Semesterproject

Development of a Neck Model to Simulate Pressure Phenomena inside the Spinal Canal during Rear-End Collision

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ABSTRACT

Aim of this project was, to improve an existing fluid system of a mechanical neck to simulate and measure the pressure changes inside the spinal canal during a traumatic neck motion.

A literature survey was carried out and the existing neck system was analysed. Possibilities of changes were considered to reach a more natural behaviour of the pressure inside the spinal canal.

The prototype developed in this project is based on the prototype that was developed and tested by Olofsson and Persson (2001). It is based on a BioRID-neck and it includes a model of the spinal canal with its outflows and outer vein system. The prototype neck has been tested with a Hybrid III head on a simple test set-up.

The changes that were done in this prototype were slight, mainly variable outflows and a bigger outer vein. The new prototype was tested on an improved test set-up.

The pressure curves in these experiments showed a fast pressure compensation, which was the aim. But the expected negative pressure dip was too small or disappeared completely. This may have two reasons, either the point where the force acts was not far enough below the centre of gravity or air bubbles remained in the water.
The amplitude of the pressure peak, which occurred in these experiments, was higher than expected. It was even out of range of the pressure transducer.

As the neck was damaged during the experiments, no further tests could have been done. Further improvements of the neck, especially of the discs, and the set-up should be done in order to be able to better interpret the obtained results.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

AIS	Abbreviated Injury Scale
BioRID	Biofidelic Rear Impact Dummy
C1	atlas, first cervical vertebra
C2	axis, second cervical vertebra
C3 - C7	cervical vertebrae in descending order
CG	centre of gravity
CSF	cerebrospinal fluid
FE	finite element method
Hybrid III	Hybrid III crash test dummy
NIC	Neck Injury Criteria
PMHS	Post-mortem Human Subjects
QTF	Quebec Task Force
T1	first thoracic vertebra
WAD	Whiplash Associated Disorders
Δv	change of velocity

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1. INTRODUCTION

Soft tissue neck injuries resulting from car collisions are a serious problem today. A lot of effort has been done to explore rear-end car collision and the consequences of traumatic neck motions. In a study by Svensson (1993) a hypothesis regarding the position and the causation of the injury, which causes the typical neck injury symptoms, was postulated. The damage is meant to take place in the spinal ganglion caused by the pressure gradients occurring in the intervertebral foramen during traumatic neck motion.

In crash tests with the dummies used today, motions and angular displacements can be measured. Accelerations and forces can be calculated out of the motions. However pressures inside the spinal canal can’t be acquired.

In order to find out more about how the pressures inside the spinal canal and the intervertebral foramen are influenced by for example the head restraint properties, a new dummy neck including a model of the spinal canal and its fluid system has been built. Olofsson and Persson (2001) developed such a model based on the BioRID-neck. Actually the model is very simple but the results of the tests done with this neck, showed similarities to results, of tests on pigs (Svensson et al. 1993). It seems to be auspicious to improve the model in order to get even better results.

1.1 Anatomy

1.1.1 The vertebra of the cervical spine

The cervical spine consists of seven vertebrae of which the upper two, the atlas and the axis differ from the others.

Each vertebra is shaped in a way that when they are stacked together, the spinal cord is protected from damage by the bones of the entire spinal column.

The vertebral body (Figure 2) is oval shaped and carries most of the weight imposed on the spine. Between the vertebral bodies, except between the first two, there is an intervertebral disc, which acts as cushion or shock absorber and also permits some movement between the vertebral bodies. It consists of a strong outer ring of fibres called the annulus fibrosis, and a soft centre called the nucleus pulposus.

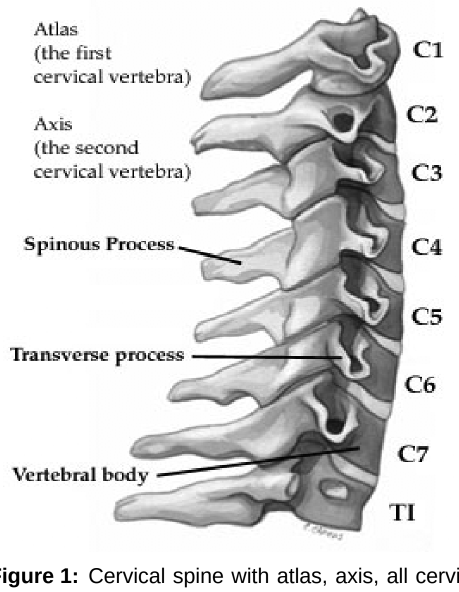

Figure 1: Cervical spine with atlas, axis, all cervical vertebrae and the first thoracic vertebra. (Adapted from www.hugston.com/hha/a.cspine.htm)

The body of each vertebra is attached to a bony ring that consists of several parts. The spinous process is short compared to that of other parts of the spine. The ligamenta flava attaches at the spinous processes and connects neighboured vertebrae. The hole, through which the spinal cord runs is called vertebral foramen and it is triangle shaped. There is a transverse process on either side of the arch where some of the muscles of the spinal column attach to the vertebrae. The transverse processes each contain a transverse foramen through which the vertebral blood vessels pass.

There are two facet joints between each pair of vertebrae one on each side, which connect each vertebra with the next vertebra above and below. They restrict the shear and lateral bending between adjacent vertebrae.

The atlas (Figure 3, left) differs from the other vertebrae, as it has no body and no spinous process. Anterior and posterior arches build a ring of bone on whose both sides cup shaped lateral masses are fixed.

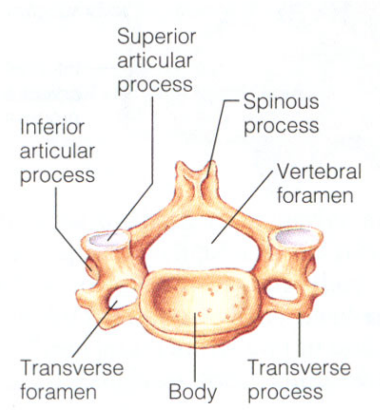

Figure 2: Typical cervical vertebra from a superior view. (Adapted from Marieb, 1998)

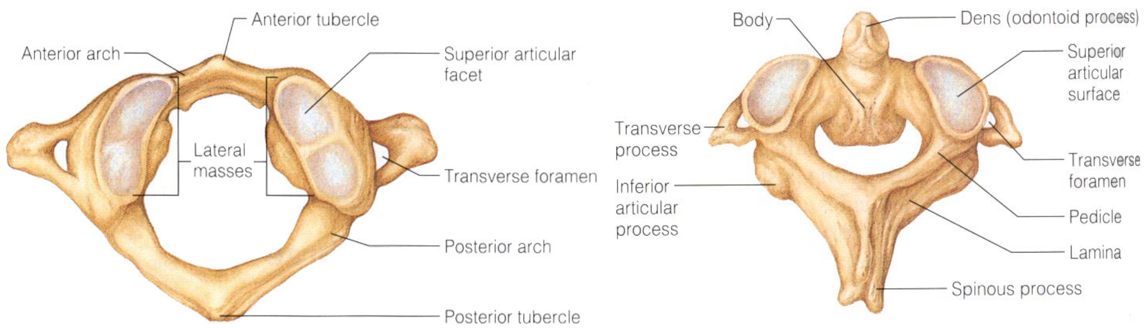

Figure 3: Atlas and axis, the two upper vertebrae C1 and C2 of the cervical spine from a superior view. (Adapted from Marieb, 1998)

The atlas carries the skull and allows flexion and extension motions of the head. Its vertebral foramen is bigger than those of the other vertebrae.

