well as exact circumstances of the injury.

When analyzing the spondylograms, groups of cases with similar radiographic pathology were identified. In case of a combined or associated fracture and / or dislocation, the most severe injury was considered primary, according to which the injuries were classified, the rest of traumatic changes were concomitant. In the groups obtained as a result of the primary analysis, the authors determined the mechanism of injury (phylogeny) to emphasize the ordered sequence of events that led to a certain morphological type of pathological changes. Phylogenetic types are named according to the probable position of the CS during the traumatic action and the initial type of injury that dominated. For example, "compression" indicates that compression is the main traumatic effect that forms pathological changes of the spinal motion segment (SMS), which are visually detected, and "distraction" indicates that stretching or displacement causes the initial most obvious structural injuries.

B.L. Allen classified 6 phylogenetic types of injury: compression-flexion, vertical compression, distraction-flexion, compression-extension, distraction-extension and lateral flexion.

During the analysis the authors did not find a specific spectrum of traumatic changes associated with rotation, therefore the rotation is considered as a secondary lateralized force in previous groups.

The proposed scheme of marking the injury level is quite non-standard. It is noted that there is a common tendency to mark a vertebral fracture by its number. For example, in case of a fracture of the fifth cervical vertebra, "C5 vertebral fracture" is indicated, and so on. On the other hand, injuries characterized by vertebral displacement without significant damage to bone structures are usually identified according to the SMS in which the displacement occurs. So, unilateral facet dislocation with displacement of the fifth cervical vertebra relative to the sixth is called "unilateral facet dislocation C5-C6". The authors note that most CS injuries are accompanied by damage to the ligamentous apparatus, therefore it is more correct to identify any damage according to the motor segment involved, rather than according to the most noticeable sign. Marking of all types of damage in compliance with SMS is offered, emphasizing the number of the vertebra in which pathological changes typical for this phylogenetic type are observed.

The classification is based on a detailed assessment of the biomechanics of injury. It is noted that the analysis of X-ray features of cervical SMS damage does not make it possible to measure the force that caused these changes, but allows identifying the conditions that determine the damage for different structural elements of the spine. This assessment gives a rough idea of the action of forces direction that cause morphological changes. Traumatic efforts in a certain direction are called by authors "injury vectors". The vector that determines the initial traumatic changes within a particular phylogenetic type of injury is the main one, and any concomitant effort in the other direction that causes additional changes is an additional injury vector. The tension spread of the main injury vector occurs

This article contains some figures that are displayed in color online but in black and white in the print edition along the path of the main load. The main and additional vectors act on different sides of the neutral axis. To facilitate understanding of the described mechanism, the authors draw an analogy with the tension that arises in the beam under the influence of the flexion moment. The concave side, towards which the bending occurs, feels the stress of compression, and the convex side - in distraction. The neutral axis separates the area of tension during compression from the area that is under distraction. The force component acting perpendicular to the neutral axis exposes the beam to a displacement stress.

Since the paper analyzes the tissue damage, rather than quantifying the stress, it is more appropriate to use the term "transitional axis" rather than "neutral axis". The latter separates the zones of stress, while the transitional axis separates zones of tissue damage that have arisen as a result of exposure to various vectors of injury. If biomechanically different pathomorphological changes occur simultaneously within the SMS, then the neutral and transitional axes will coincide, but if the changes do not occur simultaneously, but sequentially, these axes will be spatially different.

Thus, the following classification of traumatic subaxial CS injuries is based on the theses defined by the authors:

- efforts that cause fracture or dislocation of CS can be considered as the main and additional vectors of injury;
- injury vectors can be determined by X-ray examination of the CS;
- the magnitude of the vectors determines the severity of the injury;
- similar injuries occur as a result of exposure to similar injury vectors;
- within each mechanism of injury a certain range of pathomorphological changes (from minimal to gross) is formed.

When constructing the classification, a group of radiologically identical cases within the damage phenotype is called stage (S).

TYPES OF INJURY

Compressive flexion type

Compressive flexion injuries (CF) are formed when a compressive force is applied to a bent CS. In severe cases, the biomechanics of the injury determines the secondary anteroposterior directional vector, which causes the displacement of the posteroinferior fragment of the vertebral body into the spinal canal. In this case, the anteroinferior part of the body is separated and forms a triangular fragment, known as a "teardrop fracture" (CFS3 – CFS5). The causes of compressive flexion injuries are most often falling from a height, diving or falling of a heavy object on the victim's head [2]. This type of injury is most common in the fifth cervical vertebra.

Teardrop fractures are characterized by damage to the caudal intervertebral disc, as evidenced by radiological narrowing in the disc space between the posterosuperior fragment of the vertebral body and the body of the underlying vertebra. The disc space between the anteroinferior triangular (or quadrangular fragment) and the underlying vertebra is usually preserved [4]. According to C. Lee et al. [5], a sagittal vertical fracture of a fragment of the vertebral body or the arch fracture is observed in two thirds of cases of compressive-flexion injuries [6]. It is noted that the combination of teardrop fracture, sagittal vertebral body fracture and arch fracture is always associated with severe SC trauma. In case of such injuries, destruction of the posterior ligamentous complex is usually observed, which is accompanied by an increase in the interspinous space, facet joint diastasis, subluxation, spinal axis deformity and significant kyphosis [7]. The displacement of the posteroinferior body fragment dorsally is an indirect evidence of damage to the posterior longitudinal ligament.

The classification includes 5 stages of compressive flexion injuries, listed with ascending severity: **CFS1** - pathomorphological changes are represented by blunting of the anterosuperior vertebral body margin to the rounded contour. There are no signs of damage to the posterior ligamentous complex ***(Fig. 1A)***; **CFS2** - in addition to the changes characteristic of CFS1, there is a tilt of the anterior contour of the body of the damaged vertebra and a decrease in the height of the anterior and central parts of the body. As a result of deformity, the anteroinferior part of the body is a kind of "beak". There may also be an increase in the concavity of the inferior endplate and / or a vertical fracture of the central part of the damaged vertebral body ***(Fig.1B)***; **CFS3** - in addition to the changes characteristic of CFS2, the fracture line, which passes at an angle from the anterior surface of the vertebral body through the center, reaches the inferior endplate. Thus, a beak-shaped deformity fracture is formed - teardrop (Fig. 1C); **CFS4** - in addition to the deformity of the central parts and a "beak" fracture, the lesion is a mild (<3 mm) displacement of the posteroinferior vertebral body margin into the spinal canal within the damaged SMS. Osteo-traumatic changes in CFS3 and CFS4 are identical ***(Fig. 1D)***; **CFS5** - in addition to the changes characteristic of CFS3, there is a displacement of the posterior part of the vertebral body backward into the spinal canal. The spinal arch usually remains intact. There is the diastasis of articular surfaces of the facet joints and an increased distance between the spinous processes in the damaged SMS. The nature of the displacement indicates damage to both the posterior part of the anterior ligamentous complex and the entire posterior ligamentous complex. The posteroinferior margin of the above located (damaged) vertebra may be close to the endplate of the vertebra located below ***(Fig. 1E)***.

