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Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion

J. Wismans, M. Philippens, and E. van Oorschot
TNO Road Vehicles Research Institute
Delft, The Netherlands

D. Kallieris and R. Mattern
Institute for Forensic Medicine
University of Heidelberg, West Germany

ABSTRACT

At the 30th Stapp Conference an analysis was presented of human volunteer head-neck response in omni-directional impact tests.
It was shown that the relative head motion can be described by a simple two-pivot analog system.

The present study extends this analysis to post-mortem human subject (PMHS) tests conducted at the University of Heidelberg. Two test series similar to the human volunteer frontal impacts tests were carried out. One having an impact severity identical to the most severe human volunteer tests. A second series with higher exposure levels are used to verify the proposed analog system for higher impact levels. Test results including neck injury data for five PMHS tests will be given with special attention to trajectories of the head center of gravity, head rotations and head accelerations.

It is concluded that the center of gravity trajectories for the PMHS and volunteer tests are similar for both impact levels. Head rotations, however, are larger for the PMHS than for the volunteer tests. The two-pivot linkage mechanism proposed for the volunteer head-neck motions also appears to be suitable to describe the PMHS head-neck response.

THE NAVAL BIODYNAMICS LABORATORY (NBDL) in New Orleans has conducted a large number of human volunteer tests to study omni-directional head-neck response in an impact situation. A detailed description of the NBDL instrumentation and test methods is provided by Ewing et al. (1-4)*. As part of our research program a large number of the NBDL tests conducted between 1981 and 1985 have been analyzed in order to develop performance requirements for a mechanical neck for crash dummies. Detailed results of these analyses have been presented in (5-8). It was shown that the volunteer relative head motion can be described quite well by a simple two-pivot analog system.

The purpose of the present study is to extend this analysis to post-mortem human subjects (PMHS) tests conducted at the University of Heidelberg. These subjects have been exposed to frontal impacts using a similar sled seat and restraint system as in the NBDL human volunteer tests. A detailed description of the test set-up and test results of the PMHS tests will be presented. Results will be compared with a representative set of nine tests out of the most severe frontal human volunteer tests conducted at NBDL. In these NBDL tests five different subjects were exposed to a 15 g sled acceleration. Table 1 summarizes these tests together with the important test conditions.

METHODS AND MATERIALS

TEST PROCEDURE - The post-mortem human subject (PHMS) tests were conducted on the decelerator of the Institute for Forensic Medicine of the University of Heidelberg. The experimental set-up was similar to the frontal NBDL volunteer tests (3). 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 (Fig. 1). The arms were restrained by an additional belt at the mamillar level to prevent flailing.

Twelve tests have been conducted. Tabel 2 summarizes the most important test conditions. The first five tests are pre-test and can not be analyzed here due to limited visibility of the photographic targets. In two further tests (i.e. 8703 and 8705) no film-data are available. As a consequence five tests are suitable for a more detailed analysis. Two tests are of a similar impact severity as the NBDL volunteer tests (15 g sled acceleration), while three tests are more severe (23 g).

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* Numbers in parentheses designate references at end of paper.

Table 1. Test characteristics of 9 selected human volunteer tests in frontal impacts.

Test no.	Subject no.	Imp. Vel. (m/s)	Peak Sled dec. (g)	Sex	Initial neck length1) (cm)	Anthropometric measurements at NBDL					
						Weight (kg)	Standing height (cm)	Sitting height (cm)	Head		
									Circumf. (cm)	Breadth (cm)	Length (cm)
3957	H00132	16.75	14.6	M	14.1	79.8	172.9	89.6	57.9	15.7	19.7
3959	H00127	16.84	14.8	M	16.2	62.1	172.3	89.8	54.2	14.9	18.5
3963	H00133	16.69	14.5	M	16.5	61.2	161.7	86.8	56.1	14.7	19.4
3965	H00135	16.67	14.6	M	15.0	68.9	171.6	90.7	53.5	14.6	17.9
3970	H00135	17.26	15.6	M	15.0	68.9	171.6	90.7	53.5	14.6	17.9
3982	H00132	17.47	15.6	M	14.2	79.8	172.9	89.6	57.9	15.7	19.7
3986	H00133	17.31	15.6	M	16.5	61.2	161.7	86.8	56.1	14.7	19.4
3987	H00131	16.76	14.5	M	15.6	67.6	167.0	90.0	57.5	15.4	19.6
3990	H00131	17.26	15.4	M	15.6	67.6	167.0	90.0	57.5	15.4	19.6

1) Defined as the average value of the initial distance between T1 and head anatomical origin in several tests.

Table 2. Test conditions, subject anthropometry and post test AIS values.

PMHS Test	Imp. Vel. (m/s)	Peak Sled dec. (g)	Sex	Initial neck length1) (cm)	Anthropometric measurements							AIS	Remarks
					Weight (kg)	Standing height (cm)	Sitting height (cm)	Head					
								Circumf. (cm)	Breadth (cm)	Length (cm)	Vol. (lit.)		
8615	16.4	15.5	M	-	80	176	96	61	17	24	-	0	pre-test
8616	16.4	15.0	M	-	66	170	92	60	17	19	4.4	1	pre-test
8618	16.4	15.1	F	-	58	175	84	55	15	18	4.1	1	pre-test
8620	16.4	16.4	F	-	78	165	91	55	15	18	4.6	2	pre-test
8621	16.4	14.8	F	-	72	166	91	55	15	18	4.8	0	pre-test
8622	16.4	16.0	M	16.7	80	182	95	57	15	19	4.6	1	-
8701	16.7	15.2	F	14.9	74	168	89	54	15	18	3.9	1	-
8703	16.7	15.2	M	-	66	154	85	55	15	19	4.0	1	no film
8705	16.7	15.2	M	-	71	175	92	59	17	19	4.0	1	no film
8706	16.4	23.0	M	16.0	72	172	91	59	16	19	5.2	1	-
8709	16.7	21.5	M	15.5	74	170	97	58	15	14	4.8	1	-
8710	16.7	23.3	F	13.6	53	175	90	53	14	18	3.3	2	-

1) Defined as the initial distance between T1 and head anatomical origin.