The axis (Figure 3, right) does not differ very much from the other vertebrae. Additional there is the odontoid process, a bony knob, which projects upright from the body and sticks up through the vertebral foramen of the atlas. It may be considered as the missing body of the atlas and it serves as vertical rotation axis of the head. This means, that the axis allows horizontal rotation of the head.

1.1.2 Ligaments

The spine gains its stability through a lot of different ligaments, which are either joining neighboured vertebrae or run along the whole spine. The ligamenta flava, the only stretchable ligament, connects neighboured spinous processes. The ligaments, which run along the whole spine, are the long longitudinal anterior ligament and the long longitudinal posterior ligament. The anterior ligament is thinner and runs closer to the spine, while the posterior ligament is stronger and runs between and outside the process. Shorter ligaments connect two, three or four vertebrae to each other.

1.1.3 Muscles

Another important component for the stability and the flexibility of the neck are the muscles. They can be divided into three groups. Short muscles, the deep muscles, run between close vertebrae. They connect the vertebrae with each other and control the movement of individual vertebrae. Longer muscles run from the head to the vertebrae. They belong to the superficial muscle group of the neck. The muscles of the last group, the intermediate muscle group, run from the head to the clavicle or the upper part of the thoracic spine.

1.1.4 The spinal cord

The spinal cord runs inside the spinal canal. It consists of the gray and the white matter, which can be considered as semi-fluid cohesive masses. The gray matter is shaped like a butterfly and is surrounded by the white matter. It consists of a mixture of neurone cell bodies.

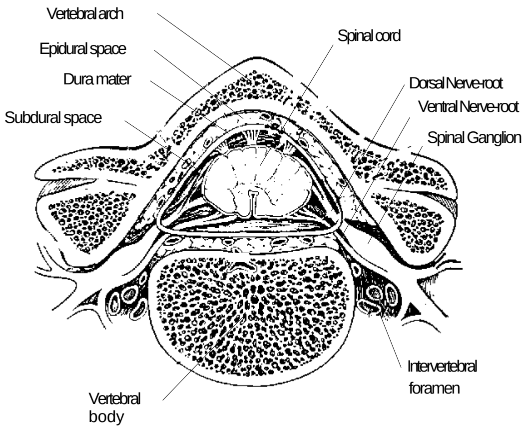

Figure 4: A horizontal cross-section of a cervical vertebra with the soft tissues of the spinal canal and intervertebral foramina. (Adapted from Sances et al., 1984)

The white matter consists of nerve fibres, which allow communication between different parts of the spinal cord or between the spinal cord and the brain. It is covered by the pia mater, which is again surrounded by the arachnoid.

The spinal cord can't move up and down axially within the canal but it adapts itself to the changing of lengths during motions of the spine by plastic deformation.

Dorsal nerve roots are leading from the spinal cord to the spinal ganglion, which is situated in the intervertebral foramen.

Both spinal cord (covered by pia mater) and the spinal ganglions are surrounded by the Cerebro Spinal Fluid (CSF) and covered by the dura mater.

1.1.5 The vein system

The vertebral vein system is a low-pressure system. It is divided in three different parts, which intercommunicate with each other: the internal vein network, the in- and out-leading bridging veins and the external vein plexus (Figure 6).

The internal vein network is the largest one, surrounding the dura mater.

It consists of two vein networks (plexus), which are situated posterior and anterior within the spinal canal. The two plexus (posterior and anterior) are joined through several vessels respective small networks.

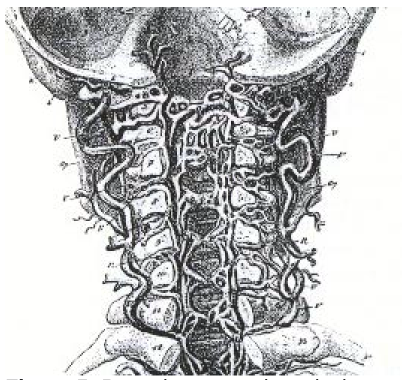

Figure 5: Posterior external cervical venous plexus.
(Adapted from Batson, 1957)

The volume capacity of these plexus is about 100 ml or even more. This is about 20 times the arterial capacity; it is much larger than required to return the blood brought in by the arteries.

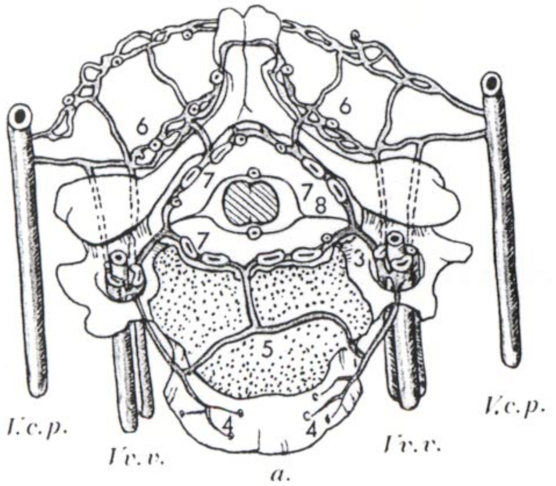

Figure 6: Charting of the internal and external cervical venous plexus: a = Cervical vertebra; Vv. v. = Venae vertebralis; V. e. p. = Venae cervicalis profunda; 3. Venae intervertebralis; 4. Anterior external cervical venous plexus; 5. Venae basivertebralis; 6. Posterior external cervical venous plexus; 7. Internal cervical venous plexus.
The vertebra is displayed a bit contorted in order to show the front and the back of the vertebra.
(Adapted from Clemens, 1961)

It seems to be clear that bringing out blood is not the main job of these plexus. More probable they serve as regulator to balance the volume and pressure changes during movements of the cervical spine and to the storage of blood. Out of this reason they don't have any valves. The blood is able to flow in any direction within the plexus.

A similar vein plexus is outside the cervical spine (Figure 5), the external vertebral venous plexus (anterior and posterior). These external venous plexus are connected with the internal ones through two different types of veins. The intervertebral veins (Venae Intervertebralis), which lead in groups through the intervertebral foramen on both sides of the vertebral body, and the basivertebral veins (Venae Basiventebralis), which lead in radial direction through the vertebral body.

Vein	Diameter in mm
Internal vertebral cervical venous plexus, anterior	2.0 – 2.5
Internal vertebral cervical venous plexus, posterior	2.5 – 3.0
Intervertebral cervical veins	< 5.0
Basivertebral cervical veins	1.0 – 2.0
External vertebral cervical venous plexus, anterior	0.1 – 0.5
External vertebral cervical venous plexus, posterior	2.0 – 4.0

Table 1: Diameters of injected vertebral veins. (Clemens, 1961)

1.2 Whiplash motion

Soft tissue neck injuries occur in rear-end impacts at low velocities usually less than 20 km/h. This may happen in traffic jams where cars drive close back-to-back. It may occur, that a driver brakes tardily and bumps into the car in front. At the impact the driver of the front car is pushed forward by the seatback, but as the head is not sustained it will lag behind. This brisk extension-flexion motion is sometimes called whiplash motion.

A scale to classify the gravity of injuries of car crashes has been introduced, the AIS (Abbreviated Injury Scale). In this scale 0 would mean no and 6 would mean lethal damage.

