Cervical Human Spine Loads During Traumatomechanical Investigations

Dimitrios Kallieris, Andreas Rizzetti, Rainer Mattern
University of Heidelberg
Jan Thunnissen, Mat Philippens *TNO Crash-Safety Research Center*

ABSTRACT

The last decades improvements in automotive safety resulted into a significant decrease of fatal injuries. However, due to the use of belts and airbags it can be observed that cervical spine injuries, non-severe and severe, have become more important. It seems that inertial loading of the neck by the head is an important loading mechanism causing these injuries.

Until now local deformations and load paths in the cervical spine can not be determined accurately from cadaver experiments due to the lack of adequate measuring techniques. At this moment the loads at the occipital condyles can be estimated by analyzing high speed film and the linear and angular accelerations of the head. These loads show a correlation with (local) cervical spine injuries in car crashes.

The head-neck response, the neck loads and the sustained injuries obtained from human cadaver experiments in the frontal, lateral and rear-end collisions were investigated to increase the knowledge of the traumatomechanics of the cervical spine. The severity of these experiments, e.g. sled deceleration, varies from 11 to 15 g for frontal, and 7 g for rear-end collisions; for lateral impacts, the shoulder was accelerated with 100 to 130 g through the intruded side wall of the car.

It was observed, that rotational accelerations of 1000 rad/sec^2 do not lead to recognizable injuries during post mortem loadings, while rotational accelerations of 2000 - 3000 rad/sec^2 or bending moments of 80 - 100 Nm can lead to injuries of ligaments, intervertebral discs and compression fractures of vertebral bodies. Shear forces in frontal collisions of 1000 - 1500 N at the level of the occipital condyles cause strength of the joints in this region. The resultant acceleration at the head centre of gravity varies from 20 to 45 g.

THE IMPORTANCE OF CERVICAL SPINE INJURIES has increased, especially claim damages related to “whiplash” traumas. Based on these facts, in the last years numerous experimental research with volunteers, cadavers and dummies, under rear-end collision conditions were performed to investigate the relationship between head-neck response and injury risk of the cervical spine (McConnel et al., 1993, 1995, Szabo et al., 1994, Geigl et al., 1994, 1995, Deutscher, 1994). The objective of the current study is to expand the current knowledge about injury mechanism, loading and injury severity by using cadavers in frontal, lateral and rear-end impact conditions.

A number of crash experiments with human cadavers are conducted at the University of Heidelberg. These experiments are analyzed to obtain more specific data on the loading of the neck by calculating the loads at the occipital condyles and to relate them to the results of the post-experiment autopsy. Instead of measuring the neck loads at the occipital condyles joint, the loads are determined from high-speed film and the linear and angular acceleration measurements i.e. the head is assumed to be a rigid body and the loads are calculated by applying Newton's equations.

MATERIAL AND METHOD

SUBJECTS - The test subjects were unembalmed human cadavers ranging from 23 to 66 years. The most important anthropometric data of the test subjects and the test conditions are summarized in Table 1.

Table 1: Loading conditions and the anthropometric specifications of the cadavers.

Run No.	Collision direction	Impact velocity [km/h]	Average sled decel. [g]	sex	age [years]	bodymass [kg]	Standing height [m]
1	frontal	60	11	m	37	80	182
2		60	11	f	24	74	168
3		60	15	m	50	72	172
4		60	15	m	27	74	170
5		60	15	f	43	53	175
6	rear-end	25	7	m	40	65	166
7		24	6	m	66	61	167
8	lateral	25	--	f	23	63	168
9		25	--	m	52	87	179
10		25	--	m	25	102	183
11		25	--	m	40	72	174
12		25	--	m	43	83	177

PRETEST PREPARATION OF THE SUBJECT - Before to the experiments, the head and neck were examined by X-ray's. To define the Frankfort plane, infraorbital notches and auditory meati, were marked with small lead balls. The position of these landmarks and positions of the film targets and instrumentation were documented (Fig.1).

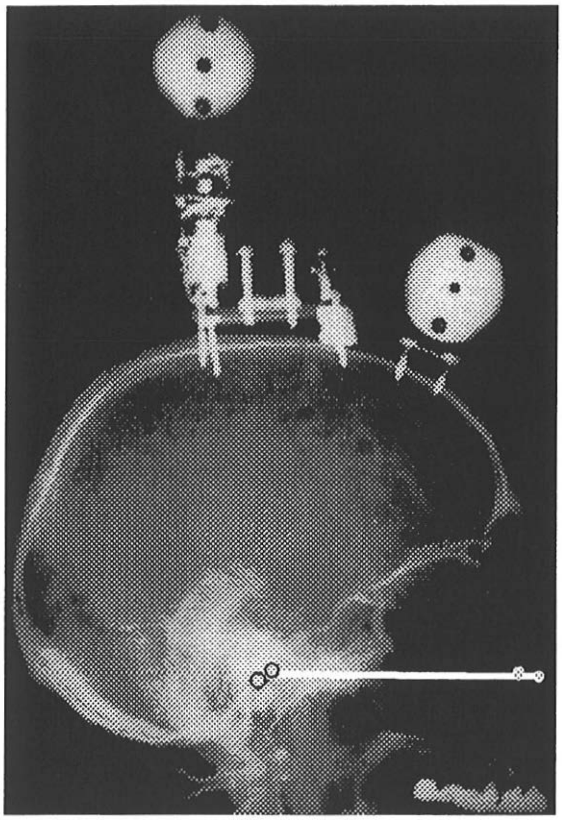


Fig. 1:
Lateral view of the skull with marked Frankfort plane, mounted 9-accelerometer array and film targets.

TEST CONDITIONS

FRONTAL - The experimental set-up was similar to the frontal human volunteer experiments conducted by Ewing and Thomas at the Naval Biodynamics Laboratory (NBDL) in New Orleans (Ewing et al., 1975, Wismans et al., 1987). The subjects were placed on a 90 degree rigid seat and restrained by shoulder straps, a lap belt and inverted V-pelvic strap tied to the lap belt. The arms were restrained by an additional belt at the mamillar level to prevent flailing (Fig.2).

