RESPONSE AND INJURY SEVERITY OF THE HEAD-NECK UNIT DURING A LOW VELOCITY HEAD IMPACT

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ABSTRACT

Skull, brain and cervical spine injuries through direct head impacts are reported.

14 head impacts (frontal, lateral or occipital and rigid or padded) with cadavers and 6 padded head impacts by using Hybrid III and EURO-SID dummies at a velocity of 20 km/h were performed. A pneumatic impactor with a movable mass of 23 kg was used; the impact surface was a disc with 150 mm of diameter.

Accelerations at the top of the head and the epidural pressure at the contre coup site were measured. The impact situation was documented laterally with a high speed camera of a rate of 1000 pic/sec.

According to the acceleration measurements at the top of the head the evaluated acceleration at the head c.g. amounts between 70 g (padded) and 160 g (rigid); the rotational acceleration of the head around the rotation axis varies between 2700 rad/sec^2 (padded) and 11000 rad/sec^2 (rigid). Furthermore, the epidural pressure is between -20 kPa and -46 kPa.

The evaluated resultant acceleration in the center of gravity for padded impacts of the cadavers is in agreement with the values observed for the dummy, whereas the HIC-values of the dummy tests are clearly higher than those of the cadavers.

Except for one test, all the rigid impacts show skull fractures. These fractures are located at the impact area and include usually the basis of the skull.

The brain injuries include contre coup subarachnoid haematomas of different size; the haematomas were observed independent of the rigid or padded impact and were found in 54 % of the investigated cases. Possible mechanisms for causing of subarachnoid haematomas are interactions between the skull-brain interface.

This paper is kindly dedicated to Prof. Dr. med. Günther Reinhardt to his 65th birthday.

Skin lacerations were observed in rigid frontal impacts and scalp contusions in occipital rigid head impacts.

It is concluded that padding prevents skull fractures but not brain injuries. Only in two cases the cervical spine was uninjured. Usually, strains of soft tissue and ruptures of ligaments were found.
Response and injury mechanism are critically discussed with those existing in the literature.

THE FREQUENCY OF SEVERE skull-brain trauma for all types of accidents amounts 70 %, 40 to 50 % are caused in car accidents (Parzhuber et al., 1996, Silver et al., 1993).

The investigation of skull-brain trauma is relevant for safety aspects like a better protection of road users as well as for legal aspects.

A lot of work has been done in the last 30 years on injury mechanics and response of the skull-brain trauma; the most important papers are summarized in the SAE PT-43. Due to new equipment of protection devices for the car safety and the development of mathematical models, further work is needed.

The forensic pathologist is called to examine the victims of trauma because his or her scientific findings will often find their way into legal proceedings. His expertise lies in the interpretation of these scientific findings for the law with reference to the injury mechanics and mechanical response. The collection of data and careful description of injuries provide a basis for research of causes, treatment and prevention of accidents.

For the definition of protection criteria for the head, relationships between the mechanical response like force, pressure, linear and rotational acceleration and injuries are needed. Protection criteria include injuries of AIS 3, which stands for serious, not live threatening injuries. Volunteers can not be exposed to this injury severity, therefore, cadaver testing is required. The current linear acceleration-time dependent head injury criterion (HIC) seems not to be a suitable criterion. Rotational acceleration or strains are additional injury related physical parameters to characterize the brain trauma; further experimental work is needed to define an optimal head injury criterion.

Regarding this aim, traumatomechanic research is done at the University of Heidelberg in cooperation with the Technical University of Berlin, which has to equip a FE model of the head.

METHOD

TEST SUBJECTS - 14 fresh cadavers ranging from 26 to 86 years, the Hybrid III dummy and the EUROSID were used. A repressurisation of the vascular system of the brain was not performed, but post-mortem the vascular system is partially blood stained. The time between death and test amounted 24 to 48 hours.Table 1 shows the test matrix for the cadavers, table 2 for the dummy tests.

