VERTEBRAL COLUMN INJURIES IN 90-DEGREES COLLISIONS
A STUDY WITH POST-MORTEM HUMAN SUBJECTS

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ABSTRACT

A total of 58 90-degrees car to car lateral collisions was performed. The impact velocity of the striking vehicle amounted 40, 45, 50 and 60 km/h, of the struck vehicle 0 km/h. Post-mortem human subjects (PMHS) in the age range of 19 to 65 years were used as test subjects. The case of the restrained near-side occupant was simulated. The acceleration instrumentation included the 12-accelerometer array and head temporal left and right; the collision phase was documented with high-speed cameras.

The average acceleration at the Th 1 amounted to 100 g, the one at the Th 12 120 g.

The lateral bending of the head increases with the velocity and reached its maximum at 70-80 ms after the crash. In the 40 km/h tests, head bending angles of 70 degrees were observed, in the 60 km/h test they amounted to 90 degrees.

Spinal column injuries occurred in 43 of the 58 test subjects, predominantly in the area of the cervical spine and the upper thoracic vertebral column.

In consideration of the kinematic analysis one can conclude that in the loading phase of the spinal column a tension load occurs far-side and a compression near-side.

In the spinal column injuries 25 cases were observed as AIS 1 and 15 cases as AIS 2. In two further test subjects injury severities of AIS 3 and in one AIS 5 were observed.

Considering the frequency and severity of spinal column injuries in the simulated accidents one can conclude that spinal column injuries are not critical; the thoracic injuries (rib fractures) and abdominal injuries (liver ruptures, right side impact) are decisive for the injury severity in the lateral collision.

INTRODUCTION

Acute strains of the cervical spine occur the most in rear end impact accidents, the term "whiplash" for these injuries was first used by Crow in 1928 (11). "Whiplash" is a poorly defined term including ligamentous and muscular strains, hematomas and disc injuries. The same kind of injuries may also occur in belt protected occupants during a frontal collision (flexion injuries) or in near-side occupants at lateral car to car impacts (lateral bending injuries).

Spinal column injuries are of secondary importance in real side impact accidents. According to an accident analysis of Rouhana and Foster (8), skeletal injuries are ranked as number 1 among the injuries $\geq$ AIS 3, while vertebral injuries are ranked as number 3 and 4. Serious neck injuries occurred in more than 50 % of the case, indirectly by head contact (impact force).

Minor vertebral column injuries (strains, lacerations) not detectable through x-rays, but felt as pains by the car occupants, are mostly not described in the literature on severe car to car lateral impacts, whereas serious injuries of other body regions prevail.

Often, no detailed investigation of the spinal column with x-rays takes place in the primary clinical treatment; the early diagnosis of spinal column injuries is therefore neglected.

Quite often, the injured person complains of spinal column pains after the healing up of more outstanding injuries, the connection with the accident is then uncertain.

Through detailed investigations of the isolated spinal column in PMHS, minor and severe injuries are recognizable if they are present as morphologic alterations.

The paper presents results of spinal column injuries which were investigated by the use of PMHS as belt protected near-side occupants at 90 degrees car to car lateral collisions with impact velocities of 40 km/h up to 60 km/h.

TEST SUBJECTS

58 human male and female PMHS in the age range of 19 up to 65 years were used as test subjects (Tab.1). The test subjects were located in the position of near-sided car passengers and restrained with a 3-point belt.

Table 1: Test matrix according the impact velocity and the impact direction (5)

IMPACT VELOCITY km/h	IMPACTED SIDE right	left
40	5	4
45	10	10
50	12	12
60	0	5

METHOD

Striking vehicle

The striking vehicle was a car, the front of which carried a special deformation element (Fig. 1). The deformation behaviour of this element corresponds to the front structure of a middle-class European car at a frontal impact (3). Each element was only used for one test. The mass of the car amounted 950 kg and was accelerated by means of a falling weight (6). The velocity of the striking vehicle amounted 40, 45, 50 and 60 km/h.

Struck vehicle

An Opel Kadett body, in-white, mounted onto a movable platform (dolly) was used as the struck vehicle (Fig. 1). The mass of the struck vehicle, consisting of dolly, car-body, seat, test subject and supplemental mass also amounted 950 kg. The vehicle was impacted under an angle of 90 degrees and at both sides; the velocity of the struck vehicle was 0 km/h.

INSTRUMENTATION

Striking vehicle: Deceleration along the x-axis.
Struck vehicle: Acceleration at the dolly along the y-axis. Accelerations at the inner side of the struck door and the B-pillar along the y-axis; in most cases the intrusion at the inner side of the impacted door was measured with an inductive motion sensor.

