Thesis for the degree of Licentiate of Engineering

AIS 1 neck injuries in rear-end car impacts

BIOMECHANICAL GUIDELINES AND EVALUATION CRITERIA

based on accident data and parameter studies

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Cover: Volvo S80, rear end impacted. The bumber is removed for inspection.

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ABSTRACT

AIS 1 neck injuries, often called whiplash injuries or Whiplash Associated Disorders (WAD) represent one of the most significant types of injury in car crashes with regard to both frequency and long-term consequences.

The method used in this study is a holistic approach combining various activities. The results indicated the importance of giving evenly distributed support to the whole spine of the occupant, plus the fact that different individual characteristics and occupant behaviour are important. Gender, occupant stature, seating position and horizontal distance between head and head restraint are some of the parameters found to influence the risk of AIS 1 neck injuries in rear-end impacts.

Knowledge gained from rear-end impact accident data was used for parameter studies in a mathematical occupant model. Parameters such as horizontal distance between head and head restraint, height of head restraint, characteristics of head restraint and crash pulse amplitude were studied using the mathematical occupant model. The occupant model was a medium-sized male occupant model in MADYMO 2D incorporating 24 spinal segments.

Biomechanical guidelines, based on the modelling results, accident data and literature data, were defined in this study to form guidance with regard to tolerable occupant response in a rear-end impact for mitigating AIS 1 neck injuries. The three biomechanical guidelines were:

1. Reduction of occupant acceleration
2. Minimising relative movement between adjacent vertebrae and in the occipital joint
3. Minimising forward rebound into the seat belt

Evaluation criteria were suggested as a quantitative assessment for each biomechanical guideline. These evaluation criteria were derived using sled tests simulating three different occupant situations. A hypothesis was formulated, based on accident data, stating that occupants in rear-seats are at a lower risk and occupants with increased distance to head restraints are at a higher risk in comparison with a front-seat occupant in a regular sitting posture. The evaluation criteria derived from this study were:

- Occupant acceleration
- Average Relative Spine Velocity (ARSV), calculated by accelerometers along the spine
- Total maximum belt force or Torso rebound velocity

The evaluation criteria are suggested for use in test procedures, involving a humanlike crash test dummy, for mitigating AIS 1 neck injuries in rear-end car impacts.

The significance of this study is that the method presents a holistic approach, which has proved possible to implement into car design process, the development of Volvo's WHIPS-seat. In the ambition to reduce the total number of AIS 1 neck injuries, this method is also recommended for the evaluation of AIS 1 neck injuries in other impact directions.

Keywords: Neck injury, Rear-end impacts, Whiplash, Accident data, Car crashes, Occupant modelling, Seat evaluation.

LIST OF PAPERS

This study is based on the following scientific papers, referred to by Roman numerals.

I. Jakobsson, L., Norin, H., Jernström, C., Svensson, S.-E., Johnsén, P., Isaksson-Hellman, I. and Svensson, M. Y. **Analysis of Different Head and Neck Responses in Rear-End Car Collisions using a New Humanlike Mathematical Model**. Proc. of Int. IRCOBI Conference on Biomechanics of Impact, Lyon, France, 1994: pp. 109-125.

II. Jakobsson, L., Lundell, B., Norin, H. and Isaksson-Hellman, I. **WHIPS-Volvo's Whiplash Protection Study**. Presented at 1999 Whiplash Associated Disorder World Congress, Vancouver, Canada, 1999. Published in Accident Analysis and Prevention, 32, 2000: pp. 307-319.

III. Jakobsson, L. and Norin, H. **Suggestions for Evaluation Criteria of Neck Injury Protection in Rear End Car Impacts.** Proc. of Int. IRCOBI Conference on Biomechanics of Impact, Sitges, Spain, 1999: pp.271-282. Submitted for publication in Crash Prevention and Injury Control.

The findings, conclusions and opinions expressed in this thesis are my own.

The co-author Irene Isaksson-Hellman mainly carried out the statistical computations in (I) and (II). The co-author Clas Jernström in (I) was responsible for developing and running the MADYMO model.

LIST OF ABBREVIATIONS AND TERMS

AIS	Abbreviated Injury Scale
ARSV	Average Relative Spine Velocity, evaluation criterion developed in this study
BioRID	Biofidelic Rear Impact Dummy (BioRID I is a prototype version and BioRID II is a production version of BioRID P3)
DeltaV	Change of velocity
EBS	Equivalent Barrier Speed
EU	European Union
FEM	Finite Element Model
Hybrid III	Hybrid III crash test dummy, developed mainly for frontal impacts
ISO	International Organisation for Standardisation
IV-NIC	Internal Vertebral Rotation- Neck Injury Criterion
MADYMO	Mathematical Dynamic Model; MBS modelling software by TNO
MBS	Multi Body System
NIC	Neck Injury Criterion
Nij	Neck injury criterion estimating risk of injury from axial load and bending moment to the upper neck region
RID neck	Rear Impact Dummy neck
RID2-α	Rear-end impact dummy prototype developed in an EU-project
T1	Uppermost thoracic vertebra
TRID neck	TNO- Rear Impact Dummy neck
WHIPS	WHIplash Protection Study and WHIplash Protection System
WAD	Whiplash Associated Disorders

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♥ My family: Bengt, Sandra, Emil and Flisa for patience and for helping me remember the most important things in life.

Lotta Jakobsson
Göteborg, November 2000

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INTRODUCTION

Neck injuries, often called whiplash injuries or whiplash associated disorders (WAD), (Spitzer et al 1995), are classified as AIS 1 (AAAM, 1990). Although they have a low threat-to-life risk, these injuries can have long-term consequences (Nygren et al 1984). WAD represents a broad set of symptoms, such as neck pain, neck stiffness, weakness in the shoulder area, dizziness, headache, and memory loss (Spitzer et al 1995).

