# BRAIN INJURIES UNDER HIGH SPEED LOADINGS - A STUDY WITH MODELS AND CADAVER HEADS

by

Dimitrios Kallieris and Georg Schmidt
University of Heidelberg

Eberhard Häusler
University of Saarland

In various types of injuries the head is a very vulnerable part of the human body; in cases where the head is unprotected its injury frequency amounts to more then 80 percent (RAMET and CESARI, 1976, STÜRTZ, 1976).

In practice we are almost always confronted with dynamical influences, i.e. with short-time shock loads.

The mechanical conditions leading to brain damage can be generally classified into two categories:

1. Direct dynamical load of the head (collision).

2. Indirect dynamical load of the head (rotational motion).

The first category may be roughly divided into two groups according to whether the duration of the loading is small or large compared to the time required for a disturbance to travel across the head; this time is called the characteristic time. It is of the order of 100μs. In the first case, wave propagation effects will be important, while in the latter, damage most likely occur due to effects caused by the acceleration of the brain mass, similar as under category 2.

Up to now, animal and cadaver experiments have been carried out for the investigation of brain injuries (SELLIER and UNTERHARNSCHEIDT, 1963, STALNAKER et al, 1975, STALNAKER et al, 1977, NAHUM et al, 1977); impact loadings are in the millisecond range. On the other hand, loadings in the microsecond range have been studied by use of physical and mathematical models.

FRANKENBERGER (1968) and RAUCH (1975) derived from physical models that cavitation leads to brain injuries during short-time shock loads. ENGIN and AKKAS (1978) assert from mathematical models that short-time shock load is found to be less damaging as far as brain injuries are concerned.

In this paper we try to investigate whether these statements are physically well-founded. Therefore, impact tests were conducted with two- and three-dimensional models and cadaver skulls in order to investigate the effect of the short-time shock load on the brain.

At first, one has to consider the connection between pseudo-cavitation and loading time and then the spatial extension of the pressure pulse caused by load in dependence on the skull geometry.

It seemed necessary to us to conduct tests with biological material in order to see its reaction to short-time shock loads, as so far, no experimental results are known but conclusions were drawn only from physical and mathematical models.

In order to investigate the effect of short-time shock loads on the brain, reproducible impacts with a pneumatically operated gun were conducted on two- and three-dimensional models, a skull imitation and cadaver skulls. The impact velocity varied between 14m/s and 30m/s, the impact duration was about 50µs. A polyvinyl cloride (PVC) or steel cylinder with a length of 15mm and a diameter of 4mm served as impact element. The models and the skull were non-destructively loaded. The model material showed similar mechanical properties as the skull bone.

The models were filled with water or oil, both materials can be compared in regard to the sound velocity with the brain mass.

The two-dimensional models (15mm broad cylindric shell, 15mm broad sagittal cut from the skull imitation) were shadow-optically investigated. Fig. 1 shows the test set-up of the shadow-optical investigation.

For the three-dimensional models (3 cylindric shells with a diameter of 160mm and a thickness of 4, 5 and 6mm), the skull imitation (in the impact area 10mm thick) and the human head, the pressure distribution was determined at various distances from the anti-pole with pressure transducers of high time resolution.

Fig. 2 shows the block diagram for the piezo-electrical investigation of the pressure distribution. Fig. 3 shows the impact places of the head in the forehead area as well as the corresponding insertion of the pressure transducer in the occiput; the impact area was free of head rind.

A total of 10 skulls were loaded with the pneumatically operated gun. Test subject specifications and test parameters can be seen in Table 1.