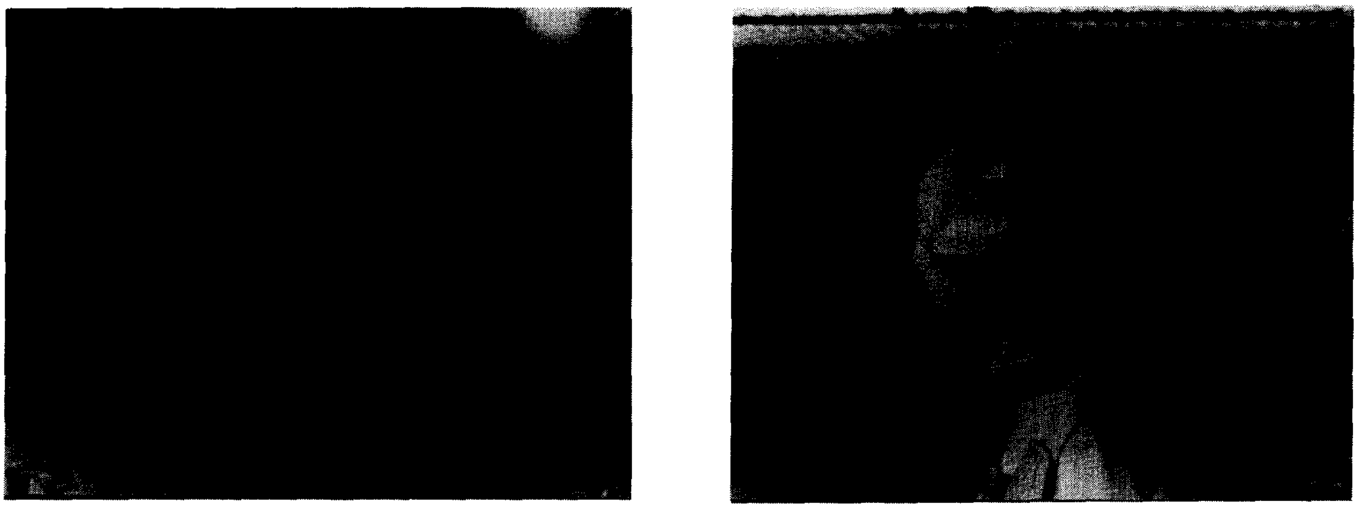

Fig. 1 Test set-up for PMHS tests (initial conditions).

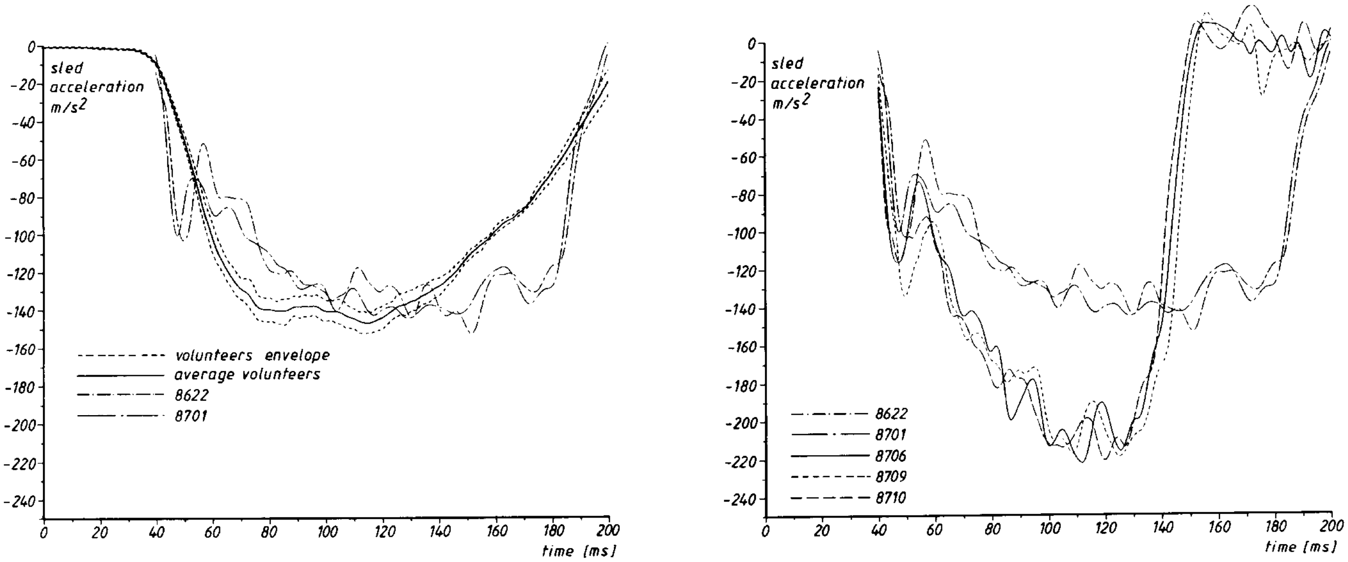

Fig. 2 Sled accelerations. Left: PMHS tests with volunteer envelope 15 g. Right: 15 g and 23 g PMHS tests.

INSTRUMENTATION - The positions of head and the first thoracic vertebral body (T1) were registered by a sled mounted high speed camera running at 1000 frames/second, assumed to be parallel to the plane of motion. Two photo targets are mounted to the head as well as T1. The positions of the head and T1 anatomical coordinate systems were related to these targets by two dimensional x-ray analysis. Sixteen channels of time-history data were recorded for each test. The instrumentation included a nine-accelerometer module as described by Padgaonkar (9) screwed to the top of the skull, a tri-axial accelerometer unit screwed at the clivus and a tri-axial accelerometer unit screwed to T1. All accelerometers used are ENDEVCO 2264-2000. Mass of the head instrumentation is about 0.165 kg. The signals were sampled at 10 kHz and filtered with a low pass 100 Hz 4th order Butterworth digital filter. The orientation of accelerometers in relation to the anatomical landmarks were obtained from lateral and anterior-posterior x-rays.

SLED ACCELERATION - Fig. 2 (left) shows the envelope of the NBDL sled acceleration-time histories in the nine volunteer tests together with the sled pulse in the two 15 g PMHS tests. It can be seen that the PMHS sled deceleration compares well with the volunteer tests. The velocity change of all PMHS tests is identical, which results in a shorter duration of the 23 g deceleration pulse as shown in Fig. 2 (right). The time bases of all PMHS tests has been shifted 40 ms in order to align the T1 acceleration time history of the volunteer and PMHS 15 g tests.