One variant of CFS5 injury is a "quadrangular" fragment fracture described by K. J. Favero and P. K. Van Peteghem [8]. The pathomorphological picture is represented by a large anteroinferior fragment, a significant displacement of the vertebral body backward, angular kyphosis and damage to the disc and posterior ligamentous complex (Fig. 1F). Thus, two "columns" are actually formed: the upper one, consisting of the posterosuperior fragment of the body with all cranially located vertebrae, and the lower one, formed by the anteroinferior fragment and caudally located vertebrae. The trauma is characterized by complete damage to all disco-ligamentous components that connect these columns [3].

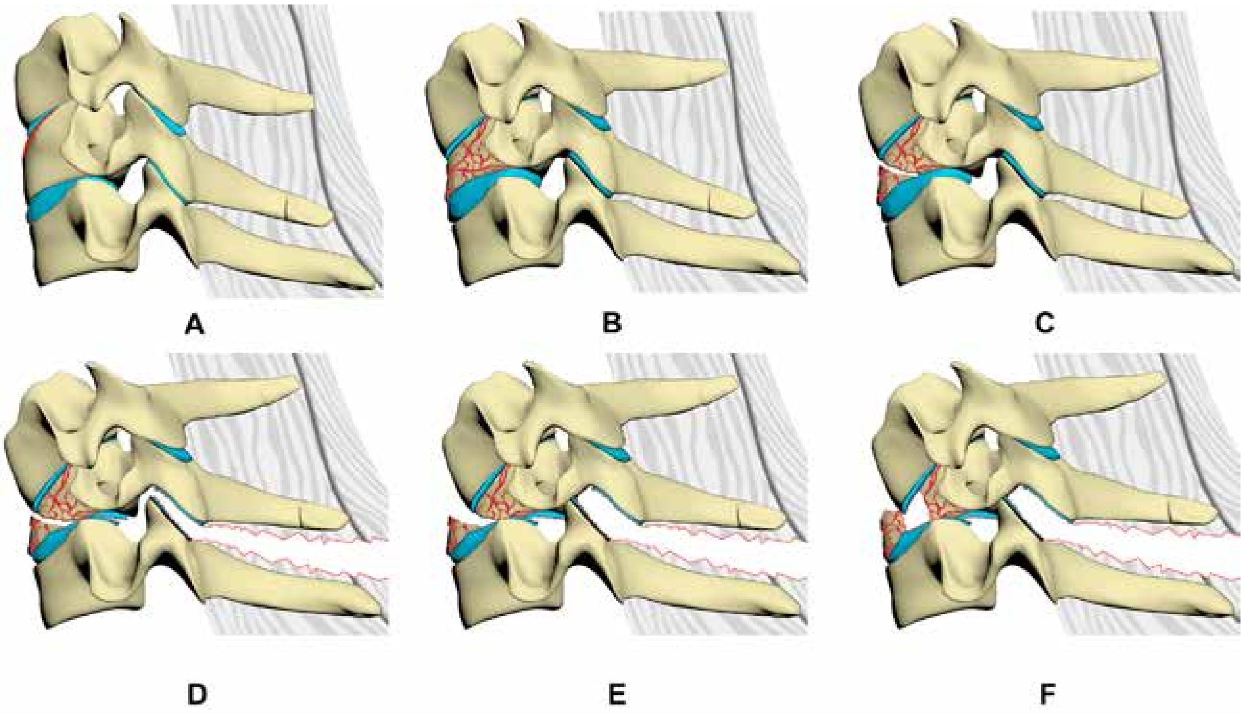

Fig. 1. Stages of compressive-flexion injuries: A - CFS1; B - CFS2; C- CFS3; D - CFS4; E- CFS5; F - CFS5 («quadrangular» fracture)

Neurological disorders in compressive-flexion injuries of the initial stages (CFS1 – CFS2) are rare, the main cause of which is the traumatic disc herniation. Higher degree fractures are usually unstable injuries and can lead to serious neurological disorders. According to K.S. Kim et al. [9], in 56% of patients with teardrop fractures there is a clinic of complete injury to the SC, in 31% - a partial neurological deficit. Among incomplete injuries, anterior spinal syndrome is a common manifestation, associated either with direct ventral compression of the SC with a displaced bone fragment, or with impaired blood supply in the anterior spinal artery. Centromedullary syndrome or Brown-Séquard syndrome are much less frequently registered (in sagittal fractures with posterior displacement of one fragment). According to the authors of the classification [1], neurological disorders in CFS3 were noted in 25% of cases, in CFS4 - in 38%, in CFS5 - in 91%.

Treatment strategy

Compressive-flexion fractures due to the formation of wedge-shaped deformity of the body are always characterized by segmental kyphosis, the degree of which is largely determined by the severity of the injury. In addition, the backward displacement of the fragments of the damaged vertebra, which is observed in more severe stages, determines the pronounced instability and increases the frequency of SC injuries.

Conservative treatment is reasonable in neurologically intact patients without damage to the posterior ligamentous apparatus and significant kyphotic deformity (<11 °) or shear displacement (<3.5 mm). This category includes most patients with stages CFS1-CFS2 [10].

Therapeutic approach for patients with injuries of CFS3 stage (teardrop fractures without retrolisthesis) are chosen individually. In order to identify patients with a high risk of late instability, the progression of kyphosis and, accordingly, the development of neurological deficits, some authors recommend using the criteria of A. A. White and M. M. Panjabi [11].

At the initial stages of injury for conservative treatment, fixation of the CS with a rigid neck brace for 8–12 weeks is used. A prerequisite is regular spondylographic examination while wearing the orthosis and performing radiography with functional tests after its removal to confirm the preservation of the relative position of bone structures. It is noted that the halo device can be used in patients with higher stages of damage in the absence of neurological disorders. However, a number of studies have shown that residual kyphosis in conservative treatment is significantly greater than after ventral decompression-stabilization intervention.

Surgical management. The presence of neurological disorders and instability are absolute indications for surgery for compressive flexion injuries. Stages CFS4-CFS5 are unstable injuries that are accompanied by significant damage to the posterior ligamentous complex and / or intervertebral disc and require surgical stabilization even in the absence of neurological deficit. CFS3 injuries are also often subject to surgical correction, especially in the presence of significant kyphotic deformity. In case of CFS3-CFS5 injuries, surgical stabilization provides earlier mobilization and rehabilitation.