Another scale, which further specifies the kind of injury, is the QTF (Quebec Task Force) or WAD (Whiplash Associated Disorders) classification. It consists of five grades (0 – IV) of whose I – III correspond to AIS 1 classified injuries.

Grade	Clinical Presentation
0	No complaint about the neck; No physical sign(s)
I	Neck complaint of pain, stiffness or tenderness only; No physical sign(s)
II	Neck complaint **AND** Musculoskeletal sign(s) [a)]
III	Neck complaint **AND** Neurological sign(s) [b)]
IV	Neck complaint **AND** Fracture or dislocation

a) Musculoskeletal signs include decreased range of motion and point tenderness.
b) Neurologic signs include decreased or absent deep tendon reflexes, weakness, and sensory deficits.

Table 2: Classification of the WAD scale.

Although the whiplash injury is classified only as AIS 1 injury, it causes for the affected people long time suffering. Symptoms of whiplash injuries could be neck pain, headache, neck stiffness, vision disorders, sensory disturbances, numbness or vertigo.

The common whiplash extension-flexion motion consists of tree phases (Figure 7):

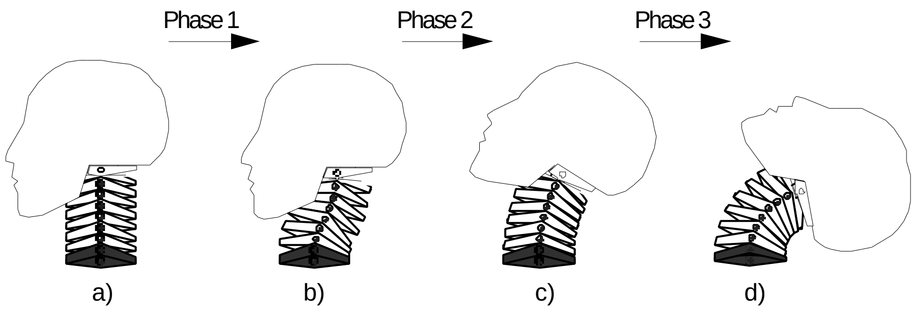

Figure 7: The three phases of a whiplash motion: 1. Linear reward motion starting from the initial posture 2. The head starts rotating rearward 3. Rearward rotation until fully extended position.
(Adapted from Svensson et. al, 1993)

The first phase lasts up to ~100ms. The seatback pushes the torso forward while the head stays still. This can be considered as a linear reward motion of the head relative to the torso. There is no angular motion of the head occurring. Hence the spine adopts an S-shape. In this motion the upper part of the cervical spine goes into flexion and the lower one into extension.

When both parts reach their limits for maximum flexion respective extension the linear reward motion will stop and the head starts rotating rearward.

In the second phase (~100ms to ~150ms) the extension motion of the upper cervical spine still accelerates, but the lower part of the cervical spine goes into a less extended position. During this phase of the motion, there is a clear pressure dip in the lower part of the neck cognisable.
In the third phase (~150ms to ~250ms) the whole cervical spine goes into full extension until it is stopped by the structures of the neck.
Afterwards the head moves forward again and the cervical spine goes into flexion. This flexion part is normally much less violent than flexion motions that are seen in frontal collisions and it is much slower than the initial extension motion.

1.3 Hypothesis about the injury

The injury is assumed to take place during the second phase of the traumatic neck motion, in which the spine changes from the S-shape into the extended position.
The tissues and fluids inside the spinal canal can be considered as incompressible. This means that fluid transportation, to and from the cervical spinal canal takes place during the flexion-extension motion of the spine. The capacity of the venous system of the cervical spine is immense and so the compensation of the pressure happens very fast. However, there will be for short time a pressure gradient between the inside and the outside of the spinal canal, caused by fast changes of the flow direction.
The greatest pressure gradients occur along the intervertebral canals in the lower half of the cervical spine. They are assumed to be responsible for the tissue injuries to the spinal ganglion.
In experiments with pigs, tissue damage was found in the spinal ganglia situated in the intervertebral foramina (Svensson et al. 1993). There have not been found any injuries to vertebrae, discs or ligaments.
Mechanical stresses and strains to the ganglia and surrounding tissues may probably cause the typical injuries of traumatic neck motions. Much higher isotropic pressure increases actually don’t harm the spinal ganglia, as it should be able to withstand them. Hence the negative portion of the pressure seems to cause the injuries of the spinal ganglia.

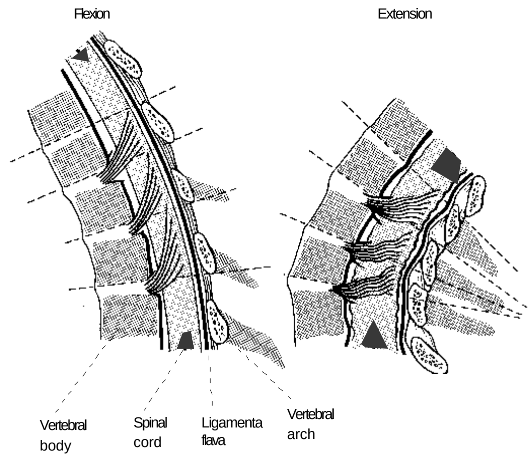

Figure 8: The change of volume within the spinal canal during flexion-extension motion. (Adapted from Svensson et. al, 1993)

According to a mathematical model of Bosröm et al. 1998 pressure drops are caused by a “water hammer” effect. This effect occurs, when the flow of the venous blood along the spinal canal suddenly changes direction.

2. PREVIOUS RESEARCH

In the last few years some effort has been done to explore the injury mechanism of traumatic neck motion. I will mention here three studies, which are of relevance for my project. One study about experiments with pigs (Svensson et al. 1993) on whose theory my project is based. One about test with post-mortem human subjects and one about the development of a FE model to calculate the pressure phenomena inside the spinal canal.

2.1 Animal experiments

In order to explore the injury mechanism, experiments with pigs have been done (Svensson et al. 1993). Anaesthetised pigs were exposed to a swift extension-flexion motion. Linear and angular displacements as well as accelerations have been gauged. Two of the animals served for pressure measurements. The other twelve pigs underwent a histopathological examination. Eight of them were exposed to a swift extension motion and four were used as sham-exposed controls.

In the histopathological examination no bleedings, fractures of vertebral structures or ruptures of ligaments have been detected. But membrane dysfunction of the neural spinal ganglia cells in the lower half of the cervical spine appeared.

For the pressure measurements, three pressure transducers were used. One was mounted in the frontal bone of the cranium, measuring the CSF pressure inside the cranium, one at the level of C1 respective C4 in different readings, and one at T1, which served as reverence. The curves of the levels C1 and C4 differed fairly. At the level of C4 a clear pressure drop could be registered in the second phase of the whiplash motion, which could not be seen at C1. Hence the pressure had the largest values in the lower half of the cervical spine. At the same place tissue injuries have been found in the histopathological examination.

