Neck injuries in car collisions -
Injury mechanisms

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Injuries and symptoms

The symptoms of injury following neck trauma in rear-end collisions include pain, weakness or abnormal responses in the parts of the body (mainly the neck, shoulders and upper back) that are connected to the central nervous system via the cervical nerve-roots(Table A). Vision disorder, dizziness, headaches, unconsciousness, and neurological symptoms in the upper extremities are other symptoms that have been reported (Deans et al., 1987; Hildingsson, 1991; Nygren et al., 1985; Spitzer et al., 1995; Sturzenegger et al., 1995; Watkinson et al., 1991). The neck injury symptoms appear to be very similar for all impact directions (Minton et al., 2000).

Table A: Common WAD-symptoms

Pain in neck, shoulders and upper back
Weakness in neck, shoulders and upper back
Vision disorder
Dizziness
Headaches
Unconsciousness
Neurological symptoms

It is important to distinguish between initial symptoms and long term symptoms (Krafft, 2000). Long term (chronic) whiplash symptoms appear to be associated with central pain sensitisation (Sheather-Reid and Cohen, 1998; Johansen et al., 1999). The exact origin of this pain sensitisation has not been established. Successful treatment methods could possibly provide a clue. Byrn et al. (1993) reported significantly reduced symptoms during a time period after sub-cutanious sterile water injections on the back of the neck. Bogduk (2000) reported pain relief in about 50 percent of the patients after coagulation of the small nerves that innervate the facet joint that is associated with the painful dermatome.

Soft tissue injuries have been found in several different structures and locations in the neck region in experimental studies and autopsy studies. In a recent study Yoganandan et al. (2000) reported injuries to several ligaments, the intervertebral discs and the facet joint structures. Siegmund and Brault (2000) and Brault et al. (2000) presented indications of muscle injury due to eccentric muscle loading in the early phase of the neck motion in rear impacts. Taylor et al. (1998) reported interstitial haemorrhage in cervical dorsal root ganglia in an autopsy study of victims who had sustained severe inertial neck loading during impacts to the torso or to the head. The structures around the ganglia were mostly uninjured. These findings correlate to experimental findings in pigs of nerve cell membrane dysfunction in cervical spinal root ganglia reported by Svensson et al. (2000).

It appears likely that several types of neck injury may appear as a result of a whiplash trauma (muscles, ligaments, facet joint, discs, nerve tissue etc.) (Table B). Several injury types may be present in the same patient at the same time. The relation between these possible injuries and the large set of known whiplash symptoms is unclear. It would be of particular interest to know which one (ones) of these injuries that would result in long term symptoms and central pain sensitisation. It would then also be of interest to know which injury mechanism is responsible for this particular injury.

Table B: Possible WAD-injury locations in the neck region

Muscles Ligaments Facet joints Intervertebral discs Nerve tissue

At the initial symptom stage, arm pain and high symptom intensity seem to correlate to an increased risk of long term consequences (Sturzenegger, 1995; Karlsson et al., 2000). The apparent influence of the crash pulse on the risk of long term consequences in patients with initial symptoms (Krafft, 2000) indicate that there could be a separate injury and a separate injury mechanism behind the long term symptoms. This particular injury could in the acute stage often co-exist with other injuries that normally heal without causing residual pain. Sturzenegger et al. (1995) found a higher risk of long term symptoms in those patients that were injured in a rear end collision and this may indicate that one particular injury (which may cause long term symptoms) is more likely to occur in a rear impact.

In more peripheral parts of the body most of these injury types (tissue types) normally recover without long term pain and central pain sensitisation. Is there something special about the neck region that makes one or several of these injuries result in long term pain? Cavanaugh (2000) for instance, explained that the facet joint capsules are particularly rich in nerve endings why an injury at this point would be a likely reason for long lasting pain. This pain may cause referred pain in e.g. the shoulder region. Facet joint capsule strain and pinching has been shown in post mortem human subjects in rear impact testing (Yoganandan and Pintar, 2000b; Deng et al., 2000). It is however not known whether the same type of mechanisms may occur also in side impacts and frontal impacts. Is there some type of structure that is unique for the neck? The spinal nerve root ganglia would be an example of such a structure. Cavanaugh (2000) explained that injury to the dorsal root ganglia is likely to cause radiating pain to dermatomes of for instance the shoulders and the arms. These symptoms are, as mentioned earlier, known to correlate to increased risk of long term consequences. Cervical dorsal root ganglion injuries have been observed in various impact directions (Svensson et al., 2000, Taylor et al., 1998) and would explain the similarity in symptoms between different impact directions.