Table 1: Test matrix - cadaver tests

Test No.	Impact Direction	Impact Disc	Age	Sex	Head Mass* [kg]	Impact Velocity [km/h]
C1	lateral	rigid	27	m	4,09	21,4
C2	lateral	rigid	64	m	4,26	20,7
C3	frontal	rigid	67	m	3,93	22,0
C4	lateral	rigid	58	m	4,27	21,8
C5	occipital	padded	26	m	4,6	19,9
C6	frontal	rigid	77	f	4,45	22
C7	occipital	rigid	57	f	3,92	18,8
C8	occipital	padded	69	m	4,26	19,4
C9	frontal	padded	86	f	4,27	19,9
C10	lateral	padded	45	m	4,44	20
C11	lateral	padded	60	m	4,27	---
C12	lateral	padded	45	m	3,92	19,7
C13	occipital	padded	31	m	4,60	20,2
C14	occipital	rigid	31	m	4,60	19,4

Table 2: Test matrix - dummy tests

Test No.	Impact Direction	Impact Disc	Dummy	Impact Velocity [km/h]
D1	frontal	padded	H III	21,1
D2	frontal	padded	H III	20,4
D3	occipital	padded	H III	20,8
D4	occipital	padded	H III	20,7
D5	lateral	padded	Euro-SID	19,9
D6	lateral	padded	Euro-SID	19,8

* The head mass was calculated according the circumference of the head in two directions. The used formula was derived from a data set consisting of 12 head masses (ascertained through water displacement) and 5 anthropometric measures of the heads.

IMPACTOR - The tests were performed using a linear piston pneumatic impactor. The impact surface was a flat rigid aluminium plate, 15 cm of diameter. In some experiments, a 40 mm thick polyurethane foam (density: 165 g/dm³, standard dashboard padding material) was used to attenuate the head impact energy and distribute the impact forces. Frontal, lateral and occipital head impacts were performed. The axis of the impactor was aligned with the head center of gravity. Figure 1 shows the pre-impact situation of the test subject prepared for a rigid occipital impact. The impactor mass amounts 23 kg, the impact velocity ranged from 19 km/h to 21 km/h.

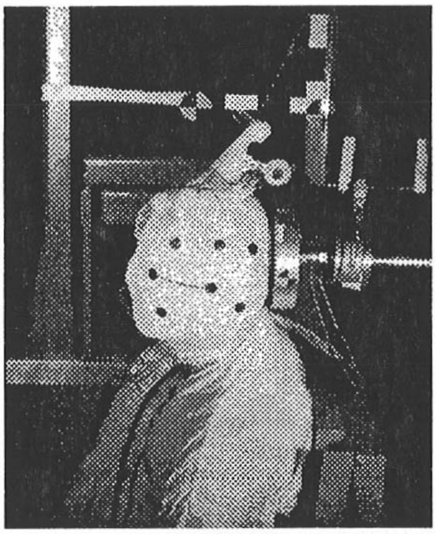


Fig. 1: Pre-impact (occipital rigid impact) situation of the head with impact surface and marked Frankfort Plane.

INSTRUMENTATION - The instrumentation included a nine accelerometer module, as described by Padgaonkar et. al.(1976), which was attached to the top of the skull. The accelerometers used were Endevco 2264-2000.

The location of the nine-accelerometer array to the head center of gravity (c.g.) and occipital condyles was measured in the lateral x-ray view (Fig. 2). Furthermore, the impact forces and in some tests also the epidural pressure at the contre coup site were measured.

DATA ANALYSIS - The data were recorded in analog format, and digitized at 10,000 samples per second. The data of the 9-accelerometer array were digitally filtered with CFC 60 and the resultant head center of gravity (c.g.) linear acceleration, the angular velocities and accelerations were calculated according to the Padgaonkar (1976) method. For the evaluation of the head injury criterion (HIC) the signals were filtered with CFC 1000 as proposed by SAE J211a.

