NECK INJURIES IN REAR END CAR COLLISIONS.

BIOMECHANICAL CONSIDERATIONS TO IMPROVE HEAD RESTRAINTS.

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Introduction

Volvo has been engaged in a continous effort to design the car to give a high degree of occupant protection. This work comprises the body structure, and the restraint systems as well as other safety features. An example of the latter is the head restraint.

The head restraint has been a standard feature in the Volvo car since 1969, although it was offered as an option as early as 1964.

Three different functions can be established for the head restraint:

- In rear end impacts - prevention of extreme rearward motion of the head
- In frontal impacts - prevention of head injuries in the rebound phase
- In all types of accidents - prevent front and rear seat passengers to get into contact with each other

As the course of events for the occupant is different depending on the accident type, different requirements apply for each of the functions. This means that the head restraint must fulfill a variety of conditions with regard to geometry, strength, energy absorbtion of material etc.

The existing legal requirements can be divided into three main categories as follows:

- Geometrical requirements which also considers the different sizes of occupants.
- The level of energy absorption, e.g. deceleration figures in a simulated head impact.
- Strength of the head restraint and the seat back.

However, these requirements can not be considered to completely cover the different aspects of injury prevention.

In the following presentation the Volvo accident statistics will be examined with respect to neck injuries. The aspect of long term consequencies is also discussed. Accidentological and biomechanical aspects of the injury mechanisms are reviewed and parameters that are considered crucial for the causation of injuries are discussed. The final part of the paper outlines some of the future work that have to be done. Ways of improving the collection of accident data and how to learn more about the long term effects are some items.

Neck injuries in rear impacts

The incidence of neck injuries has been described in many accident studies. There are several injury mechanisms that can cause neck injury. Hyperextension and hyperflexion of the neck (often named as whiplash injury) as well as lateral jerking motion are some common mechanisms. Neck injuries can also arise from head- and neck impacts without extensive bending of the neck. Furthermore a relative motion between the head and the torso can cause a vertebral shearing. As there is no common definition of neck injury mechanisms and as the neck injury mechanism often is unknown we will in the further discussions only speak of "neck injuries".

The incidence figures show a wide variation between different accident studies. Since in all collection of data, the available material is sampled according to some criterion, the nature of the sampling is crucial in understanding these variations. Studies based on "no fault" insurance claims show incidence figures for front seat occupants that vary from 10% - 15% (22) to 35% - 50% (31)(3).These results can also be influenced by differences in the proportion of effective head restraints available within the different sample studies.

Samples based on injured occupants will naturally tend to pick up neck injury cases. Thus the higher figures quoted in these studies are not surprising, since neck injury is widely acknowledged to be the dominant type of injury in rear impacts. The figures from Langwieder (13) and Kahane (12) for example suggests a neck injury incidence of 80% - 90% for injured occupants.

Because of the different sampling methods and injury details available in different studies, it is difficult to conclude an overall effectiveness figure for head restraints. Some studies have found no significant effect of the incidence of neck injury associated with the provision of head restraints (6)(10)(29)(30). However, the majority of studies that have shown head restraints to be effective have indicated a reduction in the incidence of neck injury in rear end impacts in the range of 13% to 20% (12)(13)(22)(23)(29).

Volvo has been collecting accident data for Volvo cars since 1970. The accident material now available is based on a repair cost criterion (20). A recent analysis (Volvo 1985) contains 229 rear impacts, i.e. collisions with a principal direction of force of 05, 06 or 07 o'clock according to the CDC-system. All of the Volvo cars were equipped with head restraints in the front seat but not in the rear seat.

The neck injury frequency for the 403 occupants involved shows a higher figure for the driver (35%) and front seat passenger (25%) than for the rear seat occupants (16%). The vast majority of the injuries were rated AIS 1.

In the literature there is also consistent agreement that the incidence of neck injury among rear seat passengers is lower than among front seat occupants (13)(22)(29).