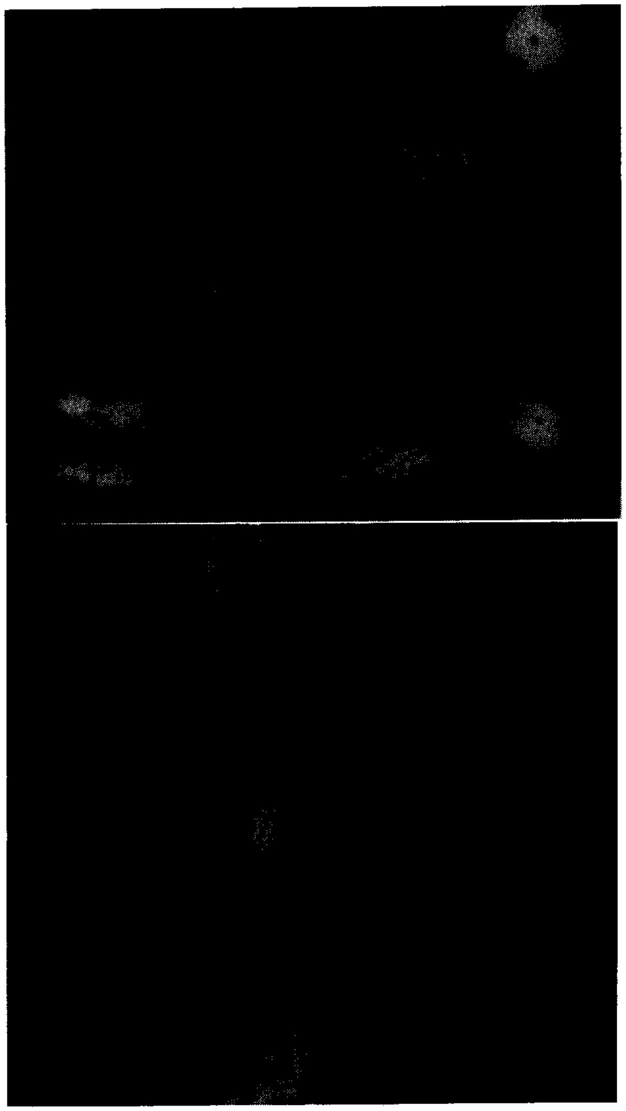

Fig. 3 Anterior-posterior and lateral x-rays with instrumentation and lead balls at the anatomical landmarks.

PRETEST PREPARATION OF POST-MORTEM HUMAN SUBJECTS - In an attempt to simulate the muscletone of living people, 100 ml 10% solution of formaldehyde was injected in the rear and side muscles of the neck of each post-mortem human subject PMHS. The time between the injection and the test amounted, in most cases, to more than 20 hours. By that it was attained that the contraction condition of the muscular system in the neck area was controlled in all tests. Fluctuations as they usually occur in the condition of rigor mortis, were reduced because of this measure. This means, that in the cases with a relaxed rigor mortis a contraction condition has been established which can be compared with a medium strong muscular tension in a living person. In a fully marked rigor mortis an additional contraction by means of formaldehyde injection could not be obtained. The fully marked rigor mortis corresponds to a very strong muscular tension in a living person.

The anatomical landmarks defining the Frankfurt plane, infraorbital notches and auditory meati, were marked with small lead balls. The position of these landmarks and positions of the optical targets and instrumentation were documented by anterior-posterior and lateral x-rays (Fig. 3).

POST-TEST PROCEDURE OF THE POST-MORTEM HUMAN SUBJECTS - A fully autopsy with a detailed investigation of the vertebral column has been performed after each test, as desribed by Mattern (10). The injury severity of observed lesions was scaled in accordance with AIS (11) (Table 2). Injuries not separately mentioned in the AIS vocabulary were scaled by analog application of the AIS criteria. Injuries in the PMHS were diagnosed as acute strain if hemorrhages occurred in the deep spinal column muscular system between the muscle bundles or in the region of the ligamental system, as well as in the vertebral joints and discs. Such cases were estimated with AIS 1. Macroscopically visible cuttings of above mentioned tissues did not occur in the investigated cases. Lacerations of ligaments, of intervertebral disc tissue and tear drop fractures of the vertebral bodies have been estimated with AIS 2.

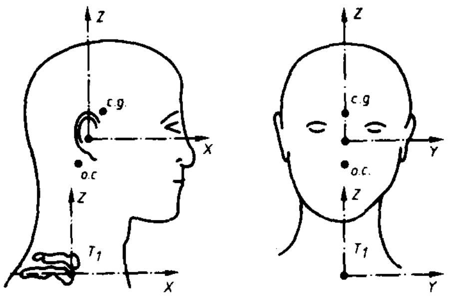

Fig. 4 Location of anatomical coordinate systems according to NBDL (o.c. = occipital condyles, c.g. = center of gravity).

COORDINATE SYSTEMS AND ANTROPOMETRY

COORDINATE SYSTEMS - Fig. 4 illustrates the location of the head and T1 anatomical coordinate system. The anatomical origin of the head is positioned at the midpoint of the connection of the auditory meati. The positive x-axis is defined as the line between this origin and the midpoint of the line connecting the infraorbital notches. The y-axis is perpendicular to the xz plane and positive toward the left ear. The plane defined by the x and y axis is approximately the Frankfurt plane. The origin of the spine (T1) anatomical coordinate system is at the anterior superior corner of the first thoracic vertebral body (T1). The orientation of the T1 coordinate system used for the analysis is taken parallel to the laboratory system.

HUMAN SUBJECT ANTHROPOMETRY - The most significant anthropometric data are summarized in Table 2. Definitions for these variables can be found in (3). These definitions are similar to the ones used by NBDL for the volunteers.

The volume of the PMHS head was measured by submersion (included in Table 2). The initial neck length is the distance between head and T1 anatomical origin as obtained from film-data at the start of the test.

TEST RESULTS

MEDICAL FINDINGS - No injuries occurred in three of the twelve conducted tests. In seven cases strains in the vertebral discs and small lacerations of the ligamenta flava and within the joints have been observed. In two tests, a severity of AIS 2 was determined: the first caused by a fracture in the upper front edge of the T2 vertebrae (Run no. 8620), the second caused by a laceration of the ligamentum flavum T2/T3 (Run no. 8710). Spinal column injuries for each test are reported in detail in Appendix A.

SPINE (T1) MOTION - Fig. 5 presents resultant T1 acceleration time-histories. In Fig. 5 (left) the two PMHS tests with a similar severity as the most severe human volunteer tests are presented together with the human volunteer envelope. It follows that the acceleration pulse is located near the lower boundary of the envelope and for a large portion within the envelope. This indicates that the input to the head-neck system is similar in the PMHS and the human volunteer tests. Fig. 5 (right) summarizes the T1 accelaration-time histories in all five PMHS tests. It can be seen that there is only a small difference in T1 accelerations between the 15 g and 23 g PMHS tests.

