Eur Spine J (2001) 10 : 38–43
DOI 10.1007/s005860000212

ORIGINAL ARTICLE

J. Patijn
J. Wilmink
F. H. J. ter Linden
H. Kingma

CT study of craniovertebral rotation in whiplash injury

Received: 17 May 2000
Revised: 9 August 2000
Accepted: 23 August 2000
Published online: 22 November 2000

J. Patijn (✉)
Division of Neurology,
Foundation for
Manual/Musculosketal Medicine,
Stratumsedijk 26,
5611 ND Eindhoven, The Netherlands
e-mail: smg@worldonline.nl,
Tel.: +31-40-2116380,
Fax: +31-40-2112644

J. Wilmink
Department of Neuroradiology,
University of Maastricht,
University Hospital Maastricht,
The Netherlands

F. H. J. ter Linden
Department of Radiology,
Diaconessenhuis Hospital,
Eindhoven, The Netherlands

H. Kingma
ENT Department,
University of Maastricht,
University Hospital Maastricht,
The Netherlands

Abstract The present study investigates the diagnostic value of rotatory computed tomography (CT) examinations in normal subjects and patients with whiplash associated disorders (WAD), with the aim of reproducing earlier findings of rotatory CT studies. Forty-seven WAD patients with persistent complaints after a rear-end collision (non-cranial contact acceleration/deceleration trauma) were enrolled in this study. To guarantee a maximally homogeneous study population, only WAD patients with a marked passive cervical retroflexion restriction were included. Transversal CT slices in left and right rotation were made for all cervical levels (the skull included). CT slices in neutral position were used to reconstruct partially depicted vertebrae. Absolute rotatory values were estimated according the method of Penning and Dvorak. For all levels the relative rotatory (RR) value was calculated by dividing absolute rotation values of a particular cervical level by the corresponding total cervical rotation. The measuring error was estimated by comparing the findings of two separately performed measuring procedures. Two age groups of WAD patients were formed. A younger group was matched for age with 26 normal healthy volunteers (the original data of an earlier study). The use of neutral CT slices for reconstruction of a partially depicted cervical vertebra resulted in a measurement error of 1.9° at the level of C0/C1 (occiput/atlas) and 3.5° at C1/C2. Suspected hypermobility as defined by Dvorak was rare in our WAD patients (6.4% C0/C1 and 10.6% C1/C2). RR values at C0/C1 were significantly larger in 79% of the WAD patients. Discriminant analysis of the RR values showed 80% correctly classified WAD patients. Only 11.5% of the normal subjects were classified as false-positive. Since no hypermobility was found at C1/C2, a traumatic lesion of the alar ligaments is less likely. It was concluded that the use of absolute rotation values in rotatory CT scan procedures has a low diagnostic value in WAD patients. Excessive RR values were only found at C0/C1. A traumatic lesion of the ligaments at C0/C1, which prevent vertical translation of the skull with regard to the atlas, is hypothesised. The results of the discriminant analysis of the RR values make this method applicable for the individual WAD patient in daily practice.

Keywords WAD · Rotatory CT scan · Alar ligaments · Relative rotation value · Cervical spine

Introduction

In whiplash associated disorders (WAD [18]), most radiological imaging techniques for the cervical spine are inconclusive with respect to the possible presence of soft tissue injuries. Conventional radiograms are notorious for their negative outcome in WAD patients. Soft tissue lesions can only be deduced from indirect signs in these patients. New techniques such as magnetic resonance imaging (MRI) did not solve this problem, the more so as MRI of the cervical spine showed abnormalities in 19% of non-symptomatic subjects [3]. MRI abnormalities in WAD patients in the acute phase were not correlative with the patients' subjective symptoms and clinical signs [10]. Two MRI studies in WAD patients revealed higher percentages of MRI abnormalities of the cervical spine than in normal subjects, ranging from 25 to 34% [11,17]. In one of these studies [11], 38% of the patients had clinical symptoms of a radicular syndrome 6 weeks after the trauma, which corresponded well with the MRI findings in 63% of this group. At operation, fresh disc ruptures were found in ten patients. Extensive ruptures of the zygopophysial capsules were seen in two operated patients [11]. These findings support the hypothesis that the zygopophysial joint can be regarded as an important source of pain in WAD patients [2].