Twelve tests have been conducted, however, only five tests were suitable for more detailed analysis (Wismans et al., 1987). Two tests of a similar impact severity as the NBDL volunteers (impact velocity of 60 km/h and an average deceleration of 11g), while three tests are more severe (an averege deceleration of 15g), see Table 1. The average deceleration of the sled was determined by the velocity change and the stopping distance of the sled.

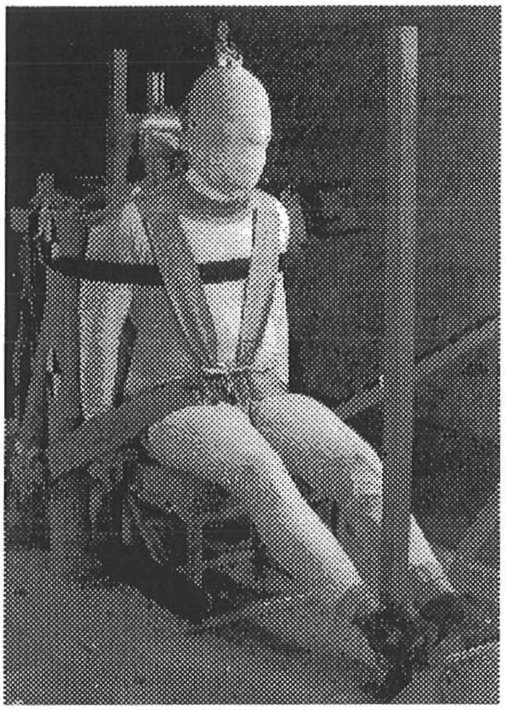


Fig. 2:
Frontal Collision - Seated and restraint subject, pretest situation

REAR-END - For the rear-end collision the subject was placed on a 90 degree rigid rearward facing seat, which was mounted on the sled and restrained by diagonal shoulder straps and a lap strap; the arms were restrained by an additional belt (Fig. 3). It is expected that loading of the cervical spine is higher than in reality due to the rigid seatback positioned at 90 degrees. The impact velocity was 25 km/h, the average sled deceleration 6-7g, two tests have been conducted (Table 1).

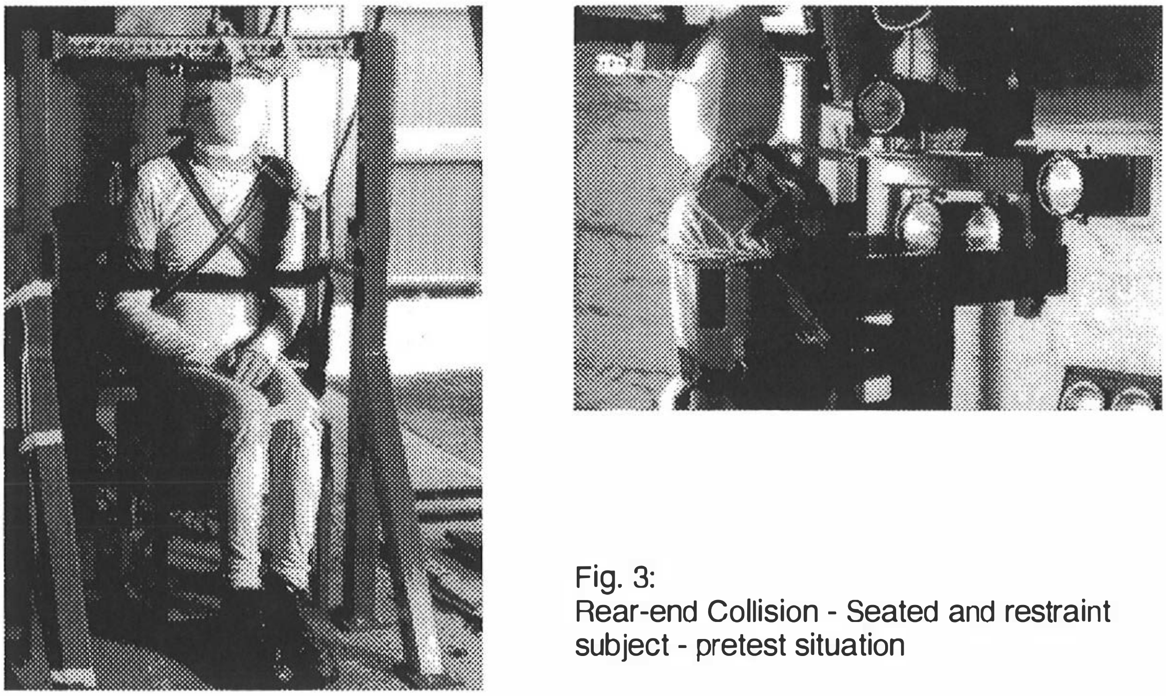


Fig. 3:
Rear-end Collision - Seated and restraint subject - pretest situation

LATERAL - The lateral experiment simulates a 90° car to car collision at 50 km/h. The subjects were located in the near side front passenger seat and restrained by a 3-point belt. Prior the impact, the vehicle was stationary, it was impacted on the right side (Fig. 4, Table 1). Five tests have been conducted.

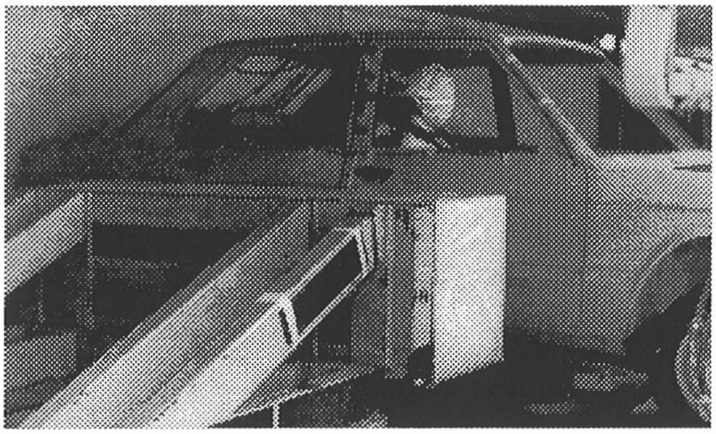


Fig. 4:
90 degree car - car lateral collision

INSTRUMENTATION

The positions of the head and the first thoracic vertebral body (T1) were registered by a sled mounted high speed camera running at 1000p/s, assumed to be parallel to the plane of motion. Two photo targets were mounted to the head as well as T1. The positions of the head and T1 anatomical coordinate systems were related to these targets by X-ray analysis (Wismans et al., 1987).