Subjects: The test subjects were instrumented with accelerometers on the outside of the head, right and left two-axial (4), in some of the tests at the clivus 3-axial cluster, at the thorax the 12-accelerometer array (8). Further accelerometers were mounted at the sacrum 3-axial cluster. The respiratory system and the lungs were inflated and the pressure was measured in the trachea.

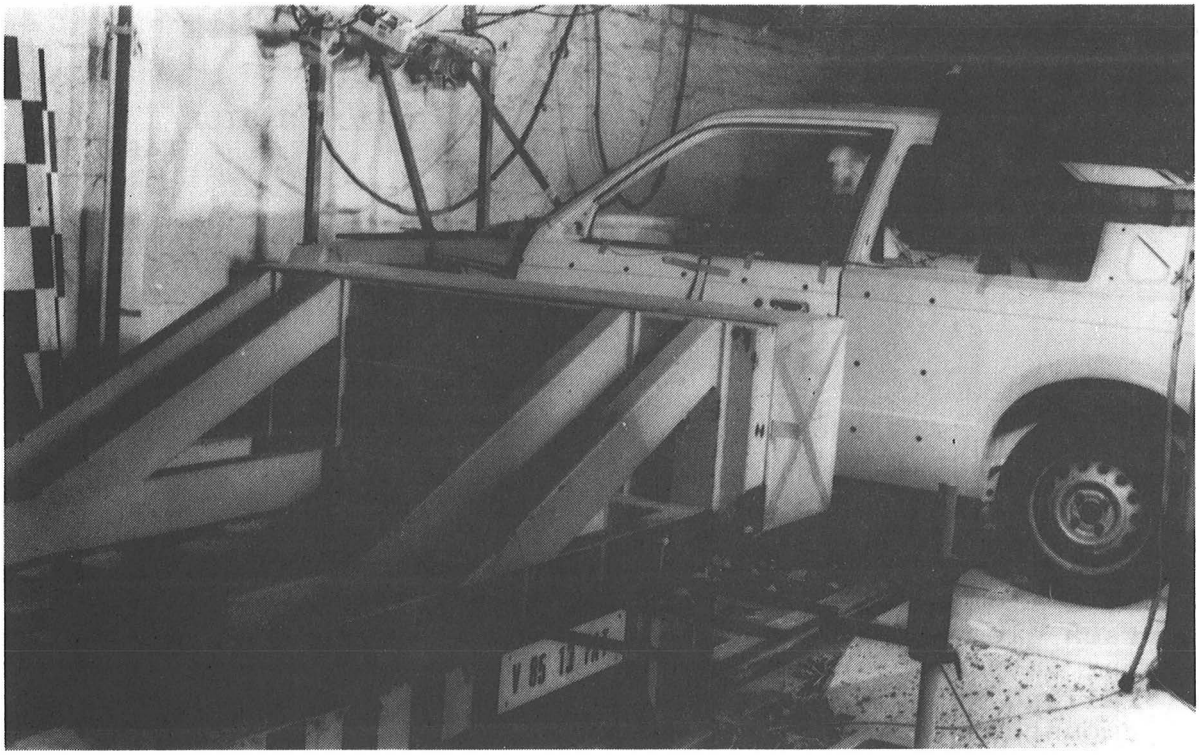


Fig. 1: Overall view of the striking and struck vehicle before the crash.

PHOTOGRAPHIC DOCUMENTATION

Photos were taken before and after the test. The collision phase of the test subject was documented on high speed films in frontal and rear view.

MEDICAL INVESTIGATION

The determination of the injury pattern of the vertebral column was done according to a special technique (7), if necessary, x-ray pictures were taken. The injury severity was scaled in accordance with the AIS 1980 (1). Injuries not separately mentioned in the AIS vocabulary were scaled by analog application of AIS criteria.

RESULTS AND DISCUSSION

Vertebral column injuries

The distribution of the spinal column injuries according to AIS for the left and right impact groups can be seen in the following Tab. 2.

AIS	IMPACT DIRECTION left	right
0	5	10
1	15	10
2	9	6
3	1	1
4	-	-
5	1	-

Tab. 2: Frequency of the severity of spinal column injuries, classified according to the impact direction - frequency of the AIS scales -

This analysis of the injury severity of the spinal column shows that in a total of 40 tests either none (15 tests) or only minor (25 tests) injuries occurred. Strains, predominantly at the cervical vertebral column were identified as minor injuries (AIS 1), in PMHS they can be seen as hemorrhages. Hemorrhages into the longitudinal ligaments, into the intervertebral discs, into the interspinal muscle and ligamentous system or into the joints of the vertebral arc belong to these strains. Hereby, a lateral accentuation of the injury pattern dependent on the impact direction was only recognizable in single cases.