Until recently, functional radiological studies have been inconclusive with regard to the precise localization of the injured cervical structures [9]. Most functional radiological studies were performed in the sagittal plane and only focused on cervical motion segments (C2/C3–C6/C7) with an intervertebral disc. Findings such as monosegmental hyper- or hypomobility, estimated by measuring the angle between two vertebrae in different cervical postures, were interpreted as an injury of the corresponding intervertebral disc [12,13].

Introduction of CT made possible the radiological analysis of cervical function in the horizontal plane of the cervical spine [16].

In normal subjects, the largest rotation (55%) is seen at the C1/C2 motion segment, whereas no rotation exists at the C0/C1 motion segment [16,22].

Dvorak et al. [5] defined criteria for suspected rotatory instability or hypermobility of the spine in WAD patients. As a normal group they used the measurements of nine healthy volunteers [1,7] and the data of a study in 27 normal subjects by Penning and Wilmink [16]. Cervical rotatory CT in cadavers [4] and patients [1, 5, 7,8] led to the hypothesis that rotatory instability in WAD patients is based on a lesion of the alar ligaments. In all rotatory CT studies of whiplash patients [1, 5, 7,8], only subjects with soft tissue injuries were included. No further inclusion criteria were mentioned. Until now, no MRI reliability study has confirmed such a lesion in WAD patients [3, 19, 20,23].

The purpose of our study was to reproduce earlier findings of rotatory CT procedures in a more homogeneously defined group of WAD patients.

Materials and methods

Subjects

Forty-seven patients classified as WAD [18] (male = 21, female = 26) with persistent complaints (>6 months) after a rear-end collision (only non-cranial contact acceleration/deceleration trauma) were enrolled in this study. Further inclusion criteria were:

1. No neurological deficit
2. No traumatic abnormalities on standard cervical X-rays
3. Age brackets 20–30 years and 30–40 years
4. To maximise the chance of finding abnormal rotatory CT results, only WAD patients in which the cervical passive retroflexion was the most restricted, when compared to passive cervical rotations, lateralflexions and anteflexion, were included [14]

Data of the younger WAD group were compared with those of 26 age-matched normal healthy volunteers (the original data of Penning and Wilmink [16]). Data from both WAD age groups were compared with one another. Statistical analysis, *t*-test (paired samples two-tailed) and discriminant analysis (Wilks stepwise) were performed with the SPSS statistical package (standard version).

CT scan procedures

The patient was supine in neutral position on the CT table (Philips Tomoscan, 350, 120 kV, 150 mAs, and slice thickness 9.0 mm). A lateral scout view was used for estimation of the direction of the scan levels and the total scanning section. The angularity of the scan levels was defined by the line through the anterior and posterior tubercles of the atlas on the scout view. The scanning section was bordered cranially by the external acoustic meatus and caudally by the body of the seventh cervical vertebra. After the completion of the neutral scan, the head was passively rotated as far as possible to the left, and fixed by tape. After the scanning, this procedure was repeated with maximal passive rotation of the head to the right. To get clear transversal CT slices of the vertebrae, lateral flexion was avoided as much as possible during rotations. The same scanning section was used for left and right rotation. The shoulders remained in the horizontal plane and the patient's position on the CT table was not altered during the whole scanning session.

Measurement procedures

On all neutral CT slices of the different motion segments (C0/C1–C6/C7 (skull = C0) corresponding anatomical landmarks on each side of the midline were estimated. For the skull (C0), both caudal borders of the hypoglossal canals were used. For the seven cervical vertebrae the vertebral foramina were chosen. A line was drawn through the two anatomical landmarks at the cervical levels C0–C7. The lines of the eight neutral levels were transported to the corresponding left and right rotatory CT scans. By superposition of the rotatory CT slice on the corresponding neutral CT slice, the line of the neutral CT slice was traced on the rotatory CT slice. In this way, the similarity of the anatomical landmarks at all levels was guaranteed to be as accurate as possible. As a rule, the tilting of a vertebra leads – due to lateral flexion during rotation – to a partial representation of the transversal cross-section of this vertebra. The cross-section of this partially represented vertebra was re-

constructed by superposition on the corresponding neutral CT slice, with a line drawn through both anatomical landmarks. Hereafter, the line of the neutral CT slices was traced on the rotatory CT slice. The rotations at the eight cervical levels were defined by the angle between the line through the identical anatomical landmarks and the horizontal plane, represented by the lower margin of the picture.

The rotation value between two vertebrae of a certain cervical motion segment was calculated by subtraction of the individual rotation values of the two constituent vertebrae and expressed in whole degrees.