In order to correct kyphotic deformity and decrease shear displacement, preoperative and intraoperative traction can be used. Displacement of body fragments into the spinal canal usually requires ventral corpectomy and decompression of nerve structures. The anterior column is reconstructed using a bone graft or body replacement implant, usually a mesh cage in combination with a ventral plate, which provides a primary stable spondylodesis. The use of dynamic plates for such injuries is not recommended. It is noted that until the 1990s, posterior stabilization was considered the best method due to the higher frequency of complications when using ventral fixation systems. With the advent of titanium locking plates, which provide rigid stabilization with monocortical screws, the complication rate associated with these devices has significantly decreased.

When comparing the anterior and posterior surgical approaches in the treatment of compressive flexion injuries, it is shown that ventral decompression and fusion interventions provide complete restoration of the spinal canal diameter and regression of neurological disorders [12]. In most cases an isolated anterior approach is sufficient to achieve adequate decompression and stabilization [13]. However, in case of CFS5 injury, especially in case of a "quadrangular" fracture, 360 ° stabilization is preferred [14].

Vertical compression

Injury with a vertical compression (VC) mechanism is the result of exposure to a straight or physiologically curved spine of axially directed vector of traumatic force. Axial compressive load leads to damage to the endplates earlier than the intervertebral disc, as a result of the material of the nucleus pulposus is integrated into the vertebral body [15]. More severe injuries are characterized by displacement of bone fragments into the spinal canal, but there is no damage to the posterior longitudinal ligament, except in the presence of a minimal flexion element. Injuries with a mechanism of vertical compression are most typical for the C6 and C7 vertebrae. In some cases, damage to the posterior support complex is registered simultaneously, which leads to even greater instability of these injuries. Based on the severity of the described pathomorphological changes, B.L. Allen identifies 3 stages of injury with a mechanism of vertical compression:

VCS1 - injury is characterized by a fracture of the superoir or inferior endplate of the vertebral body with its "cup-shaped" deformity. The fracture is always central, not anterior. Signs of damage to the ligamentous apparatus are not determined ***(Fig.2A)***;

VCS2 - changes are represented by fractures of both endplates of a vertebra with "cup-shaped" deformity. Fracture lines passing through the center of the vertebra can be observed, but the displacement of the fragments in this case is minimal ***(Fig. 2B)***;

VCS3 - injuries are characterized by more pronounced damage compared to VCS2 damage to the vertebral body. Its center is fragmented, and the fragments are displaced to the periphery in several directions. If several large fragments remain, then a vertical fracture line can be verified, which is similar to CF, but significant body fragmentation is expressed. The posterior part of the vertebral body can be displaced into the spinal canal. Damage to the posterior support complex is variable. In some cases, the spinal arch is completely intact and no signs of damage to the ligamentous apparatus, in others multiple fractures of the arch with a gross damage of the posterior ligamentous complex are observed ***(Fig. 2C)***. In case of an arch fracture, damage to the ligaments between the injured and the underlying vertebra is recorded. Stage 3 injuries, in which the spinal arch is intact, are characterized by significant kyphotic deformity at the level of injury.

Thus, within the VCS3 stage, the authors actually identified two injuries subtypes, which are determined by the position of the CS at the final stage of axial load effect: late flexion subtype, which is characterized by local kyphotic deformity, and late extension subtype, which, in addition to these injuries, the displacement/ or fractures of the arch is observed.

Treatmen strategy

The main criteria that determine the treatment strategy for subaxial CS injuries with the mechanism of vertical compression are the presence of neurological disorders, the degree of compression of the spinal canal and instability, the signs of which are verified damage to the posterior support complex or solution of contiguity of the vertebrae in the injured SMS [16,17]. Trauma to the structures of the spinal canal in this type of injury is determined mainly by the displacement of fragments of the vertebral body backward. It is noted that usually the radiologically determined degree of spinal stenosis in vertical compression injuries does not fully determine

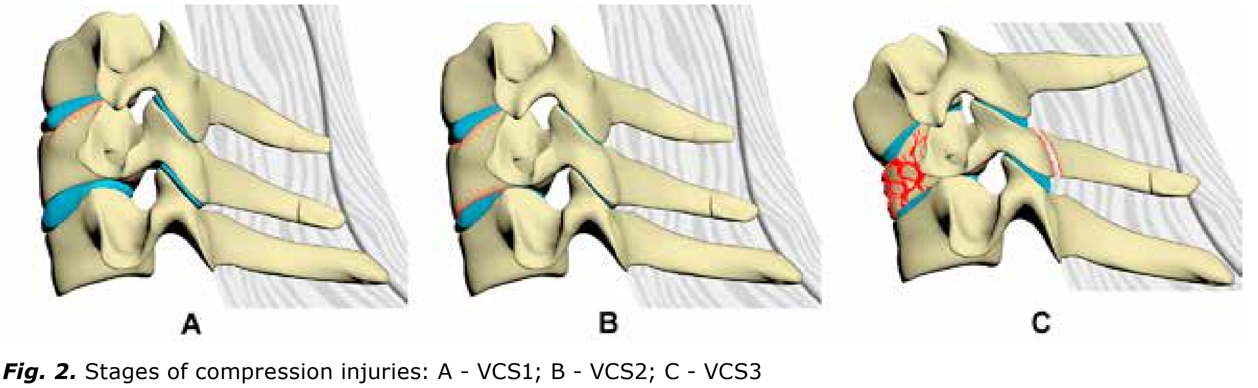

Fig. 2. Stages of compression injuries: A - VCS1; B - VCS2; C - VCS3

the severity of neurological disorders, since the actual displacement of body fragments into the canal at the time of injury is more pronounced than during study.This phenomenon is determined by passive ligamentotaxis due to the preserved posterior longitudinal ligament [17].

Conservative treatment is acceptable for VCS1 or VCS2 stages, which are characterized by damage to one or two endplates with minimal loss of body height without significant angular deformity or shear displacement. In the absence of disco-ligamentous injury, spinal stenosis and neurological deficits, which are observed in most patients with such injuries, fixation with a cervical collar is used for 12 weeks. Some authors recommend the use of a halo device to achieve greater rigidity of fixation in VCS2 injuries [18]. A prerequisite is the performance of radiography with functional tests after the date of probable consolidation has been reached.

Surgical management is indicated in the presence of neurological deficits, significant stenosis of spinal canal or violation of spinal axis. Fragmentation of the vertebral body, loss of its height, kyphotic deformity or damage to the posterior support complex, which is characteristic of VCS3, cause a high degree of instability of such injuries and, accordingly, are often accompanied by neurological disorders. Anterior corpectomy surgery followed by body replacement with a mesh cage in combination with a ventral plate or body replacement implant provides a statistically significantly more pronounced regression of neurological disorders compared to non-surgical methods of treatment [19]. Anterior approach is virtually non-alternative for traumatic injuries caused by vertical compression. Significant fragmentation of the injured vertebral body to a certain extent facilitates the performance of a corpectomy, and its fragments are used as a filler of the body replacement structure. Additional posterior fixation for compression injuries is practically not used. The exception is neurologically completely intact patients, in whom the use of posterior monosegmental transarticular / pedicle fixation allows preserving more mobile SMS. The use of preoperative traction of CS for partial indirect decompression due to ligamentotaxis is permissible, especially in cases when surgery is postponed due to medical indications [20,21].