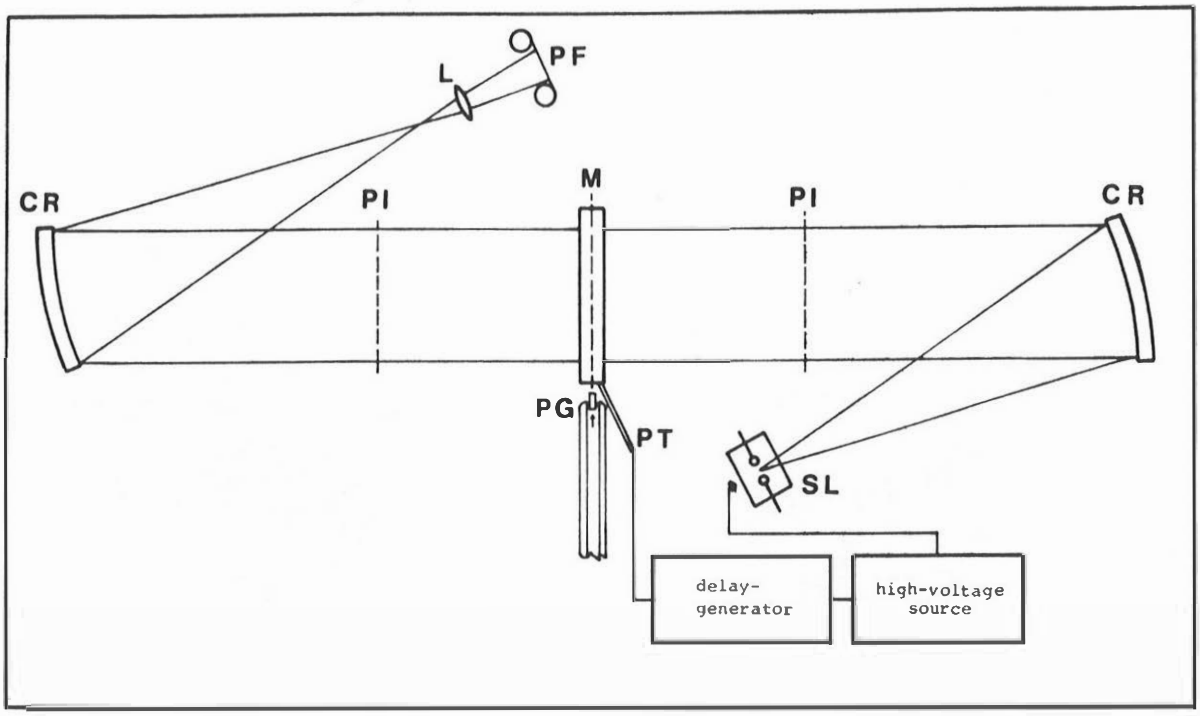



Fig. 1: Test set-up of the shadow-optical investigation (M: model, PG: pneumatical gun, PT: pressure transducer for the triggering of the source of light, SL: source of light - light period ~ 1µs , CR: concave reflector, PI: plane of image, L: lens, PF: plane of film)

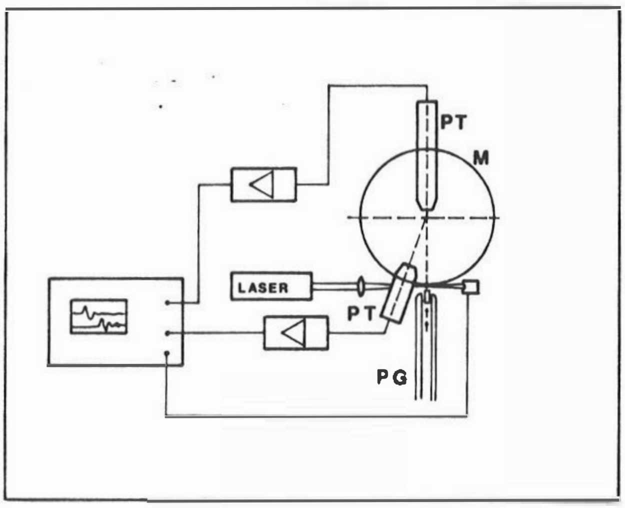



Fig. 2: Block diagram for the piezo-electrical investigation of the pressure distribution (M: model, PG: pneumatical gun, PT: pressure transducer)