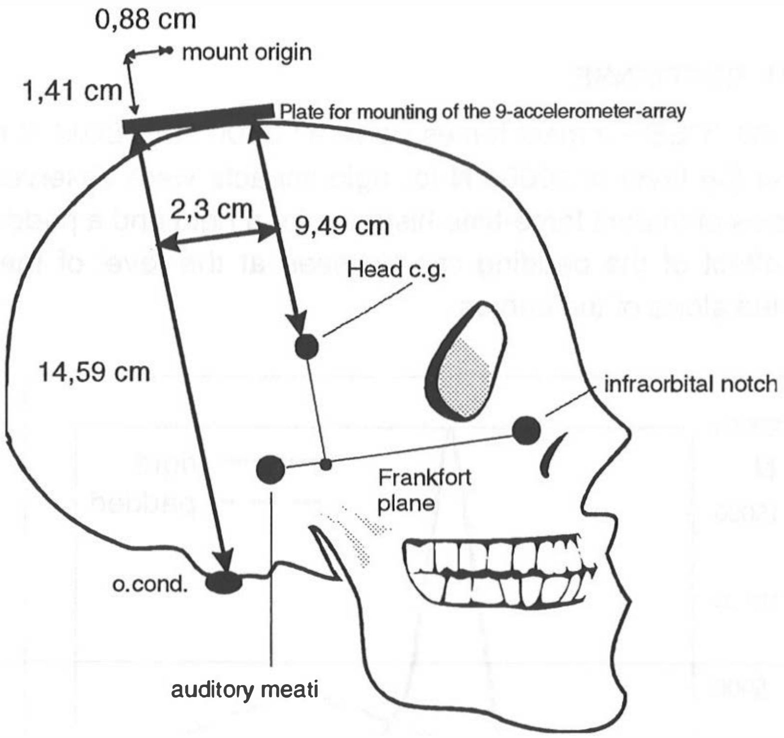


Fig. 2: Example for distances between the nine-accelerometer array to the center of gravity and to the occipital condyles by marked Frankfort plane.

KINEMATICS - One high speed camera was used to document the impact in lateral view with a frame rate of 1000 pic/sec.

MEDICAL INVESTIGATION / INJURY SEVERITY - The medical investigation included the body surface inspection of the soft tissue, the head autopsy with macroscopical findings of the skull, the fresh and with formaldehyde fixed brain, furthermore the microscopical investigation of specific brain regions.

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.

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

RESULTS

MECHANICAL RESPONSE

IMPACT FORCES - Impact forces between 3600 N to 8400 N for damped impacts and at the level of 20000 N for rigid impacts were observed. Figure 3 shows examples of impact force-time histories for a rigid and a padded occipital impact. The effect of the padding can be seen at the level of the force, the duration and the slope of the curves.

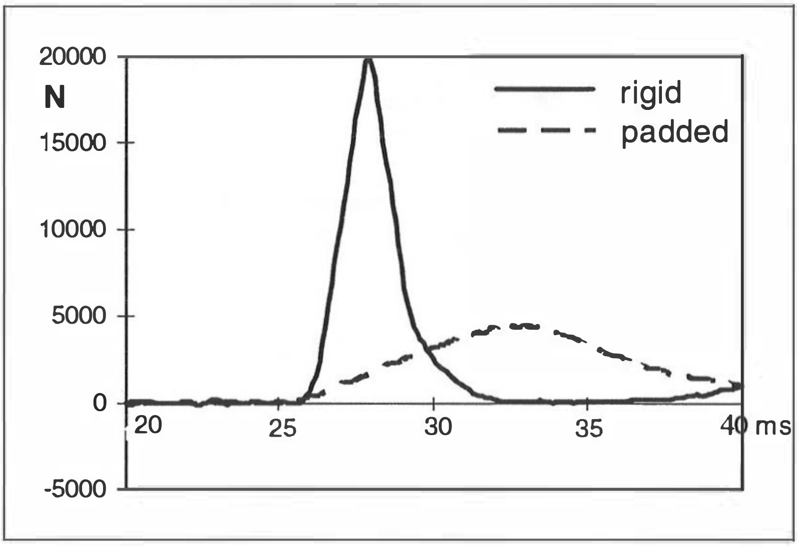


Fig. 3: Occipital impact: impact force-time histories

LINEAR ACCELERATION / HIC - The evaluated maxima of the linear acceleration at the head c.g. amount for the damped impacts between 70 g to 92 g with corresponding HIC values of 200 to 525. Table 3 and 4 summarizes the available mechanical responses for the cadaver and dummy tests. An example of acceleration-time history of an occipital impact with and without padding is shown in figure 4. This illustration shows also the effect of the padding.