Statistics from several countries have shown an increase in the occurrence of neck injuries in car accidents in recent decades. (Ono et al 1993, van Kampen 1993, Galasko et al 1993, von Koch et al 1994 and Morris et al 1996). In Sweden, AIS 1 neck injuries account for about 50% of all traffic injuries with long-term symptoms, and are thus very costly to society (von Koch et al 1994). By reducing the occurrence of neck injuries, a reduction of human suffering and costs for society can be brought about.

AIS 1 neck injuries are reported in all types of accidents (von Koch et al 1995, Morris et al 1996, Jakobsson 1998, Temming and Zobel 1998). The highest risk is found in rear-end impacts (Morris et al 1996, Lundell et al 1998a). For this reason, this study focuses on AIS 1 neck injuries in rear-end impacts.

Accident data

Based on accident data, many reports have presented possible correlations between risk of neck injuries and occupant/vehicle parameters. One of the most prominent parameters related to the risk of neck injury in rear-end impacts is gender, with women having a higher risk (States et al 1972, Lövsund et al 1988, Krafft et al 1996, Morris et al 1996, Minton et al 1997, Otte et al 1997, Temming and Zobel 1998, Lundell et al 1998a). Several studies indicate that front-seat occupants are at higher risk than rear-seat occupants (States et al 1972, Carlsson et al 1985, Lövsund et al 1988). Neck injuries are reported at a wide range of impact severity (Jakobsson 1998, Otte et al 1997, Lundell et al 1998a). In rear-end impacts it has been found that people sustain neck injuries frequently even in crashes with very low impact severity (Olsson et al 1990, Morris et al 1996, Siegmund et al 1997). The effect of crash pulse characteristics rather than change of velocity has been emphasised by Krafft et al (2000). The distance between the head and head restraint has been pointed out as being related to neck symptoms lasting more than one year (Olsson et al 1990). In a study by Chapline et al (2000), it was found that females with adequately positioned head restraints were significantly less likely to report neck pain than females with poorly positioned head restraints, height of the head restraint being the primary factor. Nygren et al (1985) showed that the vertical relationship between head and head restraint is important, but also emphasised that there are parameters other than head restraint position that are important in reducing neck injuries in rear-end impacts. In order to enhance improved protection against AIS 1 neck injuries, there is still a great need to better understand the influence of different parameters.

Injury mechanisms and criteria

Several neck injury mechanisms have been suggested by different researchers. Most of the proposed hypotheses with regard to neck injury mechanisms refer to the initial relative motions in the cervical spine (Aldman 1986, Svensson et al 1993, McConnell et al 1993, Ono et al 1997a, Yang et al 1997). Also, mechanisms related to the rebound phase are suggested (von Koch et al 1995, Muser et al 2000). No single one of the proposed injury mechanisms explains the whole spectrum of WAD symptoms resulting from a rear-end car impact.

A couple of criteria for evaluation of neck injuries have been suggested. Based on the injury mechanism theory of Aldman (1986) and findings of Svensson et al (1993) and Örtengren et al (1996) a criterion called NIC (Neck Injury Criterion) was suggested (Boström et al 1996). NIC is based on the relative velocity and acceleration between the upper and the lower neck. Several evaluation series have indicated that NIC has a correlation to risk of AIS 1 neck injury (Boström et al 1997, Boström et al 1998, Eichberger et al 1998, Eichberger et al 2000, Boström et al 2000).

Forces and moments measured in the upper and lower part of the neck are used as criteria for analysing serious and severe neck injuries (Mertz 1984). Some researchers have also investigated the use of moment measurements for AIS1 neck injuries (Prasad et al 1997, Boström et al 1998). A recently developed criterion, called Nij, combines moments and forces measured in the upper part of the neck (Eppinger et al 1999). Nij has not yet been evaluated for AIS 1 neck injuries. Based on experiments with cervical vertebrae specimens, Yang et al (1997) suggested that axial compression together with shear force are responsible for the higher frequency of neck injuries observed in rear as well as frontal impacts. No injury criterion was formulated.

Panjabi et al (1999) hypothesised that a neck injury occurs when an inter-vertebral rotation exceeds its physiological limit. The authors developed the Inter-Vertebral-Neck Injury Criterion (IV-NIC). IV-NIC has not yet been validated.

Mechanical and mathematical occupant models

Standard anthropomorphic test dummies (mainly Hybrid III), which were primarily designed for high-speed frontal impact testing, have not proven to be applicable for replicating human spinal motion in rear-end impact testing (Scott et al 1993, Szabo et al 1994, Cappon et al 2000). A more biofidelic neck, the RID-neck, for use with the Hybrid III dummy in low-speed, rear-end impact testing, was developed by Svensson and Lövsund (1992). The RID neck was updated to the TRID-neck by Thunnissen et al (1996). The performance of the RID as well as the TRID neck is restricted by the rigid thoracic spine of the HIII dummy (Lövsund and Svensson 1996, Davidsson 2000). In volunteer testing, it has been found that an essential part of the neck kinematics is due to the torso-straightening motion exerting compression forces in the cervical spine, and the angular motion of the T1 (Mc Connell et al 1993, Siegmund et al 1997, Ono et al 1997a, Ono et al 1997b, Davidsson 2000). A dummy with these properties, named BioRID, was developed as a Swedish joint venture (Davidsson et al 1998, Linder et al 1998, Davidsson et al 1999a, Davidsson et al 1999b, Davidsson 2000). Another dummy designed specifically for rear-end impact is being developed in an EU -project (Cappon et al 2000). The dummy is called the RID2-α and is in a prototype development phase.