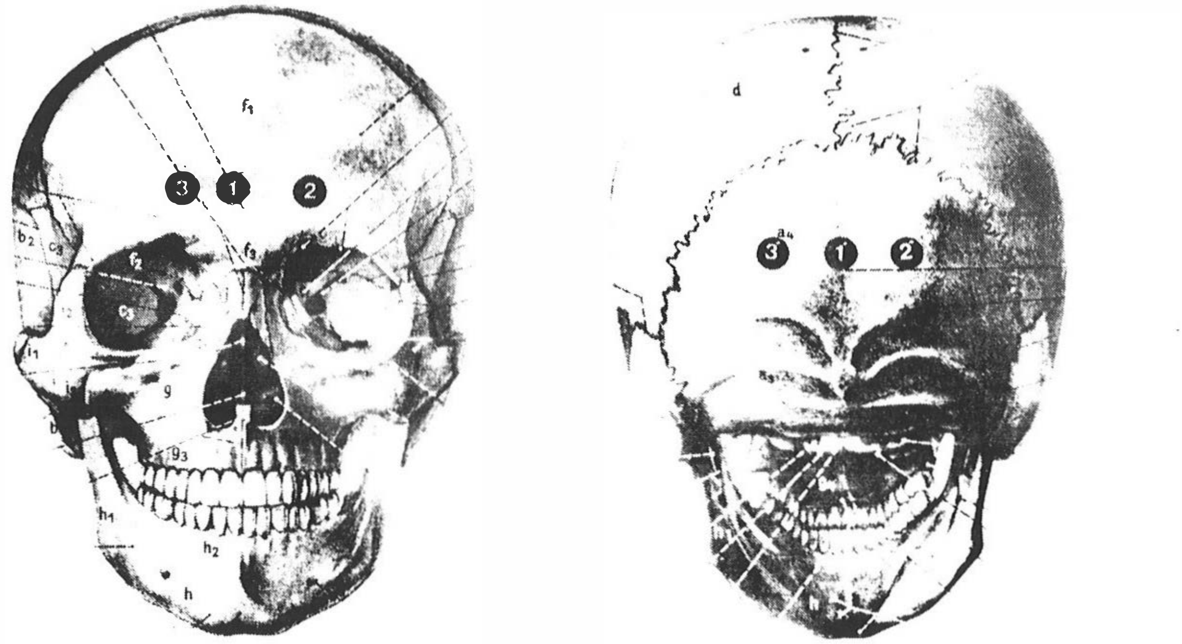



Fig. 3: Impact places of the head in the forehead area as well as the corresponding insertion of the pressure transducer in the occiput

| Test No. | Sex | Age (Years) | Cause of Death | Time Between Death and Test (Hours) | Average Skull Thickness (mm) | Impact Energy (Nm) |
|---|---|---|---|---|---|---|
| 1 | m | 19 | poisoning | 100 | 6,0 | 0,27 |
| 2 | m | 23 | poisoning | 28 | 6,0 | 0,27 |
| 3 | f | 19 | poisoning | 35 | 6,5 | 0,27 |
| 4 | m | 60 | poisoning | 60 | 6,0 | 0,27 |
| 5 | m | 33 | poisoning | 33 | 7,0 | 0,14 |
| 6 | m | 27 | drowning | 58 | 6,0 | 0,14 |
| 7 | f | 41 | heart failure | 42 | 5,0 | 0,24 |
| 8 | f | 43 | heart failure | 28 | 6,0 | 0,24 |
| 9 | m | 43 | pneumonia | 23 | 6,0 | 0,27 |
| 10 | m | 31 | heart failure | 38 | 6,0 | 0,27 |

Table 1: Test subject specifications and test parameters

Fig. 4 shows in a shadow graph series the wave propagation process in the cylindric shell versus time. The wave field, primarily stimulated by the impact is created, focusses because of the geometry of the model and then diverges again. The second wave field arises due to the implosion of the cavitation bubbles.

The next shadow graph series (Fig. 5) shows the time course of the wave propagation process in the skull imitation. Here also occur the above mentioned effects, however, because of the different geometry, there is weaker focussing.

On the three-dimensional models pressure measurements were conducted. At first the pressure measurements were made at the anti-pole; then, in same distances to the impact pole. The next Fig. 6 shows the pressure time record for the 4mm thick, water-filled cylindric shell measured at a distance of 28mm from the anti-pole.

The duration of the period of the first positive and negative pressure pulse amounted to about 30µs; the first positive and negative pressure pulse was caused by the impact of the shell, the following through the reflection of the primary wave.

In order to receive a dependence of the pressure distribution from the anti-pole, the positive and negative maxima (1,2,3, 1',2',3') were evaluated.