In an unpublished Volvo study of neck injury frequency for rear seat occupants, it was found that the relation between occupant height and back rest height was important. No neck injuries were found for occupants whose seventh cervical vertebrae (C7) did not reach above the seat back rim. Most of these short occupants are children whose proneness to get injuries differ from adults.

If we therefore exclude occupants shorter than 150 cm we have the following proportions:

OCCUPANT	NECK INJURY FREQUENCY
Driver	35%
Front seat occupant	25%
Rear seat occupant	22%

These differences are not statistically significant. However, the high injury frequency for the front seat occupants, particularly for the driver, needs further study especially as there were head restraints in the front seat but not in the rear seat and since the majority of studies show a protective effect of head restraints.

In the accident material (Volvo 1985) the average height of drivers is 177 cm while front seat and rear seat passengers have average heights 169 and 170 respectively (occupants shorter than 150 cm are excluded).

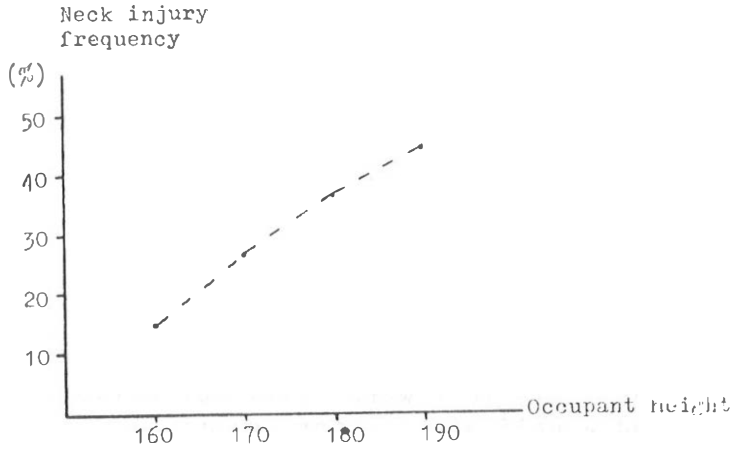

Fig 1. Neck injury frequency vs height of grown-up front seat occupants (Volvo 1985)

There is a statistically significant correlation between height and neck injury, i.e. the neck injury frequency increases with increasing occupant height. Thus if taller occupants run a larger risk of neck injury in a rear end impact, this would explain the larger injury frequency of the drivers who were taller than the other occupants. Also the sampling method must be taken into account. In this study (Volvo 1985) when there were no report from the hospital, the minor injuries were mostly reported by the driver who may have a better knowledge of his own injuries than injuries of other occupants.

The lack of difference in injury frequency between front seat and rear seat passengers (drivers excluded) is remarkable and needs an explanation. Here the hat shelf and the sturdier back rest in the rear seat may protect the passengers' necks. The seat backs of rear seats are also often more upright.

In several accident studies higher figures of injury prevention have been obtained for fixed restraints than for adjustable ones (12)(22)(29).This is in conjunction with the relationship in fig 1 since it is known that most adjustable head restraints are left in their lowest position (2)(29)(30). This is not the only explanation though. Several design parameters influence the effectiveness of head restraints as will be discussed later.

Although neck injuries in most accident material are coded AIS 1 (minor), the consequences for the injured individual and for the society can be extensive because of the long lasting symptoms. The slow recovery of "whiplash" injuries has been described as far back as 1953 (7), and in subsequent decades the problem complexity has been discussed in a number of studies (8)(15)(27). In brief these early studies show that protracted pain after "whiplash" injury is frequent. This sequential condition is particularly common among injured occupants whose cervical vertebrae already had degenerative disc changes (21).

Both Nelson (19) and Mertz (18) mentioned the possibility that some of the persistent neck pain results from abnormal motion of the joints within the cervical spine. It was suggested that damage to the ligaments results in some degree of instability of the cervical spine.