The instrumentation included a nine accelerometer module, as described by Padgaonkar et. al.(1976), which was screwed to the top of the skull and a triaxial accelerometer unit screwed to the T1 vertebral body. The accelerometers used were Endevco 2264-2000 and 7264-200.

The location of the nine-accelerometer array to the head centre of gravity (c.g.) and occipital condyles was measured in the lateral x-ray view (Fig. 5).

For the lateral experiments the cadavers were not instrumented with the nine accelerometer module but only with 3-accelerometer units at the clivus and at T1.

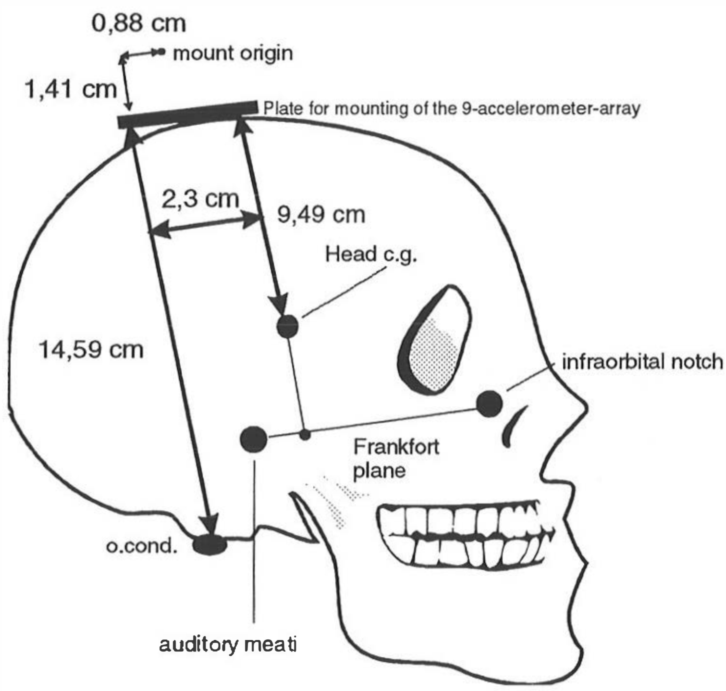


Fig. 5:
Example for distances between the nine-accelerometer array to the center of gravity and to the occipital condyles.

POST TEST PROCEDURE OF THE SUBJECTS

A full autopsy with a detailed investigation of the vertebral column has been performed after the test. The spinal column with the base of the skull was separated from the rest of the body. Three sagital cross-sections were made i.e. midsagital and two sagital planes through the lateral joints.

Dissection was performed with the spine in frozen condition. The injury severity of the observed lesions was scaled in accordance with the AIS 90.

DATA ANALYSIS

The data were recorded in analog format, and digitized at 10,000 samples per second. The data of the 9-accelerometer array was processed further by the Mertz3D program (Mertz and Patrick, 1972). From this data the resultant head center of gravity (c.g.) linear acceleration, the angular velocities and accelerations, the neck forces and moments at the occipito-atlando junction were calaculated. During this procedure a CFC 100 filter was used for the frontal and the rear-end experiments. For the lateral experiments the signals of the head were filtered with CFC 1000 filter, for T1 with CFC 180 filter.

RESULTS

MECHANICAL RESPONSES

Frontal Collision -Time histories of the resultant acceleration at the head c.g., the rotational acceleration of the head about to the y-axis, the resultant neck force and the resultant neck moment at the level of the occipital condyles for the 15 g and 11 g levels are shown in repectively the figures 6 and 7.

The maximum resultant acceleration at the head c.g. ranges from 31 g to 44 g, the duration for all three tests takes about 70 ms for the 15g loading level (Fig. 6a). The time-resultant neck force histories are shown in Fig. 6c. The resultant forces are determined from the product of the resultant acceleration at the head c.g. and head mass of 4.54 kg, as used in the Mertz3D program.

The resultant neck moment at the occipital condyles ranges from 100 Nm to 120 Nm, with a time duration of 20 ms to 25 ms (Fig. 6d).

The maxima of the rotational accelerations of the head about the y-axis ranges from 2600 rad/s² to 3300 rad/s² and shows the same duration as the neck moments (Fig. 6b). Equivalent observations are shown in Fig. 7 for the 11g loading condition. The two less severe tests show lower maxima with longer durations compared to the 15g loading level. The maximal values of the evaluated parameters for the frontal experiments are summarized in table 2.

Table 2: Maximal Frontal Head-Neck Response and Injury Severity of the Cervical Spine. Impact Velocity: 60 km/h.

Run No.	Average Sled Dec. [g]	Resultant Acc. Head c.g. [g]	Rotation [rad/s^2]	Neck Force [N]	Neck Moment [Nm]	AIS Neck
1	11	33	2768	1513	105	1
2	11	30	2719	1156	95	1
3	15	31	2588	1423	99	1
4	15	39	3292	1782	120	0
5	15	44	3265	1985	104	2

The evaluated neck forces and moments are dereived by using a standard head mass of 4.54 kg and the definition of the location of the center of gravity. The center of gravity was determined in connection with the Frankfort plane and using mean distances in the x-z plane according to the study of Beier et al. (1980).

Fig. 8.a and 8.b show examples for displacements of the center of gravity relative to T1 in the sagital plane for the frontal collision at an impact velocity of 60 km/h and a sled deceleration of 15 g's and 11 g's. An uniform shape is observed for the two impact severities.