The 15 test subjects with moderately severe spinal column injuries (AIS 2) showed lacerations of the longitudinal ligaments and intervertebral discs, sometimes in two, rarely in several segments; in single cases small fractures of the bony vertebral structures occurred without a greater compression of the vertebral bodies and without a recognizable spinal cord injury.

The cases with spinal column injuries of AIS 3 (serious) and AIS 5 (critical) are defined in detail as follows and are combined with loading indicators in Tab. 3.

LOADING INDICATORS	RUN NO. 8434	8503	8319
Spine AIS	3	3	5
Impact velocity (km/h)	45	45	60
Impacted side	R	L	L
Age (years)	59	47	40
Body length (cm)	172	158	175
HIC Analogon * near-side	347	716	788
HIC Analogon * far-side	287	499	822
Accel.max. Head near-side (Res.g)	65	163**	104
Accel.max. Head far-side (Res.g)	79	83	131
Accel.max. Th 1 (Res.g)	156**	147	136
Accel.max. Th 12 (Res.g)	104	138	190

Tab. 3: Spinal column injuries≥AIS 3 with the most important anthropometric data and the loading on head and spinal column. (* HIC-value evaluated from the result. accel. on the outside of the head; ** above average high accel. maxima)

When looking at the loads in Tab. 3, the values for the maximum of the resultant head acceleration, at the 1st thoracic vertebra (Run No's 8434, 8503) are surprising as well as the maximum of the resultant head acceleration, impacted side at Run No. 8503. These values are above the mean values of the corresponding test group, the head acceleration of Run.Nr. 8503 showed the highest value ever measured at this location in the 45 km/h group.

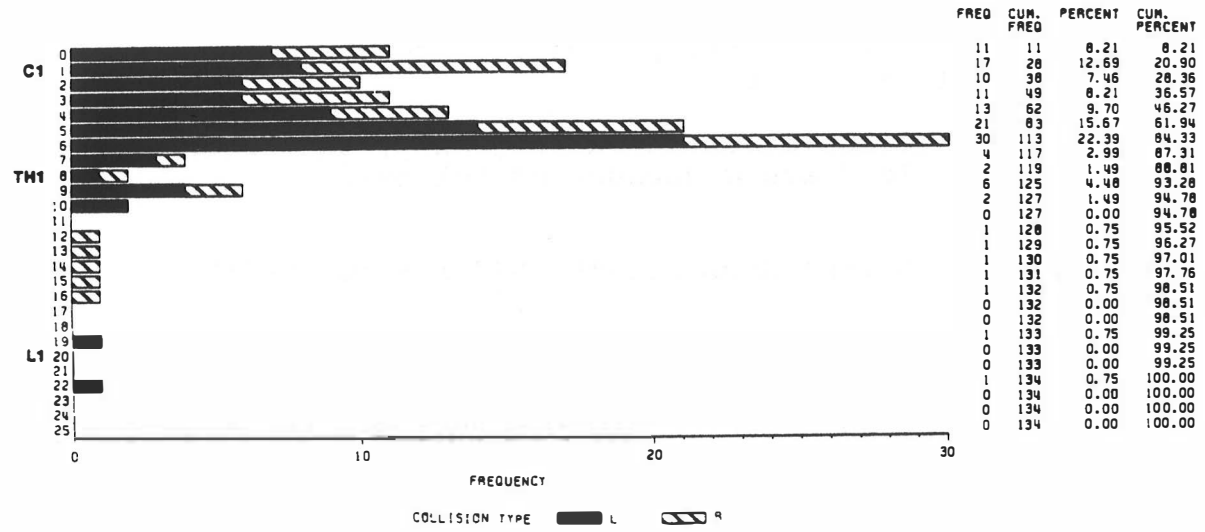
Run No. 8434 (Spinal column AIS 3):
45 km/h right-side impact, male test subject, 59 years old, MAIS 6 (partial separation of the brain stem from the pons), thorax AIS 4, abdomen AIS 0. Instable spinal column injury between C 6 und C 7 with laceration of the anterior and posterior longitudinal ligament, severence of the intervertebral discs and laceration of the interspinal muscle and ligamentous system, hemorrhage into the left and right joint. Further hemorrhages at C 4/C 5 and Th 2/Th 3.