Distractive flexion type

Distractive flexion (DF) injuries are a common type of subaxial CS injury. The most common cause of such injuries is a traffic accident where the distraction is the result of acceleration. In some cases, such injuries occur when falling. In fact, distractive flexion injuries are represented by anterior dislocations, the degree of which varies from the facet capsule distraction to complete displacement. According to C.D. Allred and J.B. Sledge, distractive flexion injuries account for about 61% of all closed subaxial CS injuries [22]. Neurological disorders of varying severity are registered in 30-90% of cases [23]. Distractive flexion injuries are more common in men aged 30-40 years. Most often the motor segment C6-C7 is damaged, less often - C4-C5 and C5-C6 [24].

The orientation of the facet joint in CS is coronal, while the inferior articular facet of the cranially located vertebra is localized backward from the superior articular facet of the caudal vertebra. Therefore, flexion in combination with distraction leads to widening of the interspace of the facet joint and damage to the ligamentous apparatus, which causes an abnormal range of motion between the articular surfaces. The superior dislocation is formed in those cases when the pole of the inferior articular process of one vertebra rests on the superior articular process of the underlying vertebra. In case of facet dislocation, which is interlocked the inferior articular process is located in front of the superior articular process. In front of the superior facet of segments C3-C6 in most cases there are the nerve root of the spinal nerve and the vertebral artery. Consequently, such displacements can lead to root compression with paresis of the corresponding muscle group or injuries of the vertebral arteries.

There are 4 stages of distractive flexion injuries, with the descriptor «flexion» indicating the location of the CS in space at the moment of injury, and «distraction» - the direction of the main traumatic force [25].

Additional damage vectors accompanying distractive flexion effects are compression, rotation, or displacement. These vectors lead to concomitant injuries, such as compression of the superior endplate of the caudally located vertebra within the injured SMS, the formation of an interlocked dislocation, or damage to the posterior support complex [26].

DFS1 - stage is characterized by damage to the posterior ligamentous complex, as evidenced by subluxation of the facet joints with pathological widening of the interspinous space in the injured SMS when bending the neck («flexion ligament sprain») ***(Fig. 3A)***. Blunting of the anterosuperior margin of the underlying vertebra to a rounded shape, reminiscent of the changes characteristic of CFS1 is often observed. In some cases, there is more pronounced compressive injury to the body of the vertebra located below by the compression-flexion type, for example, DFS1 C4,5 CFS2 C5,6;

DFS2 - unilateral dislocation of the facet is observed at this stage. The level of injury to the ligamentous apparatus can vary from partial, sufficient only for unilateral dislocation, to complete injury to both the anterior and posterior ligamentous complex. The subluxation of the facet on the side which is the contralateral side of the dislocation site, indicates significant damage to the ligaments. Rotational displacement can be observed in the injured SMS with widening of the uncovertebral joint on the side of dislocation and displacement of the spinous process towards the dislocation ***(Fig. 3B)***;

DFS3 - this stage is represented by bilateral dislocation of facets, which is accompanied by a displacement of the vertebral body forward up to 50%. The inferior facet of the cranial vertebra is located forwardly of the superior facet of the caudal vertebra, which is characteristic of a dislocation that is interlocked, or a superior subluxation is observed. In some cases, rounding of the anterosuperior margin of the vertebra located below may also be observed ***(Fig. 3C)***;

DFS4 - there is either a forward displacement of the vertebra located above the entire width of the vertebral

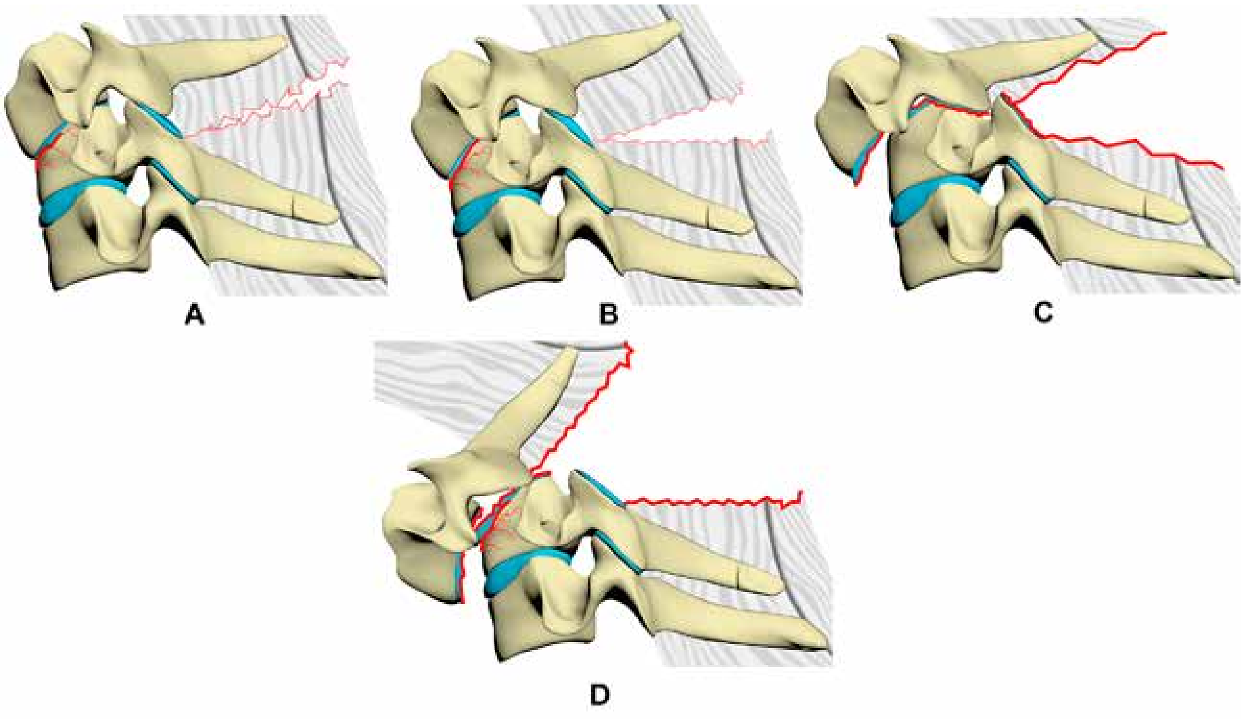

Fig. 3. Stages of distractive-flexion injuries: A - DFS1; B - DFS2; C - DFS3; D - DFS4

body, or «floating vertebra». The latter is characterized by both anterior complete dislocation and cranio-caudal diastasis in damaged SMS ***(Fig. 3D)***.