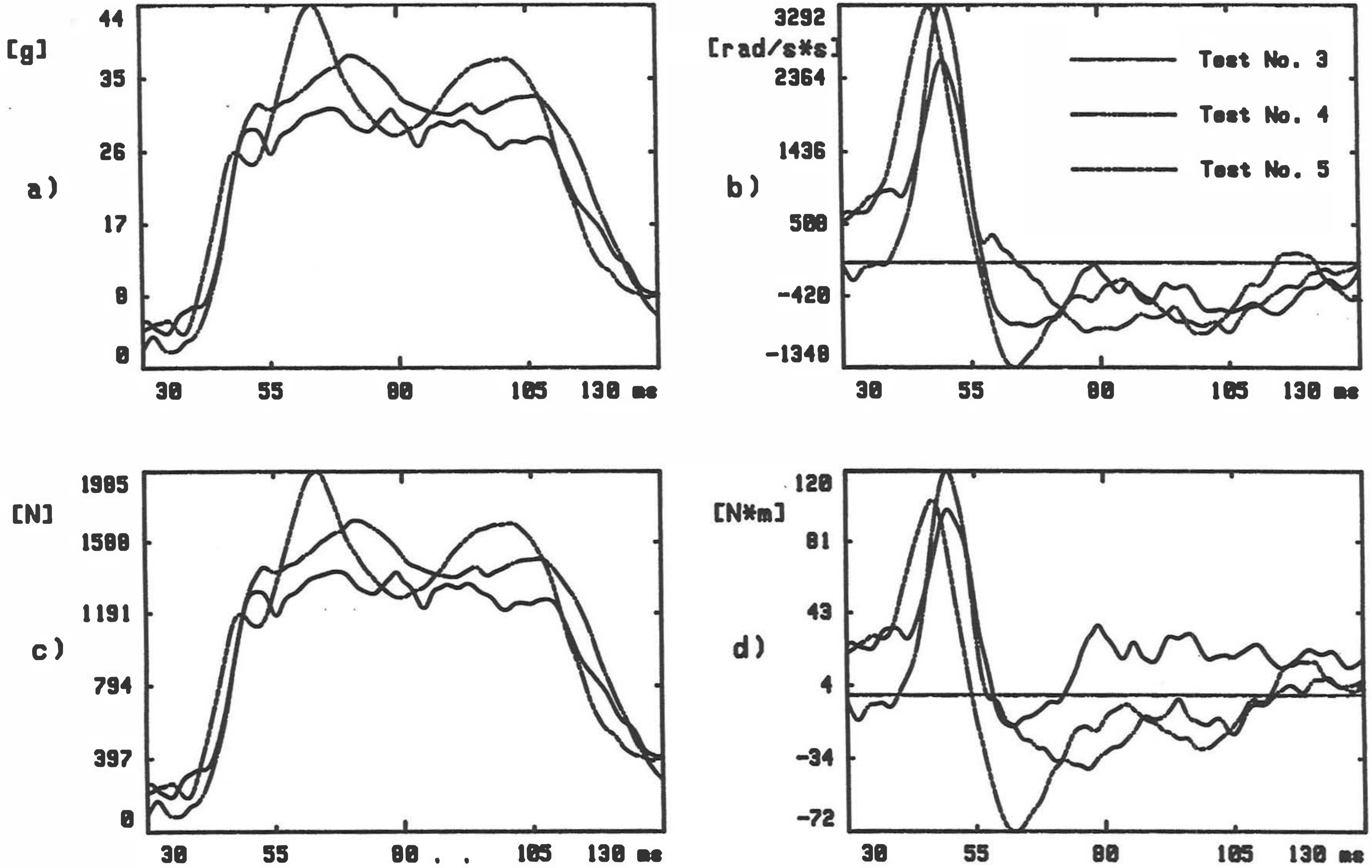


Fig.6: Frontal Collision, 60 km/h, 15 g, 3 tests
a) Res. acceleration in the c. g. b) Rotational accel. around the y-axes
c) Res.neck force d)Moment of rotation (y-axes) at the occipital condyles
(The x-axes indicates the time in "milliseconds")