Run No. 8503 (Spinal column AIS 3):
45 km/h left-side impact, female test subject, 47 years old, MAIS 4, Thorax 4, Abdomen 4. Horizontal fracture of the top of the dens without (recognizable) spinal cord injury, lacerations of the ligamentum flavum between the 1st and 2nd as well as the 2nd and 3rd cervical segment with more extensive strains to the right than to the left side, removing of the intervertebral discs and lacerations of the longitudinal ligaments between the 2nd and 3rd cervical segment. Further strains at C 6/C 7 and Th 4/Th 5.

Run No. 8319 (Spinal column AIS 5):
60 km/h left-side impact, male test subject, 40 years old, MAIS 5, Thorax AIS 4, Abdomen AIS 4, Head AIS 3. Complete separation between C 4 and C 5 with laceration of the longitudinal ligaments, the intervertebral discs and luxation of the lateral joints and dislocation of the vertebral body with crushing of the spinal cord. Laceration of the ligamentum flavum C 7/Th 1 and Th 2/Th 3, no bony injuries.

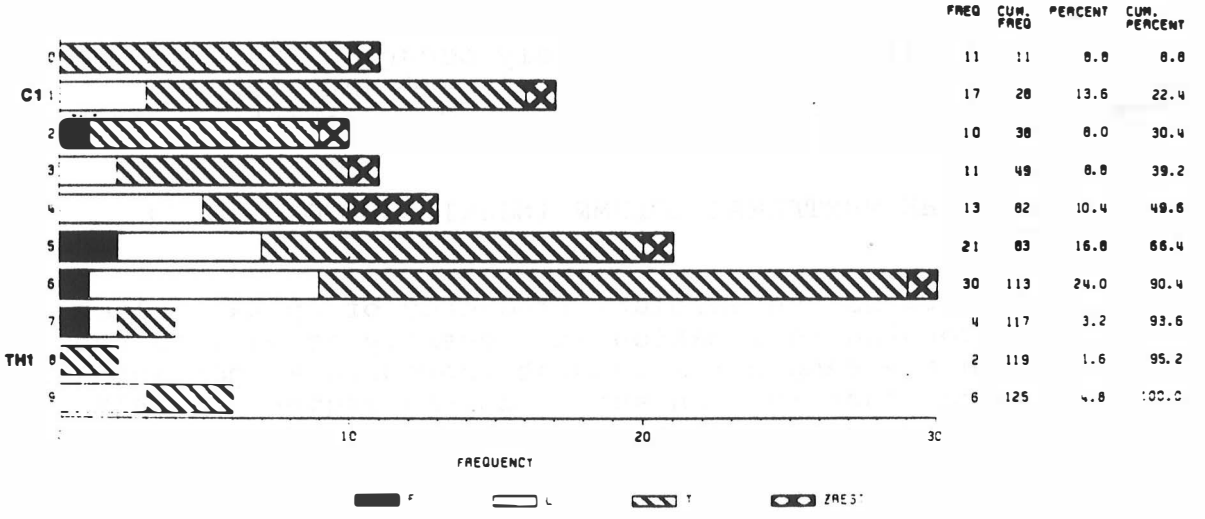
LOCATION OF THE SPINAL COLUM INJURIES

The injuries predominantly occurred in the area of the cervical spine, Th 1, Th 2 and Th 3 were concerned less frequently; Th 5-Th 9, Th 12 and L 3 were affected only one time each. An absolute distribution of the concerned spinal column segments also expressed as percentage and summarized for right and left impacts is illustrated in Fig. 2. The figure shows that the segments C 5 with



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
11	11	8.21	8.21
17	28	12.69	20.90
10	38	7.46	28.36
11	49	8.21	36.57
13	62	9.70	46.27
21	83	15.67	61.94
30	113	22.39	84.33
4	117	2.99	87.31
2	119	1.49	88.81
6	125	4.48	93.28
2	127	1.49	94.78
0	127	0.00	94.78
1	128	0.75	95.52
1	129	0.75	96.27
1	130	0.75	97.01
1	131	0.75	97.76
1	132	0.75	98.51
0	132	0.00	98.51
0	132	0.00	98.51
1	133	0.75	99.25
0	133	0.00	99.25
0	133	0.00	99.25
1	134	0.75	100.00
0	134	0.00	100.00
0	134	0.00	100.00
0	134	0.00	100.00

Fig. 2: Location of the vertebral column injuries according the impact direction
(L: left-side impact, R: right-side impact)



FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
11	11	8.8	8.8
17	28	13.6	22.4
10	38	8.0	30.4
11	49	8.8	39.2
13	62	10.4	49.6
21	83	16.8	66.4
30	113	24.0	90.4
4	117	3.2	93.6
2	119	1.6	95.2
6	125	4.8	100.0

Fig. 3: Location of the vertebral column injuries according the lesion
(F: fracture, L: laceration, T: strain, Z Rest: others)

15,7 % and C 6 with 22,4 % were injured the most; in the third place is the segment C 1 with 12,7 %. An explanation of the higher frequency in left-side impacts is that only this test group included impacts at a collision velocity of 60 km/h.