For the calculation, the signals of the 9-accelerometer were filtered according to the CFC 60. The nine-accelerometer processing is very sensitive for artifacts in the measured linear accelerations which will be pronounced visible in the calculated linear accelerations. Therefore the measured accelerations used for the 9-accelerometer processing have to be filtered at a lower Channel Filter Class than the CFC 1000 prescribed for measured head accelerations. For a comparison of these acclerations from different authors the applied channel filter class has to be taken into account.

The rigid impacts show acceleration maxima values of 130 to 160 g (HIC: 800 - 2000). The lower acceleration maxima were observed in frontal impacts because of the damping influence of the nose. The highest values were measured in occipital head impacts.

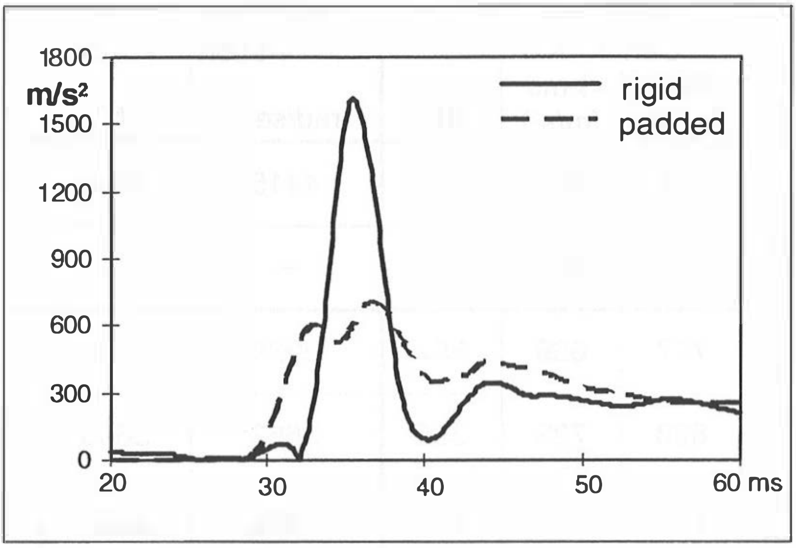


Fig. 4: Resultant acceleration time-history at the head c.g. of a padded and rigid occipital head impact.

ROTATIONAL ACCELERATION - The calculated rotational head accelerations are between 2700 rad/s² to 5100 rad/s² for the damped cadaver head impacts; for the one evaluable rigid impact this value amounts 11000 rad/s². An illustration of the rotational acceleration-time history for a rigid and padded occipital impact is shown in figure 5.

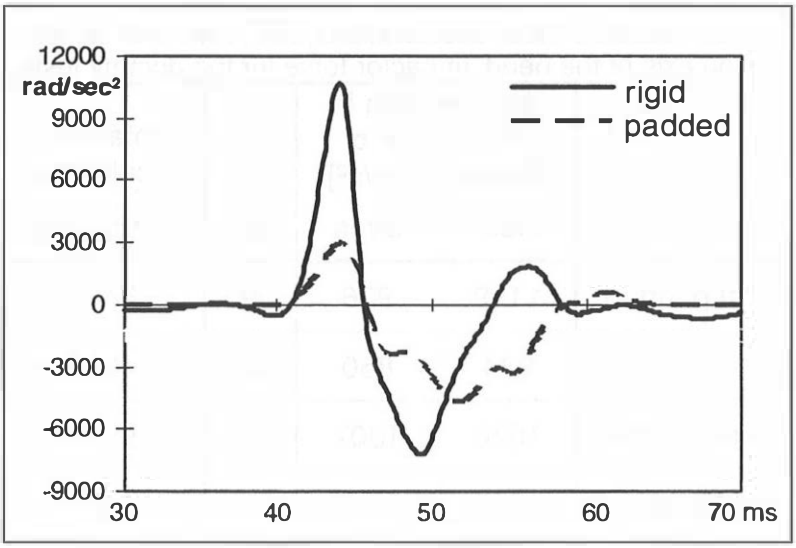


Fig. 5: Head rotational acceleration-time history around the y-axis of a padded and rigid occipital head impact.