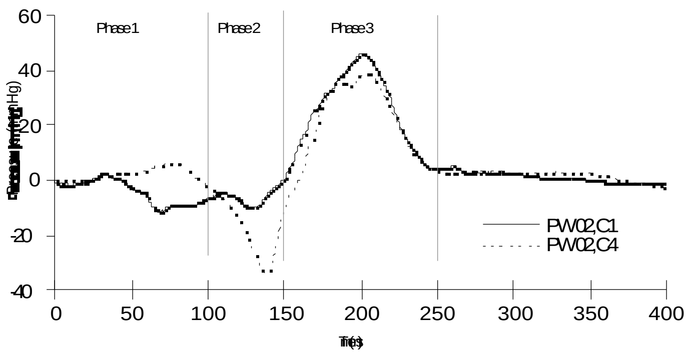

Figure 9: The average pressures versus time of six consecutive tests on the same pig at 150 N pull force. The three first tests at C1 level and the last three at C4 level. (Adapted from Svensson et. al, 1993)

There has been compliance between the neck motion and the pressure profiles obtained. This may confirm a hypothesis after which pressure pulses are caused by the hydrodynamic effects that result from the change of inner volume in the spinal canal (Aldman, 1986).

2.2 Study with PMHS

Another study to further develop the injury mechanism has been done with PMHS (Eichberger et al. 2000). The aim of this study has been to validate the pressure effect theory on human beings during rear-end impacts and to correlate the neck injury criterion to pressure in the spinal canal. The neck injury criterion (NIC) is an injury criterion, which relates pressure changes caused by sudden change of the fluid flow inside the spinal canal to neck injury (Aldman, 1986).

Four PMHS were exposed to realistic rear-end impacts. In a total set of 21 experiments, the subjects were seated on Volkswagen PKO seats, which were equipped with head restraints. The experiments were run with velocity changes of 10 and 16 km/h and also accelerations of the neck and the chest were measured.

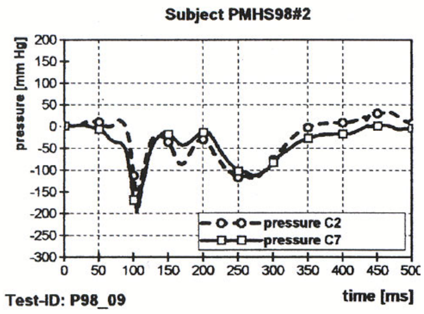

Figure 10: Pressure curves obtained in experiments on PMHS. (Adapted from Eichberger et al. 2000)

The pressure transducers were introduced in the spinal canal through an opening in the top of the cranium. The location of the opening of cranium and dura mater was considered to be remote enough in order not to influence the pressure effects. The upper pressure transducer was located at level of C1 / C2 and the lower one at C6 / C7. However the exact position of the pressure transducers could only be determined after the experiments, due to a lack of X-ray equipment. That's why the positions of the pressure transducers differ rather much. The locations of the pressure transducers significantly influence the results.

In the autopsy after the experiments each subject was checked for lesions of the neck. Only in one subject a rupture of the ligamentum longitudinale anterior between C5 and C6 could be detected. However injuries to the spinal ganglion and nerve cells have not been examined. The pressure histories obtained in these experiments showed some similarity to the results of the pig experiments. The pressure dip at phase 2 can clearly be observed. The graphs of these experiments could however not be used for comparison with the current study as head restraints were used, which strongly influence the course of the pressure.

2.3 A mathematical model

In his doctor thesis, Schmitt (2001) developed a finite element model of the cervical spine in order to analyse the pressure phenomena inside the cervical spinal canal. His model consists of the vertebrae, intervertebral discs, intervertebral joints, all major ligaments, then neck muscles, and the head. It is built up of two parts, the solid model and the fluid model.

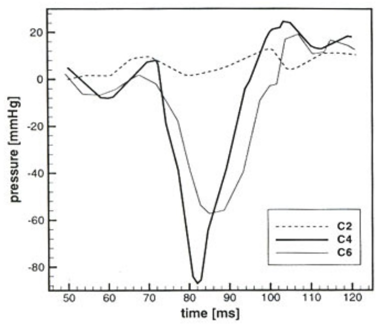

Figure 11: Pressure curves calculated in a mathematical model of the neck. (Adapted from Schmitt, 2001)

The solid model consists of the seven vertebrae of the cervical spine and the first thoracic vertebra. A typical blood vessel of the internal venous plexus with diameter 2.5 mm embodies the fluid model. He assumed an initial flow with velocity 0.2 m/s.

To imitate the impact a pulse with a peak acceleration of 4 g was used. This corresponds to an impact velocity Δv of about 15 km/h. The pulse was applied in x-direction on the first thoracic vertebra T1.

With aid of this FE model the pressure inside the blood vessel, the velocity flow fields and the shear stresses on the vessel wall could be calculated as functions of time.
The pressure was analysed at the levels of C2, C4 and C6. On the lower two levels a considerable pressure drop, which complied with the motion of the spine and also with the results found in the study of Svensson et al. (1993) was cognisable. These phenomena could not be recognisable at C2 level. The magnitude computed is slightly lower compare to the experimental results.
Further calculations with other diameters and cross-section areas of the vessel and an impact pulse of 6g have been made. They all resulted in qualitatively the same shape of pressure curve.
However Schmitt states that the pressure phenomenon is significant, but far from being a shock-like transition ("water hammer"). Supposedly shear stress amplitude of the fluid phenomenon interacts with shear stress induced by the kinematics of the motion.

3. BIORID-NECK

The neck of the Hybrid III, which is the standard dummy currently used in frontal crash test, has been found to be too stiff for the use in rear-end collision testing at low impact-velocities. Therefore Davidsson et al. (1998) developed a new neck for this kind of testing. The BioRID-neck (Biofidelic Rear Impact Dummy, Figure 12) consists of seven cervical vertebrae, which are connected by pin joints similar to door hinges. This specific design allows producing the S-shape observed in human necks during rear-end collisions, which is important to develop the injuries caused by traumatic neck motion.

The vertebrae are made of acetal plastic. Two cables are running through the segments along the cervical spine on the posterior side. They replicate the superficial muscle groups and create an improved relation between the retraction and extension components of the neck motion. Between the vertebrae there are rubber blocs fixed, which can be exchanged in order to be able to control the resistance to the motion.

Figure 12: The BioRID-neck (Biofidelic Rear Impact Dummy) has been developed for rear-end collision tests at low velocity.

The range of motion of the neck was increased in comparison to the values found in volunteer experiments, to allow some kind of hyperextension and -flexion. At present the BioRID-neck allows only flexion-extension motions. But there is some effort done in developing an Omni-Directional dummy neck (Carlsson et al. 2001).

However the BioRID may help to find out more about how seatbacks, head restraints, and other vehicle characteristics influence the likelihood of whiplash injury.

4. PREVIOUS NECK PROTOTYPE

Olofsson and Persson (2001) developed a first neck prototype. The base of this prototype was an extent of a BioRID-neck, including the seven cervical vertebrae and the basement to fix it on a table. The first vertebra is the connecting piece between the dummy head and the neck.

The cables, which are used in the original BioRID-neck, have been removed and instead of the foam blocs between the vertebrae, two-component silicone discs were used to give the neck its stability. These silicone discs are wedge-shaped, so the neck will assume a slight lordosis.