Considering the above mentioned frequency, the injuries of occiput to Th 2 are discussed as follows.

LOCATION OF THE VERTEBRAL COLUMN INJURIES ACCORDING TO THE LESION

Fig. 3 illustrates the location of spinal column injuries according to the lesions. The mostly observed injuries are strains (T), which occurred in each segment and predominantly concerned the level of C 6 with 16 %; hemorrhages observed by strains were scaled with AIS 1. Secondly are lacerations in the level of C 6 with 6,4 %. Fractures of vertebrae and other injuries (avulsion, crush, rupture, separation, sprain, transsection) were rarely observed.

LOCATION OF THE VERTEBRAL COLUMN INJURIES ACCORDING TO THE SYSTEM/ORGAN

Fig. 4 shows the absolute frequencies of the observed kinds of injuries as well as the percentage of the affected spinal column segments. According to this illustration, segment C 6 was concerned the most with 24 %. At the segments C 2-C 6 the intervertebral discs injuries are in the first place. Secondly, in the C 6 segment, is the joint injury with 5,6 %. More rarely occurred injuries of muscles (1,6 %), posterior (1,6 %) and anterior longitudinal ligaments (0,8 %) at the C 6 segment.

LOCATION OF THE VERTEBRAL COLUMN INJURIES ACCORDING TO THE SEVERITY

Fig. 5 illustrates the absolute frequency of spinal column injuries according to location and severity as well as the frequency in the respective segment expressed as percentage. It is apparent that in each spinal column segment the AIS 1 occurs most frequently (strains) followed by AIS 2 (lacerations). In two cases AIS 3 occurred in segment C 2 and C 6; in one test an AIS 5 was observed in level C 4 (with crushing of the spinal cord).

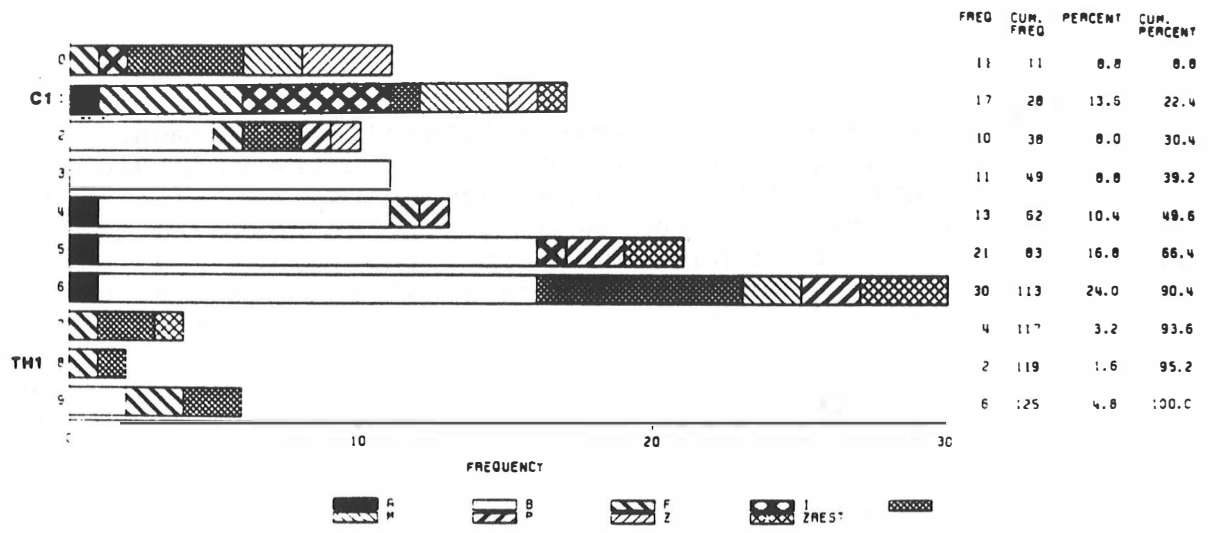


Fig. 4: Location of the vertebral column injuries according the system/organ (A: anterior longitudinal ligament, M: muscles, B: intervertebral disc, P: posterior longitudinal ligament, F: lig. flavum, Z: dens, I: lig. interspinale, J: joint, Z Rest: others)