Two techniques are used for mathematical modelling humans or dummies: Multi Body Systems (MBS) and Finite Element Modelling (FEM). Generally, MBS models are good for parameter studies and require less computer time than FEM-models, while FEM simulate material characteristics and contacts between parts more accurately. Using MBS, Volvo developed a mathematical occupant model in MADYMO 2D, with a segmented spine simulating human-like motion (Jernström et al 1993). Van den Kroonenberg et al (1997) developed a three-dimensional human model, which was extended by Happee et al (2000) to form an “omni-directional” model in different occupant sizes. Two validated rear-end impact MBS models of mechanical counterparts have been presented; a model of the Hybrid III with the RID or TRID neck (TNO 1999, Dusserre 1993, Thunnissen et al 1996) and a model of the BioRID I dummy (Eriksson and Boström 1999, Eriksson 2000). Several FEM models of the cervical spine have been presented, but none of them are validated specifically for rear-end impacts, or includes more than the cervical part of the spine (Kleinberger 1993, Dauvilliers et al 1994, Yang et al 1998, Lizee et al 1998, Halldin et al 2000, Wittek 2000).

Occupant protection principles in rear-end impacts

In a rear-end impact, the occupant is pushed by the seat. The body of the occupant will sink into the seat back-rest. When the kinetic energy has reached zero, an opposite motion (so called rebound) will take place, the amplitude being dependent on the seat back-rest properties.

Head restraints were introduced in cars in order to support the head and avoid hyperextension of the neck in a rear-end impact. Studies based on accident data with and without head restraints have shown the injury-reducing effect of head restraints to range from 14% to 55% (States et al 1972, Åsberg 1973, Nygren et al 1985). However, even with head restraints, AIS 1 neck injuries are reported in rear-end impacts (Carlsson et al 1985). The position of the head restraint will affect the head motion. Active head restraints reducing the horizontal distance between the head and the head restraint have been presented and built into several modern cars (Wiklund and Larsson 1998). A seat design with improved distance between head and head restraint, plus more even and close support for the back, a reduced acceleration pulse, and lower rebound was introduced by Volvo, and called WHIPS (Whiplash Protection System, Lundell et al 1998b).

Methods for determining injury criteria

The most straight-forward method of developing an injury criterion is to reproduce the injuries in biological models and choose the response most consistent with injury outcome (Kuppa and Eppinger 1998). Another method is replicating accident situations where the risk of a specific injury is known (Korner 1989). In order to be successful, this method requires a good knowledge of the injury mechanism, good quality replication of the situation, and a dummy with responses similar to those of a human in the crash situation and body area being analysed. It would be difficult to use the above methods in the case of AIS 1 neck injuries, where no single accepted injury mechanism explains the whole spectrum of symptoms. Therefore, to be sure of covering more than one suggested injury mechanism, a holistic method covering all possible injury mechanisms is needed.

OBJECTIVES

The overall objective of this study is to develop procedures for the evaluation of AIS 1 neck injury protection in rear-end impacts.

Specific objectives:

- Development of a holistic method, addressing the whole spectrum of neck injury symptoms, that will enable the establishment of feasible and reliable evaluation procedures in spite of the lack of an established injury site and an established injury mechanism.
- Identification of parameters potentially influencing the risk of AIS 1 neck injuries, based on accident data
- Evaluation of the influence (on the occupant) of the parameters identified, using an existing mathematical occupant model
- Definition of biomechanical guidelines for the desired occupant response in a rear-end impact
- Development of neck protection evaluation criteria.

MATERIALS AND METHODS

The holistic approach developed and used in this study is a combination of various activities, schematically shown in figure 1.

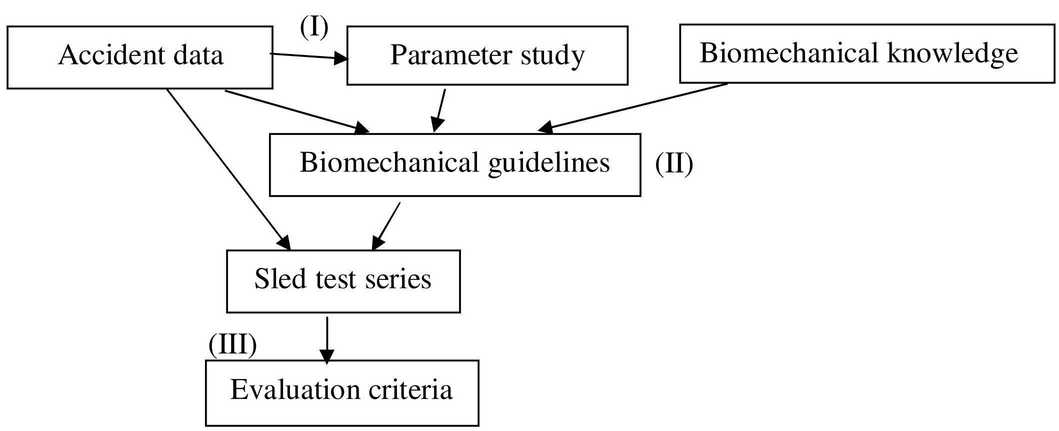

Figure 1. The tasks of the method used in this study. Arrows indicate the information flow between the tasks

Knowledge gained from analyses of accident data was used in parameter studies with a mathematical occupant model (I). Biomechanical guidelines were defined by synthesising the accident data, the modelling results and biomechanical literature data (II). The guidelines together with the accident data findings were evaluated in a sled test series in order to transform the guidelines into quantitative evaluation criteria (III).