Patients' findings were compared to the pathological values proposed by Dvorak [1,7]. In addition to this, the relative rotation (RR) values were calculated by dividing the absolute left or right segmental rotation by the corresponding total left or right rotation (C0/C1). In normal conditions, it is supposed that every motion segment (C0/C1...C6/C7) of the cervical vertebral column (skull included as level C0) accounts for a certain percentage of the total rotation. The measurement error was determined by comparing the data of two separately repeated measuring procedures.

Results

Table 1 shows the mean absolute left/right rotation values (degrees) of the normal subjects, of the two WAD age groups separately, and of the entire WAD group. Within each of the two WAD age groups, no difference was found between the absolute left and the absolute right rotation values of C0/C7, C0/C1...C6/C7 and C2/C7. The same was true for absolute rotation values of the normal group and of the entire WAD group. In both the normal group and the entire WAD group, no correlation was found between age or gender and the different absolute rotation values.

Except for the level C2/C3, the rotation of each individual level differed significantly in comparisons between the two WAD groups and in comparisons between the whole WAD group and normals. The same was true for total cervical rotation along C0/C7 and the rotation of the region C2/C7 (see Table 1).

In contrast to significant hyporotation at the majority of the levels, the C0/C1 level showed a significantly larger rotation when compared with normal values.

Only three WAD patients (6.4%) showed absolute rotation values of C0/C1 fitting Dvorak's criterion of hypermobility (rotation >7°) [1,7]. Hypermobility, defined as a pathological difference in left/right rotation at C0/C1 (difference >5°) was found in two patients (4.3%). At C1/C2, no WAD patient exceeded the value of 54°, defined by Dvorak [1,7] as pathological. An abnormal left/right rotation difference at C1/C2 of more than 8° was found in 10.6% of our WAD group [1,7]. Left- or right-sided hypomobility (less than 29°) at C1/C2 was found in 31.9% (left) and 38.3% (right) of the WAD group [1,7]. None of the WAD patients showed a paradoxical rotation at C0/C1, defined as C0/C1 rotation in the contralateral direction [1].

Based on the two separately performed measurement procedures, we found a mean measurement error for C0/C1 of 1.9° (SD 1.4), for C1/C2 of 3.5° (SD 3.1) and for the entire rotation C0/C7 of 3.2° (SD 2.4). The mean measurement error for the whole procedure was 3.1°. Within the normal group, within both WAD age groups and within the entire WAD group, left and right RR values showed no differences. There was no correlation between the age of the subjects and the RR values of the different motion segments in either the normal group or the entire WAD group.

Table 2 illustrates the mean left and right RR values (in percentages) of the normal subjects, of the two WAD age groups separately, and of the entire WAD group. At C1/C2, which normally shows the largest rotation, no difference between the two WAD age groups and normal subjects was found. In the two WAD age groups and the entire WAD group, the significantly higher RR values of C0/C1 reflect a disproportionately large a part of the total rotation of this level. In the lower cervical motion seg-

Table 1 The absolute mean left/right rotation values (degrees) and their standard deviation (in parentheses), for normal subjects and for the whiplash associated disorder (WAD) patients, for each age group separately and for the entire WAD group. The significant differences between the WAD groups and the normal group are shown

Segment	Normals, Age 20–30 years (*n*=26)		WAD, Age 20–30 years (*n*=21)		WAD, Age >30 years (*n*=26)		Entire WAD (*n*=47)	
	Left	Right	Left	Right	Left	Right	Left	Right
C0/C1	1.4 (1.4)	1.4 (1.4)	3.0* (2.1)	2.3* (2.8)	2.5 (2.3)	3.8** (2.9)	2.8* (2.2)	3.5*** (2.9)
C1/C2	42.3 (3.8)	38.9 (5.3)	32.3*** (6.2)	31.8** (7.7)	32.1*** (7.9)	31.5** (6.5)	32.2*** (7.6)	31.6*** (7.0)
C2/C3	3.0 (1.2)	3.0 (3.2)	3.4 (3.3)	3.3 (3.6)	3.0 (3.0)	3.8 (3.1)	3.2 (3.1)	3.6 (3.3)
C3/C4	6.3 (2.3)	6.6 (2.3)	2.8*** (2.1)	4.3** (2.6)	4.9 (4.4)	6.0 (4.2)	4.0** (3.7)	5.3 (3.7)
C4/C5	7.0 (2.1)	6.5 (2.6)	5.1 (3.7)	5.2 (3.5)	5.2* (3.0)	4.5* (2.8)	5.1* (3.3)	4.8* (3.1)
C5/C6	6.9 (1.8)	7.0 (2.9)	3.5** (3.7)	2.7*** (2.1)	3.3*** (3.5)	3.3** (2.7)	3.4*** (3.6)	3.0*** (2.5)
C6/C7	5.2 (2.6)	5.6 (2.2)	2.0** (1.8)	2.3*** (1.8)	2.5** (1.8)	2.8*** (1.7)	2.3** (1.8)	2.6*** (1.7)
C2/C7	28.4 (4.5)	28.8 (4.3)	17.0*** (8.2)	18.2*** (6.6)	16.1*** (7.2)	18.7*** (6.3)	16.5*** (6.9)	18.5*** (6.4)
C0/C7	72.1 (4.3)	69.1 (5.8)	51.8*** (8.2)	51.5*** (9.3)	50.2*** (11.9)	52.8*** (10.7)	50.9*** (10.3)	52.2*** (10.0)