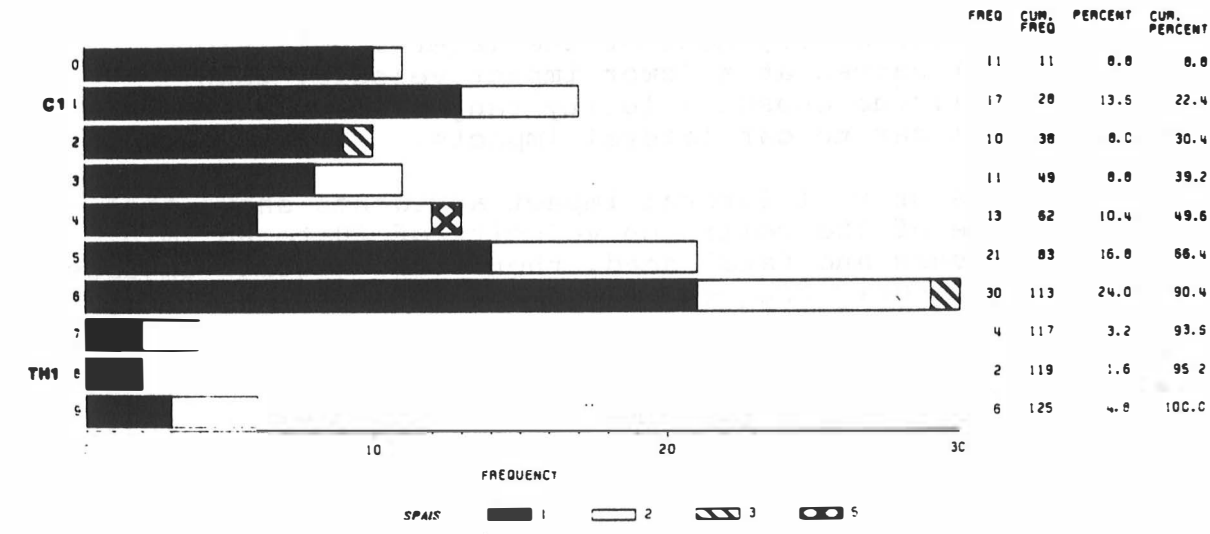


Fig. 5: Location of the vertebral column injuries according to the severity.

KINEMATICS AND INJURY MECHANICS

Most of the 16 mm high speed films of the frontal view were examined in relation to the cervical spine kinematics. The film analysis at first shows a lateral displacement of the torso against the head; according to the collision velocity a shear load at the head-cervical spine transition occurs in the time 15 ms and 30 ms after the crash; after that follows a lateral bending towards the impact side. During this loading phase in the cervical spine a tension load occurs far-side and a compression near-side (Fig.6).

The bending angle at the head-neck-torso transition increases with the collision velocity and reaches its maximum 70-80 ms after the crash (Fig. 7). In the 60 km/h collisions mean bending angles of 90 degrees were observed, in the 40 km/h collisions the bending angles amounted to about 70 degrees.

The evidence of strains at the far-side, noticeable as hemorrhages in the muscular system, in the longitudinal ligaments, in the joints or in the intervertebral discs, can be explained with the bending mechanism.
Finally a tension load takes place in the z-axis of the cervical spine (Fig. 6) after the lateral bending of the head-cervical spine complex with regard to the torso.

COMPARISON OF THE RESULTS WITH FIELD ACCIDENT DATA

The investigated velocity range is in accordance with severe car to car lateral impacts in real road accidents. The collision velocity of 60 km/h is exceeded by about 5 % of real accidents, most of the lateral collisions (about 85 %) happen at a lower impact velocity than 40 km/h (10); the chosen velocity range includes about 10 % of real car to car lateral impacts.

The analysis of real lateral impact accidents shows that in the range of the collision velocity of 40 to 60 km/h, numerous severe and fatal head, thorax and abdomen injuries occur (2,9); their frequency increases with the velocity.