Hohl (9) considered both the duration of symptoms and incidence of degenerative changes in the necks of 146 patients who had suffered soft tissue injury to the neck in car accidents, and he reached the following conclusions:

- Younger patients were more likely to recover well.
- Men were less likely to have long term symptoms than women.
- More severe injuries requiring hospitalization were more likely to lead to long term symptoms.
- Only radiating pain or numbness or both in the upper extremities was positively correlated with bad prognosis for symptomatic recovery.

Several studies try to quantify the size of the long-lasting neck injury problem. Juhl (11) reported on a study of patients treated for cervical spine injuries. Some 16 % were still suffering symptoms at follow up about two and a half years after injury.

Thomas et al (30) analysed the questionnaires returned by 52 people who had experienced cervical pain following a rear end impact. The cases were drawn from the Peugeot S.A./Renault accident file. Six years after the accident 37 % reported that they still suffered from stiffness in the back of the neck or "mood troubles". The authors observed that long term disability was most common amongst those who had previous cerebral and cervical trouble.

Norris and Watt (21) reported upon a series of 61 patients who suffered neck pain following a rear end collision. In a group containing persons only complaining of pain, 56 % were entirely free from symptoms at follow up (between one and two years after injury) while the patients that also had evidence of neurological loss were entirely free from symptoms only in 10 % of the cases at the follow up. Seven patients within the whole series had head restraints available to them at the time of the accident. Although none of these patients complained of headaches at follow up, their initial symptoms were distributed evenly amongst the severity classifications used and the authors concluded that head restraints do not seem to produce more or less severe injuries.

Nygren (22) produced an extensive analysis of data from the files of the Folksam Insurance Company. When considering front seat occupants who had sustained neck injury in a rear end collision, he found that 9.6 % ended up with permanent disability.

Few papers relate disability to the presence or not of a head restraint. However, Nygren's analysis covers this aspect (22). Whilst head restraints were found to have an effect on the incidence of neck injury, they did not appear to have a demonstrable effect on the outcome of injury, when injury did occur.

In order to find a method to detect long term injuries to the neck, a pilot study based on the Volvo accident material, was carried out. About one year old frontal or rear end impacts were sampled.

The selection resulted in 18 car occupants who were interviewed via a mail questionnaire. The questions concerned the origin of the injury, type of symptoms, duration of symptoms, etc.

11 persons were found with symptoms lasting up to one month and 7 persons had symptoms lasting longer than one month. It is notable that the rearend collisions causing the injuries were not severe. All but one had a VDI value less than 3. In 6 of 18 cases it was not possible to prove any connection between the accident and the stated neck troubles. This underlines the importance of in dept studies and accident reconstruction as a tool for further understanding of the neck injury mechanisms.

The difficulty to find clear connections between different car and occupant parameters and the risk of sustaining neckinjuries is partly due to the insufficiency of the AIS-classification which is a to blunt instrument to distinguish one type of injury from another. Even in a non-severe rearend impact in a car with headrestraints the occupant may have pain in the neckmuscles for a couple of days. This injury is codified similar to a neck injury (without clinical signs) where the neck has been stressed in a more severe flexion or extension. The long term consequences are not evident at the time of AIS-codification.

In order to improve the usefulness and reliability of clinical injury analysis, White and Panjabi (33) have suggested that biomechanical principles be used in the analysis procedure. They stated that the simple classification of an injury to the spine according to the main direction of movement such as flexion injury, lateral bending injury, etc, is not sufficient. Instead the clinical investigation of the patient should describe damages and symptoms, radiographs should be taken and they should be accompanied with a biomechanical analysis with the aim of determining a vector of force or torque, the action of which should explain the observed injuries. This vector is called Major Injuring Vector, MIV, and it should be specified with respect to direction and if possible also to magnitude. By following these recommendations, it should be easier to clarify what has happened in the injuring event and get an understanding of the mechanism of injury.

In car accident research, a similar procedure could be established for the investigation of the external event occurring in the crash. By observing the main direction of movement of the car body, location and severeness of intrusion, position of the occupants before and after the crash and looking for signs of contact between the occupants and the car structure, etc, an attempt should be made to establish what could be called a Major Acting Vector, MAV, which should be specified with respect to direction and magnitude and also cause, i.e. impact or inertial force.