Table 3: Calculated resultant linear accelerations, HIC, rotational acceleration around the rotation axis of the head, impactor force for the cadaver tests (Tests C1, C2, C3, C4 and C7 are not listed because the measured data were not evaluable).

Test-No.	Configuration	Acceleration in the Center of Gravity Res. [m/s²]	3-ms [m/s²]	HIC	Rotational Acceleration [rad/sec²]	Impactor Force [N]	MAIS and body part [AIS 90]
C9	frontal padded	725	657	248	4415	4050	2; Neck
C6	frontal rigid	1373	984	788	---	---	3; Skull
C5	occipital padded	707	669	257	2929	6000	3; Subar. Vessels
C8	occipital padded	828	733	335	2662	3600	3; Subar. Vessels
C13	occipital padded	705	576	525	4680	4521	1 Neck
C14	occipital rigid	1613	994	2012	10707	19954	3; Subar. Vessels
C10	lateral padded	734	687	254	4871	4050	1 Neck
C11	lateral padded	686	650	207	5116	8010	3; Subar. Vessels
C12	lateral padded	921	839	422	2984	8415	---

Table 4: Calculated resultant linear accelerations, HIC, rotational acceleration around the rotation axis of the head, impactor force for the dummy tests.

Test-No.	Configuration	Acceleration in the Center of Gravity [m/s²] Res.	3-ms	HIC	Rotational Acceleration [rad/sec²]	Impactor Force [N]
D1	frontal padded	1119	936	390	4429	---
D2	frontal padded	984	850	325	4093	---
D3	occipital padded	1676	1307	656	9035	---
D4	occipital padded	1612	1273	550	7606	---
D5	lateral padded	1104	983	343	4910	4752
D6	lateral padded	1188	1035	424	4101	4791

CONTRE COUP PRESSURE - In the frontal and lateral impacts the epidural pressure at the contre coup site was measured. These values are between -20 kPa and -46 kPa. An example of pressure-time history of a rigid frontal impact is shown in figure 6; a negative pressure of 36 kPa was measured.

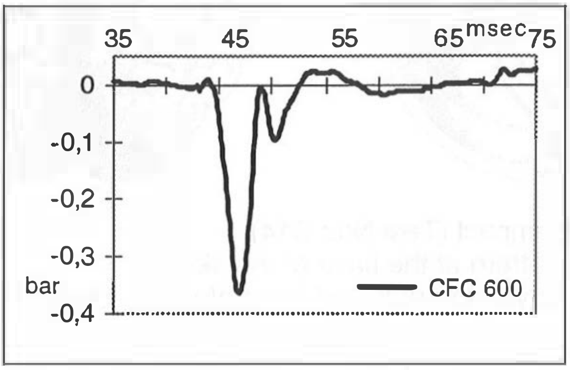
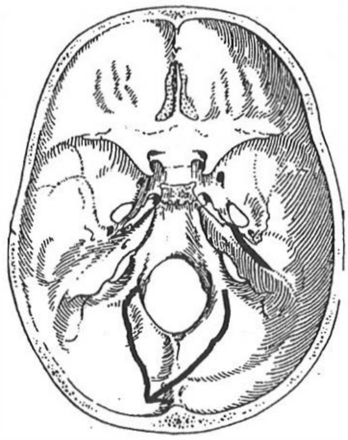


Fig. 6: Epidural pressure-time history of a rigid frontal head impact using CFC 600.

MEDICAL FINDINGS

In 50 % of the rigid impacts a laceration of the skin or contusions of the scalp was observed. Except for one test, all the rigid impacts showed skull fractures. These fractures were located at the impact area and also include the basis of the skull. In frontal impacts the fractures of the face skull were complex. In all the cases the severity of the skull fractures were rated usually with AIS 3.