*P<0.05; **P<0.01; ***P=0.000

Table 2 The mean left/right relative rotation (RR) values (as percentages) and their standard deviation (in parentheses) in the normal subjects, in both WAD age groups and in the entire WAD group. The significant differences between the WAD groups and the normal group are shown

Segment	Normals age 20–30 years (*n*=26)		WAD age 20–30 years (*n*=21)		WAD age >30 years (*n*=26)		Entire WAD (*n*=47)	
	Left	Right	Left	Right	Left	Right	Left	Right
C0/C1	2.0 (2.0)	2.0 (2.0)	6.0** (4.5)	6.3** (5.4)	5.2* (5.0)	7.1** (5.5)	5.5* (4.7)	6.8** (5.4)
C1/C2	58.3 (5.1)	56.1 (6.4)	63.0 (10.5)	62.0 (10.6)	64.4 (9.9)	60.4 (9.4)	63.8 (10.1)	61.1 (9.9)
C2/C3	4.2 (3.4)	4.2 (4.5)	7.0 (7.0)	6.3 (6.5)	5.8 (5.3)	7.0 (5.7)	6.3 (6.1)	6.9 (6.0)
C3/C4	8.7 (2.9)	9.5 (3.6)	5.2* (4.0)	8.4 (5.2)	9.3 (8.2)	11.4 (8.0)	7.5 (6.9)	10.1 (7.0)
C4/C5	9.6 (3.0)	9.4 (3.6)	10.3 (9.5)	10.0 (6.4)	10.7 (6.4)	8.7 (5.8)	10.5 (7.8)	9.3 (6.0)
C5/C6	9.6 (2.6)	10.0 (4.1)	6.7 (7.5)	5.2** (3.9)	6.7 (6.4)	6.4* (4.9)	6.7 (6.8)	5.9** (4.5)
C6/C7	7.0 (3.2)	8.1 (3.0)	4.1* (4.1)	4.8** (3.7)	5.3 (4.4)	5.2** (3.0)	4.9 (4.2)	5.0** (1.7)
C2/C7	39.3 (5.1)	41.2 (4.7)	32.2* (10.6)	35.4* (11.6)	31.7* (10.6)	35.1* (8.9)	31.4* (10.5)	35.2* (10.2)

>**P*<0.05; ***P*<0.01

Table 3 Discriminant analysis (stepwise, Wilks) with RR values of C0/C1, C2/C7, C5/C6 and C6/C7 in 26 normal subjects and in 47 WAD patients

Actual Group	Predicted group membership	
	WAD	Normals
WAD (*n*=47)	37 (79.8%)	9 (20.2%)
Normals (*n*=26)	3 (11.5%)	23 (88.5%)

A total of 81.7% of original grouped cases correctly classified

ments (C5/C6, C6/C7) significantly smaller RR values were found.

In the normal group, the 95% confidence interval of the RR value of C0/C1 ranged from 1.3% to 3.4%. Using the upper limit as the largest normal RR value, 37 patients (79%) had an abnormal RR value of C0/C1. No RR value of C0/C1 in the normal subjects exceeded the limit of 3.5%. The same was true for the RR value of the region C2/C7.

Discriminant analysis (stepwise, Wilks) showed the most accurate classification into WAD patients and normals, using RR values of C0/C1, C5/C6, C6/C7 and C2/C7. No correlation was found between the RR values of C5/C6 and C6/C7 and RR value of the region C2/C7. Discriminant analysis resulted in a correct classification of 81.7% of the original grouped cases (Table 3). Of the entire WAD group, 79,8% were correctly classified. In the normal group, 11.5% were classified as WAD patients (false-positives).