Accident data

The aim of analysing accident data in this study was to evaluate important parameters with respect to risk of AIS 1 neck injuries. Two separate studies were carried out. The first (I) was based on a small amount of in-depth data and the second (II) was based on a large amount of statistical accident material.

In (I), the accident data comprised a subset of Volvo's statistical database, which was supplemented by an additional questionnaire. A total of 163 occupants involved in a rear-end impact in Volvo cars during 1988-1989 were included. Parameters regarding the car, the accident, the occupants and their injuries was collected following the accident. The objective parameters (such as car deformation and crash situation) were based mainly on photos and police reports. Subjective parameters, such as occupant characteristics and seating position were based on a questionnaire following the accident. The questionnaire was created together with social scientists. The neck injury data in the database was reported by the occupants themselves, or found in the medical records. The additional questionnaire sent to the occupants one to two years after the accident addressed such questions as;

- sitting posture at the time of impact, including
  - sitting height
  - distance to head restraint
  - seat back-rest inclination
  - degree of support of the seat back-rest
  - whether the occupant had turned his body and/or head in any direction
- head restraint cushion type (soft/hard)
- awareness of the impending impact, such as
  - if the occupant was prepared at the time of impact
  - preparation activity
- previous neck injuries
- the state of neck symptoms (if any) induced by the impact, including questions about
  - occurrence of symptoms
  - level of symptoms
  - duration
  - consequences

In (II), a data set of large Volvo cars involved in an impact during the period 1975-1998 were selected from Volvo's statistical accident database. Only adults were included, involving approximately 2000 occupants. The parameters were collected with the same routine as in study (I) except for the additional questionnaire, which was not included. Thus, no information on neck symptom duration was available in this data set.

In both studies, the statistical method used was a comparison of the relative risk of neck injury on a parameter basis. The risk for a specific parameter, such as turned head, was compared to the risk for the population, which had not turned their heads. Risk of neck injury was defined as the number of persons with AIS 1 neck injury divided by the total number of persons involved in the specific population. Statements regarding statistical significance were based on 95% confidence intervals.

Parameter study

The aim of the parameter study in (I) was to visualise and evaluate the effect of different parameters. The parameters used were, in the accident analyses, found to influence risk of AIS 1 neck injuries. The mathematical model used in the parameter study was a medium-sized male occupant model in MADYMO 2D (TNO, 1992), comprising a mechanical equivalent of the complete spine in the sagittal plane (fig. 2). The 24 separate vertebrae were connected by pin-joints. The occupant model was placed in a MADYMO seat model made up of eight contact surfaces, which made it possible to adjust the seat's back-rest and head restraint characteristics at several levels. This model was evaluated to published volunteer test data. The biofidelity of the model was considered adequate for qualitative assessment of the influence of vehicle and occupant-related parameters on the occupant response.

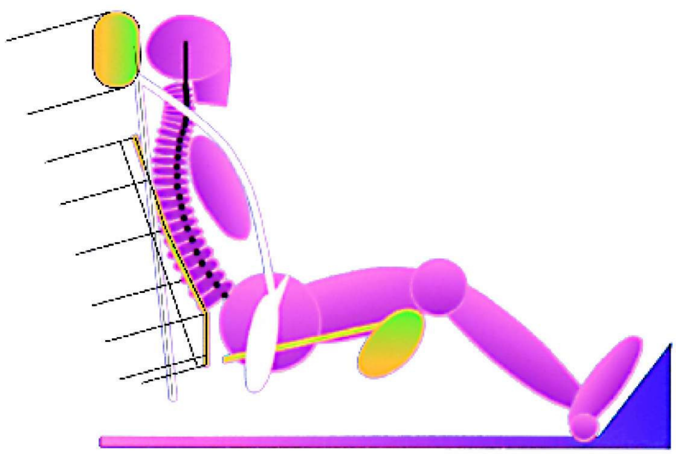

Figure 2, Mathematical occupant model in MADYMO 2D. The lines perpendicular to the seat back-rest and head restraint illustrates the borders of the different contact surfaces in the seat model.

A total of six different occupant and crash situations were simulated. Five of these were identified in the accident data to represent a higher or lower risk as compared to the reference situation. The six situations were:

- reference situation; an occupant in regular sitting posture in a standard Volvo seat, see figure 2
- increased seat back-rest inclination
- forward-leaning occupant
- lowered head support
- stiffer and less energy-absorbing head restraint and upper part of seat back-rest
- crash pulse with reduced g-level at unchanged deltaV

A total of 12 different occupant responses were measured in the model, including torque and forces between adjacent vertebrae, extension angle of the head, linear and angular head acceleration and estimated spinal canal volume-change rate. The estimation of volume-change rate was an effort to evaluate the pressure gradient measure in the injury mechanism of Aldman (1986). The 12 responses were measured for the six different occupant and crash situations, and the responses most consistent with the anticipated differences in severity of the simulated situations were assumed to be correlated to the anticipated risk of injury.

Biomechanical guidelines

Since no injury mechanisms have been established to cover all the symptoms of AIS 1 neck injuries, the objective was to develop biomechanical guidelines to be used in car design. The biomechanical guidelines should point out the aim of occupant behaviour in a rear-end impact. Biomechanical literature data, the accident data and the results and experiences from the parameter study were synthesised into guidelines regarding the dynamic biomechanical response of the occupant (II). The literature data consisted of injury mechanism theories and occupant motion analyses. The aim of these guidelines was to offer a basis for the development of evaluation criteria that could be assessed in a test procedure including for instance a crash test dummy.