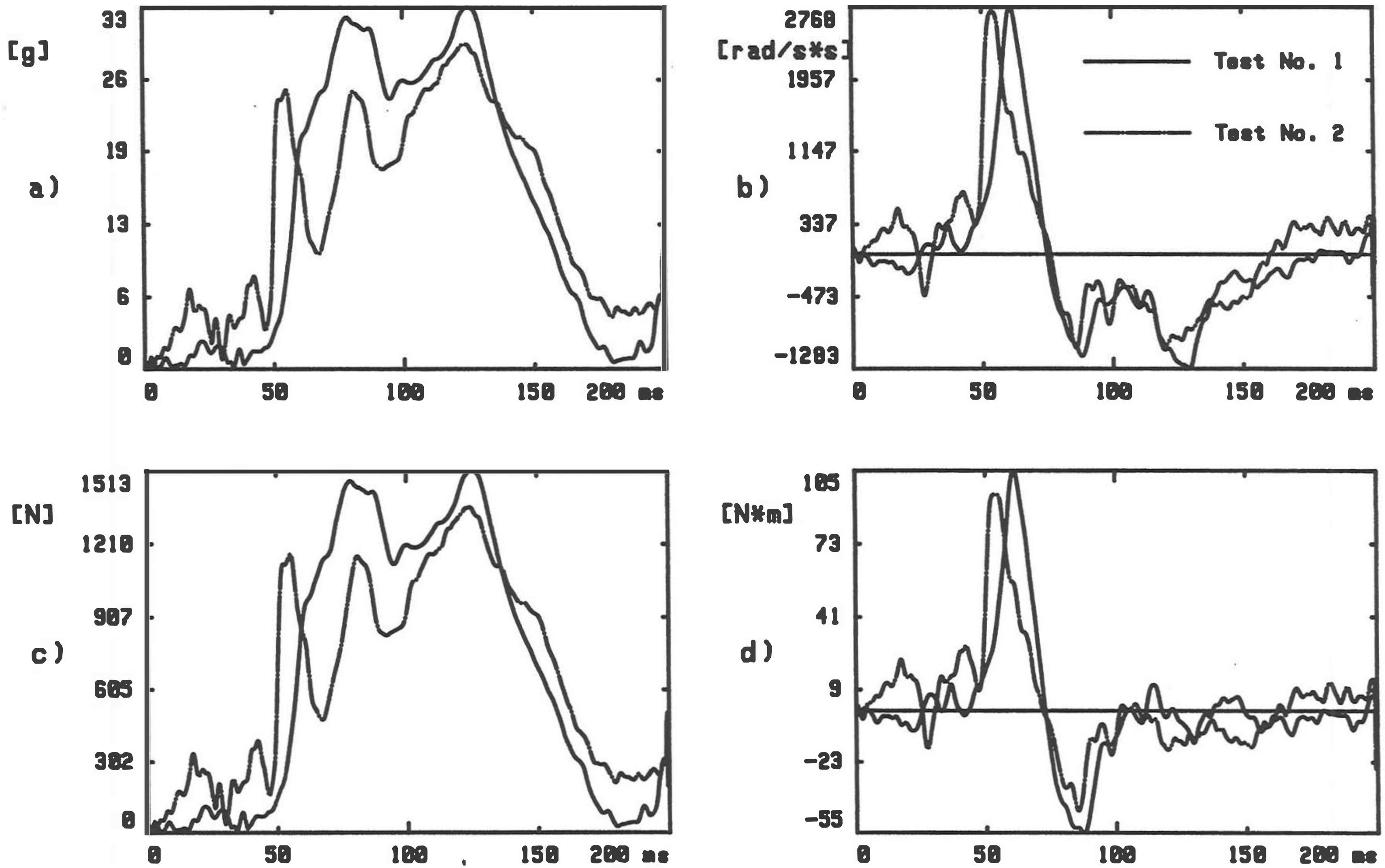
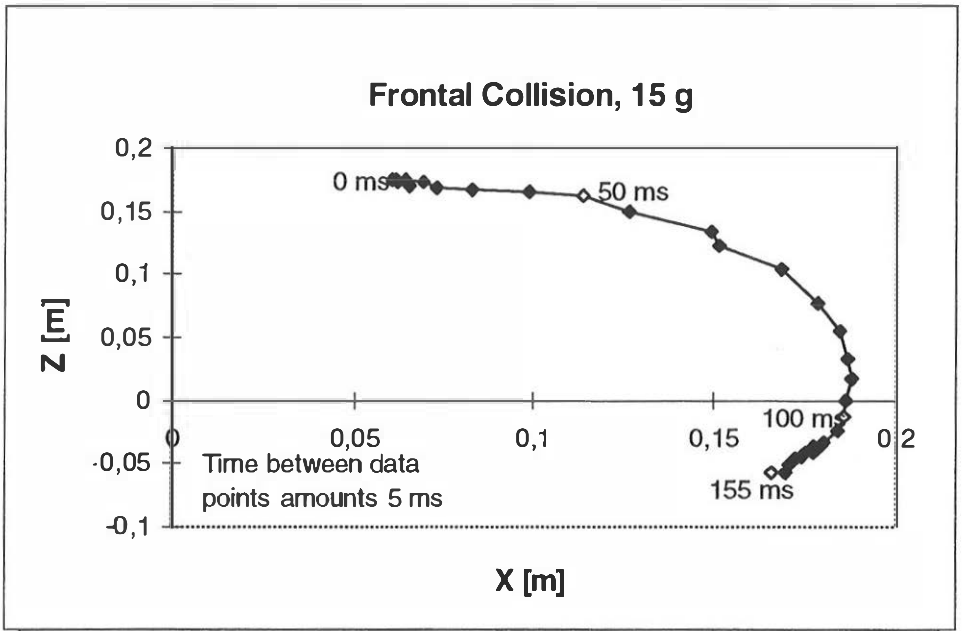


Fig.7: Frontal Collision, 60 km/h, 11 g, 2 tests

a) Res. acceleration in the c. g. b) Rotational accel. around the y-axes
c) Res.neck force d)Moment of rotation (y-axes) at the occipital condyles
(The x-axes indicates the time in "milliseconds")



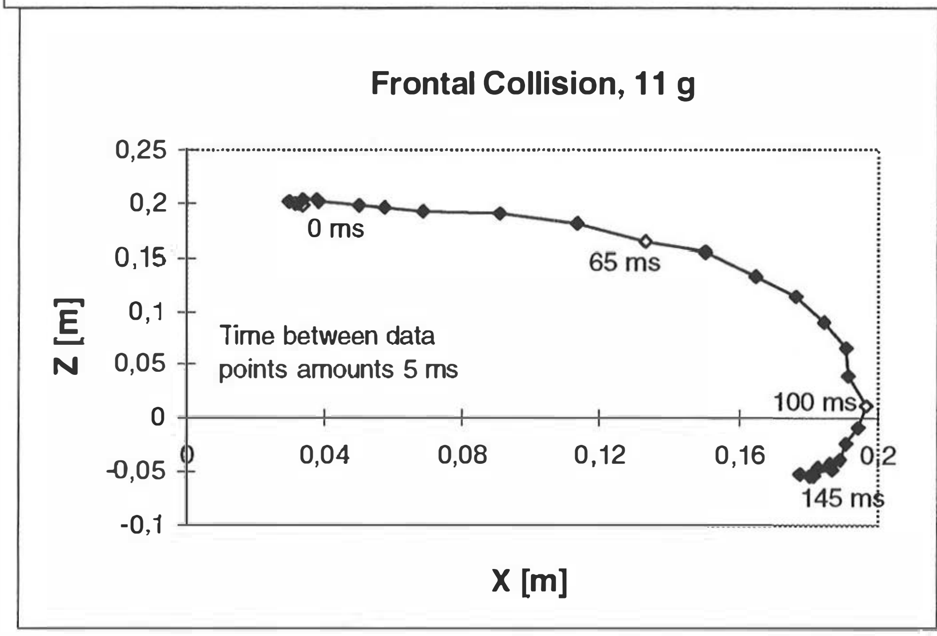


Fig. 8: Head c.g. trajectories relative to T1. Frontal collision, 60 km/h, mean deceleration 15 g and 11 g.