Discussion

In previous rotatory CT studies in WAD patients, different numbers of patients with abnormal absolute segmental rotation values or left/right rotation were found. At C0/C1, the percentages vary from 22.4% [10] to 27% [1]. Abnormal left/right differences ranged from 25% [7] to 36% [1]. In our study only 10.6% of the patients had abnormal absolute rotation values at C0/C1 and only 4.3% had abnormal left/right differences at C0/C1.

Using Dvorak's criteria for suspected rotatory instability, all our absolute rotation values of C1/C2 were normal. Dvorak and co-workers found suspected rotatory instability in 4.5% of WAD patients [7]. With respect to pathological left/right differences at C1/C2 in WAD patients, our study showed an incidence of 10.8%. In the literature, percentages range from 16% to 24% [1,7]. The discrepancy is probably due to differences in measurement methods and ill-defined patient populations. All our patients were classified as WAD [18] and all patients had a marked cervical passive retroflexion restriction. In a previous study, 80% of a WAD population showed this clinical feature [14].

A clear correlation was found between this marked cervical retroflexion restriction and the time interval between the trauma and the examination. One year after the trauma, 80% of the WAD population still showed a marked cervical retroflexion restriction. After an interval of 4 years, this percentage declined to 16%. The aetiology of this clinical finding is still unclear.

Except for at the C0/C1 level, our WAD patient population showed, in the vast majority of the other motion segments (71%), significantly lower absolute rotation values. This is probably due to the significantly lower total left and right rotation values in this group. The low percentages of pathological values for absolute rotation or left/right differences reported in previous rotatory CT studies [1, 3, 4,5] and also in our study reflects a low sensitivity of rotatory CT in diagnosing WAD injuries. We concluded that significantly lower absolute rotatory values in patients with restricted total rotation have poor diagnostic value. Therefore we introduced RR values. This approach supplied, on an individual level, a kind of norm-setting with respect to the total rotation C0/C7.

In our WAD group, analysis of the RR values showed a significant hyper-rotation of C0/C1. No difference was

found between normal subjects and WAD patients at C1/C2. The significantly smaller RR values of the lower motion segments C5/C6 and C6/C7, and of the region C2/C7 have presumably no diagnostic meaning for localization of the traumatic lesion. Neuromuscular reflexes elicited by pain, resulting in hypertone muscles around a cervical segment, can lead to rotatory motion restriction [14].

With regard to the whiplash mechanism, the craniocervical junction is the primary site of the injury in WAD patients [15]. Considering the atlas, a backwards translation of the skull takes place first, resulting in an overloading of the soft tissue structures in this area [15,18]. Structural damage to the craniocervical junction can interfere with the function of the C0/C2 complex. According to Dvorak et al., hyper-rotation values or abnormal left/right differences of C0/C1 and C1/C2 are characteristic in WAD patients. The hypothesis of an injury of the alar ligaments, resulting in hyper-rotation, is mainly based on rotatory CT studies with cadavers [6].

Whether the abnormal RR value of C0/C1 recorded in 79% of our WAD patients reflects a lesion of the alar ligaments is questionable. Until now, no solid MRI data are available that indicate isolated damage of the alar ligaments in WAD patients [6, 19,20].

Furthermore, under normal conditions the C0/C1 joints permit only anteflexion, retroflexion and lateral flexion. The shape of these joints prevents a rotation at the C0/C1 level [21].

The unique anatomical form of the joints and their capsules mainly guarantees stability of the C0/C1 joints. The anterior and posterior occipito-atloid membranes and the tectorial membrane gain additional vertical stability [21]. Rotation at C0/C1 can only occur after removal of the tectorial membrane [21].

Conclusion

The findings of large RR values at C0/C1 in our WAD patients could be explained by lesions of the ligaments that prevent vertical translation at C0/C1. The alar ligaments are of no consequence in prevention of vertical translation of the cranium. Therefore, isolated lesions of these ligaments in WAD patients, as suggested by other authors [1, 4, 5, 6, 7, 8,9], is not very likely.

Based on RR values, 81.7% of the originally grouped cases were correctly classified. This illustrates a clinical acceptability of our applied diagnostic method in the daily practice.

Additional studies in normal subjects with different age groups, are necessary to evaluate the diagnostic value of our findings in different WAD groups.