Table 3 summarizes maximum forward (horizontal) and vertical T1-origin displacements relative to the sled. The forward displacements appear to be of the same order of

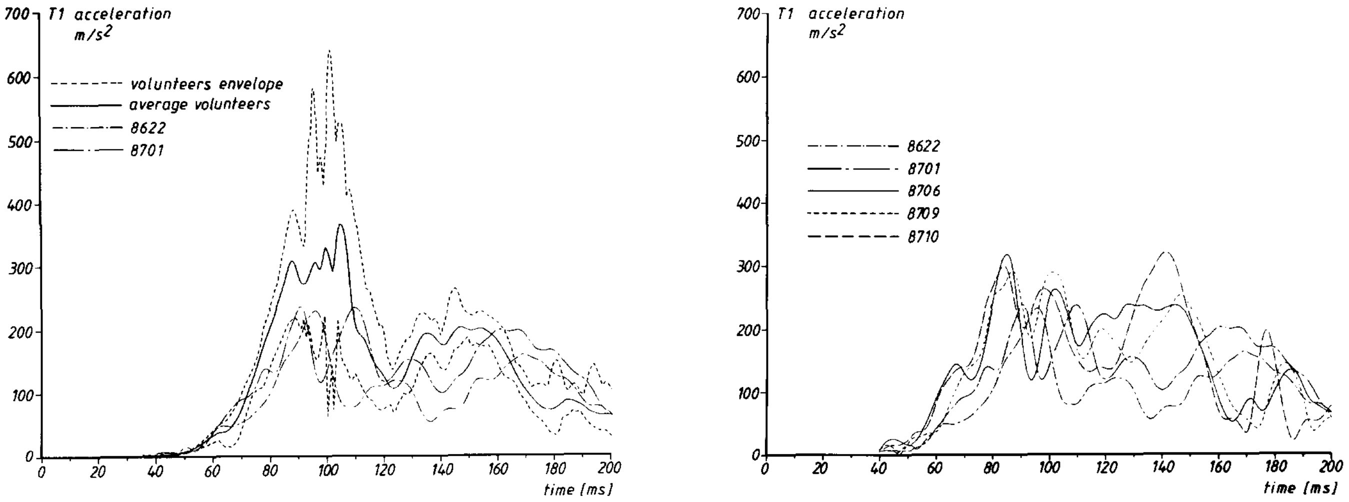

Fig. 5 Resultant T1 linear accelerations-time histories.

magnitude in the PMHS and the volunteer tests. The vertical displacements, however, show significant differences. In all PMHS tests a downward T1 displacement can be observed (up to 90 mm), while in the volunteer tests this downward motion is almost completely absent.

Table 3. T1 displacements and rotations.

Test number	Max. Displacement		Max. Rotation
	Horizontal (cm)	Vertical (cm)	(degrees)
Volunteer range	6.1/8.1	-0.1/-2.7	9.0/22.3
8622	5.2	-8.2	17.7
8701	7.9	-7.1	23.5
8706	6.8	-5.8	25.0
8709	10.8	-9.4	36.8
8710	13.2	-8.4	36.9

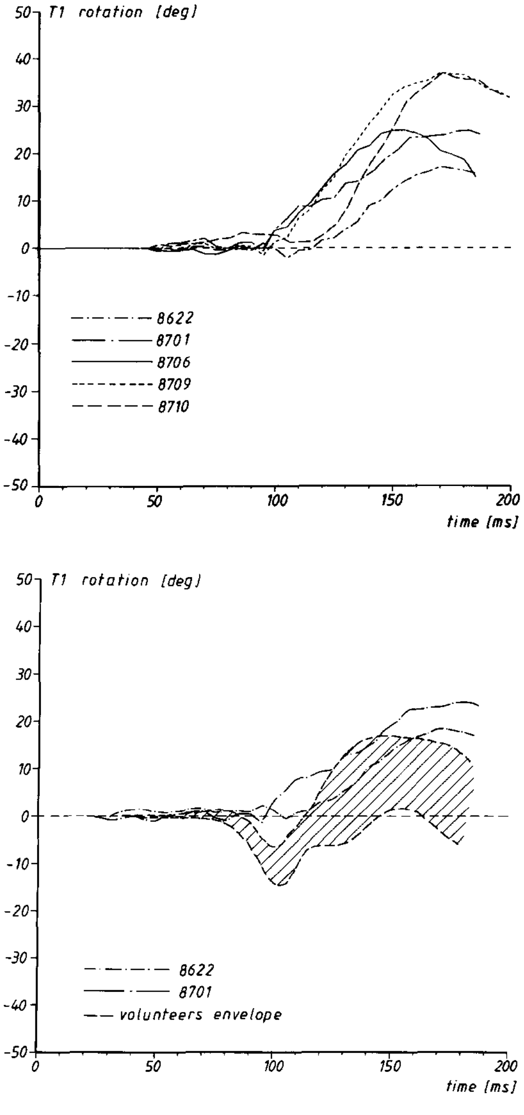

Fig. 6 T1 rotation-time histories.

A comparison of T1 rotation-time histories in the human volunteer and PMHS tests is presented in Fig. 6. Note that in the volunteer tests initially a small backward rotation can be observed, which is completely absent in the PMHS tests. The peak T1 rotation appears to be slightly larger in the PMHS tests than in the volunteer tests. In the previous studies related to the human volunteer tests these T1 rotations have been neglected. The assumption of a non-rotating T1 will also be made for the PMHS tests in order to allow a direct comparison with the human volunteer tests. Note that in the severe PMHS tests (Fig. 6 top) larger T1 rotations can be observed than in the 15 g tests.

RELATIVE HEAD MOTIONS - The method used for the analysis of the relative head motions will be quite similar to the one used for the analysis of the volunteer tests. Head motions will be expressed relative to the T1 coordi-

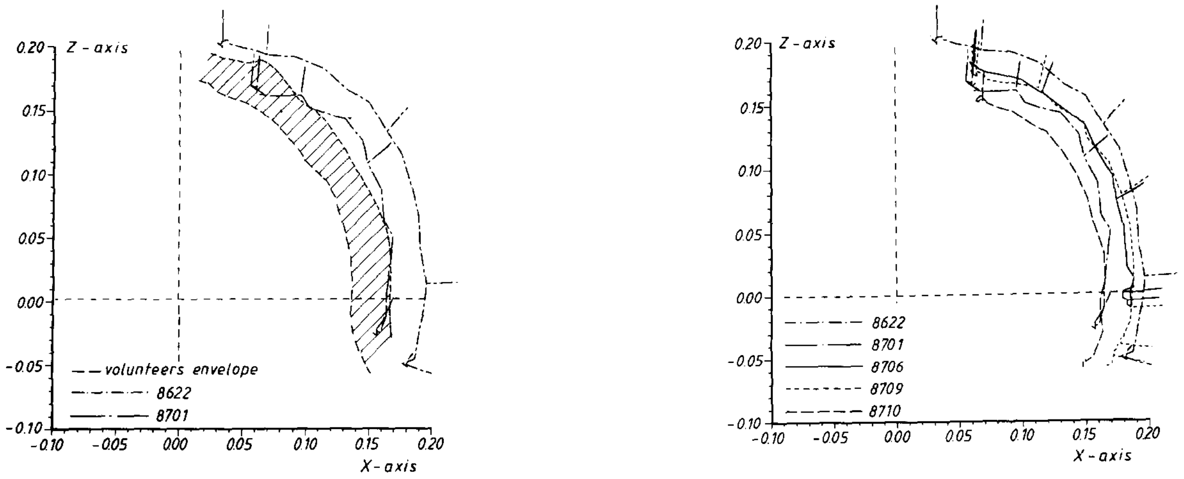

Fig. 7 Head c.g. trajectories relative to non-rotating T1 coordinate system.

nate system. Since T1 rotations will be neglected here, head motions will be presented with respect to a coordinate system which stays aligned with the laboratory system.