Rear-End Collision - The time histories for the two rear-end tests are presented in Figure 9. The maximum values are smaller compared to those obtained in the frontal and lateral tests but show a longer duration. The evaluated maxima of the resultant at the head c. g. ranges from 16 g to 18 g for both tests and a duration of approximately 150 ms. All the maximal values are listed in Table 3.

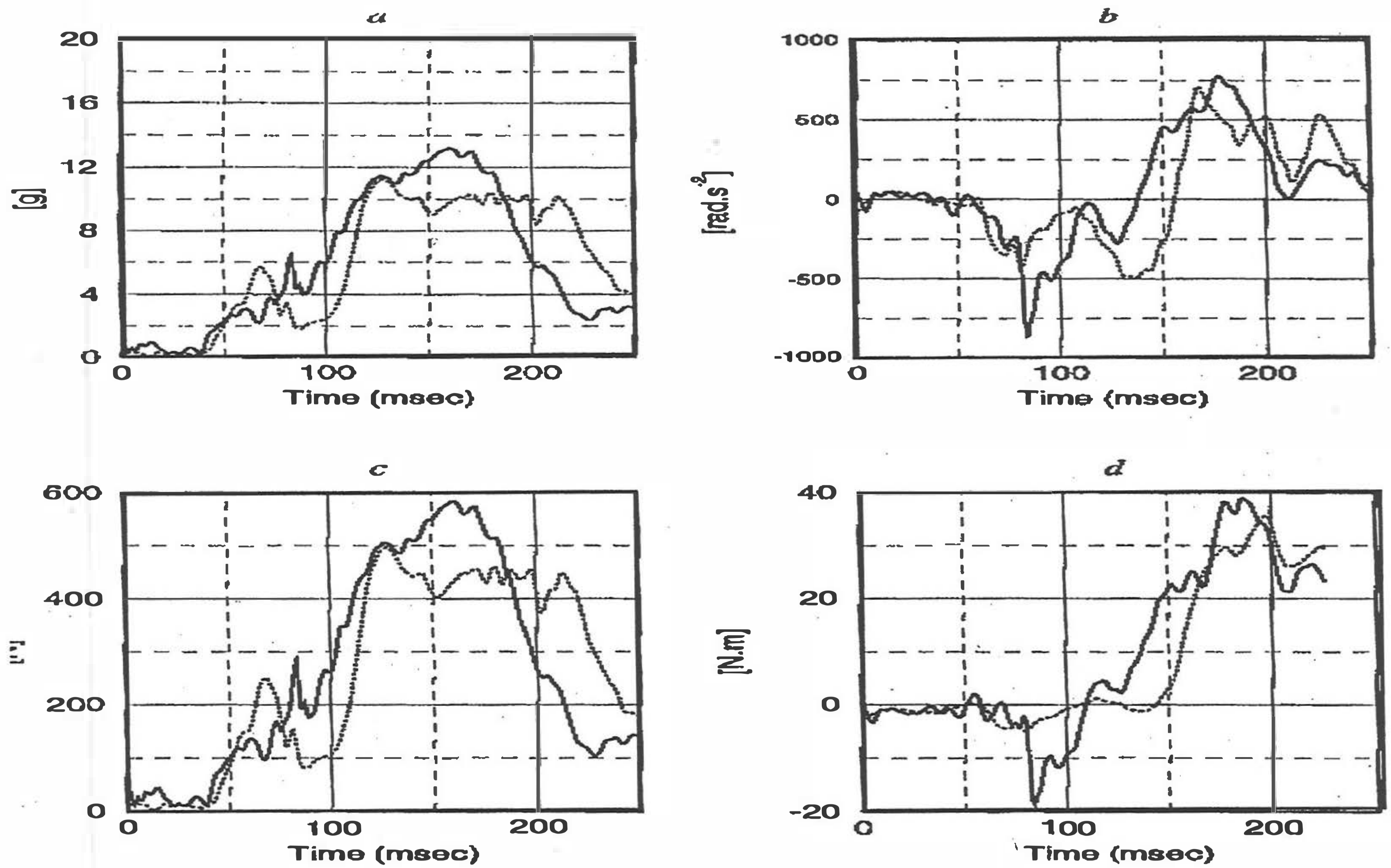


Fig.9: Rear-end Collision, 25 km/h, 7 g, 2 tests

a) Res. acceleration at the c. g. b) Rotational accel. around the y-axis

c) Res.neck force d) Result.moment of rotation at the occipital condyles

(The x-axes indicates the time in "milliseconds")

Table 3: Maximal Rear-end Head-Neck Response and Injury Severity of the Cervical Spine. Impact velocity 25 km/h.

Run No.	Average Sled Dec. [g]	Head c.g. CFC 100 [g]	Rotation [rad/s^2]	Neck Force [N]	Neck Moment [Nm]	AIS Neck
6	7	18	173	815	32	0
7	6	16	340	700	20	3

Fig. 10 shows an example for the displacement of the center of gravity relativ to T1 in the sagital plane for the rear-end collision at an impact velocity of 24 km/h and an average sled deceleration of 6 g's. The displacement in z-direction is smaller as that in the frontal collsions.