In 58 % of the impacts brain injuries, which proved to be subarachnoid haematomas at the contre coup site, were found; this frequency includes the rigid as well as the padded impacts. One example of a rigid occipital impact with the fracture pattern of the skull at the impact area and the contre coup subarachnoid haematomas at the front of the brain at both sides is illustrated in figure 7. Neurological injuries which will occur in real accidents, can not be found in cadaver tests. Spinal column injuries with AIS 2 and 3 were observed in three impacts as compression fractures of the spongy bone of the vertebral bodies, Th1/Th2 and the Th4, lacerations of the ligamenta flava C0/C1, C1/C2 and C7/Th1 (Test No. C8) and the front of vertebral bodies at the upper thoracic spine, Th1/Th2, laceration of the ligamentum flavum between C7/Th1 and Th2/Th2 (Test No. C7), furthermore as laceration of the front longitudinal ligament at the level of C4/C5 and C6/C7 (Test No. C9). AIS 1 severities usually include hemorrhages in the vertebral discs. Table 6 summarizes the injury severity of the loaded head of the 14 impacts conducted.



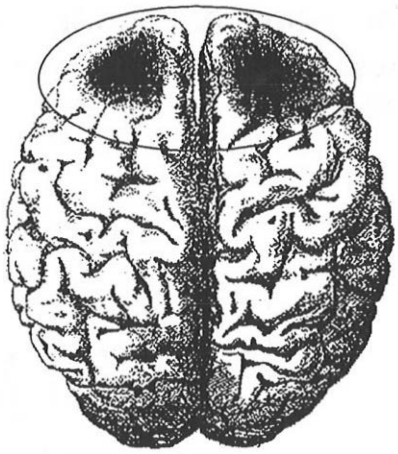


Fig. 7: Occipital rigid impact (Test No.: C14)
left: fracture pattern at the base of the skull
right: contre coup subarachnoid haematomas at both frontal lobs

Table 6: Injury severity of the 14 cadaver tests conducted according to AIS 90

		Injury Severity (AIS)				
Test-No.	Configuration	Skull	Brain	Subarachnoidal Vessels	Neck	MAIS
C9	frontal padded	0	0	0	2	**2**
C6	frontal rigid	3	0	0	0	**3**
C3	frontal rigid	3	0	0	1	**3**
C5	occipital padded	0	0	3	1	**3**
C8	occipital padded	0	0	3	2	**3**
C13	occipital padded	0	0	0	1	**1**
C14	occipital rigid	2	0	3	0	**3**
C7	occipital rigid	0	0	3	3	**3**
C10	lateral padded	0	0	1	1	**1**
C11	lateral padded	0	0	2	1	**2**
C12	lateral padded	---	---	---	---	**---**
C1	lateral rigid	3	0	0	1	**3**
C2	lateral rigid	3	0	0	1	**3**
C4	lateral rigid	3	0	3	0	**3**

DISCUSSION

In the study, the blunt impact of the head by using Hybrid III dummies, the EUROSID and human cadavers was investigated. Rigid impact conditions, with an impact velocity of 19 - 21 km/h and a movable impactor mass of 23 kg, are too severe for the cadaver head; usually rigid impacts cause skull fractures of AIS 3, which can be connected with severe brain injuries.

Generally, the maximum resultant acceleration of the head center of gravity is significantly lower for cadavers than for dummies in all impact conditions for padded impacts; the cadavers also show lower HIC-values in comparison to the dummies.

A comparison of the measured accelerations does not seem to meaningfull because the different authors use different filtering.

The rotational acceleration of the head-neck unit is higher for dummies than for cadavers in frontal and occipital impacts; while the rotational acceleration of the EUROSID is in agreement with the cadaver values.

Accelerations at the head c.g. of 140 to 160 g or HIC values of 800 to 2000 lead to skull fractures; while subarachnoid haematomas were observed at accelerations of 70 g's or HIC values of 200.

For the cause of skull and brain injuries observed in this study the linear accleration is relevant. Injuries caused by rotational acceleration, e.g. bridging vein ruputures were not found in the medical examination, therefore no correlation between the rotational acceleration and the brain injury severity is expected. The skull and brain injuries were observed at significantly lower HIC values than the existing head protection criterion HIC of 1000, and the highest HIC-value of 820 without injuries observed by Got et al. (1978).