Treatment strategy

The main task of treatment of facet joints dislocations is to maintain the functional and anatomical integrity of the SC. This is achieved by restoring the spinal axis, eliminating stenosis of the spinal canal and ensuring the stability of the injured SMS [27]. These conditions are critical for the maximum possible regression of the existing neurological deficit caused by trauma, and prevention of the development of chronic pain.

Conservative treatment of distractive-flexion injuries is considered the best option for facets subluxation in case of minor damage to the ligamentous apparatus. DFS1 injuries are usually stable and allow external fixation with a cervical collar for 6–12 weeks. To prevent the formation of subacute instability, a series of spondylograms with functional tests is indicated. In patients with a clinical picture of partial damage to the SC in DFS2 – DFS4 injuries, the earlier closed reduction provides a significantly greater degree of recovery of neurological disorders [28]. Thus, D. Newton et al. describe complete recovery of neurological disorders in 5 out of 8 patients with baseline ASIA A in case of performing reduction within the first 4 hours after injury [29].

As with any other dislocation, facet joints dislocation can be repositioned in a closed or open manner. Closed reduction of SC dislocations can be performed by two fundamentally different methods: applying the skeletal traction or closed single-step manual reposition. Nowadays, the application of skeletal traction is a common technique and is based on stretching the damaged SMS to a state that allows restoring the congruence of the facet joints. Gardner bracket or its modifications are most often used to perform manipulation [30].

According to the current recommendations, it is optimal to use the initial weight from 2.5 to 5.0 kg with its subsequent increase to an indicator calculated as 2–5 kg for each SMS, located above the damaged one [31,32]. After adding the initial traction weight, X-ray control and assessment of neurological status are performed. Additional 2–5 kg are added every 5–10 min depending on the relative position of the dislocated facets, followed by X-ray examination and clinical evaluation. After reaching the diastasis of the articular surfaces of the facets, stretching, which is gradually intensified, is combined with flexion of the CS to facilitate reposition. After repositioning the dislocation, the traction weight is reduced to 10–20 kg, and the CS is slightly unflexed to increase the contact area of the articular surfaces and reduce the risk of recurrence of the dislocation. In case of unilateral dislocation of the facet, turning the head up to 40 ° towards the dislocation can facilitate repositioning.

According to the literature, the main contraindications to closed reduction with the use of skeletal traction are impaired patient's consciousness, which excludes the possibility of assessing neurological status when performing manipulations, refusal to perform commands, for example, in case of mental and behavioral disorders due to alcohol intoxication, the presence of instrumentally verified bone fragments in spinal canal or traumatic extrusion of the intervertebral disc.

Some authors question the economic feasibility of performing magnetic resonance imaging for reposition. Thus, R.A. Hart et al. demonstrated the safety of closed reduction using skeletal traction in neurologically intact patients while maitaining consciousness [28]. G.A. Grant recommends the earliest possible reduction of CS dislocations without additional magnetic resonance imaging in patients with severe neurological disorders [33]. In addition, a number of studies have shown that closed reduction in patients with underlying medicamental sedation in most cases is safe [33, 34].

In addition to the described method, wire pulling methods for the parietal bone or zygomatic arches were previously used, but now they have historical rather than practical significance.

Closed single-step reduction is an alternative to skeletal traction. The main indication is the need for immediate elimination of the violation of the configuration of the spinal canal and compression of the SC. Definitive advantage of the method is the ability to quickly perform manipulations even in the absence of specialized technical support. Cases of successful manual reduction of dislocations due to inefficiency of skeletal traction are described. Considering the large number of methods proposed by both domestic and foreign authors, manual single-step reduction is effective in a wider range of pathomorphological changes that accompany distractive-flexion injuries ***(Fig. 4A)*** [35,36]. Closed single-step reduction is often performed with underlying general anesthesia in order to achieve adequate muscle relaxation [37]. Here is one of the common algorithms [38]:

–1st stage: traction along the longitudinal axis of the spine for several minutes with a gradual increase in effort ***(Fig. 4B)***;

–2nd stage: without weakening the effort, the direction of traction by 10–12 ° upwards is changed. In this case the flexion of CS is reached. As a result, the displaced forward articular processes are raised from the superior vertebral notch of the vertebra located below and the dislocation, which is locked, turns into a dislocation with a high standing of the articular processes ***(Fig. 4C)***;

–3rd stage: without weakening the effort, the direction of traction is changed by 20–30 ° downward, reaching the extension of the CS. In this case the condition of the articular processes is normalized, but the diastasis of the joint space is preserved ***(Fig. 4D)***;

–4th stage: gradual decrease of traction with extension of CS which continues ***(Fig. 4E)***.

Unlike common «lever» methods, the described method is based only on the principle of ligamentotaxis [36]. It does not provide for rotational movements and support on the articular process during reduction, which prevents the occurrence of traumatic intervertebral hernias or interposition of bone fragments in the presence of fractures of the elements of vertebral arches of the damaged SMS. Performing a closed single-step reduction requires certain skills and appropriate qualifications from the surgeon.

Surgical management. Open reduction and spondylodesis are indicated in case of ineffective closed reduction and contraindication to closed reduction. In addition, even in case of spinal axis restoration in DFS2 – DFS4 injuries, spondylodesis is mandatory, since such injuries are characterized by damage to both the anterior discoligamentous apparatus and the posterior ligamentous complex. Conservative management of patients with reduced dislocation of SC at the subaxial level with immobilization with a rigid head supporter is considered ineffective due to a significantly higher risk of