The two vectors, MAV and MIV, resulting from the analysis should in theory be the same which they in practice will seldom be due to uncertainties and difficulties of interpretation. A final step in the analysis of an accident is now to explain the differences and if possible correct the determination of one vector or the other.

Biomechanical Considerations and Design Implications

Design modifications, interior as well as structural ones, have improved the safety during the years . In the figure below the neck injury frequency for front seat occupants in rear end collisions is shown (Volvo 1985).

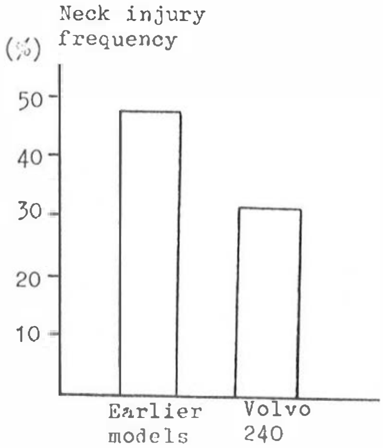

Fig 2. Neck injury frequency for front seat occupants in cars with head restraints (Volvo 1985).

The neck injury frequency is considerably lower in the later designed car models (Volvo 240 series) than in the older ones.

In the following paragraphs some factors that influence the safety are discussed.

CRASH PULSE AND RAMPING

The deceleration pulse that the occupants are subjected to is depending on the deformation characteristics of the rear end car structure, and the stiffness of the seat system. Legal requirements do not take this into account but perform the tests with a standardized sled pulse.

The lower injury frequency in newer cars can partly be ascribed to improved deformation characteristics. Further development along these lines would require that the deformation characteristics of different parts of the car be tuned to each other.

Another important factor to consider is ramping. To minimize the degree of the occupant ramping up the seat causing the head to override the head restraint, a certain strength of the seat back is required. The accident statistics are however, somewhat contradictory. States, et al (28) in an analysis of their field experience of rear end collisions felt that seat back failure offered some protection against neck injury by reducing the extension of the cervical spine. This philosophy is also supported by field studies by Garret and Morris (6), and Thomas et al (30).

However, in the mathematical model by McKenzie and Williams (14) a different result was obtained. They found that peak axial forces in hyperextension increase with decreasing seat back stiffness. Forces and bending moments likely to cause injury were of greatest magnitude in the lower cervical region during hyperextension and were potentially more damaging for decreasing seat back stiffness.

Although field studies on one hand and mathematical simulations on the other differ on the conclusions about the strength of the seat back, a certain minimum strength is required for the following reasons:

- Large seat back deflection increases the risk of ramping, causing the occupant to contact the interior
- Seat strength minimizes the risk of front and rear seat passenger interaction

Ramping is not only influenced by seat back strength but also by other factors such as the use of lap belt, floor strength, high friction seat covering materials and seat back inclination.

HEAD RESTRAINT HEIGHT

A discussion of the height of head restraints must nave as its background the previous remarks about occupant ramping. Consideration of head restraint height solely on the basis of anthropometric data is likely to be misleading.

In fig. 1 it was shown that the frequency of neck injury is related to the height of the occupant. The neck injury frequency increases with increasing occupant height.

Biomechanically, the results are not surprising but confirms the analytical conclusions that can be drawn from knowledge of the neck design. The neck is the link between the head and the torso and the neck must therefore transmit the inertial and impact forces that can occur when the state of motion of a car occupant suddenly changes. When the torso is decelerated or accelerated by the seat or the seatbelt, the inertia of the head opposes the motion causing an excessive bending in the neck, the direction of which depends on the main vector of impact force. The neck bends until the limit of motion is reached. Then tensile and compressive forces build up in the tissues of the neck to a magnitude which corresponds to the acceleration. Since the tissues also exhibit elastic properties, a rebound phase often follows.