First an analysis will be made of head c.g. trajectories and head rotations. Fig. 7 shows the c.g. trajectories relative to T1. The left figure presents an envelope resulting from volunteer test together with results of the 15 g PMHS tests. Fig. 7 (right) compares the 15 g and 23 g PMHS tests. In a similar way in Fig. 8 head rotation-time histories are presented. In agreement with earlier volunteer test analysis, head rotational motion is defined here by the angle ϕ in the plane of impact between head and anatomical z-axis and non-rotating T1 z-axis. Results presented in Fig. 8 relate to the angle $\phi-\phi_0$, where ϕ_0 is the initial head rotation angle (i.e. at time = zero). Peak c.g. translations and peak rotations are summarized in Table 4.

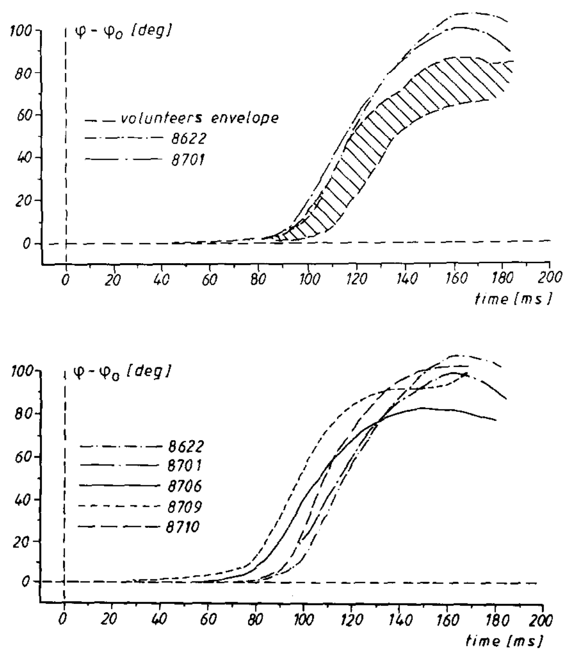

Fig. 8 Rotation of the head $(\phi-\phi_0)$

Table 4. Peak head rotations and c.g. displacement relative to T1.

Test number	c.g. displacement*		Rotation
	forward (cm)	downward (cm)	$(\phi-\phi_0)$ (degrees)
Volunteer range	11.4/15.1	20.1/23.3	68.4/94.9
8622	16.3	25.1	108.8
8701	10.9	19.5	99.9
8706	12.5	19.5	84.4
8709	12.7	23.2	102.6
8710	9.6	21.2	102.6

* relative to initial c.g. position.

The following observations can be made:

- Except for test 8622, trajectories of the PMHS tests are within or close to the envelope defined by the volunteer tests. Also peak c.g. excursions in the PMHS tests appear to be close to the peak excursions observed in the volunteer tests.
- Peak c.g. excursions and head rotations in the severe PMHS tests do not differ significantly from the peak c.g. excursions in the 15 g PMHS tests.
- Except for test 8706, peak head rotations appear to be higher in the PMHS test than in the volunteer tests.
- In the severe PMHS tests an earlier rise of the head rotation-time histories can be observed compared to the moderate PMHS tests.

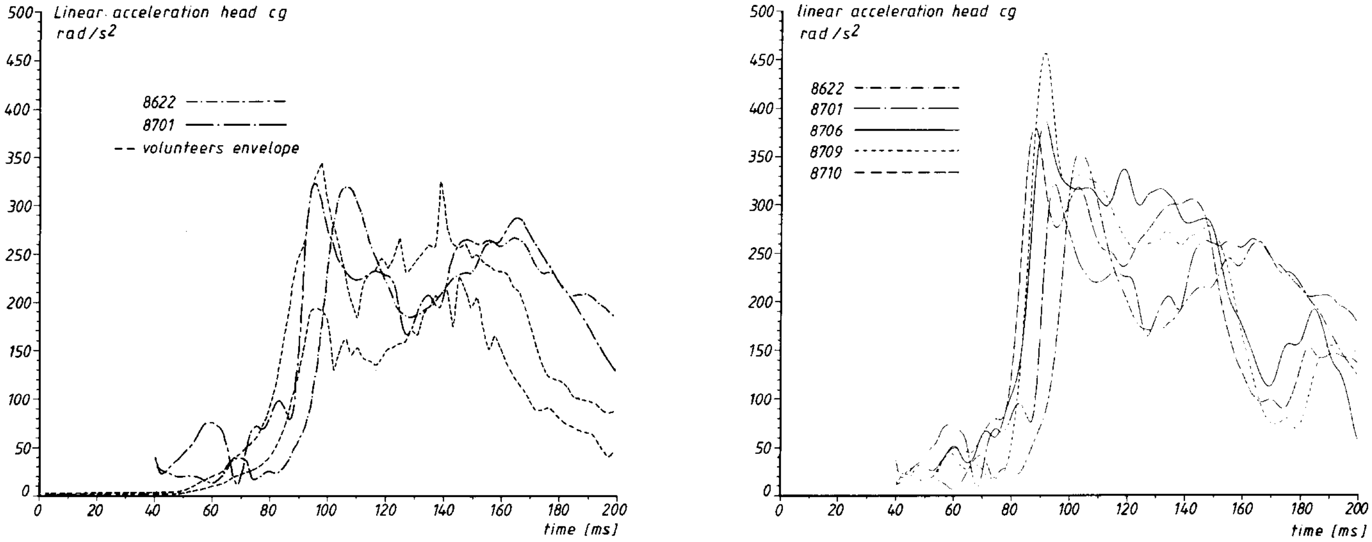

Fig. 9 Resultant linear acceleration of the head c.g.