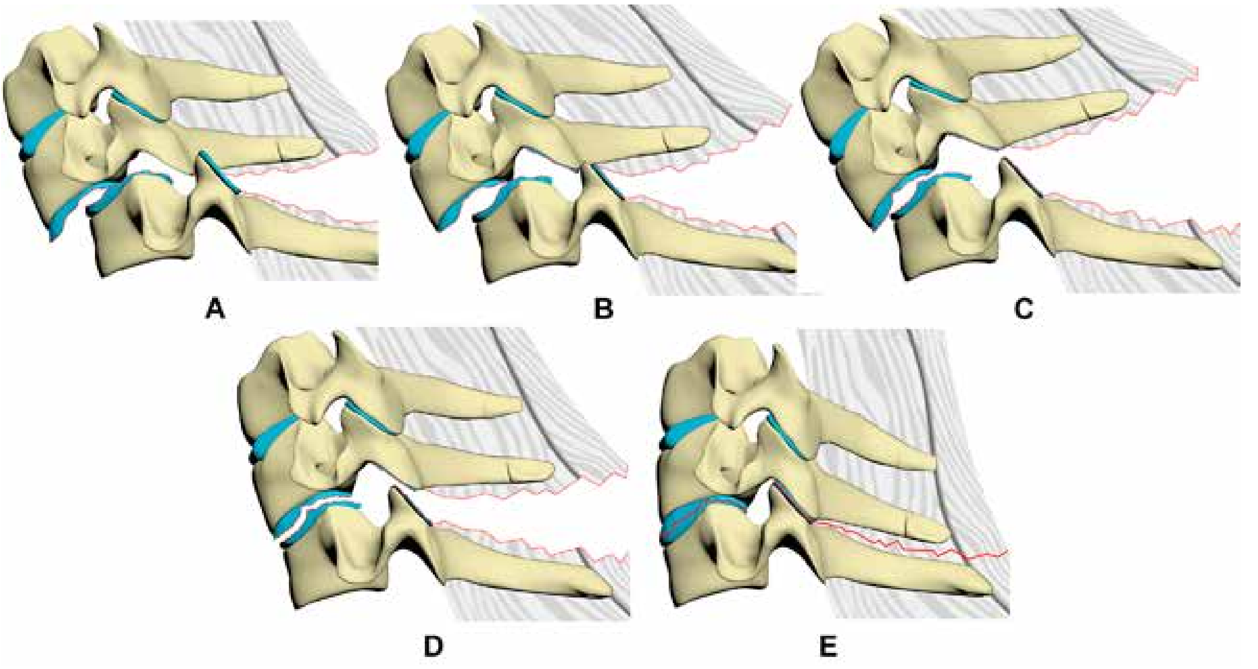

Fig. 4. Stages of closed single-moment reduction according to S.N. Nekhlopochin et al. [38]. A - the original picture; B - 1st stage: axial traction; C - 2nd stage: traction with flexion; D - 3rd stage: traction with extension; E - 4th stage: extension without traction

instability, chronic pain and distant neurological disorders with repeated dislocations [39]. Surgical approaches for unilateral or bilateral dislocations include isolated anterior, posterior, combined anteroposterior, and staged anteroposterior-anterior [40, 41]. The choice of the optimal surgical method depends on a large number of factors: the degree of instability, the presence of ventral compression, the possibility of open indirect reduction, etc. [42]. The advantages and disadvantages of various surgical approaches have been discussed earlier [43].

Compressive-extension type

The main causes of compressive extension (CE) subaxial CS injuries are falling or diving into a small body of water, when the point of contact with the surface is the forehead or face. The axial load falls mainly on the posterior support complex, causing unilateral or bilateral damage of it at the initial stages without significant displacement of bone fragments. In case of traumatic force that continues, the center of rotation of the extension moment is shifted forward and downward, causing a rupture between the anterior and posterior support complexes of the injured vertebra. The following pathomorphological stages of compressive extension injuries are proposed in the classification:

CES1 - injury is characterized by a unilateral fracture of the vertebral arch with rotation and forward displacement or without such. Arch injury can be a linear fracture of the articular process ***(Fig. 5A)***, compression of the articular process, ipsilateral fracture of the pedicle ***(Fig. 5B)*** or fracture of the lamina ***(Fig. 5C)*** or a combination of ipsilateral fracture of the pedicle and articular process. Rotational displacement can occur in any of these fractures, but is not a fundamental feature and is usually less pronounced compared to DFS2;

CES2 –injury is a bilateral fracture of the lamina without other signs of osteo - traumatic changes. It is most often observed at several adjacent levels ***(Fig. 5D)***;

CES3 - injury is characterized by bilateral fractures of the vertebral arch - articular processes, pedicles, lamina or any combination without displacement of the vertebral body ***(Fig. 5E)***;

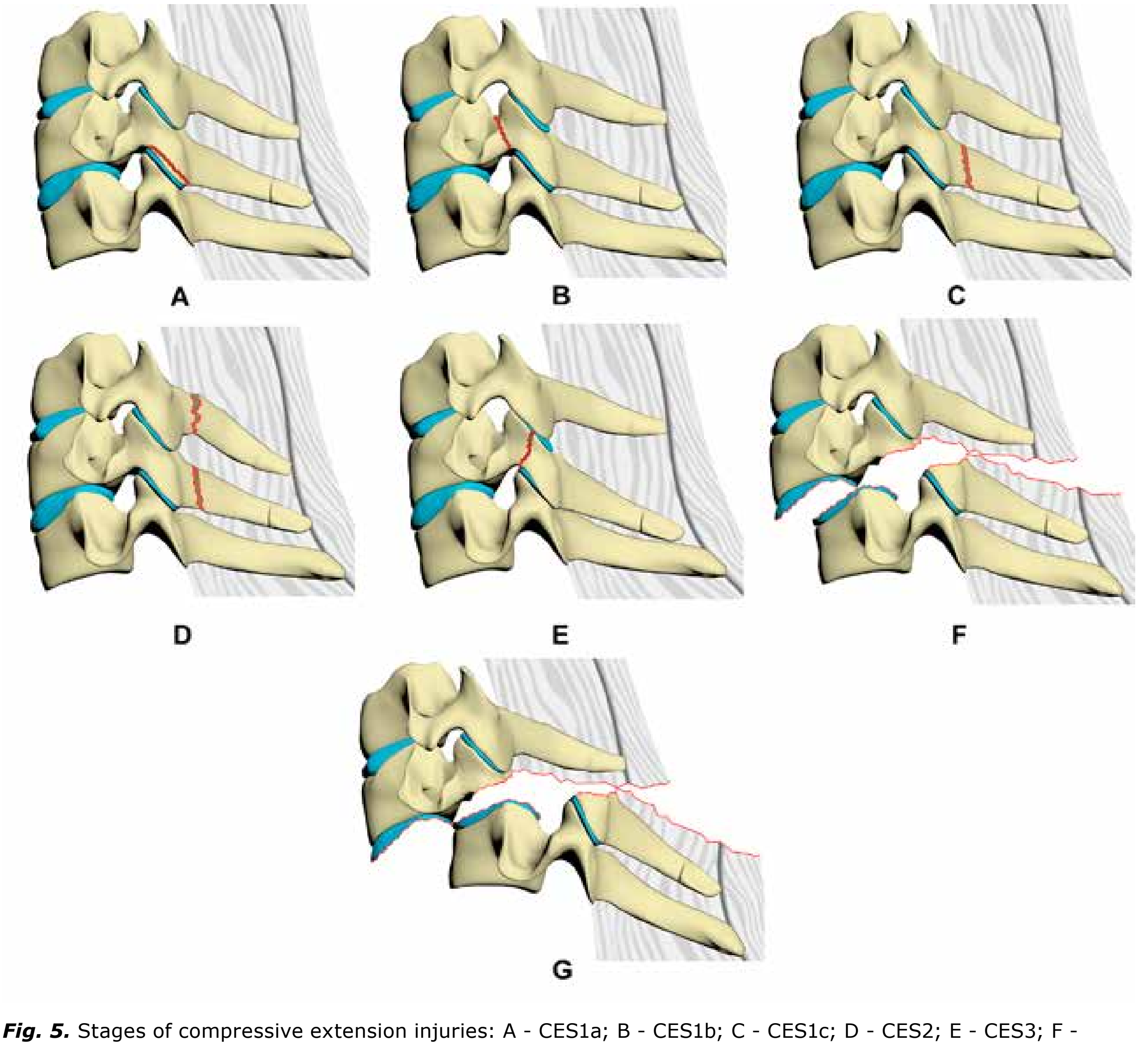

Fig. 5. Stages of compressive extension injuries: A - CES1a; B - CES1b; C - CES1c; D - CES2; E - CES3; F - CES4; G - CES5