Evaluation criteria

In order to be able to evaluate different car design systems with respect to mitigating AIS 1 neck injuries, quantitative measures were needed. These measures were derived from a sled test series (III), and were called evaluation criteria. A hypothesis, based on accident data (I, II and literature data) was formulated, stating that rear-seat occupants are at a lower risk, and occupants at increased distances to head restraints are at a higher risk compared with front-seat occupants in a regular sitting posture. This hypothesis determined the choice of three different occupant seating situations:

- front-seat occupant in regular sitting posture
- front-seat occupant leaning forward
- rear-seat occupant in regular sitting posture

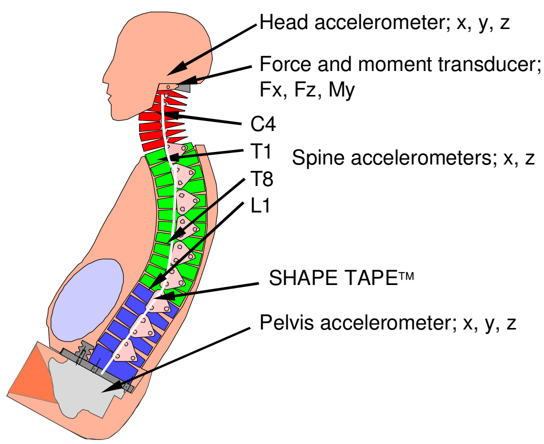

Figure 3 - The BioRID I and instrumentation

The BioRID I dummy, figure 3, was used to simulate the three situations in the sled test series. In the regular sitting postures a horizontal distance between head and head restraint of about 7 cm was obtained. Two forward-leaning postures were tested, with an increased horizontal distance between head and head restraint amounting to an additional 10 and 20 cm, respectively.

Different dummy responses relevant to the three defined biomechanical guidelines were studied. A number of combinations of output signals from the dummy were investigated. As an example, for the third guideline regarding rebound, the responses addressed such as the belt force, occupant velocity and forward trajectory. For all of the three biomechanical guidelines, the responses most consistent with the anticipated risk correlations in the hypothesis were selected as evaluation criteria.

RESULTS AND DISCUSSIONS

Accident data

Due to small numbers of occupants in study (I), no parameters with significant effects could be found. The results from the analysis of the 163 occupants in (I) can be summarised as follows:

- occupants with more than 10 cm horizontal distance between head and head restraint were at a somewhat higher risk of neck symptoms (figure 4)
- car impacts involving deformation of rigid structure of the rear-end of the impacted car showed an increased risk of neck injury compared to impacts at the same estimated speed change involving only deformations of softer structures
- occupants who have turned their head at the time of impact were at a higher risk of neck injuries lasting longer than three months as compared to those with forward-facing head, however no difference for initial risk of neck injury (fig. 5)
- increased seat back-rest inclination indicated a correlation to increased risk of neck injury
- a stiffer head restraint indicated a correlation to increased risk of neck injury
- no difference in occurrence of injury could be found between those unaware of the impending impact and those who were prepared for it

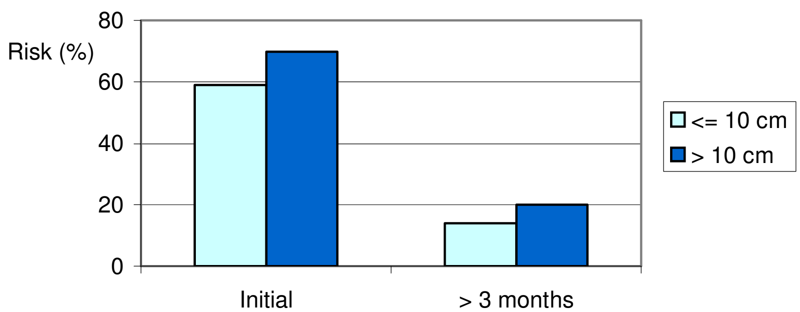

Figure 4. Neck injury frequency with respect to horizontal distance between head and head restraint, for reported initial neck symptoms and neck symptoms lasting longer than three months.

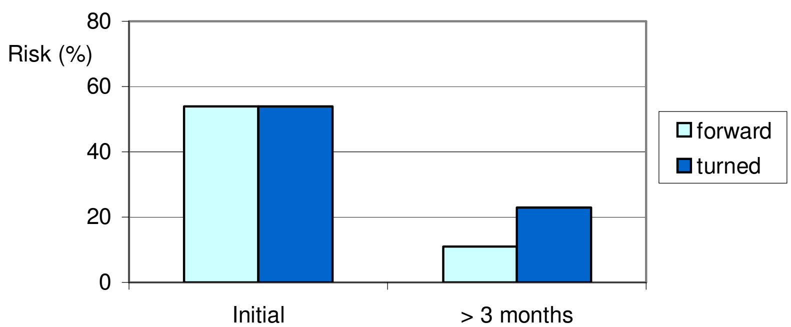

Figure 5. Neck injury frequency with respect to turned head at time of impact, for reported initial neck symptoms and neck symptoms lasting longer than three months.

The larger subset in (II) made it possible to study parameters such as occupant stature and seating position and still have sufficiently large sample sizes for statistical evaluations. Some significant conclusions could be drawn. Among the findings were:

- In rear-end impacts, AIS 1 neck injuries were by the far most common injury type, followed by thoracic/lumbar spine injuries.
- The risk of neck injury is almost constant, irrespective of level of EBS
- Involvement of rigid car structure indicates a higher risk of neck injuries compared with when the rigid structure has not been deformed
- Tendency towards higher risk for front-seat occupants compared with rear-seat passengers (figure 6)
- Significantly higher risk of driver sustaining a neck injury, compared with the passenger (figure 6)
- Females at greater risk than men, irrespective of seating position (figures 6 and 7)
- When separating the occupants by gender as well as seating position, an increase in risk of injury can be clearly related to increase in occupant stature (figure 7)
- The highest risks are in age groups 20-30 and 30-40. The lowest risk is found in the youngest age group of under 20 years