Minor and moderate injuries, observed in detailed investigations of the spinal column of PMHS may be overlooked in the clinical examination as the clinician has to treat head, thorax and abdomen injuries first. Therefore, these injuries (AIS 1, AIS 2) in muscles, ligaments, intervertebral discs and vertebrae may occur more frequently in the PMHS collective than noticed in real accidents. On the other hand, the diagnosis of strains at the far-side of the PMHS' spine, which my occur as hemorrhages into the longitudinal ligaments, the muscular system, the joints

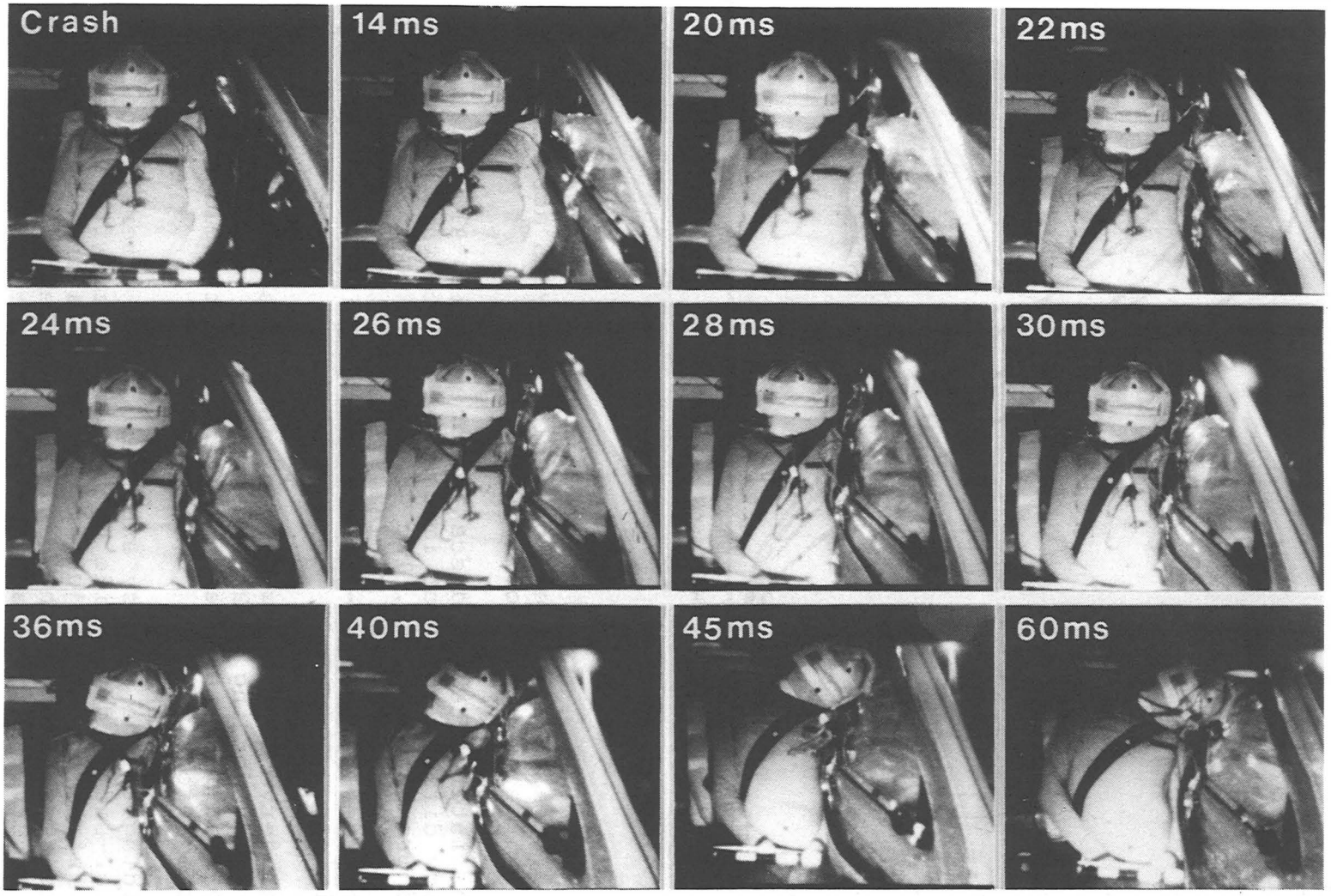


Fig. 6: Sequence photographs from high-speed movie during the crash.
Run No. 8503, lateral impact, impact velocity 45 km/h