CES4 - injury is accompanied by bilateral fractures of the vertebral arch with a forward displacement less than the width of the vertebral body ***(Fig. 5F)***;

CES5 - injury is a bilateral fracture of the vertebral arch with a forward displacement over the entire width of the vertebral body. In this case the posterior part of the arch of the injured vertebra is not displaced. Damage to the ligamentous apparatus is observed at two levels (posteriorly, between the injured vertebra and the vertebra located above, and anteriorly between the injured and caudal vertebrae). The anterosuperior part of the body of the vertebra located below is often damaged by the forward-displaced body of the cranial vertebra ***(Fig. 5G)***.

In the original publication, the CES3 and CES4 stages are presented «theoretically», since the authors did not observe such injuries in the analyzed group of patients [1]. However, their existence was subsequently confirmed by relevant clinical cases [44,45].

The actual incidence of compressive extension injuries of the SC is difficult to assess, since the initial stages may be asymptomatic. Moreover, even the CES4-CES5 stages, which are formed under the influence of significant traumatic force and are accompanied by large osteoligamentous injries, are not always accompanied by neurological disorders due to spontaneous decompression of the spinal canal and relative preservation of the spinal axis. According to E. Rebich et al., the average diameter of the spinal canal at CES4 is 20 mm, at a more severe stage of CES5 is 30 mm [45].

Treatment strategy

The treatment strategy of compressive extension injuries is determined mainly by the stability of the injury than by other criteria. The exception is traumatic extrusions of intervertebral discs, which are rarely formed against the background of ventral displacement of the damaged vertebral body.

In general, it is believed that CES1-CES2 injuries are stable, therefore the best method is conservative therapy with external fixation of CS with rigid cervical brace [46]. Surgical correction for such injuries is performed only with significant secondary rotational deformity in cases of asymmetric damage to facet joints.

External immobilization can also be used in the treatment of CES3 injuries, but only with a halo device [47]. However, a more reliable method that provides early rehabilitation is surgical stabilization [48]. It is possible to connect the anterior and posterior vertebral fragments with cannulated screws to maintain the mobility of adjacent SMS or transpedicular fixation [49]. In general, the treatment strategy of CES3 injuries are quite controversial, since this type of injury is quite rare and is only sporadically mentioned in publications.

The absolute indications for surgery are the CES4 and CES5 stages, due to the pronounced instability of the lesions. It is noted that the spinal axis deformity can be corrected by preoperative and intraoperative traction, although many authors recommend refraining from traction in any extension injuries [2]. The method of choice for such injuries is posterior monosegmental or bisegmental stabilization. In case of significant destruction of the body or the presence of ventral compression of the structures of the spinal canal, a combined anteroposterior approach is used. Isolated ventral spondylodesis is rarely used [45].

One of specific types of SC injuries, characteristic mainly for compressive extension injuries, is the centromedullary syndrome, which occurs mainly in elderly patients. At the same time the frequency and severity of neurological disorders do not correlate with the severity of osteoligamentous damage. The pathogenesis of SC injury in hyperextension is represented by several mechanisms [20]. In 1951, A.R. Taylor demonstated that CS hyperextension leads to narrowing of the spinal canal by up to 30% [50]. Therefore, the compression of the SC in compressive extension injuries is due to the narrowing of the spinal canal, which is usually already stenosed in elderly patients, the protrusion of the folds of the ligamentum flavum and the presence of osteophytes. The prognosis for recovery of neurological function is generally favorable, but significant residual hand dysfunction and transient spasticity may be observed [51]. Previously, conservative methods of treatment of centromedullary syndrome were preferred [52], but studies conducted in recent decades demonstrate a greater regression of neurological disorders in decompression performed depending on the clinical situation from anterior or posterior approach [53,54].

Distractive extension type

Distractive extension injuries (DE) account for 8–22% of all subaxial CS injuries [55,56]. The vector of traumatic force, which causes hyperextension of the CS, but does not contain a compression component, first leads to the disco-ligamentos injury of the anterior support complex without displacement [1]. If the exposure continues, then damage to the posterior support complex occurs, which is accompanied by either isolated damage to the ligamentous apparatus or osteoligamentous injury. Such injuries often result in neurological impaiments due to the SC compression between the stable lamina of the underlying vertebra and the backwardly displaced body of the cranially located vertebra. Pathological conditions that reduce the flexibility of CS (ankylosing spondylitis and diffuse idiopathic skeletal hyperostosis) lead to distractive extension injuries associated with trauma to the frontal region or face [57]. There are 2 stages of distractive extension injuries in the classification:

DES1 - injury is characterized by damage to the anterior ligamentous complex or a transverse displaced fracture of the vertebral body. If mainly the disco-ligamentous complex is injured, which is observed in most cases, then there may be a separation of the anterosuperior margin of the body of the vertebra located below. The radiographic finding of the injury is usually an abnormal expansion of the disc space. Backward displacement is not registered ***(Fig. 6A)***;

DES2 - in addition to the changes observed in DES1, there is damage to the posterior ligamentous complex with displacement of the superior vertebral body posteriorly and compression of the spinal canal. Most minor injuries of this type tend to spontaneously reduce when bending forward. Therefore on spondylograms displacement of a body dorsally to 3 mm is often registered ***(Fig. 6B)***. The most severe form of DES2 is a posterior dislocation.