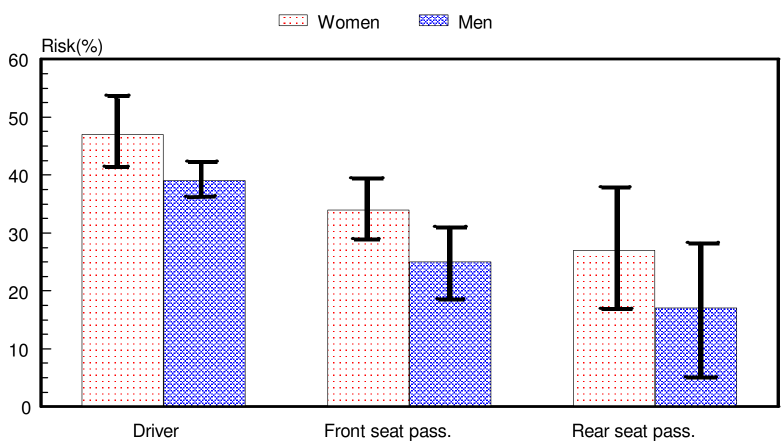

Figure 6. Neck injury frequency including 95% confidence intervals for men and women in different seating positions.

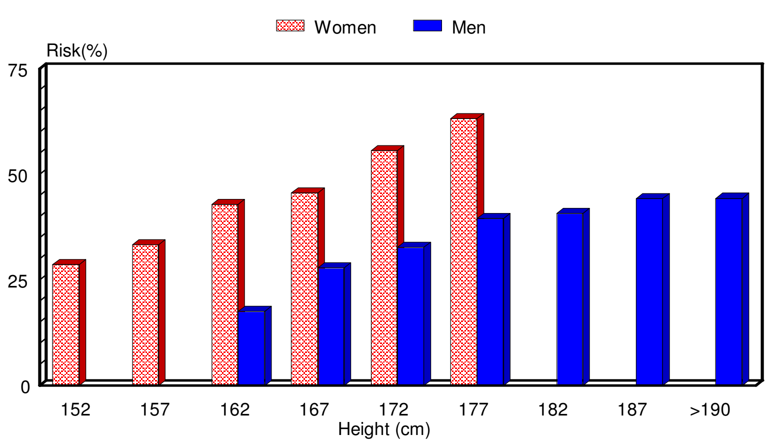

Figure 7. Risk of neck injury versus gender and stature for drivers.

The data in the two studies are based on the same type of cars and selected from the same accident material. In study (I) the cases are less, due to the additional questionnaire. The additional questionnaire gave the possibility to study parameters which were not included in the larger study (II). Parameters such as occupant sitting posture at the time of impact indicated to play an important part. Such parameters can be criticised of being too unsure since they are self-reported and also found in a questionnaire which was sent one to two years after the accident. This fact should be taken seriously, but never the less the findings in study (I) emphasises the importance of including such parameters in future accident studies.

The results in (I) and (II) confirm earlier findings that neck injuries in rear-end car impacts are reported at all impact severities, as well as in crashes with very low impact severity. Because of the relatively high frequency of rear-end impacts in lower impact severity, the emphasis should be placed on minor and moderate impact severity.

Acceleration characteristics, rather than change of velocity, have been indicated as influencing the risk of sustaining a neck injury (Olsson et al 1990, Krafft 1998). Both in (I) and (II), such indications were found by comparing neck injury outcome versus type of car body deformation. For a given estimated change of velocity, if a rigid structure was involved a higher risk of neck injury was found, compared with no rigid structure being involved. Crash-recorder data studies have also indicated the importance of acceleration level, especially for long-term neck symptoms (Krafft et al 2000). The conclusion can be drawn that it is important to focus on car design measures that reduce the acceleration of the occupants.

An increased horizontal distance between head and head restraint, indicated an increased risk of AIS 1 neck injury (Olsson et al 1990, I). This could be one explanation for the difference in risk of injury for the driver compared with the front-seat occupant (II); because the driver can be assumed to move his head and upper body during driving to a greater extent than the front-seat occupant. The fact that injuries to the thoracic and lumbar spine account for the second largest group of injuries in rear-end impacts stresses the importance of regarding the whiplash problem as an issue related to the whole spine. Minton et al (1997) found that lumbar spine and cervical spine injuries occur together. The exact relationship was not stated, however it is obvious, due to the design of a human spine, that motions in the lower part of the spine affects the motions in the upper part. Thus a good and even back support along the whole spine should be an objective.

The tendency towards a higher risk of AIS 1 neck injuries in the front-seat compared with the rear-seat could be related to seat design. The occupant's rebound motion in a conventional, well-attached rear-seat back-rest is less than in a conventional front-seat.

Individual differences in the occupants (mainly gender and stature) are important with regard to risk of sustaining neck injuries. This must be kept in mind and observed during development of test procedures and evaluation criteria.

Findings in accident data represent an important source of information. The combination of in-depth studies and larger statistical studies would have the best potential to provide wider knowledge of what the real-life situation is like. Used in a structural way, it will offer a good basis for the development of biomechanical guidelines and evaluation criteria.