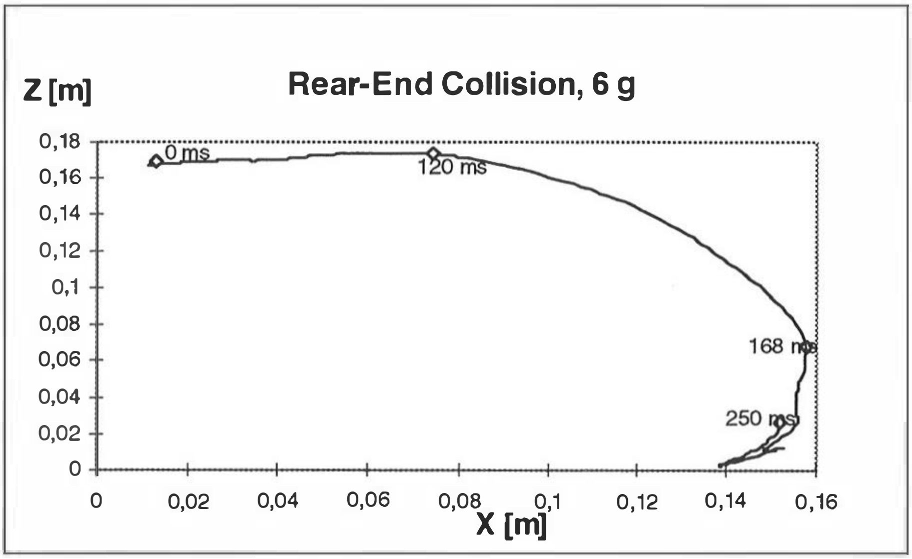


Fig. 10: Head c.g. trajectories relative to T1. Rear-end collision, 24 km/h, average deceleration 6 g .

Lateral Collision - The mechanical response of the lateral tests is evaluated by film analysis and the linear accelerations of the clivus and T1. A relative movement between the torso-neck unit and the head of a duration of 10 - 30 ms was observed through the film analysis, which means that in this time a shear force at the level of the occipital condyles acts. Important for this shear force is the acceleration of the head in y-direction.

The measured acceleration at the clivus is assumed to be the same than the center of gravity acceleration; therefore the clivus acceleration in y-direction was multiplied by a head mass of 4.54 kg to calculate the shear forces. The maximal shear forces and the maximal resultant Clivus and T1 accelerations of the five lateral impact tests are summarized in Table 4.

Table 4: Maximum Resultant Accelerations at T1 and Clivus, the Lateral Component of the Clivus Acceleration and calculated Shear Forces at the Level of the Occipital Condyles.

	Clivus CFC1000		T1		Clivus		Neck
Run No.	maximum [g]	time [ms]	maximum [g]	time [ms]	y-direction [g]	shear force [N]	AIS
8	68	39	85	31	68	3035	3
9	62	45	77	28	50	2232	1
10	45	48	76	32	45	2006	1
11	59	38	115	31	43	1919	1
12	100	32	116	24	100	4464	3

MEDICAL FINDINGS - By using a detail investigation of the vertebral column, injuries between the base of the skull and the upper thoracic spine are observed. The most frequent injuries are hemorrhages (AIS 1) of the intervertebral discs from the middle to the lower cervical spine, strain of the lig. apicis dentis (AIS 1), furthermore hemorrhages of the muscles and joints at the level between C0 and C2 (AIS 1). In one case, 15g frontal impact test, a laceration of the ligamentum flavum T2/T3 (AIS 2) and a compression fracture of T2 (AIS 2) was observed.

The sclerotic front longitudinal ligament was fractured at the lower edge of C3 in one rear-end collision test. The same subject showed a fracture of the front edge of the vertebral body T4 , furthermore the upper plate of T4 was loosened from the spongy bone (AIS 3).

In two cases of the five lateral tests fractures of the near side condylus were found (AIS 3) (Fig. 11). The injury severity classification of the observed cervical spine injuries are presented in the last columns of table 2, 3 and 4.

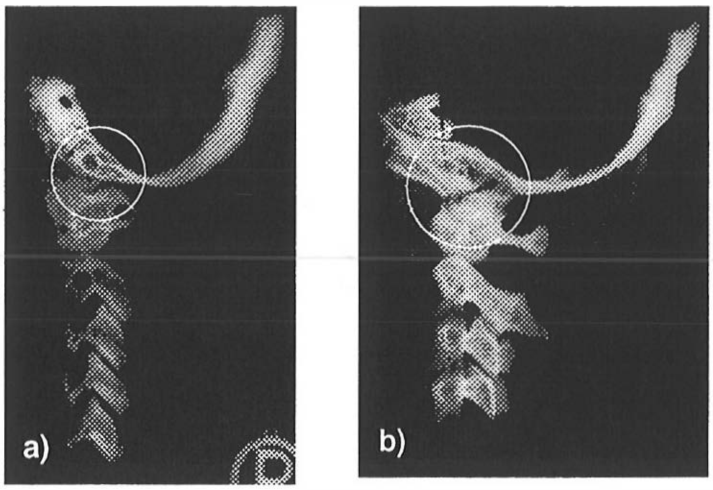


Fig. 11:
Fractures of the occipital condyles a) Run No.: 8
b) Run No.: 12

DISCUSSION

Cervical spine injuries are noticed when extreme excursions of the head-neck system occur in frontal and lateral flexion and extension. In the last years the compensation cases for insurance companies dealing with cervical spine injuries are increasing. The performed study should provide information about injury mechanism, loading and injury severity by using cadavers. Twelve midsevere and severe cadaver tests (5 frontal, 5 lateral and 2 rear-end) have been conducted and analyzed.

FRONTAL - The calculated rotational accelerations of the head-neck unit in frontal collisions are between 2600 rad/sec² to 3300 rad/sec² and are higher than the highest value of 1700 rad/sec² determined by Wismans et al. (1987) in 15 g runs of the human volunteer tests conducted by Ewing and Thomas at NBDL.

Neck forces at the level of the occipital condyles from 1156 N to 1985 N were observed which are at the same force level (450 lb = 2043 N) as found by Mertz and Patrick (1975) without producing ligamentous or bony damage in cadavers. However, in our case a compression fracture of the T2 vertebral body and the ligamentum flavum at the same level was observed; the force at the level of the occipital condyles was 1885 N. This force, however, can not be related with the injuries observed; the fracture is caused through bending, whereas the ligament rupture is caused by strain. The calculated forces are shearing forces.

REAR-END - Compared to the frontal experiments, lower rotational accelerations (173 rad/sec² and 340 rad/sec²) for the rear-end collision were calculated. These values are similar as those derived from the analyzed high speed film data from volunteer tests presented by McConnel et al. (1995); however, they are clearly lower as the measured angular accelerations (400 rad/sec² to 1580 rad/sec²) of the same volunteer tests.