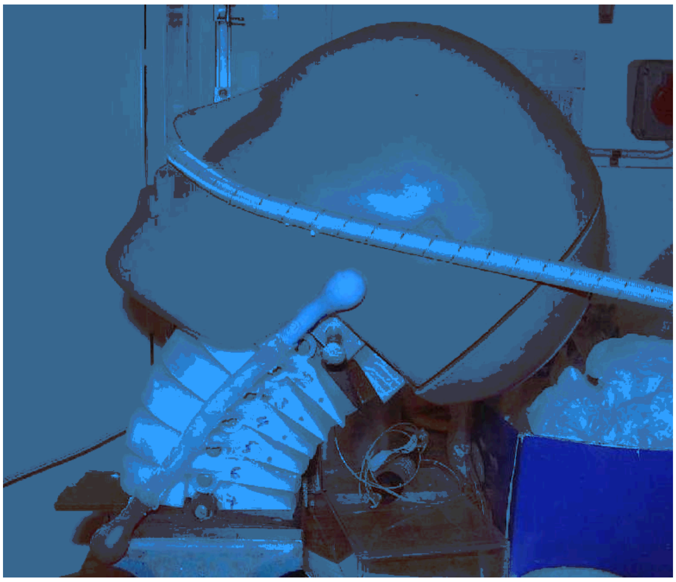

Figure 13: Previous neck prototype in fully extended position during the experiment. (Adapted from Olofsson & Persson, 2001)

4.1 Components

4.1.1 Spinal canal

To build the spinal canal, a hole was drilled with diameter 20 mm vertically through the centres of the faces on the posterior side of the vertebrae C2 to C6 and also through the centre of all silicone discs.

The discs are fixed with glue between the vertebrae; hence the canal will be tight. It will lead along the whole neck.

As the discs are soft, they can be compressed and stretched. Therefore the volume change inside the spinal canal during flexion-extension motion can be simulated.

4.1.2 Spinal cord

A silicone tube with diameter 15 mm is leading through the centre of the canal. It consists of the same material as the discs and it is able to move freely inside the spinal canal. The tube is fixed on one end at the first vertebra and on the other end at the basement. It should represent the spinal cord that can be considered as an elastic semi-liquid substance.

4.1.3 Out-leading veins

On the right side of the neck horizontal, lateral holes were drilled in the vertebrae C2 to C6 leading into the spinal canal. Some plastic tubes with inner diameter 2 mm, which represent the veins connecting the internal with the external cervical venous plexus, are plugged in those holes.

4.1.4 External cervical venous plexus

A silicone tube with inner diameter 6 mm, in which all the connection tubes led, rebuilds the external cervical venous plexus. On both ends of the tube there is a balloon fixed. These balloons cushion the volume changes of the spinal canal during the swift extension motion of the spine.

4.1.5 Inlet

On the left side of the spine there is on vertebra C2 another hole with diameter 10mm, which is used as inlet for the fluid. It was plugged during the experiments. In order to get rid of the air bubbles in the water, they let the water rest for a while.

4.1.6 Blood and CSF

The system is filled with tap water representing the vein blood inside the spinal canal.

4.1.7 Pressure probe

The pressure probe was introduced through the hole representing the vein in vertebra C4 and it was lead to the lower part of the neck.

4.2 Experiment

For the experiment, a standard Hybrid III head was used.

The neck base was clamped on a table. To simulate the traumatic neck motion a pre-stressed rubber cord was spanned around the head to the posterior side. It was important to span the rubber cord a little below the head centre of gravity (CG) in order to obtain the typical S-shape of the neck occurring at traumatic neck motions. Spanning the band above the CG would cause an immediate rotation of the head, spanning it too deep below the CG would probably cause a forward rotation of the head in the beginning.

The head was torn by hand to its original position and then disengaged.

During the experiment, the pressure inside the spinal canal was measured as a function of time.

4.3 Results

The pressure curve shows a similarity to the pressure curve obtained in the animal experiment. The most important point, which is meant to be the reason of the tissue injury, the pressure dip in phase 2, is clearly recognisable. However the pressure inside the spinal canal rises continually. This means that no fast pressure equalisation inside the spinal canal takes place.

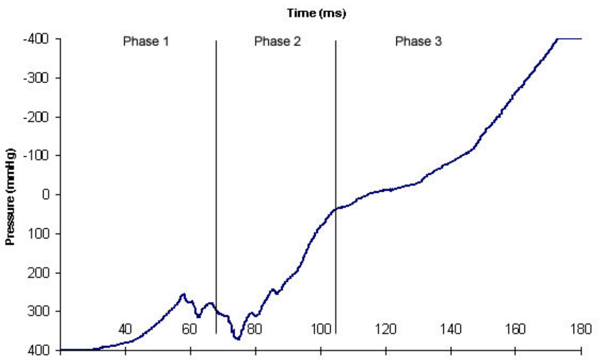

Figure 14: Pressure curve obtained in tests with the previous neck prototype. Clearly cognisable the pressure drop at 70ms.

4.4 Improvements

The vein system of the cervical spine is very complex and it’s almost impossible to rebuild it as a simple model. If we want to have the same flow conditions as in a real human neck the dimensions of this system filled with tap water must be adapted. The flow resistance is smaller in a blood vessel compared to a water filled tube of the same size. However the model is very simple and a satisfactory pressure curve has to be found by changing the number or diameters of the outflows and the outer vein.
Our theory was that by increasing the diameters of the outflow, the compensation of the pressure would be faster but the pressure dip at phase 2 could still be the same.

If it is possible to optimise the number and dimensions of the outflows in order to get a pressure curve, which is very similar to that obtained in animal experiments, and the system turns out to be auspicious, even more changes could be done to improve the system. For example could the elasticity of the silicone rubber be optimised. And it is also worth thinking about making the system symmetric.

The fluids of the spinal canal are not only flowing out of the canal during traumatic neck motion, but also along the canal. Although the flow of CSF is assumed to be of minor importance, the flow of blood is not negligible.
The flow along the whole spinal canal has not been taken into concern.

5. FINAL SOLUTION

The final solution differs only slightly from the previous prototype. It is based on the same system.

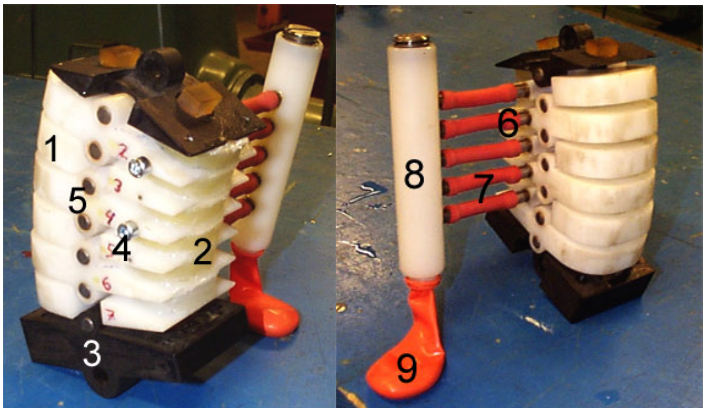

Figure 15: Posterior (left) and anterior (right) view of the final prototype: 1. Vertebrae (C2 – C7); 2. Silicone discs; 3. First thoracic vertebra and chucking; 4. Holes for pressure transducer; 5. Pin joints; 6. Outlets; 7. Rubber tubes; 8. Outer vein; 9. Balloon

5.1 Components

5.1.1 Spinal cord

For the spinal cord I used the same system as had been used in the previous prototype. A silicone tube of the diameter 15 mm and length 85 mm builds up the spinal cord. It is fixed on the upper and lower end on the first and last disc. Inside the canal it is freely moveable.