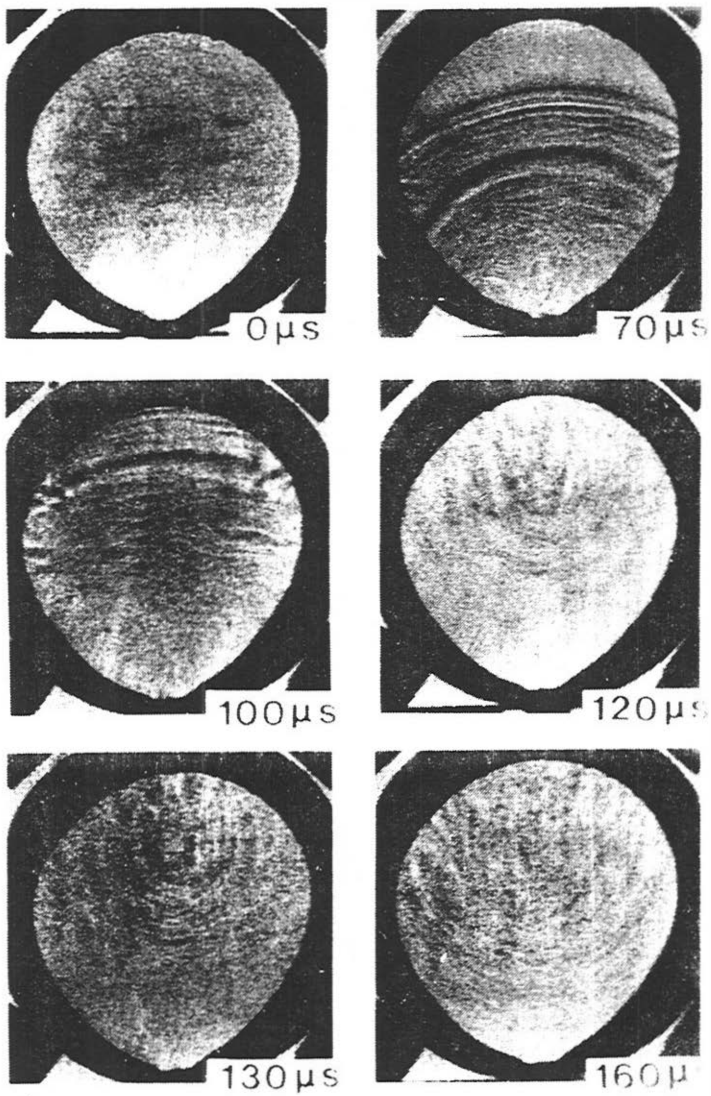
The pressure measurements in the brain of the loaded head were conducted in the same way as in the three-dimensional models. Fig. 7 shows the pressure time history measured at a distance of 8mm from the anti-pole. The duration of the primary pressure wave (first positive and negative pressure maxima) amounted about 70µs. The duration of the elastical waves in the brain is generally longer than the one in water of the models.

In order to receive a dependence of the pressure distribution from the anti-pole the positive and negative maxima (1,2,3,1',2', 3') were evaluated.

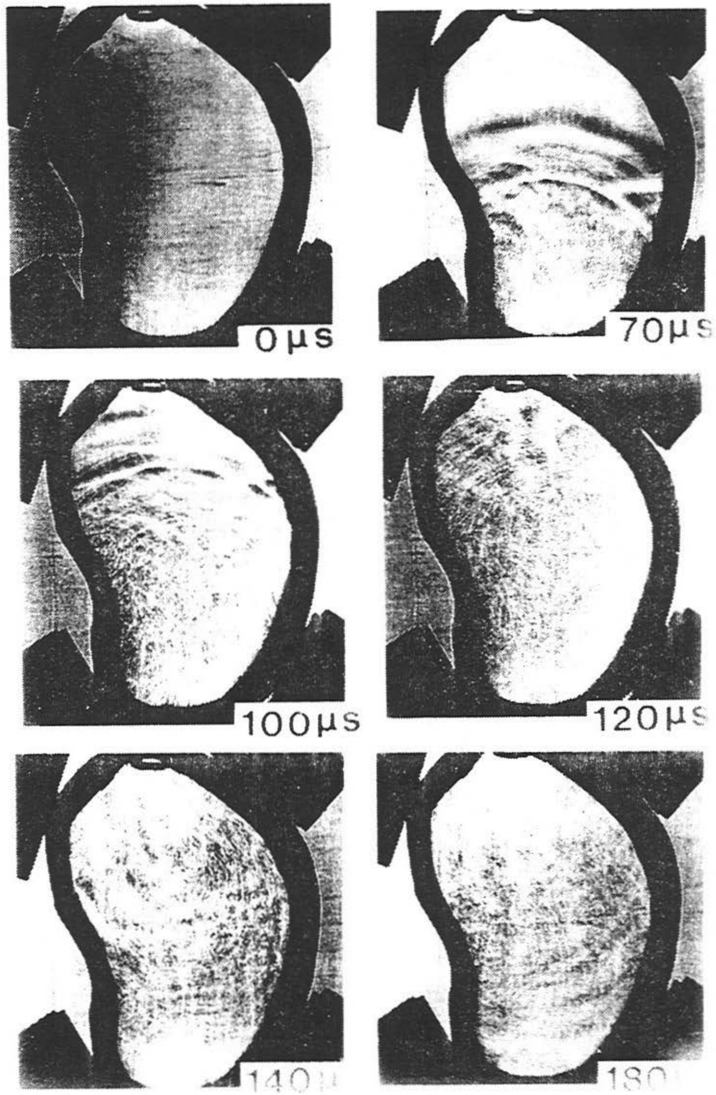
The dependence of the measured pressure in the filling mass or brain from the distance to the anti-pole was recorded for the three-dimensional models (water - oil-filling) and the head tests.