The sternum and the shoulders serve as natural stops for the motion of the head in flexion and in lateral bending. For extension there is no similar limiting structure. The normal range of flexion - extension in the neck is 100 to 130 degrees and it varies between individuals depending on for example age. Beyond normal range of motion the turning moment for extension (in unembalmed cadavers) in semistatic motion is 0.35 - 0.65 Nm/degree (5). Figure 3 shows the result of a piecewise linear approximation based on linear regression of the data by Gadd et al. (5). The earliest audible tissue ruptures were noticed at an angle of 60 degrees, corresponding to a turning moment of 20 - 25 Nm.

Voluntary static neck strength data were reported by Mertz and Patrick (17). In normal head position, the resistance against neck extension was 14 Nm and against neck flexion 32 Nm. The strength increased somewhat when the head was either flexed or extended. These figures are much lower than the peak instantaneous turning moment of 90 Nm at the occipital condyles that the same authors found in their Gx sled tests with a volunteer who was not injured in the experiment.

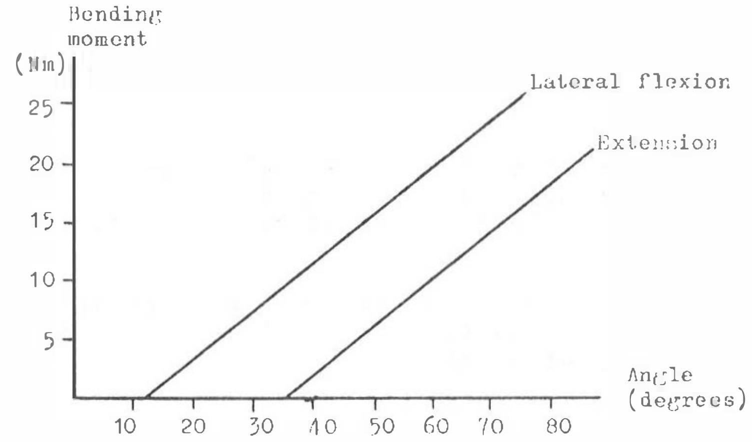

Fig 3. Two piece linear approximation of neck stiffness in extension and lateral flexion (5).

When the neck is subject to large forces as in an accident, excessive bending occurs and tension as well as compression forces are likely to exceed the values that occur within normal limits of movements. When this occurs an excessive stretching and a narrowing of the spinal cord can take place affecting medulla oblongata and the spinal cord. Since these tissues are sensitive to stretching and deformation, this may be an explanation of the degrading function of the nervous tissues after an accident.

The function of the cervical spine when subject to axial tension has been investigated by Sances et al (25) who experimented on live monkeys and cadavers of monkeys as well as humans. They found in the monkeys that the cervical spine failed functionally at a load of 1100 N statically applied (0.2 cm/s) and at 2600 N dynamically (100 cm/s). The static stiffness was 1170 N/cm and the dynamic was 1410 N/cm, which means that the force increases comparatively more when the rate of extension is larger. The human cadavers were stronger, tissue damage in an intact neck was obtained at 3780 N in a dynamic test. The extension was then 20 mm yielding a stiffness of 1860 N/cm. In isolated column specimens the relation between dynamic and static strength was the same as in the monkeys.

As to the injury mechanism of the cervical spine subject to transient loads, the experiments by Sances et al (25) on live monkeys showed that neural transmission is adversely affected at lower tensile loads than when macroscopic tissue damages or circulation disturbances occur. The somatosensory evoked response amplitude was reduced markedly at about half the tension at which the spine failed completely (disrupted) in static experiments. The dynamic experiments could not be interpreted in this respect since they immediately reached damaging extension levels. In an incremented dynamic experiment there was no change in evoked response amplitude until the axial extension of the neck reached 11 mm. Failure did not occur until the cervical displacement was 17 mm.

These results were later confirmed by the same authors when the monkeys were subject to -Gx acceleration (26). Using electron microscopy they could identify abnormal tissue changes not visible in a light microscope. A similar study was performed by Unterharnscheidt (32) who was able to demonstrate that the amplitude reduction of the evoked response was concomittant with spinal cord injuries in the suboccipital region, obviously caused by the deceleration forces.