5.1.2 Out-leading veins

On one side on the transverse plane holes with diameter 8 mm are drilled in the vertebrae C2-C6 leading into the spinal canal. Inside these holes there is a thread. Outlet screws with different sizes of drilled centre holes can be screwed in. Thus, it is possible to have different sizes of outflows at different levels of the neck. The threads were sealed with a special thread sealing substance.
To start with, we choose outlets of the diameter 5 mm, which was the maximal possible diameter. Smaller outlet diameters could have been chosen for further experiments. On the other end of those screws natural rubber tubes can be connected.

5.1.3 External venous plexus

A plastic tube with inner diameter 17 mm represented the external vein system. The upper end of the tube was plugged; on the bottom there is a balloon fixed, which serves as water reservoir. Along the tube there are five metallic outlets, on which the rubber tubes can be connected. Their inner diameter is 6 mm. It's the same size as the inner diameter of the rubber tubes and it's bigger than the biggest outlet of the vertebrae. Hence the outlet of the vertebrae will bee the main limiting factor of the system.

5.1.4 Discs

Between adjacent vertebrae the wall of the spinal canal was represented by rubber rings (Figure 16). For the rubber discs I used the same material and the same dimensions as in the former prototype. But as in its report nothing has been said about the dimensions of the discs, I had to recalculate them. Hence they might differ a little from the dimensions of the previous discs.

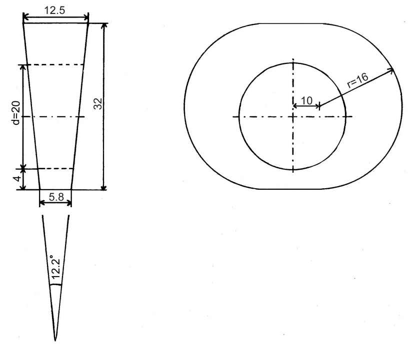

Figure 16: Dimensions of the silicone discs.

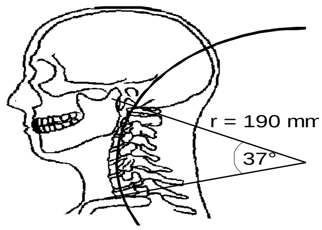

Figure 17: Geometries of the neck. (Adapted from Linder et al. 2000)

The angle between the superior and inferior disc faces was 12.175º. Hence the whole neck was given a lordosis of 37° (Figure 17). Out of this data and the drawing of the vertebrae, I could calculate the dimensions of the silicone discs.

Also the composition of the two component silicone and with this the properties of the material may differ. However this may not cause any problems, because the exact required properties of the material has not been determined.

5.2 Materials

For the discs and the spinal cord I used the same two-component silicone rubber, that was used for the first prototype. It is called CG 100 Silikongummi and it’s a pourable, addition-curing, two-component silicone rubber that vulcanises at room temperature. As I did not know the proportions of the two components that was used for the first prototype, I had to find it out by trying. Therefore the stiffness of the discs may differ a little bit to the ones of the first prototype. I used the proportions of the components A and B 9:4.

However this type of silicone turned out not to bee suitable for this application, as it is very difficult to glue. It got brittle after the use of the glue primer and I had to reglue the neck several times during the experiments. The silicone actually survived only a few tests. And in the last test, the discs became very stiff and brittle.

The screws used for the changeable outflows were made out of steel and the outflow tubes consisted of an elastic rubber. The outer vein consisted of a rigid plastic tube.

Because of the water and the solvent of the primer and the glue the steel outflows started to oxidise.

As in the previous experiment, tap water was used to represent the fluids inside the spinal canal. In order to get rid of the air bubbles in the water, I let the filled up neck rest for about half an hour and filled up the rest of the water afterwards.

For the last test I boiled the water in order to get rid of the air bubbles.

5.2.1 Glue

The silicone rubber is very difficult to glue. It took me some time trying to find suitable glue. The glue used in the previous prototype seemed to corrode the silicone as it got brittle. But as we didn't find better glue we used the same as used earlier. It was Loctite 406 composed with primer-3 (Swerotec).

6. THE EXPERIMENT

Out of a lack of time we decided to adopt the simple test set-up used in the previous project. Four tests were run with the following test conditions.

Nr.	Initial force [N]	Transducer position	Attach position mm below head CG	Outflow diameter	Comments
1	150	C6	30	5 mm all	damage of the disc at level C6/C7
2	150	C4	20	5 mm all	leakage at the bottom
3	150	C2	20	5 mm all	lowest disc replaced; only little leakage
4	150	C6	40	5 mm all	boiled water; neck stiffnes increased; big leakages at several levels

Table 3: Test conditions of pressure experiments

No further experiments could be run, because the condition of the silicone discs was very bad. In order to mend it for new tests new discs would have to be made.

6.1 The set-up

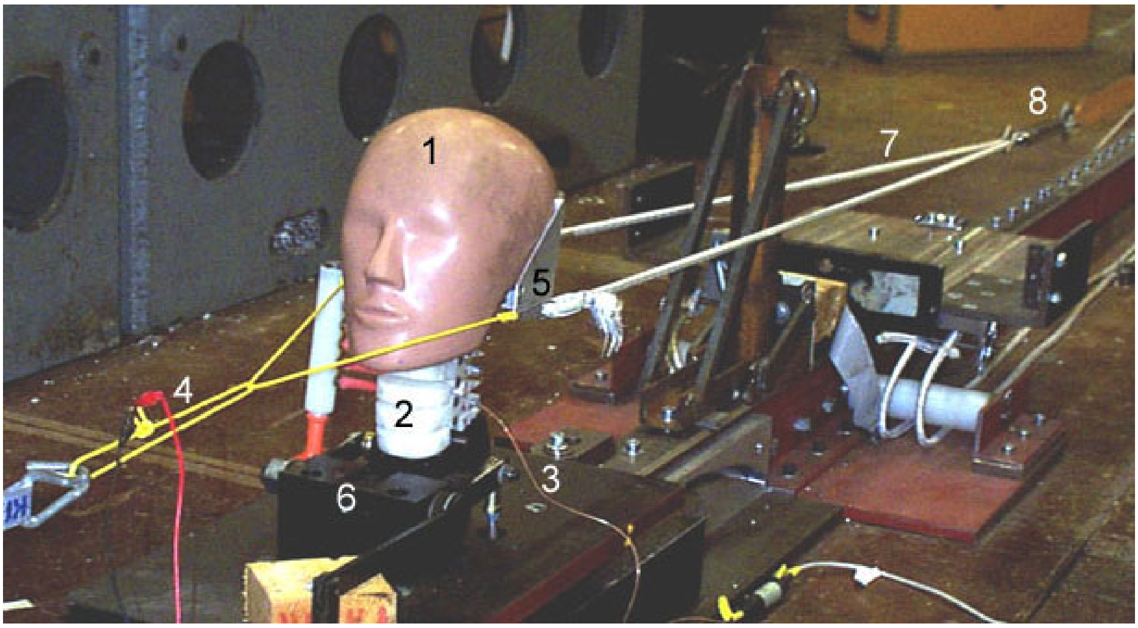

Figure 18: The test set-up: 1. Hybrid III dummy head; 2. BioRID-neck with outer vein; 3. Pressure transducer; 4. Trigger circuit and release mechanism; 5. Attach mechanism; 6. Chucking; 7. Elastic rubber cord; 8. Scale

As in the previous experiment, the neck was fixed at the level of T1. To improve the repeatability of the motion of the neck, I made a special appliance to fix the rubber cord at a predefined position below the centre of gravity (CG) of the head. The point where the force acts has to be at that point as it includes the mass of the neck. With a special construction it was possible to attach the rubber cord at three different positions; 20 mm, 30 mm, and 40 mm below the head CG.