The pressure variation with the distance to the anti-pole is similar with the water and oil-filling for the three-dimensional models (KALLIERIS, 1980). The pressure amplitude decreases with increasing wall thickness of the cylindric shells (Fig. 8).

Close to the side of the model which is turned away during the impact, pressure magnifications were observed which can be explained by focussing and they are in agreement with the shadow-optical investigations. Positive and negative pressure maxima show about the same height.




<u>Fig. 4:</u> Shadow-graph series. The wave propagation process in the cylindric shell versus time




<u>Fig. 5:</u> Shadow-graph series. The wave propagation process in the skull imitation versus time

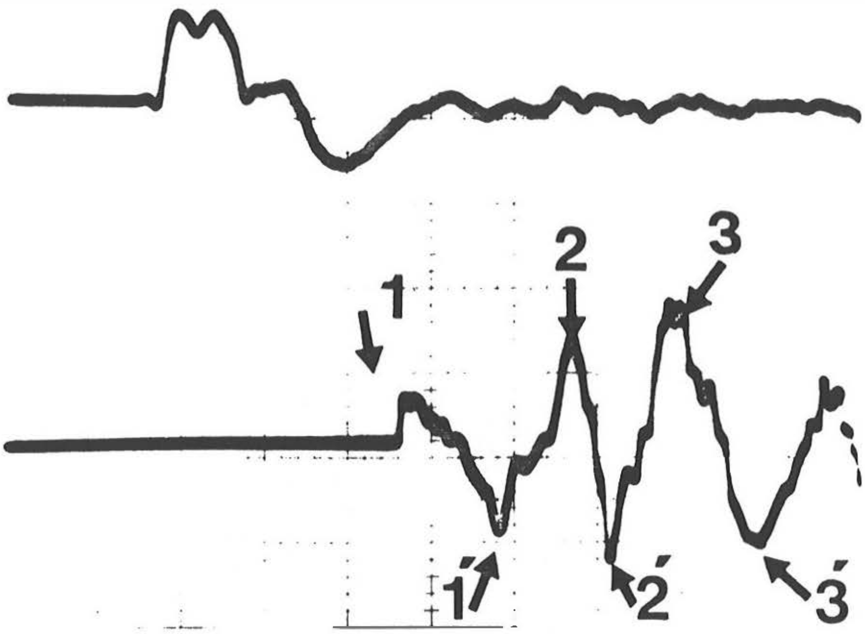



Fig. 6: Pressure-Time-History
(4mm thick spherical shell,
upper record near to the impact pole;
lower record near to the anti-pole)