It is interesting to note that neural transmission is functionally disturbed at loads lower than those causing structural damages in the tissues. These findings should influence data collection and analyses of future car crashes. More attention should be paid to neurological signs showing up not only immediately after the accident but also such signs which are likely to develop after some period of time.

Experimental studies of the height parameter and the influence of seat back strength could be made on a crash simulation sled. By using the Hybrid III dummy (34) biomechanically relevant data can be measured, e.g. flexion and extension torque, tensile, compressive, and shear forces.

DIFFERENTIAL MOVEMENT BETWEEN HEAD AND TORSO

The magnitude of the forces in the neck depends on the acceleration of the head and torso. If the acceleration forces are larger than the strength of the tissues of the neck, then the tissues must be damaged. However, maximum damage to a particular tissue component does not need to occur when the acceleration forces are maximal because the load will be distributed differently to tissues of different strength depending on the relative position between head, neck and torso. For example, when the neck is subject to axial tension, both anterior and posterior ligaments will be loaded, while in extension during a "whiplash" movement the anterior ligaments alone will take up the tensile load.

In the light of this injury mechanism it is evident that differently designed seats, present a different crash environment to the occupants. This can be one explanation of the different injury frequency results for different positions in the car.

The concept of differential rebound was introduced by States, et al (29). They hypothesized that some injuries were explained by the existence of different spring rate characteristics in the main section of the seat back and the head restraint. As the occupant compressed the seat cushion in the first part of the impact sequence energy was stored by the seat and head restraint. Head restraints are usually covered with slow recovery foam whereas the spring structure of the seat back returns energy much faster. The result was thought to be that the torso rebounded much faster off the seat than did the head from the head restraint, with the consequence that hyperextension of the neck was produced during this rebound phase. Such movement patterns have been demonstrated in experiments performed by Prasad et al (24); however the simulation results of Fox and Williams (4) and McKenzie and Williams (14) show that the maximal accelerations decrease when the stiffness of the seat back increases.

In the design work it is important to provide a good alignement for the head and the torso by tuning the spring characteristics of the head restraint and seat back to each other. Current safety regulations do not recognize this aspect of seat design.

Several studies have shown that the load generated between the head and head restraint is highly dependent on the initial horizontal spacing between the two. For example, Mertz and Patrick (16) noted in their sled testing with cadavers that loads of 1.96 and 1.38 kN were measured when the initial spacing was 9.0 cm whereas the loads were reduced to 0.67 and 0.76 kN with no initial separation.

Loads can be reduced by use of a suitable padding but for optimum results the padding must be tuned to anticipated head spacing. There seems to be a general agreement that the head restraint should be placed as close to the occupant's head as is practically possible.

To stop the head motion in a controlled way, the head restraint frame can be padded with energy absorbing material. This padding should also provide some support for the neck itself so that flexion of the neck between the headrest and the backrest could be avoided. Also, the top part of the head restraint should be designed to cope with a possible head contact.

A face or head impact on the back surface of a front seat head restraint from an unrestrained rear seat occupant is a likely occurence. Thus, the head restraint must be designed with this aspect in mind.

There are also vertical loads applied to a head restraint during an accident. Probably the most common reason is due to a degree of occupant ramping. This can give an upward loading "pulling" the head restraint or, a downward loading "pushing" the head restraint downwards. Especially adjustable restraints must be designed and tested with this in mind.

Summary.

The aim of this work has been to find guidelines for the improvement of head restraints. As a basis we have taken an overall look on research within this area. Both statistics, in-depth studies and biomechanical research show that the occurence of neck injury in a rear end impact is depending on several parameters. Car related parameters such as seat stiffness, distance to the head restraint and head restraint height differ between different seating positions in the car. Furthermore, individual parameters like sex, size, age, awareness of the accident and proneness to state pain, varies.