The elastic rubber cord had a length of 2 m; hence there will be the distance between the head and the ends of the band of 1m. The pulling force of the rubber cord is 125 N for 100 % expansion. We run the tests with a pulling force of 150 N. The force was measured by a dynamometer.

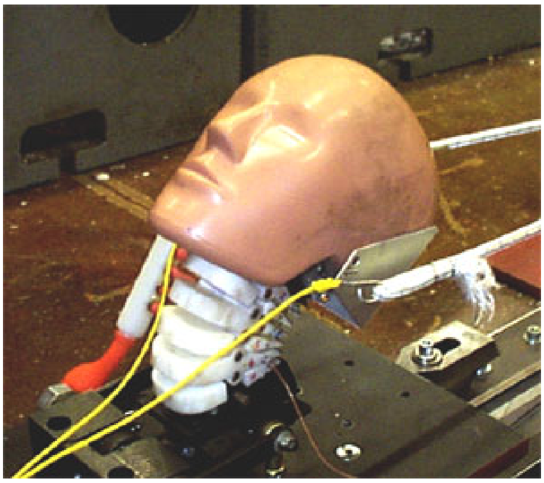

Figure 19: Neck after the measurements in fully extended position.

By the rearward motion of the head the rubber cord relaxes and the pulling force decreases. For this short distance, we assume linear decrease, which will be 2.5 N/cm. This means, at a reward motion of the head of 5 cm, we lose a force of 12.5 N.

The head was stabilised before the experiment by a cable, attaching at the same points as the rubber cord, but pulling in opposite direction. The cable was connected to the trigger. Cutting the cable released the head and started the measurement, as the trigger circuit was not closed anymore. After the measurement the neck stayed in fully extended position (Figure 19).

6.2 Pressure measurements

The pressure transducers were introduced into the spinal canal through transversal holes on the right side of the vertebrae. These holes were tightened with rubber tube and screws. In order to have the possibility to measure the pressure at different levels of the neck, we drilled holes in vertebrae C2, C4 and C6.

For the pressure measurement MicroTransducer Catheters (ppg MTC) were used. They use an excitation voltage of 5 V, d.c., an input impedance of 10 kΩ and a sensitivity of 5 μV/V/mmHg.

The data was stored by a data brick (GMH Engineering) and evaluated with its special software on a PC.

7. RESULTS

The pressure curves obtained in the first three measurements, level C2, C4 and C6 are shown in figure 20. They all start with a small negative pressure dip, which is very slightly bigger for the upper levels of the neck. The curve of the C6 level shows a very sharp peak at about 100 ms.

The curve of level C4 shows a non-negative pressure dip at about 135 ms, which can't be detected at level C2 and C6. At 160 ms all curves show a high pressure peak, which was out of range for C2 and after that a clear negative pressure dip. In the end, the pressure balances at a level slightly higher than the starting level.

The test at level C6 has been redone (Figure 21) with a lower attach-point of the rubber cord and the use of boiled water in order to get rid of air bubbles. The second measurement of level C6 showed a strange pressure history that, in the beginning, is almost symmetric along the x-axis to the previous run. The graph shows two small negative pressure dips at 12 ms and 38 ms and a pressure peak at 60 ms.

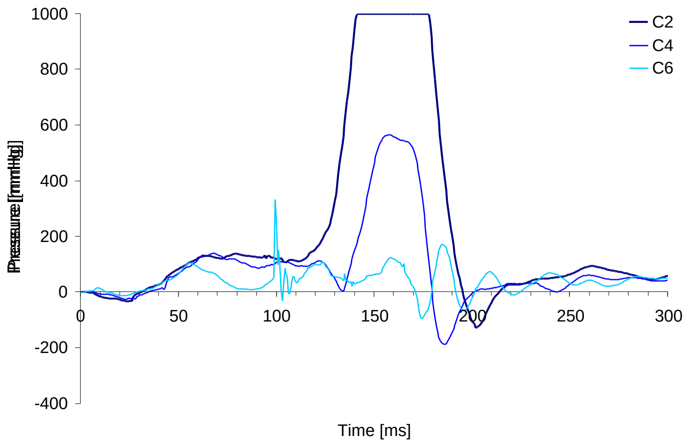

Figure 20: Pressure curves at all three levels, C2, C4 and the first run of C6 for a pulling force of 150 N and 5 mm outflow diameters.

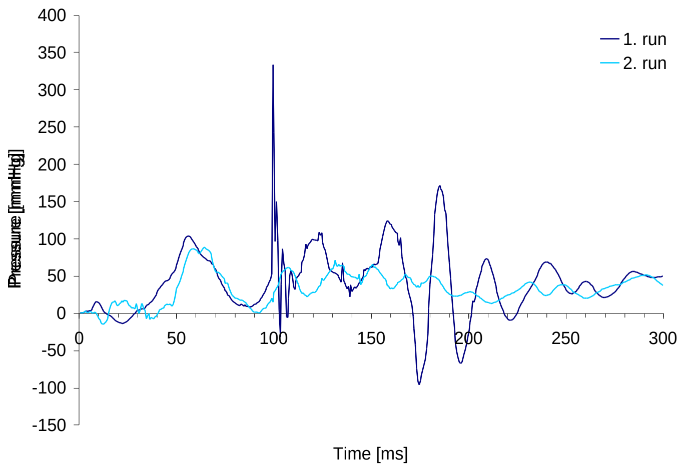

Figure 21: Pressure curves of both measurements at level C6 with a pulling force of 150 N and 5 mm outflow diameters.
For the first run the point where the force acts has been 30 mm below the head CG, for the second run 40 mm below the CG.

8. DISCUSSION

As we expected, the increase of the outflow diameters caused a faster pressure and volume compensation than obtained in the tests with the first prototype. The pressure after the swift extension motion levelled off on a higher level than at the start, as the neck remained in total extension and the balloon, which stored the water, applied pressure on the system.

We may estimate the weight of the dummy head inclusive neck filled with water of ~5 kg. With 150 N pulling force it evokes an initial acceleration of about 3 g. This corresponds to at least 300 N pulling force in the pig experiments (Figure 23). Therefore we may compare the results in the current experiments with the results of 300 N pulling force in the animal experiments.

The pressure peak obtained in the animal experiments for a pulling force of 300 N occurs at ~160 ms. Also in the current study at all levels a pressure peak appears at ~160 ms (Figure 22). At that point of time the neck might reach its full-extended position. This peak is much bigger than expected at the levels C2 and C4. It's even out of range at C2 level. The magnitude of this peak is difficult to explain. There seems to be a possibility that the hook of the rubber cord struck against the outer vein and the rubber tubes collapsed what made the pressure increase. However this theory does not seem very likely to me, as there should have been enough space for the hook to move.

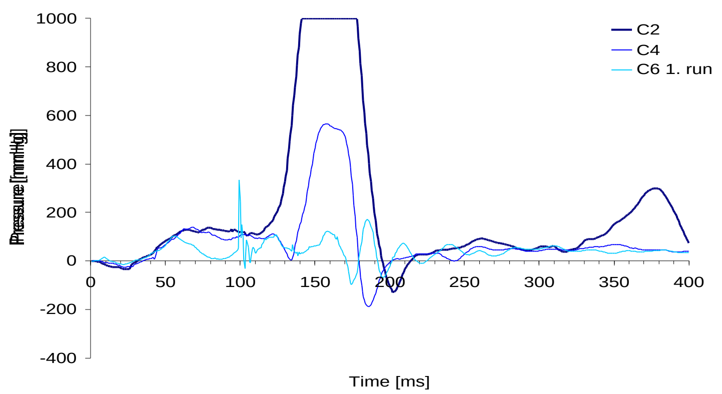

Figure 22: Pressure curves at the level C2 and C4 obtained in the current study with a pulling force of 150 N.