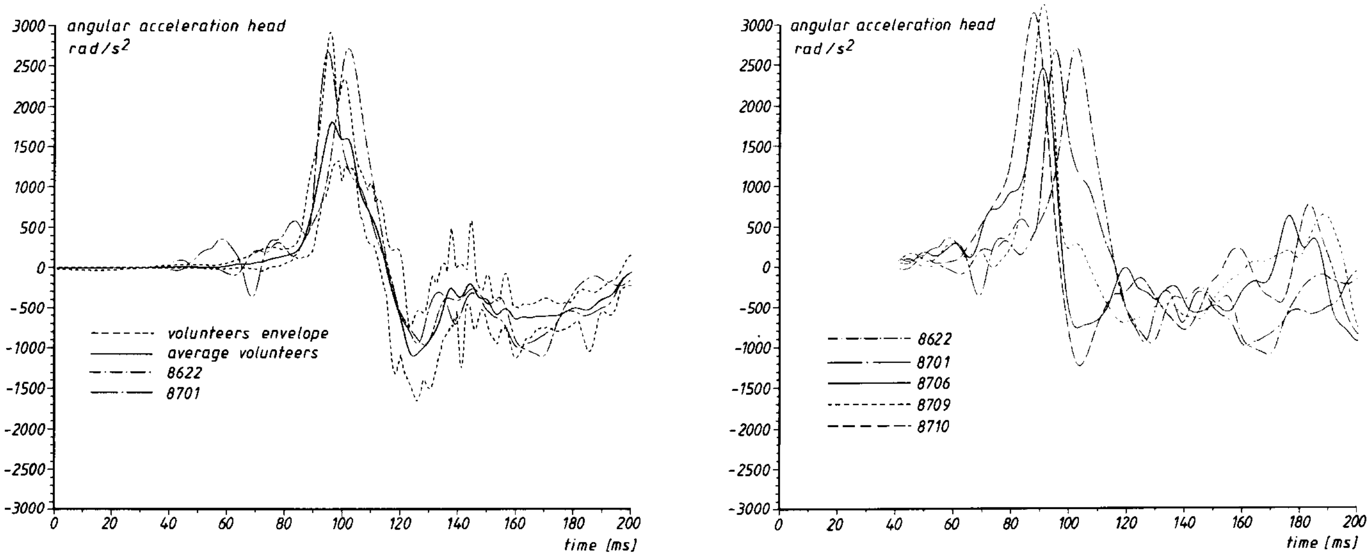

Fig. 10 Angular acceleration of the head.

LINEAR AND ANGULAR HEAD ACCELERATIONS - Fig. 9 presents head c.g. acceleration-time histories. Fig. 9 (left) presents results for two 15 g PMHS tests together with an envelope defined for the human volunteer tests. Fig. 9 (right) compares the c.g. accelerations in all PMHS tests. Fig. 10 presents in a similar way the head angular accelerations measured in the tests (i.e. the angular accelerations about the head local y-axis).

The linear head accelerations in the 15 g PMHS test are within the volunteer envelope for the first 170 ms and slightly higher for the remaining time. The linear head accelerations in the severe tests are higher than found in the 15 g tests except during the last 50 ms. This could be expected because the duration of the 23 g sled deceleration pulse is shorter.

The angular acceleration of the head for the 15 g PMHS tests appears to be well within the volunteers envelope. The first peaks are near the maximum values of the envelope. The 23 g tests show a peak of the same amplitude with a slightly smaller duration than the angular accelerations in the 15 g tests.

THE TWO-PIVOT LINKAGE MECHANISM - Results of the volunteer tests presented in previous studies (5-8) have been expressed in terms of geometrical properties and rotations of a two-pivot linkage mechanism. Fig. 11 illustrates this mechanism. This mechanism was found to be suitable for frontal, lateral as well as oblique impacts. The upper link represents the head, the middle link the neck and the lower link the torso. The upper pivot is located in the occipital condyles and the lower pivot in the center of the circular arc approximating the occipital condyle trajectories. This lower pivot is a pin joint i.e. a joint with one degree of freedom with the rotation axis perpendicular to the plane of impact. The rotation in this joint is denoted by θ and is defined as the angle between neck link and z-axis of the T1 coordinate system.

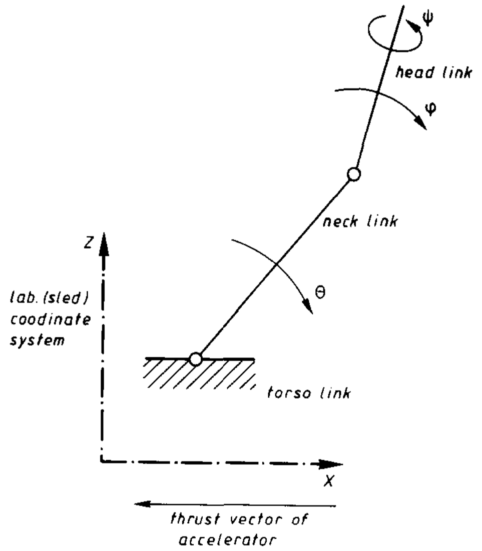

Fig. 11 Analog system for the description of the relative head motions.

The upper pivot is a joint with two degrees of freedom. The first degree of freedom allows the head link to rotate relative to the neck link in the plane of the impact. This rotation angle, denoted by ϕ, was defined in the preceding section. The second degree of freedom of this upper joint is the rotation Ψ of the head about the head anatomical z-axis indicating the head torsion or twist. In frontal impacts this twist motion can usually be neglected.

The geometrical properties of this mechanism (i.e. the neck link length and the lower pivot location relative to the torso) have been determined for the human volunteers using least squares estimation techniques (8). A neck link length of 0.129 m appeared to be a very realistic estimation for all volunteers tested and all impact directions. The same neck link length has also been applied to approximate the occipital condyle trajectories in the present PMHS tests. Table 5 shows the position of the lower pivot relative to the T1 origin, the maximal fitting error in the occipital condyle trajectory (devmax) and the residual standard deviation (sdw) corresponding to this neck link length. For reference purposes this table also includes the mean value resulting from the frontal volunteer tests.

Table 5. Lower pivot location relative to T1 origin and fitting accuracy (neck link length of 0.129 m).

	Xpivot (mm)	Zpivot (mm)	Max.fit. error (devmax) (mm)	Res.stand. deviation (sdw) (mm)
Volunt.*	-31.0	11.0	7.05	2.185
8622	-13.0	19.0	5.999	3.395
8701	-12.0	6.0	16.483	7.009
8706	- 1.0	9.0	7.440	3.737
8709	- 5.0	4.0	10.674	3.961
8710	-14.0	10.0	8.492	2.738

* average value for 46 volunteer tests (8).

The fitting error for most of the tests appears to be larger than the mean values for the fitting error in the volunteer tests. The coordinates of the lower pivot locations resulting from these numerical estimation techniques appeared to lie all within a distance of 2 cm from the T1 origin. Based on these estimations for the linkage geometrical properties the neck link rotation as function of time can be calculated for the PMHS tests.