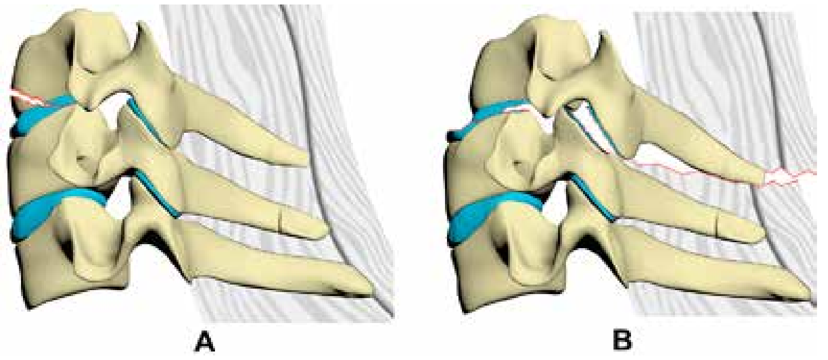

Fig. 6. Stages of distractive extension injuries: A - DES1; B - DES2

Treatment strategy

The treatment strategy of distractive extension injuries are still not clearly defined. Thus, DES1 as relatively stable lesions, according to some authors, are subject to conservative therapy with fixation of the CS using halo device [58]. However, applying a halo device, in addition to the associated risks of infection, does not completely prevent secondary displacement, even in DES1 injuries [47]. In the presence of ankylosing spondylitis or other connective tissue pathology, surgical stabilization is indicated regardless of injury level. A.R. Vaccaro et al. when analyzing one of the numerous series of patients it was found that surgery for DES1 injury was performed in 64% of cases [59]. ACDF (ventral discectomy and stabilization) is most commonly used.

All DES2 type injuries are subject to surgical stabilization, preference is given to posteroanterior approaches (posterior open direct reduction with removal of fragments of the posterior support complex if necessary and stabilization followed by anterior fixation).

Distractive extension injuries are accompanied by high mortality, partly due to the significant age of patients. Mortality in the postoperative period reaches 31%, with conservative therapy - 63% [59].

Lateral-flexion type

Lateral flexion (LF) type of injury is formed by tilting the head to one side, respectively, any compression effect leads to an asymmetric fracture of the vertebral body and unilateral fracture of the elements of the posterior support complex, with the fracture line lying in the sagittal plane. Neurological disorders in such injuries are rare and can be caused mainly by compression or avulsion of the roots [2]. There are 2 stages of lateral-flexion injuries in the classification:

LFS1 - injury is an asymmetric compression fracture of the vertebral body in combination with a fracture of the arch on the ipsilateral side without displacement of fragments on the anteroposterior spondylograms. Compression of the articular process can be determined on computed tomograms. Asymmetric damage to the vertebral body can be manifested in the form of uncovertebral fracture with slight compression of the adjacent cranial body in the area of the uncovertebral joint ***(Fig. 7A)***;

LFS2 - injury is characterized by lateral asymmetric compression of the vertebral body, ipsilateral fracture of the arch with displacement of fragments, defined on the anteroposterior spondylograms and / or rupture of ligaments on the contralateral side with diastasis of articular surfaces ***(Fig. 7B)***.

Treatment strategy

Most LFS1 injuries are treated conservatively. Surgery is used mainly for root decompression. More severe injuries (LFS2), which are accompanied by rupture of the ligamentous apparatus on the contralateral side, are potentially rotationally unstable and require stabilization. In addition, in some cases, laterolisthesis may occur, which also requires surgical correction [60]. Depending on the clinical situation, anterior or posterior approach can be used [61].

In 2020, the WFNS Spine Committee published updated guidelines on the principles of management of traumatic subaxial CS injuries [62]. The following are the main strategic aspects of the treatment of CS injuries, which are based on the classification of B.L. Allen ***(Table 1).***

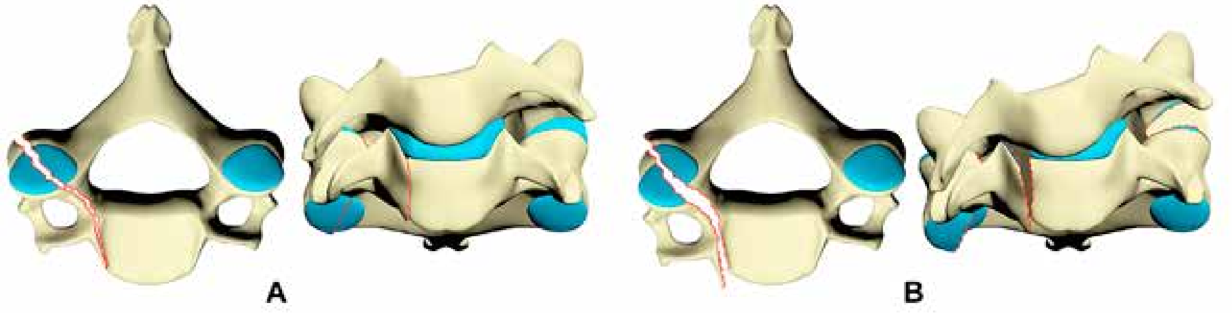

Fig. 7. Stages of lateral flexion injuries: A - LFS1; B - LFS2

Table 1. Therapy of subaxial cervical spine injuries according to the morphology of the injury (according to S. Sharif et al.[62])

Type / stage of injury according to the classification of B.L. Allen	Treatment
VCS1–VCS2	External fixation for 8-12 weeks
VCS3	- Halo brace immobilization for 12 weeks in the absence of neurological disorders - In the presence / appearance of neurological disorders - ACCF (ventral corpectomy and stabilization) or posterior transarticular / transpedicular fixation
CFS1–CFS2	External fixation for 8-12 weeks
CFS3–CFS4	ACCF (ventral corpectomy and stabilization)
CFS5	- ACCF (ventral corpectomy and stabilization) - Combination of ACCF with posterior stabilization in case of significant damage to posterior ligamentous apparatus or multilevel corpectomy
DFS1	Rigid external fixation for 8-12 weeks
DFS2	Closed posterior or anterior open reduction
DFS3–DFS5	Open anterior or posterior reduction
CES1–CES2	Rigid external fixation for 12 weeks
CES3	Halo brace immobilization
CES4–CES5	- Multilevel posterior transarticular / transpedicular fixation - In case of significant damage to the vertebral body - additional ACCF
DES1	ACDF (ventral discectomy and stabilization)
DES2	- Posterior reduction and stabilization + ACCF / ACDF in case of damage to the anterior support complex - In case of restoration of the spinal axis with light traction - multilevel posterior stabilization - If recovery is not possible – posterior reduction and stabilization + ACCF
LFS1	Conservative treatment
LFS2	Posterior stabilization of one motor segment

Conclusions

The data presented in the review quite convincingly, in our opinion, demonstrate that the classification of traumatic subaxial cervical spine injuries, developed by B.L. Allen, is a convenient tool for assessing pathomorphological changes. Determining the type and stage of traumatic injuries with proper practical skills is not difficult for professionals. The availability of detail and a large number of publications allow you to choose the optimal method of treating the patient in a specific clinical situation.

Disclosure

Conflict of interest

The authors declare that they have no conflicts of interest.

Ethical approval

This article is a literature review, therefore no ethics committee approval was required.

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