The large amount of important parameters makes it difficult to understand the injury mechanisms without a more thorough analysis that strives to describe the typical injuries for differently applied traumas. Then it will be possible to draw conclusions on injury preventive design of head restraints. Such work is only meaningful if it is based on an injury classification that describes the severity of the injury consequences. The AIS scale is not sufficient, its resolution and sensitivity is far to low and it does not take the risk of disability into consideration.

The improved accident analysis should lead to the development of laboratory methods and measuring techniques. Thus the injury mechanisms can be further studied and quantified and the importance of different head restraint design parameters can be evaluated.

The design of a head restraint must minimize the effect of individual differences and optimize the preventive properties of the restraint. The head restraint must be treated as one part of a protection system, where the seat is one important part. These two parts must be matched together.

Many investigations compare fixed and adjustable head restraints. The adjustability is of course no injury parameter in itself and the understanding of the actual drawbacks with the adjustable head restraints of today must be investigated. Height is the most obvious difference but we know that fittings to the seat, stiffness etc also varies.

List of References

1 Bohlin N, et al. "A Statistical Traffic Accident Analysis" in Reports on Traffic Accident Research, AB Volvo Car Division, Gothenburg. March 1973.

2 Cameron, M.H. and Wessels, J.P. "The Effectiveness of Australian Design Rule 22 for Head Restraints" Dept. Of Transport Australia, Office of Road Safety, Canberra, Report No. CR 5, March 1979.

3 Cameron, M.H. "Effect of Seat Belts and Head Restraints on Neck Injury" Dept. of Transport Australia, Office of Road Safety, Canberra, Report No. CR 19, May 1981.

4 Fox, J.C. and Williams, J.F. "Mathematical model for investigating combined seatback -head restraint performance during rear end impact". Medical and Biological Engineering, 14, 263-273, 1976.

5 Gadd, C.W., Culver, C.C. and Nahum, A.M., "A Study of Responces and Tolerances of the Neck". Proceedings of the 15th Stapp Conference, pp. 256-268. 1971.

6 Garrett J.W. and Morris, D.F. "Performance Evaluation of Automobile Head Restraints" SAE, Warrendale, Paper No. 720034, 1972.

7 Gay, J.R. and Abbott, K.H. "Common Whiplash Injuries of the Neck" J.A.M.A., August 29, 1953, Vol.152, No 18, pp.1698-1704.

8 Gotten, N. "Survey of One Hundred Cases of Whiplash Injury After Settlement of Litigation" J.A.M.A., October 27, 1956, Vol. 162, No. 9, pp. 865-7.

9 Hohl, M. "Soft-Tissue Injuries of the Neck in Automobile Accidents". J. Bone and Joint Surgery. Vol. 56-A, No.8, December 1974, pp. 1675-82.

10 Huelke, D.F. and Marsh J.C. "Analysis of Rear End Accident Factors and Injury Patterns" Proceedings of the 8th Conference of the American Association for Automotive Medicine, pp. 174-199, AAAM, Arlington Heights, Illinois 1974.

11 Juhl, M. and Seerop K.K. "Cervical Spine Injuries: Epidemiological Investigation Medical and Social Consequences" Proceedings of the 6th International IRCOBI Conference on the Biomechanics of Impacts, pp. 49-58, IRCOBI, Bron, France 1981.

12 Kahane, C.J. "An Evaluation of Head Restraints Federal Motor Vehicle Safety Standard 202" NHTSA, Washington, Report No. HS-806 108, 1982.

13 Langwieder, K., Hummel, T., Sagerer, F. "Characteristics of Neck Injuries in Car Occupants" Proceedings of the 6th International IRCOBI Conference on the Biomechanics of Impacts, pp. 78-97, IRCOBI, Bron, 1981.

14 McKenzie, J.A. and Williams, J.F. "The Dynamic Behaviour of the Head and Cervical Spine During 'Whiplash'" J. Biomechanics, 1971, Vol 4, pp. 477-490.

15 Macnab, I. "Acceleration Injuries of the Cervical Spine" J. Bone and Joint Surgery, Vol. 46-A, No. 8, December 1964, pp. 1797-99.