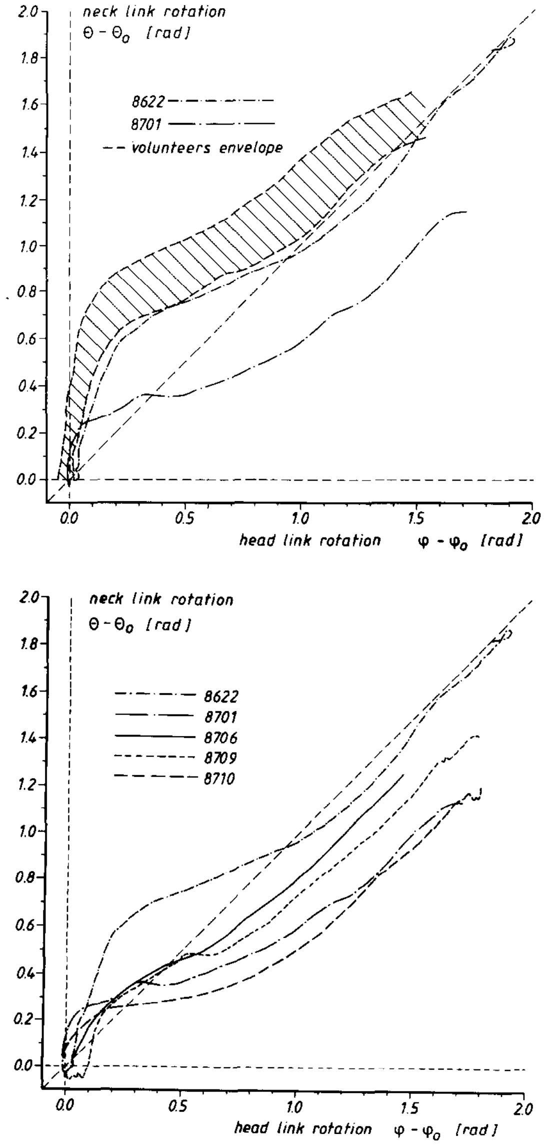

Fig. 12 Neck link rotation $\theta-\theta_0$ as function of head rotation $\phi-\phi_0$.

Fig. 12 presents the resulting neck link rotation $(\theta-\theta_0)$ as function of the head link flexion $(\phi-\phi_0)$ where θ_0 represents the initial rotation angle of the neck link. Fig. 12 (top) includes the envelope resulting from the volunteer tests.

One of the major findings in the volunteer tests was the translational nature of the initial head motion. The maximum relative rotation (i.e. $(\theta-\theta_0)-(\phi-\phi_0)$) between head and neck link appeared to be about 30 degrees in the frontal test (8). In the present PMHS test, however, this rotation is almost absent (except in test 8622). A second interesting finding from the volunteer tests was that the head flexion is smaller than the neck link rotation. In the PMHS test the opposite can be observed: Head flexions become larger than the neck link rotations in the second part of the motion. The most likely explanation for this response is the absence of muscle activity in the PMHS tests.

DISCUSSION

Twelve post-mortem human subject (PHMS) tests have been conducted at the decelerator of the University of Heidelberg. The set-up for these experiments was almost identical to the Naval Biodynamics Laboratory (NBDL) human volunteer tests, analyzed in an earlier phase of our research program.

All post-mortem human subjects were exposed to frontal impacts. In eight of the tests a similar sled pulse was applied as used for the most severe frontal human volunteer tests (15 g). In three tests a more severe pulse (23 g) was applied. Two of the 15 g tests and all three 23 g tests have been analyzed in detail in the present study. First the findings in the 15 g tests will be discussed here.

Due to the different type of sleds used at NBDL (HYGE) and the University of Heidelberg (decelerator), sled acceleration-time histories obtained in both laboratories show slight differences (Fig. 2, left). Peak sled accelerations and sled velocity change however are identical. The effect of the differences in pulse shape on subject response is small as illustrated by the T1 acceleration-time histories: resultant T1 accelerations appear to be located for a large portion within the envelope defined by the volunteer T1 accelerations (Fig. 5, left).

Horizontal T1 displacements, relative to the sled, appear to be of the same order of magnitude in the PMHS and the human volunteer tests. Vertical displacements, however, show a significant difference: in the PMHS tests a relatively large downward T1 motion (up to 9.5 cm) can be observed which is almost completely absent in the human volunteer tests. The absence of muscle activity in the post-mortem subjects seems to be the most likely explanation for this difference. In conjunction with this downward T1 motion a slightly larger T1 rotation can be observed in the PMHS tests. The human volunteer tests initially show a backward T1 rotation (about 10 degrees). This rotation appears to be absent in the PMHS tests. Sliding of the T1 mount relative to the vertebral body, due to skin compliance and interaction between instrumentation straps and restraint system, is probably responsible for this backward T1 rotation in the volunteer tests.

The two-pivot linkage analog system introduced in the previous studies to describe the characteristic head-neck motions in the human volunteer tests also appears to be adequate to describe the head-neck response in the PMHS tests. An identical neck link length (i.e. 0.129 m) as used for the human volunteer tests was selected. The fitting accuracy for the occipital condyle trajectories appeared to be slightly less than in case of the volunteer tests.

The most important finding of the present study is that the observed relative c.g. displacements in the PMHS tests are similar to the volunteer tests. Head rotations however appear to be larger in the PMHS tests. This response is clearly illustrated by the motions at the two-pivot analog system. Using this linkage concept head link rotation (i.e. head flexion) can be expressed as a function of neck link rotation (occipital condyle excursions Fig. 12). The upper pivot rotations in the PMHS tests appear to differ significantly from the human volunteer tests. The initial backward rotation in this pivot, which was about 30 degrees in the human volunteer tests appears to be much smaller in the PMHS tests. In the second phase of the volunteer head-neck motion the head flexion appears to lag behind the neck link rotation: head and neck link are almost "locked". This locking phenomenon however is absent in the PMHS tests: head link rotation becomes larger than the neck link rotation. This response which could be described by the term "overtipping" is most likely caused by the absence of muscle activity in the rear neck muscle group.

The head response as function of time in the PMHS and volunteer tests can be analyzed by a direct comparison of the head accelerations. For a large portion both the resultant linear c.g. and angular acceleration-time histories appear to fall within the envelopes defined for the human volunteer tests. In other words the observed differences in relative head motion between PMHS and human volunteer tests are not reflected in the head accelerations.

A major reason to conduct the PMHS tests is the head-neck response at higher impact levels. It follows that a more severe impact level (23 g) does not result in a significant increase of c.g. displacements and head rotations. In the NBDL volunteer tests the effect of impact severity (up to 15 g) on the head-neck response was studies extensively (8). In general larger head translations and rotations were obtained for higher impact levels. The absence of a significant increase in head excursions in the PMHS tests indicates that possibly the anatomical limits have been reached. A further increase might probably be realized by more excessive load conditions in conjunction with injuries and/or large flexions in the thoracic column.

It should be noted here that the relative head motions (i.e. head c.g. translations and head rotations) have been expressed relative to a non-rotating T1 coordinate system. In other words, a coordinate system which retains the same orientation as the laboratory coordinate system during the test. Consequently c.g. trajectories and head rotations presented here incorporate the influence of thoracic column flexibility which appears to become quite large in the 23 g PMHS tests. If relative head motions are expressed in a rotating T1 coordinate system in general smaller c.g. trajectories and head rotations will be observed. Separate performance requirements could be formulated on the basis of such an analysis. This type of requirements particularly would be beneficial for the evaluation of the performance of dummy designs in which realistic upper thoracic column flexibility has been introduced.

A full autopsy has been performed after each test. No injuries occurred in two of the 15 g and one of the 23 g tests. In seven tests strains in the vertebral discs and small lacerations were observed (AIS 1), mainly in the upper region. In two tests AIS 2 injuries were noted in the upper thoracic region (T2/T3), one test being a moderate and one test a severe impact.