The neck moments evaluated at the level of the occipital condyles amount 20 Nm and 32 Nm for the two tests conducted. Both values are clearly lower than the proposed 48 Nm by Mertz and Patrick (1972) and Mertz et al. (1973) as non-injury level and 68 Nm for ligamentous damage. Which cannot be confirmed by the injuries found in test 7.

LATERAL - According the measurements performed in the side collisions, only the shearing forces at the level of the occipital condyles can be evaluated. This type of loading is also related to the injury pattern observed at the occipital condyles. The evaluated forces are between 1900 N and 4500 N. During the shearing the near side occipital condyle is loaded through the C1, during the far side occipital condyle is moved away from C1. For the highest values of 3035 N (Run No. 8) and 4464 N (Run No. 12) the near side condyle was broken.

NON SEVERE INJURIES - In 50% of the cases an injury severity of AIS 1 (hemorrhages) was observed, which means the diagnosis distorsion of the cervical spine (in reality results into pains). Most injuries were located at the level of the upper cervical spine, which can be caused by mainly shearing (Walz and Muser, 1995), but also at the cervico-thoracic junction as result of bending forces. Generally is concluded, that this research was performed under mid-range to severe impact conditions compared to the low velocity impacts with distorsion trauma of the cervical spine.

By using cadavers it is possible to experimentally determine correlations between responses and injuries. Microtraumas, like small muscle- or nerve strains, ruptures, small hemorrhages, neurologic symptoms, disturbed functions etc. are not found in cadaver tests and therefore tolerance limits for such injuries and their consequences can not be determined.

Tests with young volunteers or with tests subjects, who are prepared for the crash are also non transferable to reality. Besides the age (degenerative or healthy cervical spine) also the head position prior to impact is relevant during the time of collision. In the rear-end collision, the adjustment of the head restraint is important for the behavior and injury of the cervical spine; this is very different in the reality. The observations in spinal column injuries in rear-end collisions with volunteers are also different by the various investigators. While Danner (1991) and Deutscher (1993) excluded a spinal column trauma at a velocity change less than 15 km/h in car/car and sled rear-end collisions with volunteers by using correct (top of the head corresponds to top of the head restraint) adjusted head restraints. Whereas McConnell et al. (1993, 1995) observed in car/car collisions with volunteers, however with adjusted head restraints at the level of the head center of gravitity, that a velocity change of 6 to 8 km/h is probably at or near the human threshold for very mild, single event musculoskeletal cervical strain injury.

Further experimental work and research on realistic cases by using the magnetic resonance imaging tomography (MRI) is necessary to investigate the spinal column trauma.

CONCLUSIONS

1. Microtraumas, like small muscle- or nerve strains, ruptures, small hemorrhages, neurologic symptoms, disturbed functions etc. are not found in cadaver mid-range to severe tests and therefore, these injuries and their consequences are underestimated in this study.

2. Tests with young volunteers or with tests subjects, who are prepared for the crash are also non transferable to reality.

REFERENCES

Beier G, Schuler E, Schuck M, Ewing CL, Becker ED, Thomas DJ, (1980)
Center of Gravity and Moments of Inertia of Human Heads,
Proc. Ircobi Conference, pp. 218-228

Danner M, (1987) Halswirbelsäule - Verletzungen bei PKW-Insassen und daraus resultierende Versuche im Allianzzentrum für Techink (Versuchsdurchführung und Trends), Gesellschaft der Gutachterärzte Östereichs, Forschung und Praxis der Begutachtung, Heft 30

Deutscher, C, (1994)
Bewegungsablauf von Fahrzeuginsassen beim Heckaufprall
Eurotax (International) AG, ISBN 3-9520040-9-X

Ewing CL, Thomas DJ, Lustick L, Becker E, Willems G, Muzzy WH (1975)
The Effect of the Initial Position of the Head and Neck on the Dynamic Response of the Human Head and Neck to - Gx Impact Acceleration. SAE paper No.: 751157, Proc. 19th Stapp Car Crash Conference, pp. 487-512

Geigl BC, Steffan H, Leinzinger P, Roll P, Muhlbauer M, Bauer G, (1994)
The Movement of Head and Cervical Spine During Rear-End Impact
Proc. Ircobi Conference, pp. 127-137

Geigl BC, Steffan H, Dippel Ch, Muser MH, Walz F, Svensson MY, (1995)
Comparison of Head-Neck Kinematics During Rear-End Impact Between Standard Hybrid III, RID-Neck, Volunteers and PMTO's
Proc Ircobi Conference, pp. 261-270

McConnell, WE, Howard, Rp, Guzman, HM (1993)
Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts, Intern. Cong. and Exposition, SAE, Warrendale, Paper No. 930889

McConnell WE, Howard Rp, Poppel JV, Krause R, Guzman HM, Bomar JB, Raddin, JH, Benedict JV, Hatsell CP (1995)
Human Head and Neck Kinematics after Low Velocity Rear-end Impacts Understanding "Whiplash" SAE paper No.: 952724, Proc. 39th Stapp Car Crash Conference, pp. 215-238

Mertz HJ, Patrick LM, (1972)
Strength and Response of the Human Neck
15th Stapp Car Crash Conference, pp. 207-255

Mertz HJ, Neathery RF, Culver CC, (1973)
Performance Requirements and Characteristics of Mechanical Necks
Human Impact Response: Measurement and Simulation, pp. 263-288.
Eddited by W.F. King and H.J. Mertz, Plenum Press, New York

Padgaonkar AJ,Krieger KW, King AI, (1976)
Measurement of Angular Acceleration of a Rigid Body
Using Linear Accelerometers
Journal of Applied Mechanics

Walz FH, Muser MH, (1995)
Biomechanical Aspects of Cervical Spine Injuries,
SAE paper No. 950658, Advances in Occupant protection Technologies
for the Mid-Nineties, SP-1077, pp. 45-51

Wismans J,. Philippens M, Oorschot H, Kallieris D, Mattern R, (1987)
Comparison of Human Volunteer and Cadaver, Head-Neck Response
in Frontal Flexion, SAE paper No.: 872194
31st Stapp Car Crash Conference, pp. 1-13