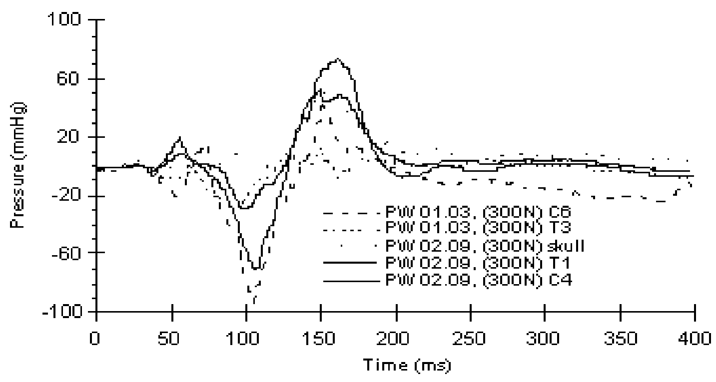

Figure 23: Pressure curves obtained in experiments on pigs for a pulling force of 300 N at different levels of the spine. (Adapted from Svensson et. al, 1993)

After the pressure peak, significant pressure drops appear between ~170 ms and ~200 ms at all levels (Figure 22). Those drops didn't occur in any of the previous studies. They can be explained by the fact, that the rubber cord keeps the neck in total extended position. However the discs have elastic deformation properties, hence the neck would tend to return forward in flexion motion. The flexion motion is however stopped by the rubber cord, which pulls the neck back in its fully extended position. Therefore fast flow changes, which evoke the appearance of the negative pressures, may occur inside the spinal canal as a result of oscillations in the neck, head, rubber cord system.
There is a slight negative pressure drop just in the beginning of the motion, which might appear at the first change of the upper part of the neck when it goes from the extended position of the lordosis into flexion motion. A slight pressure drop before the main one can also be seen in the graphs of the animal experiments and the FE model at the levels of C4 and C6 but not in the graphs of the experiments with PMHS.
At level C2 no further pressure drop occurs, which also accords with the previous research. The major pressure drop at level C4 obtained in the current experiments at ~130 ms is very small and not even negative. This may happen out of different reasons. The attach-point of the rubber cord was chosen 20 mm below the head CG. This might not be enough considering the mass of the neck. Therefore the head may have started its rotation immediately and the S-shape may not have developed. Besides there might have remained some air bubbles in the water. In order to get rid of the air bubbles we let the neck, filled with water, rest for at least half an hour. However as the silicone discs became brittle because of the primer, some air could have remained in the canal and also more air could have entered through the leakages. The air bubbles expand during pressure decrease and therefore decrease the pressure dip. In case air entered the spinal canal in the early neck motion this could have caused the extensive pressure peak found at C4 and C2 level in tests 1 and 2.
At C6 level a very sharp pressure transient occurs at about 100 ms in test 1 (Figure 22). However the main pressure peak and also the following pressure drop appear similar to the other spinal levels. A possibility for the deflection could be a sudden rip in the silicone disc or between the disc and the vertebrae at that level. This seems to be likely, as the lowest disc has been damaged after the first measurement.

If we compare the second run at level C6 with the curves of the other levels (Figure 24), we note that nothing happens at the places where something was expected to happen. Pressure dips and peaks, which can be seen at the other levels, are missing, even though the point where the force acts has been 40 mm below the CG, deeper than in all other measurements.
The neck has been in a very bad condition during the last measurement. It became very stiff by the lot of glue, which was used to mend the leakages. During the measurements, the silicone discs ripped off the vertebrae at several levels of the neck and water was pouring out of the canal. This may be the reason that there have been no significant phenomena in this pressure curve.

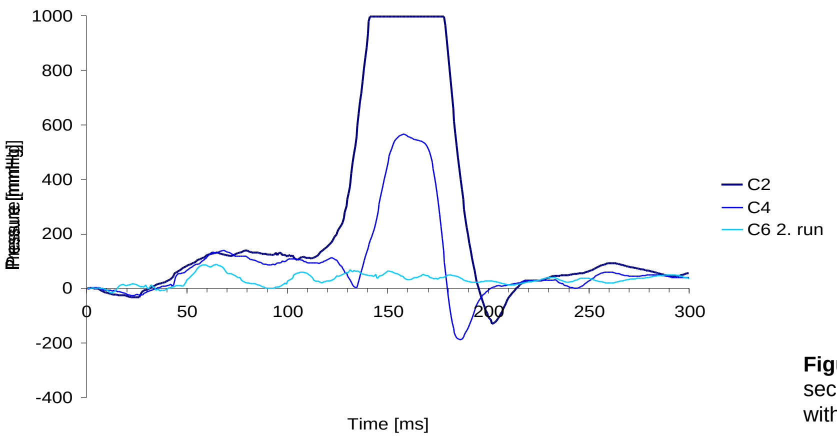

Figure 24: Pressure curve of the second run at level C6 compared with the other levels.

9. CONCLUSIONS

- By enlarging the dimensions of the outflows, fast pressure equalisation after the swift extension motion has been reached.
- The significant negative pressure dip in the second phase of the traumatic neck motion disappeared. This might not be a design problem but a problem with the test set-up.
- The pressure peak obtained in this study is much larger than in the previous research.

10. RECOMMENDATIONS

Design changes

This simple model turned out to be auspicious and quite good results could be obtained. Nevertheless some design changes could be taken into consideration.

First of all the quality of the discs should be improved. They should be able to withstand several tests without any damage of the neck. That's the only way to get repeatable and reliable results in the tests.

Further changes could be to make the neck more nature like; e.g. the system could be built symmetric. Also the fluid exchange along the whole spinal canal has not jet been taken into consideration.

A further project could be, to adapt it to the Omni-directional dummy neck, which is being developed at the same department (Carlsson, 2001).

Test set-up

A lot of changes have to be done to the test set-up. With the current set-up it has been very difficult to interpret the obtained pressure curves, as we couldn't compare the position of the head with the pressure.

This means, acceleration measurements of the head should be done and a high-speed video of the motion should be taken. The pressure should be measured at different levels parallel during the same run. Thus they could be directly compared with each other.

In order to get a very realistic motion with a clear retraction phase; the exact point where the force is applied to the head has to be found. After the rearward motion the head should return to its initial position. Thus the negative pressure dip after the main peak may be avoided.

Anyway it would probably be the best to fix the neck on a mini-sled in order to get more realistic loading conditions. That way a very realistic rear-end impact and traumatic neck motion cold be imitated.

LIST OF FIRMS

CG100 Silikongummi:	Centri AG, Datavägen 6, S-17543 Järfälla Phone: +46 8 580 311 65 Fax: +46 8 580 811 28
Loctite 406:	Loctite AB, Box 8823, S-402 71 Göteborg Phone: +46 31 750 54 00 Fax: +46 31 750 53 91
Primer-3:	Swerotec AB, Box 92108, S-54102 Skövde Phone: +46 500 47 16 00

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