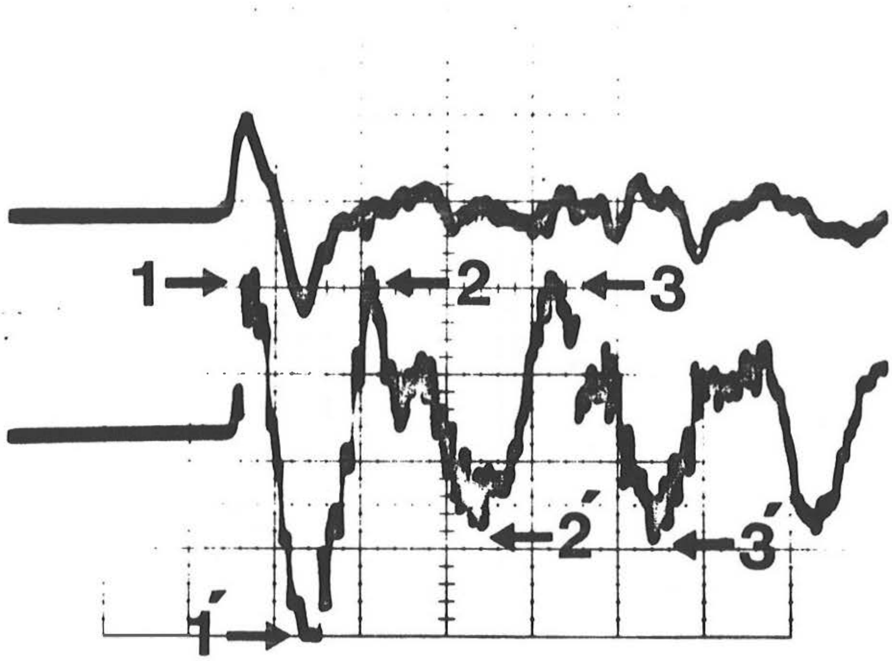



Fig. 7: Pressure-Time-History
(Cadaver head,
upper record near to the impact pole,
lower record near to the anti-pole)