Acknowledgements The authors would like to thank Prof. Dr. L. Penning for the use of his original data and his constructive help and comments in preparing this paper.

References

1. Antinnes JA, Dvorak J, Hayek J, Panjabi M, Grob D (1994) The value of functional computed tomography in the valuation of soft-tissue injury in the upper cervical spine. Eur Spine J 3:98–101
2. Aprill C, Dwyer A, Bogduk N (1990) Cervical zygapophyseal joint pain patterns. II. A clinical evaluation. Spine 15:458–461
3. Boden SD, McCowin PR, Davis DO, Dina TS, Mark AS, Wiesel S (1990) Abnormal magnetic-resonance scan of the cervical spine in nonsymptomatic subjects. J Bone Joint Surg Am 72:1–84
4. Dvorak J, Panjabi M, Gerber M, Wichmann W (1987) CT-functional diagnosis of the rotatory instability of upper cervical spine. 1. An experimental study on cadavers. Spine 12:197–205
5. Dvorak J, Hayek J, Zehnder R (1987) CT-functional diagnostics of the rotatory instability of the upper cervical spine. 2. An evaluation on healthy adults and patients with suspected instability. Spine 13:726–731
6. Dvorak J, Schneider E, Saldinger PF, Rahn B (1988) Biomechanics of the craniocervical region. The alar and transverse ligaments. J Orthop Res 6: 452–461
7. Dvorak J, Penning L, Hayek J, Panjabi M, Grob D, Zehnder R (1988) Functional diagnostics of the cervical spine using computer tomography. Neuroradiology 30:132–137
8. Dvorak J, Grob D, Antinnes JA (1992) Computertomographie bei Halswirbelsäuleverletzungen. In: Fischer A J E M, Kingma H, Patijn J (eds) The whiplash problem. Data Medica
9. Dvorak J, Panjabi M, Grob D, Novotny E, Antinnes JA (1993) Clinical validation of functional flexion/extension radiographs of the cervical spine. Spine 18:120–127
10. Fagerlund M, Björnebrink J, Pettersson K, Hildingsson C (1995) MRI in acute phase of whiplash injury. Euro Radiol 5:297–301
11. Jónsson H Jr, Cesarini K, Sahlstedt B, Rauschning W (1994) Findings and outcome in whiplash-type neck distortions. Spine 19:2733–2743
12. Kamieth H (1990) Das Schleudertrauma der Halswirbelsäule. WS in Forschung und Praxis, vol 111. Hippokrates, Stuttgart
13. Kamieth H (1985) Röntgenfunktionsdiagnostik der Halswirbelsäule. WS in Forschung und Praxis, Bd 105. Hippokrates, Stuttgart
14. Patijn J, Brouwer R, Kingma H, Erven-Sommers van J (1995) Clinic and diagnostics of manual/musculoskeletal medicine in whiplash injuries. Symposium on Whiplash Injuries, Symposium Syllabus. Foundation for Manual/Musculoskeletal Medicine, Eindhoven, pp 15–22
15. Penning L (1994) Hypertranslation de Kopfes nach hinten: Teil des Scheuderverletzung mechanismus der HWS? Orthopade 23:268–274
16. Penning L, Wilmink JT (1987) Rotation of the cervical spine: a CT study in normal subjects. Spine 12:732–738
17. Petterson K, Hildingsson C, Toolanen G, Fagerlund M, Björnebrink J (1994) MRI and neurology in acute whiplash trauma. Acta Orthop Scand 65:525–528

18. Spitzer WO, Skovron ML, Salmi RS Cassidy JD, Duranceau J, Suissa S, Zeiss E (1995) Scientific monograph of the Quebec task force on whiplash-associated disorders: redefining "whiplash" and its management. Spine. 20 [Suppl 8]
19. Volle et al (1997) Strukturdefekte der Ligamenta alaria in der offenen Funktionskernspintomographie. Manuelle Med 35: 188–193
20. Volle et al (1996) Funktionelle Darstellung der Ligamenta alaria in der Kernspintomographie. Man Medizin 34:9–13
21. Werne S (1959) The possibilities of movement in the craniovertebral joints. Acta Orthop Scand 28:165–173
22. White AA III, Panjabi MM (1990) Clinical biomechanics of the spine. JB Lippincott, Philadelphia, pp 203
23. Willauschus WG, Kladny B, Beyer WF, Glückert K, Arnold H, Scheithauer R (1995) Lesions of the alar ligaments: in vivo and in vitro studies with magnetic resonance imaging. Spine 20:2493–2498