Parameter study

For the six different occupant and crash situations in the parameter study in (I), the following occupant responses were most consistent with the anticipated risk of injury:

- shear force between adjacent vertebrae in upper cervical spine and upper thoracic spine
- tensile force between adjacent vertebrae in upper cervical spine and upper thoracic spine
- head angular acceleration
- the volume-change rate of the lower cervical spine

The influence of shear and tensile forces correspond to the suggestions of relative forces between adjacent vertebrae as possible injury mechanisms (Mc Connell et al 1993, Ono et al 1997a). The volume-change rate was aimed at evaluating the pressure gradient measured in the injury mechanism of Aldman (1986). In this study it correlated to the expected injury risk in the lower cervical spine but not in the upper cervical spine. This is in line with the findings of Svensson et al (1993) where it was found that the pressure generated by the motion of the lower cervical spine superimposes on and appears to override the influence of the pressure generated in the upper cervical spine. Also, the knowledge gained from analysing the occupant motions in the simulations adds to the knowledge from accident data, emphasising the importance of regarding the whiplash problem as an issue concerning the whole spine. Rapid motion in the cervical spine area could also be seen as the effect of local hard impact in the lumbar area. Owing to the design of the attachments between adjacent vertebrae in the mathematical model (pin-joints), the forces between adjacent vertebrae in the model correlate to the relative motion between adjacent vertebrae in a human spine. This stresses the importance of reducing the motions within the spine during the impact.

Biomechanical guidelines

Based on the findings in accident data, biomechanical literature data and the response of the mathematical occupant model, three biomechanical guidelines were defined. The three biomechanical guidelines were:

1. Reduction of occupant acceleration
2. Minimising relative movement between adjacent vertebrae and in the occipital joint
3. Minimising forward rebound into the seat belt

The guidelines summarise a holistic approach to the whiplash protection problem. They address most of the suggested injury mechanism hypotheses and cover a variety of different scenarios (Jakobsson 1998, Lundell et al 1998a, Lundell et al 1998b and II).

The first guideline; aiming at reduction of occupant acceleration, does not have a direct connection with any suggested injury mechanism for neck injuries. In accident analysis the crash pulse shape rather than impact velocity has been found to relate to injury risk (Olsson et al 1990, Krafft et al 2000 and II), indicating that reducing occupant acceleration should be favourable. Volunteer tests have also shown that below certain occupant accelerations the likelihood of sustaining an injury is expected to be minor for most healthy persons.

Relative motion of the spine as a cause of whiplash injuries is a finding in this study. It has also been suggested by several researchers as a possible mechanism causing injury (Aldman 1986, McConnell et al 1993, Ono et al 1997a, Yang et al 1997). The knowledge gained from space technology, and also from the performance of rearward facing child seats in a frontal impact (Aldman 1964), tells us that the ultimate aim is to keep the spine as evenly supported as possible. If the spine is completely stationary, no injuries are likely to occur.

The third guideline aims at reducing the resulting occupant rebound in order to minimise the interaction with the seat belt. Seat belt interaction has been suggested as causing injury (von Koch et al 1995). The exact injury mechanism of these findings is not known.

It is believed that if the three biomechanical guidelines are used in the car design process, then the risk of neck injuries in rear-end impacts can be reduced. Since the biomechanical guidelines are not conventional biomechanical injury criteria corresponding to established biomechanical injury mechanisms, it is impossible to assign specific thresholds at this stage. However, the ultimate goal would be to achieve zero loading, while every reduction may be regarded as a step in the right direction. Furthermore, since the biomechanical guidelines are to some extent related to different injury mechanism hypotheses, all three guidelines must be addressed at the same time. Increased response of any of the biomechanical guidelines should be avoided, since reductions in the other responses may be countered and no real positive effect achieved.

Evaluation criteria

Based on the sled test series in (III), evaluation criteria were chosen for quantitative evaluation of the three biomechanical guidelines.

- It is suggested that occupant acceleration be measured along the spine and in the pelvis in a horizontal direction
- Average relative velocities along the spine (ARSV) are suggested as reflecting the relative spine movements
- Based on this test series, NIC_{max} was judged to be an adequate criterion
- It is suggested that the effect of forward rebound be evaluated either by Total Maximum Belt Force or Torso Rebound Velocity

Relative spine velocity resembles relative acceleration, between six stepwise positions, integrated over time, and is a result of external forces acting on the back. The maximum values (in the seat back-rest loading phase) of each stepwise relative velocity along the spine are combined to form an average output value. The relative velocity was assumed to correlate to internal displacements and loads in the spine, since the relative velocity between adjacent spinal elements was put to stop mainly by the resistance of the internal structures of the spine. These loads are potentially injury inducing and thus the ARSV was considered to reflect the second guideline on relative movements between adjacent vertebrae. One important advantage of ARSV is that it is easy to apply in a crash test dummy, since it only requires that a number of accelerometers be attached to the spine. However, in order to better detect local changes in stiffness of a seat back-rest, a more direct and precise measurement should be developed; mapping local as well as global bending of the dummy's spine. For this purpose, a measurement system is needed which enables the monitoring of the shape of the spine during the impact motion. The SHAPE TAPE™ (ref. Measurand), which was included in the dummy during the tests but not yet fully evaluated, is possibly such a measurement system.

NIC_{max} was developed to monitor the initial relative cervical motion, and in this study it did not seem to take into account the less elastic response of the rear-seat, which is believed to be the most prominent advantage of the rear-seat. NIC_{max} did distinguish between the situations with different distances between head and head restraint. Based on this, NIC_{max} was judged to be an adequate criterion for some situations in the guideline of relative spine movements. However, based on this study, it cannot be recommended as a single criterion in a rear-end impact test evaluation.

Two evaluation criteria for forward rebound were suggested. Probably, the Torso Rebound Velocity would be the criterion to be primarily recommended, since the belt force is dependent on force transducer location and initial belt tension, which could be difficult to control between different test set-ups.

Ultimately, it would be desirable to have a single criterion addressing a single injury. This is not possible for AIS 1 neck injury today, thus a holistic view, addressing all possible injury mechanisms, is the best way of evaluating risk of neck injury. The exact injury type and location as well as the injury mechanism have not been established. It is not clear whether the broad set of symptoms can be explained by a single injury or if there are several injury locations. Moreover it is unclear whether short and long-term symptoms originate from the same injury.