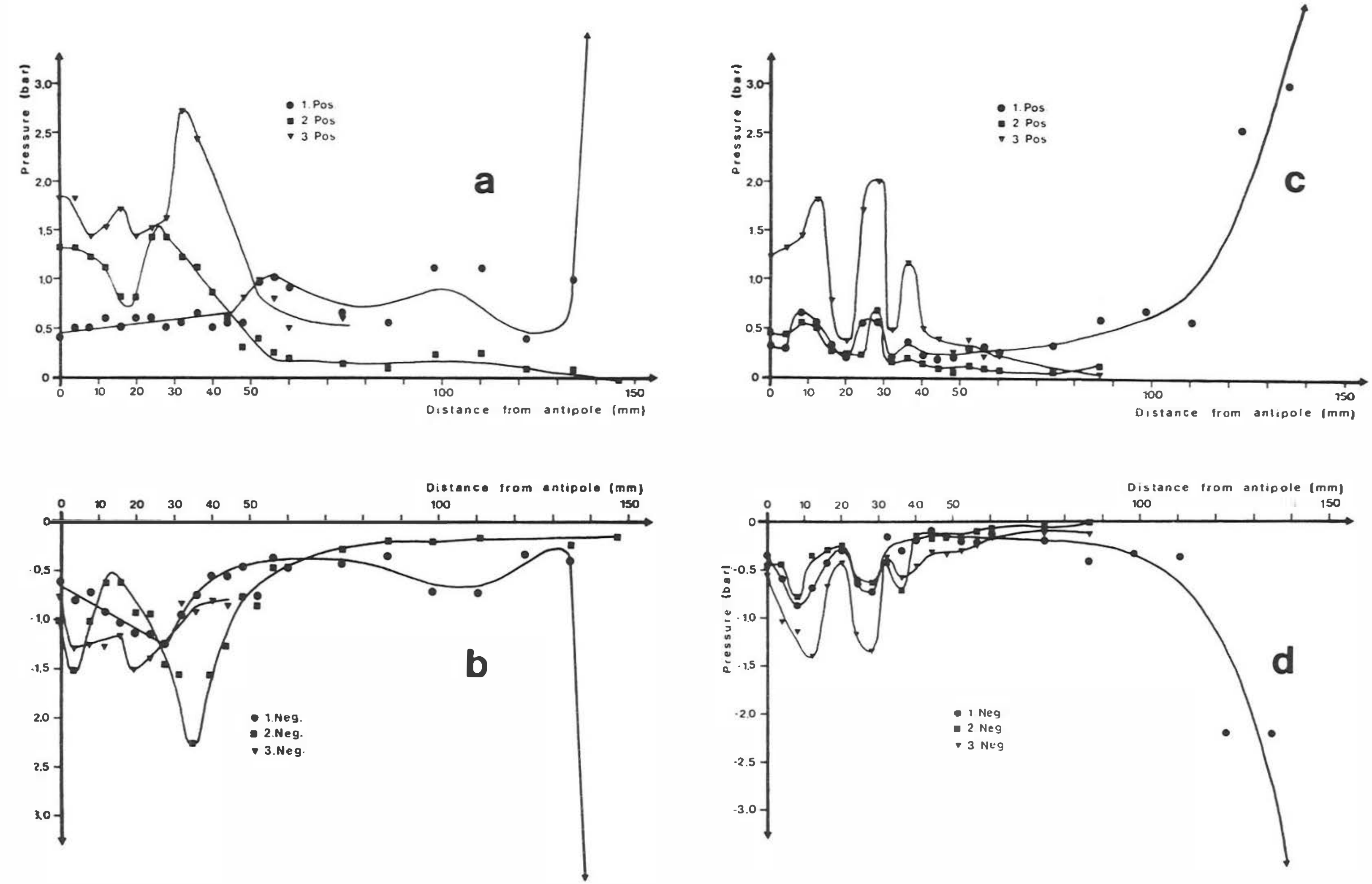



Fig. 8: Dependence of the pressure distribution of the anti-pole distance (a,b: 4mm thick spherical shell, c,d: 6mm thick spherical shell)

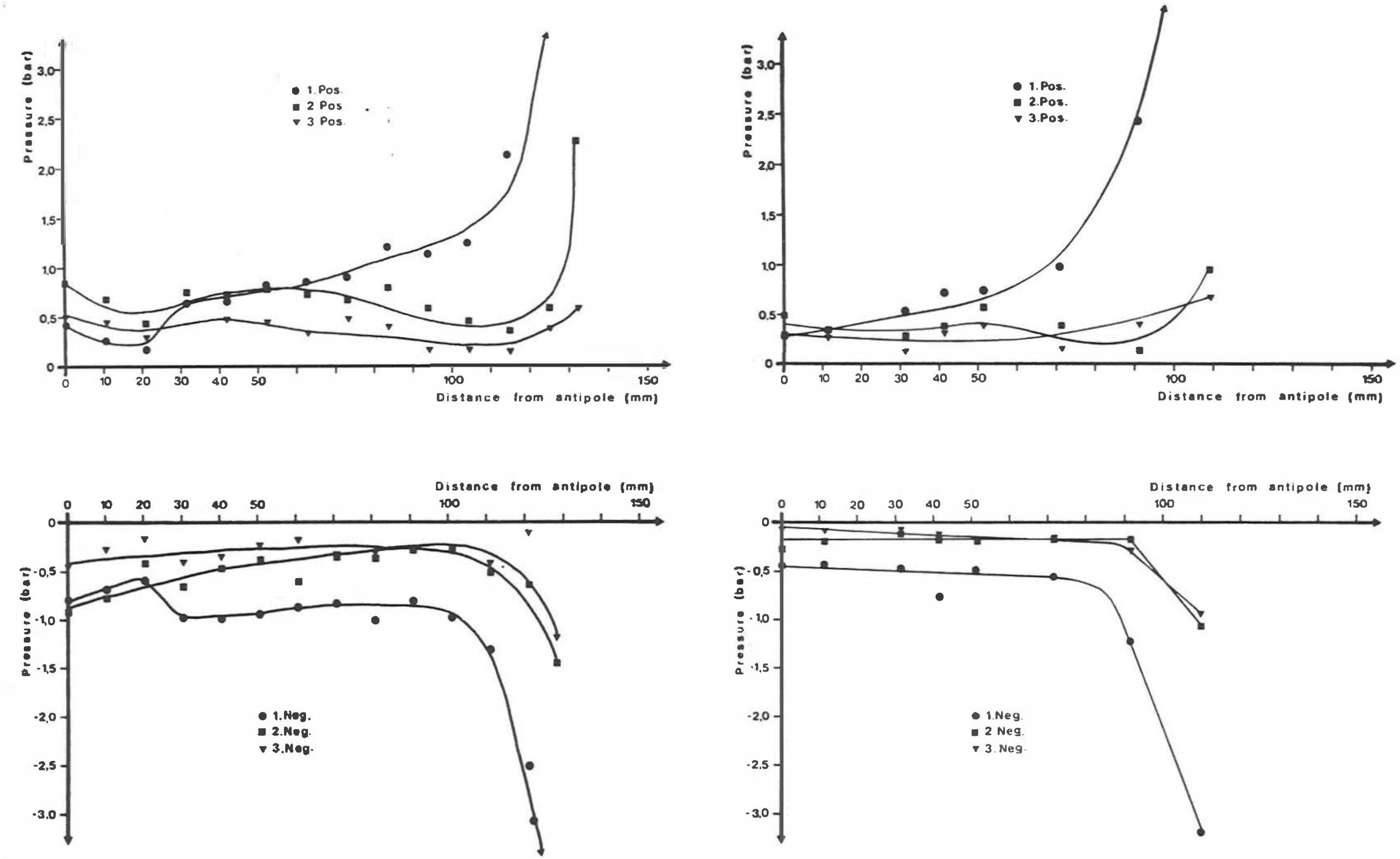



Fig. 9: Dependence of the pressure distribution of the anti-pole distance (cadaver heads)