16 Mertz, H.J. and Patrick, L.M. "Investigation of the Kinematics and Kinetics of Whiplash" Proceedings of the 11th Stapp Car Crash Conference, pp. 175-206, SAE, Warrendale, Paper No. 670919, October 1967.

17 Mertz, H.J. and Patrick, L.M. "Strength and Responce of the Human Neck" Proceedings of the 15th Stapp Conference, pp. 207-255, SAE, Paper No. 710855. 1971.

18 Mertz, H.J. "Neck Injury In Biomechanics and Its Applications to Automotive Design" SAE, Warrendale, Publication No. P.49, January 1973.

19 Nelson, C.L. "Detection of Soft-Tissue Injuries of the Cervical Spine" Proceedings of the 14th Conference of the American Association for Automotive Medicine, pp. 47-62, AAAM, Arlington Heights, Illinois, 1970.

20 Norin, H. and Korner, J. "Volvo Traffic Accident Research SAE February 1985.

21 Norris, S.H. and Watt, I. "The Prognosis of Neck Injuries Resulting from Rear-end Vehicle Collisions" Journal of Bone and Joint Surgery, Vol. 65-B, No. 5, November 1983, pp.608-11.

22 Nygren, A. "Injuries to Car Occupants - Some Aspects of the Interior Safety of Cars" Acta Oto-Laryngologica, Supplement 395, 1984, Stockholm.

23 O'Neill, B., et. al. "Automobile Head Restraints - Frequency of Neck Injury Claims in Relation to the Presence of Head Restraints" A.J.P.H., March 1972. pp. 399-406.

24 Prasad, P., et.al. "Dynamic Response of the Spine During -Gx Acceleration" Proceedings of the 19th Stapp Conference, pp. 869-897 SAE Paper No. 751172.

25 Sances, Jr., et.al. "Experimental Studies of Brain and Neck Injury" Proceedings of the 25th Stapp Conference, pp. 149-194, SAE Paper No. 811032. 1981

26 Sances, Jr., et.al. "Pathophysiology of Cervical Injuries" Proceedings of the 26th Stapp Conference, pp.41-70 SAE Paper No. 821153. 1982.

27 Snyder, R.G. "Human Impact Tolerance" 1970 International Automobile Safety Conference Compendium, pp. 712-782, SAE, Warrendale, Paper No. 700398, 1970.

28 States, J.D., Korn, M.W., Masengill, J.B. "The Enigma of Whiplash Injuries" Proceedings of the 13th Conference of the American Association for Automotive Medicine, pp. 83-108, AAAM, Arlington Heights, Illinois, October 1969.

29 States, J.D., et.al. "Injury Frequency and Head Restraint Effectiveness in Rear-End Impact Accidents" Proceedings of the 16th Stapp Car Crash Conference, pp. 228-257, SAE, Warrendale, Paper No. 720967, November 1972.

30 Thomas, C., et.al. "Protection against Rear-End Accidents" Proceedings of the 7th International IRCOBI Conference on the Biomechanics of Impacts, pp. 17-29, IRCOBI, Bron, 1982.

31 Trinca, G.W. "Patterns of Injury in Car Occupants" Proceedings of Commemorative Conference "Road Safety Initiatives 1980", Melbourne, Victoria, Victoria Road Safety and Traffic Authority, pp. 79-94.

32 Unterharnscheidt, F., "Neuropathology of the Rhesus Monkey undergoing -Gx Impact Acceleration". In Impact Injury of the Head and Spine (C.L. Ewing, D.J. Thomas, A. Sances Jr, and S.J. Larsson, eds.). Charles C. Thomas, Springfield, Il. 1982.

33 White, A.A., III & Panjabi, M.M., "Clinical Biomechanics of the Spine". Lippincott, Philadelphia. 1978.

34 Foster, J.K., Kortge, J.O. and Wolanin, M.J., "Hybrid III - A Biomechanically-Based Crash Test Dummy". SAE 770938