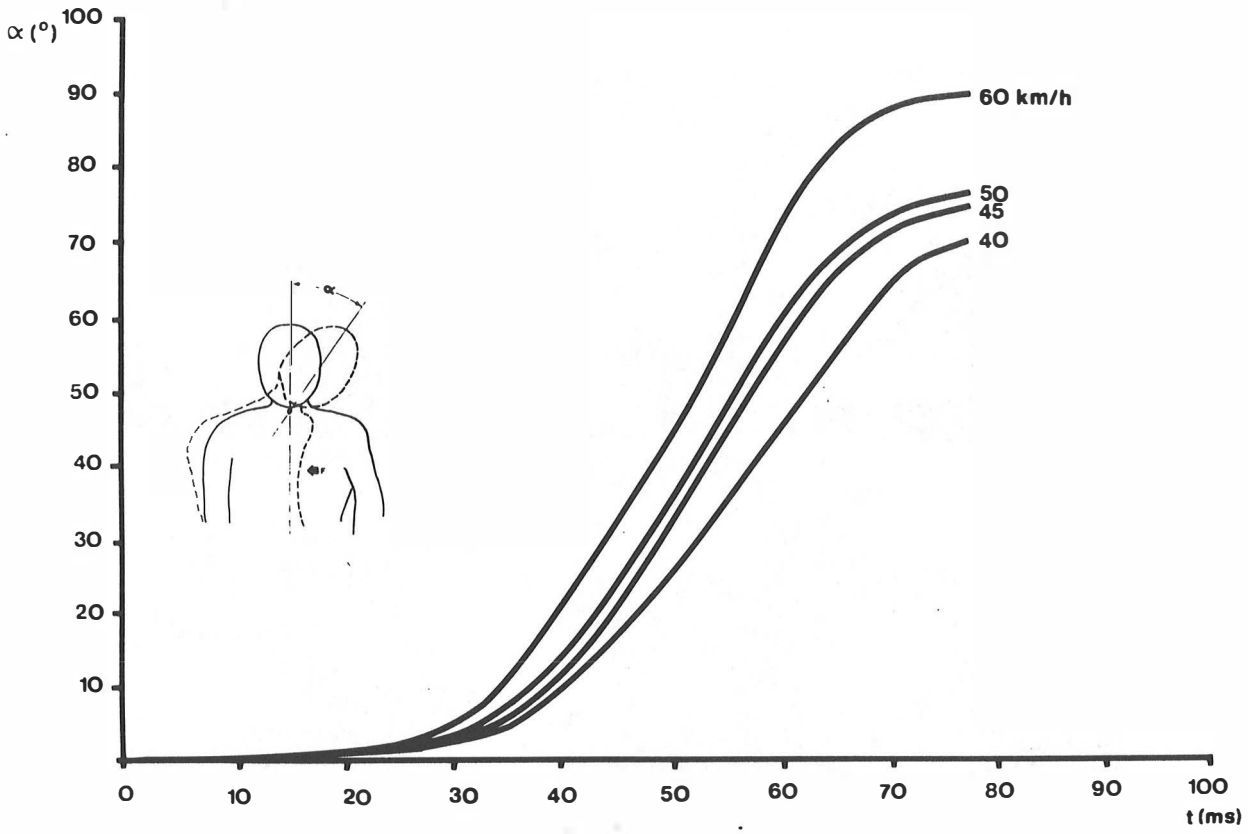


Fig. 7: Mean head deflection angles for PMHS according the impact velocity.

or the intervertebral discs (minor injuries AIS 1), indeed is very difficult if not impossible due to the absence of blood pressure in PMHS. The same applies to injury sequels with compression which my lead to articular cartilage hemorrhages in the far-side vertebral joints under vital conditions.

Spinal nerve injuries with functional loss are not detectable in PMHS; according to Rouhana and Foster (9), however, spinal nerve injuries are rare in lateral impact field accident investigations.

According to the autopsy experience with lateral impacts of near-side and far-side belted occupants with extrem high intrusion, the injury mechanics of a shearing load at the transition of the head-neck complex and a bending of the cervical spine are confirmed.

Consequences of the shearing load are fractures of the occipital condyles and the dens. Furthermore, hemorrhages, lacerations of ligaments and intervertebral discs, dislocations, transsection of the upper cervical spinal cord and vertebrae fractures occur as consequences of the lateral bending of the cervical spine. Generally, the fatal injuries concern head, thorax and abdomen.
The spinal column injuries in lateral collisions are therefore not noticeable referred to the injury severity, also observed by Walz et al. (12).

CONCLUSIONS

1. The severity of spinal column injuries is of secondary importance in car to car 90 degrees collisions; head, thorax and abdomen injuries are more decisive for the injury severity.

2. Spinal column injuries, which were observed in PMHS at simulated 90 degrees car to car lateral collisions are comparable with the ones in real accidents.

3. According to our experience from thorough detail investigations of spinal columns after experimental 90 degrees lateral collisions, vertebral pains in the sense of whiplash injuries should be expected in externally uninjured persons after severe lateral collisions.

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