GENERAL DISCUSSION AND CONCLUSIONS

The complexity of the various human, car and crash related factors causing the broad set of symptoms included in the diagnosis of WAD is tremendous. No single injury mechanism has so far been proposed as being responsible for all the symptoms. This means that a method, which covers the whole spectrum of symptoms, must be used. The method chosen in this study is a holistic approach, combining knowledge regarding parameters in the crash situation influencing risk of neck injury as well as presenting injury mechanism hypotheses. The method was proven feasible, as a seat (WHIPS, Lundell et al 1998a, II) was developed and put into production based on the work in this study. The method developed in this study could be used in other areas, especially where the injury mechanisms are unclear. A version of this method was used for the study of ankle injuries in frontal impacts (Forssell et al 1996).

Analyses of accident data constitute an important source of knowledge and add to the understanding of possible injury mechanisms as well as set the direction for improved design of safety systems with the aim of mitigating AIS 1 neck injuries. In this study, the results of accident analyses emphasise the importance of considering the whole spine of the occupant as well as taking into consideration different individual characteristics and behaviour at the time of impact. It would be desirable to have a large body of statistical material containing in-depth information including occupant characteristics (gender, age, weight, stature) measurements of sitting posture, follow-up of symptoms, psycho-social information, and detailed information about the car and crash. Usually, however, the information is either too narrow in scope or the cases too few. Thus a combination of a large body of statistical material (with less detailed information) and in-depth studies (with more details) was the best approach today. In the future, an aim should be to include more details relating to sitting posture and behaviour, details regarding type and duration of neck symptoms and, where possible, crash severity data from crash recorders.

By using a mathematical occupant model, it was possible to visualise the effect of the different parameters and important measures were identified. Forces between adjacent vertebrae and head angular acceleration were responses consistent with the anticipated severity of the different parameters, emphasising the objective of keeping the spine supported as evenly as possible. At the time when the parameter study in (I) was carried out, the mathematical occupant model used was the most advanced rear-end impact occupant model that was practical in parameter studies. It comprised the important features of individual vertebral segments as well as the possibility of changing several characteristics of the seat back-rest. Today, there are more advanced models, making it possible to carry out more detailed studies of neck movements during rear-end impacts. Mathematical models are important complements to mechanical dummies. They more easily facilitate the study of the effect of different occupant characteristics. Today, the easiest occupant characteristics to evaluate are stature and weight, but one should aim to obtain enough knowledge of the influence of other characteristics such as gender in order to evaluate these parameters using mathematical occupant models.

The heart of this method is the definition of the biomechanical guidelines. The three biomechanical guidelines were:

1. Reduction of occupant acceleration
2. Minimising relative movement between adjacent vertebrae and in the occipital joint
3. Minimising forward rebound into the seat belt.

The biomechanical guidelines can be criticised for being too general and not as precise as injury measures usually are. However, they serve their purpose by pointing out the aim of occupant behaviour, and constituted a necessary step in proceeding towards improvement measures in car design. Quantitative measurements were achieved by breaking the biomechanical guidelines down into evaluation criteria. Using a sled test series and a hypothesis based on accident data, the evaluation criteria derived were:

1. Occupant acceleration
2. Average Relative Spine Velocity (ARSV) together with NIC_{max}
3. Total maximum belt force or torso rebound velocity

The set of evaluation criteria suggested in this study was an initial attempt at defining robust measures for evaluating safety designs. Effort should be put into evaluating more influential parameters so as to improve the evaluation criteria and best reflect the origin of the biomechanical guidelines. Also, as injury mechanisms become better understood, there should be an emphasis on defining evaluation criteria corresponding to the new improved injury mechanism.

The choice of evaluation criteria is very much dependent on the test procedure, especially the choice of dummy. A humanlike dummy, validated for rear-end impacts, is necessary. There are many different objectives regarding test procedures. They could be designed for use in the development of car safety systems (mainly the seat), but could also be used for evaluating different systems on a ratings basis. The development of official test procedures for evaluation of whiplash protection is in its infancy, and is very intense, with ongoing discussion in a number of groups (e.g. ISO). The most important aspects for test procedures in developing safety systems are taking into consideration the spectrum of different situations in which these injuries occur, and of course taking the whole car into consideration. Since the occurrence of injury is spread over a large range of impact severity, a safety system must possess the quality of addressing the whole severity span as well as the span of occupant sizes and sitting postures. Development of test procedures should, however, be carried out with caution and with an eye on all relevant findings in accident data and research into injury mechanism.

Currently, AIS 1 neck injury research has mostly focused on rear-end impacts. However, neck injuries occur in other types of accident as well (von Koch et al 1995, Morris et al 1996, Jakobsson 1998, Temming and Zobel 1998). It is important to consider all types of crash configurations in order to reduce the total number of AIS 1 neck injuries. The method used in this study is also recommended for the evaluation of AIS 1 neck injuries in other impact directions.

The significance of this study is that the method presents a holistic approach. It has also proved possible to implement this in the process of safety systems development (II). It represents a robust approach for addressing an injury where the mechanism of injury has not been defined, taking low risks, and implementing a safe direction in the development of new safety designs.

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Study I

Analysis of Different Head and Neck Responses in Rear-End Car Collisions using a New Humanlike Mathematical Model

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Study II

WHIPS-Volvo's Whiplash Protection Study

Jakobsson, L., Lundell, B., Norin, H., Isaksson-Hellman, I.

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Study III

Suggestions for Evaluation Criteria of Neck Injury Protection in Rear End Car Impacts

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