Furthermore no correlation was found between the rotational acceleration of the head and the injury severity of the cervical spine. The anthropometric data, e.g. age, degeneration etc., seem to be more important for the neck injury severity.

The accelerations evaluated in padded frontal head impacts are generally lower as reported by Nusholtz et al. (1984) in 20 km/h padded (ensolite) head impacts.

The same observations are made for the rotational accelerations and impact force values of the Nusholtz et al. study.

At the contre coup site, a negative epidural pressure of -20 kPa to -46kPa was measured which begins at about the same time as the head acceleration in impact direction. The measured values are lower than the ones observed by Stalnaker et al. (1975), who report that a negative pressure magnitude greater than 68 kPa can produce brain tissue damage.

According to the impact condition, the contre coup theory explains the brain damage.

In 57 % of the impacted heads subarachnoid haematomas were found; this type of brain injury is the only one observed in cadaver testing. In our study the vascular system of the brain was not repressurized. We don't think that the missing of brain injuries, e.g. cortical contusion haematomas, is a problem due to the lack of blood pressure. Also Nusholtz et al. (1984) didn't find brain injuries in each impacted head of the repressurized brain vascular system in cadavers' head and Stalnaker et al. (1977) observed subarachnoid haematomas without repressurization. Similar observations are made by Got et al. (1978) in falling tests with cadavers were the brain has been repressurized. Because of the overstressing of the superficial blood vessels, post-mortem lacerations occur of blood stained vessels and are evident in a small visible escape of blood. However, an enlargement of the haematomas through blood flow by existing blood circulation as in the real case is missing. According to our opinion, the condition of the brain (fresh, decay influenced or thawed cadaver) is important for the cause of subarachnoid haematomas.

Possible mechanisms for causing of subarachnoid haematomas are interactions between the skull-brain interface. It is assumed that the negative pressure, local movement of the skull with respect to the brain, leads to tension stresses and therefore to lacerations of the superficial blood vessels of the brain (Nahum et al. 1980). Furthermore, rotational motion of the skull with respect to the brain may cause the subarachnoid haematomas (Nusholtz et al., 1984). Fronto-basal subarachnoid haematomas are explained with relative movements between the base of the skull and the brain.

Nusholtz et al. (1984) observed in frontal padded impacts subarachnoid haematomas, generally at the frontal lobes of the cerebrum. They explain this location of the injuries with the skull deformation which directly causes the subarachnoid haematomas. This injury mechanism is not confirmed with our findings. According to the experience with forensic autopsies of fall cases at first the contre coup injury is observed, by a higher energy potential, additional brain contusions at the coup site are found through deformation of the skull.

According to the impact, an energy transfer from the skull to the brain causing a pressure gradient in the brain, positive at the coup site and negative to the contre coup site will be assumed (Kallieris et al., 1980); the brain material is more sensitive to the negative pressure (extension) and lesser sensitive to the compression, therefore at first, the contre coup injury is observed.

In all the padded impacts conducted, no skull fractures were observed in comparison to Nusholtz et al. (1984) who found in two padded frontal head impacts (impact speed: 14 km/h, 18 km/h) frontal bone, basilar and parietal fractures.

The fracture pattern of the experimentally produced fractures is comparable with those investigated in autopsy cases in real accidents. Furthermore the experimentally observed brain injury mechanism is comparable with accident cases, but the intensity of the damage is usually different between the experiment and the real case. Generally the brain injury severity in cadaver testing is underestimated because neither the comotio nor the brain oedema or the diffuse axonal injury (DAI) post mortem can be found. In the real cases however, the impact severity is mostly higher than in the experimental cases. In the real cases, severe brain contusions through ruptures of the capillaries in the brain cortex were found. For the lack of this type of injuries in experimental work with cadavers, two reasons can be given: the first one, is the impact severity, the second one, the lack of filling of the capillaries of the brain cortex during the repressurization.

It is concluded that the tolerance limits of skull-brain trauma are exceeded by the impact severity investigated in this study. Padding prevents skull fractures, but not brain injuries.

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