The pressure dependence from the distance to the anti-pole in the brain is similar to the one in the model; because of the thickness of the skull and a therefore stronger energy absorption of the skull, the pressure amplitudes are smaller. Caused by the skull geometry, no pressure magnifications were observed nearby the anti-pole (Fig. 9).

The pressure distribution for the three-dimensional models (cylindric shell) could be reconciled with the shadow-optical investigation of the cylindric shell for the water as well as for the oil-filling. Focussing with positive and negative pressure maxima in the upper third of the shell interior (anti-pole side) was observed. The highest positive and negative pressures were measured at the impact pole.

In the experiments with the pneumatically operated gun (bullet 4mm ∅) occurs a small, locally limited force influence with a time duration of about 50µs. The models as well as the human head were non-destructively loaded. The impact velocities were higher than the one compared in literature (two-dimensional models: 20-30m/s, three-dimensional models: 15m/s, and human head: 14-20m/s); the impact energy was because of the small mass of the bullet relatively low. In spite of it, relatively high pressures were measured at the anti-pole, the impact pole and the intermediate line.

At this type of load there is no essential movement of the head and therefore the conditions can be compared to a fixed head which receives an impact. Because of the small energy of the bullet there are no relative movements between the skull bone and its content; according to that injuries at the impact pole or anti-pole can not be explained by mechanisms which suppose such a relative movement. Only the elastical wave and indeed its negative part can be considered to induce injuries. Is the negative pressure effective it results in cavitation which leads to tissue damage.

The height of the negative pressure that leads to cavitation is dependent on the load duration (HÄUSLER and HIRTT, 1978). The longer the load duration, the lower the negative pressure leading to cavitation; (an impact time in the millisecond range leads to cavitation at a negative pressure of 1 bar, at an impact time of 500ns at an negative pressure of 18 bar).

In our loads, which were conducted in a time duration of 50µs, negative pressures of about 15 bar can be expected for the occurrence of cavitation. As such negative pressures occurred in the cylindric shell models one can expect that tissue damages can be proved in the skulls loaded in the same way.

The tissue investigation showed tissue changes in three of the ten tests which can be understood as traumatic and have to be attributed to this patho-mechanism. Micro injuries in form of capillary ruptures and lacerations of the nerve fibres occurred, caused by cavitation bubbles. The cavitation bubbles are visible at a diameter of 0,1mm and reach at negative pressures of 20 to 30 bar a maximum diameter of about 1mm. The diameter of a capillary lays at 0,01mm, the intercellular and interaxonal distances are much lesser. Because of the cavitation in the capillary and the interstitium structure lacerations can be caused due to the sudden space displacement.


## Summary

Impacts with a pneumatically operated gun were made on two- and three-dimensional models, a skull imitation and cadaver skulls. The impact velocity lay between 14m/s to 30m/s. A polyvinyl cloride (PVC) or steel cylinder with a length of 15mm and a diameter of 4mm served as impact element. The model material had similar mechanical properties as the skull bone. The models were filled with water or oil. The two-dimensional models were shadow-optically investigated; the three-dimensional models and the human skull by local load measurements in the filling mass of the models and in the human brain.

According to the shadow-optical and piezo-electrical results one can reckon with a similar behavior as against the impact load between the model tests and the human skull tests.

The negative part (negative pressure) of the elastical wave can be considered to be the injury originator. If the negative pressure is effective, cavitation takes place which leads to tissue damages. Dependent on the thickness of the wall of the model or the skull negative pressure occurred in the dimension up to 10bar.

The histological examination of the brains of the loaded skulls showed the following: hemorrhages of the arachnoid membrane, blood vessel lacerations with hemorrhages, lacerations of the arachnoid and pial membranes, the cortex as well as the cerebrum white matter fibres.



## Acknowledgement

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