Results obtained in the present study are mainly based on five PMHS tests. A more reliable validation of the results requires a greater number of tests to be analyzed. Calculation of the loads on the neck structure will be necessary to specify dynamic properties of the pivots in the two-pivot analog system. This will require a detailed analysis of the accuracy of the test methodology and will probably result in application of 3D x-ray and high speed 3D photogrammetric techniques. If results of load calculations become available an attempt could be made to correlate injuries to neck torque and shear and tension forces.

The PMHS tests conducted up to now do not effect significantly the human volunteer based performance requirements, except for the absence of the "locking mechanism", resulting in an increase in head flexion.

CONCLUSIONS

1. Twelve post-mortem human subject tests have been conducted. Five of these tests have been analyzed in detail.
2. The two-pivot analog system originally proposed to describe human volunteer head-neck motions appears to be adequate to characterize relative head-neck motion in the PMHS tests.
3. Head c.g. trajectories are of the same order of magnitude in human volunteer and post-mortem human subject test. Head rotations (flexion) however are higher in the post-mortem human subject tests.
4. Higher impact levels for the PMHS tests do not show a significant increase in relative head motions.
5. Injuries up to AIS 2 were observed.
6. Recommendations for future work include:
   - additional frontal flexion and hyperextension PMHS tests using 3D X-ray and 3D film techniques.
   - calculation of neck loads and correlation with neck injuries.
   - evaluation of existing and future dummy neck designs with respect to the findings of the PMHS tests.

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APPENDIX

Run No. 8615 DOT

Subject : Male, 50 years, body weight 80 kg, body length 176 cm

Cause of death : poisoning

Vertebral column condition : Small degenerative alterations in the cervical- and thoracic vertebral column area.

Medical findings : No injuries.

Run No. 8616 DOT

Subject : Male, 51 years, body weight 66 kg, body length 170 cm

Cause of death : poisoning acute

Vertebral column condition : Medium severe up to severe degenerative alterations in the cervical spine area; hardening of parts of the vertebral bodies near to upperplate at C6/C7.

Medical findings : Hemorrhage in the intervertebral disc C6/C7 (NCTJ1)

Run No. 8618 DOT

Subject : Female, 61 years, body weight 58 kg, body length 155 cm

Cause of death : suffocation

Vertebral column condition : Medium severe up to severe degenerative alterations in the cervical and thoracic vertebral column area. Discreet protrusion of intervertebral discs underneath the posterior longitudinal ligament in the level of C2/C3 and C3/C4 in the vertebral canal.

Medical findings : Small laceration of the ligamentum flavum Th5/Th6 (NPLJ1). Hemorrhage in the intervertebral discs Th2/Th3, Th3/Th4 dorsal (BCTJ1). Hemorrhage in the intervertebral discs Th1/Th2, Th3/Th4, Th4/Th5, Th5/Th6 ventral (BCTJ1).

Run No. 8620 DOT

Subject : Female, 51 years, body weight 78 kg, body length 165 cm

Cause of death : drown

Vertebral column condition : Moderate degree of degenerative alterations in the central thoracic spine in the sense of a reduction and exsiccation of the intervertebral discs and discreet intensity of Schmorl's node. The spongy bone appears altered. In the cervical spine area occurred a partial fusion of the vertebral bodies 3 and 4.

Medical findings : Hemorrhage in the intervertebral disc C5/C6 dorsal (NPTJ1). Fracture of the upper front edge of the Th2 with extension to the center of the vertebral body (BAFV 2).

Run No. 8621 DOT

Subject : Female, 46 years, body weight 72 kg, body length 166 cm

Cause of death : poisoning acute

Vertebral column condition : Medium severe degenerations of intervertebral discs of the lower thoracic vertebral and upper lumbar vertebral column with protrusions underneath the posterior longitudinal ligament, reduction of the intervertebral discs and several Schmorl's nodes.

Medical findings : No injuries.

Run No. 8622 DOT

Subject : Male, 37 years, body weight 80 kg, body length 182 cm

Cause of death : poisoning acute

Vertebral column condition : Moderate up to medium severe degenerative alterations of the intervertebral discs in the lower thoracic column with exsiccation and reduction.

Medical findings : Hemorrhage in the intervertebral disc C3/C4 left dorsal (NPTJ1). Hemorrhage in the intervertebral discs C3/C4, C4/C5 ventral (NATJ1).

Run No. 8701 DOT

Subject : Female, 24 years, body weight 74 kg, body length 168 cm

Cause of death : poisoning acute

Vertebral column condition : No degenerative alterations.

Medical findings : Strain in the ligament apparatus between top of the clivus and top of C2 (NCTJ1).
Hemorrhage in the intervertebral disc C5/C6 (NPTJ1).

Run No. 8703 DOT

Subject : Male, 59 years, body weight 66 kg, body length 154 cm

Cause of death : poisoning acute

Vertebral column condition : Exsiccation of the intervertebral discs in the cervical spine region, main point C5/C6 with reduction in the dorsal segment; small protrusion of the intervertebral disc C6/C7 below the posterior longitudinal ligament.

Medical findings : Hemorrhage in the joint between base of the skull and C1 right (NRTJ1).

Run No. 8705 DOT

Subject : Male, 38 years, body weight 71 kg, body length 175 cm

Cause of death : poisoning acute

Vertebral column condition : No degenerative alterations.

Medical findings : Hemorrhage in the joint between C1 and C2 left (NLTJ1).

Run No. 8706 DOT

Subject : Male, 50 years, body weight 72 kg, body length 172 cm

Cause of death : poisoning acute

Vertebral column condition : Moderate severe degenerative alterations in the intervertebral discs of the thoracic vertebral column, increased thoracic kyphosis.

Medical findings : Hemorrhage in the intervertebral disc C4/C5 dorsal (NCTJ1). Hemorrhage in the joint between base of the skull and C1 left (NLTJ1). Hemorrhage in the muscles between base of the skull and arc of C1 (NLTM1).

Run No. 8709 DOT

Subject : Male, 27 years, body weight 74 kg, body length 170 cm

Cause of death : cardiac infarction

Vertebral column condition : No degenerative alterations.

Medical findings : No injuries

Run No. 8710 DOT

Subject : Female, 43 years, body weight 53 kg, body length 175 cm

Cause of death : suffocation

Vertebral column condition : Moderate severe degenerative alterations of all intervertebral discs of the thoracic vertebral column, increased thoracic kyphosis.

Medical findings : Laceration of the ligamentum flavum between Th2 en Th3 (BPLJ2). Fracture of the lower front edge of Th2 (BAFS2). Small hemorrhage in the intervertebral disc Th2/Th3 (BATJ1). Hemorrhage in the joint between C1 and C2 left (NLTJ1). Hemorrhage between the front area of axis and rear side of atlas (NPTJ1).