Neck kinematics

A number of experimental studies on volunteers and post mortem human subjects have been reported. There is a relatively good view of the overall body kinematics in different crash directions. Derived from the kinematics, several biofidelity requirements have been formulated and were used as a basis for the development of rear impact dummies. The typical neck loading in a car accident is caused by the acceleration of the torso resulting in an initial neck bending motion illustrated in Figure 1a. This event is usually followed by a rebound of the body due to the elastic recoil of the seatback. At the end of the rebound motion the neck may undergo a motion similar to the illustration in Figure 1b. The thoracic spine normally undergoes some type of bending motion in this type of event. In rear end collisions the thoracic kyphosis is straightened resulting in an elevation and a rearward tilt of the T1 vertebra (Davidsson et al., 1998; van den Kroonenberg, 1998; Ono et al., 2000). Several studies have focused also on the detailed motion of the cervical spinal segments during rear-end impact loading (Ono et al., 1997; Panjabi et al., 1999; Winkelstein et al., 1999; Youganandan and Pintar, 2000b; Deng et al., 2000). The intervertebral motion appears to deviate from normal physiologic human neck bending motion.

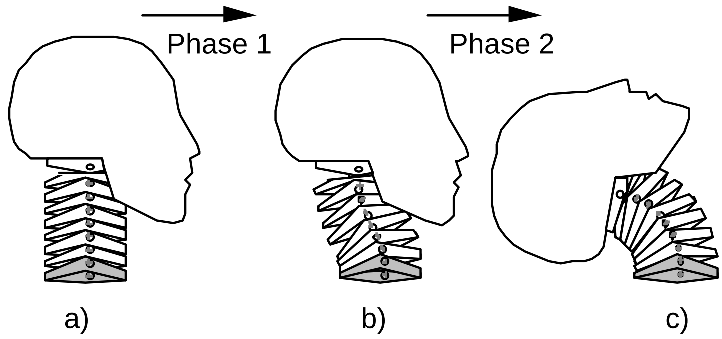

Figure 1a: Schematic drawing of the head-neck motion during the early part of a rear-end collision.
Phase 1: Retraction motion
Phase 2: Extension motion

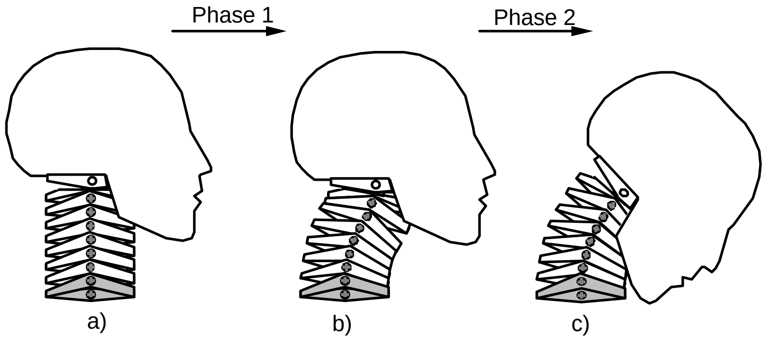

Figure 1b: Schematic drawing of the head-neck motion during rebound or during a frontal collision.
Phase 1: Protraction motion
Phase 2: Flexion motion

Injury Mechanisms and Injury Criteria

Several neck injury mechanisms and neck injury criteria have been proposed during recent years. Two criteria, Nij (Kleinberger et al., 1998; Kleinberger et al. 1999) and Nkm (Muser et al., 2000), use combinations of upper neck loads to predict the risk of injury to the skeletal spine.

The neck injury criterion, N_{ij}, was proposed to assess AIS 2+ neck injuries (not normally classified as “whiplash injuries”) in frontal impacts including those with airbag deployment. This criterion could potentially be of interest if a high speed rear impact test was to be included. AIS 2+ neck injuries are however rare in rear impacts. Nij is based on dimensional analysis of the load to the neck. It combines the effects of force and moment measured at the occipital condyles and is based on both the tolerance levels for axial compression and bending moment. The N_{ij} criterion is calculated by:

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \qquad (1)$$

where F_z represents the axial force and M_y represents the flexion/extension bending moment. The index "int" gives a critical intercept value for the load and the moment, respectively. The intercept values for the 50th percentile Hybrid III male are proposed to be F_{int}(tension) = F_{int}(compression) = 4500N, M_{int}(flexion) = 310 Nm and F_{int}(extension) = 125Nm according to Eppinger *et al.* (1999). The threshold for injury levels based on N_{ij} is 1. Since the intercept values for the forces are based on the corresponding values for the Hybrid III and do not represent human physiological values, they must be redefined if a dummy other than the Hybrid III is used. . The Nij may be of interest in high severity seat back integrity tests. There is however currently no validated dummy available and the frequency of AIS 2+ injuries in rear impacts is relatively small (>10% of the neck injuries in rear impacts according to GIDAS and CCIS databases).

The N_{km} criterion (Muser et al., 2000; Schmitt *et al*., 2001) was proposed to assess neck injuries in rear impacts. It is a combination of moments and shear forces. The N_{km} criterion is calculated as

$$N_{km} = \frac{F_x}{F_{int}} + \frac{M_y}{M_{int}} \quad (2)$$

where F_x represents the shear force and M_y the flexion/extension bending moment. The index "int" gives a critical intercept value for the load and the moment. The intercept values for the 50th percentile Hybrid III male where F_{int}(anterior) = F_{int}(posterior) = 845N, M_{int}(flexion) = 88.1Nm, and M_{int}(extension) = 47.5Nm (Schmitt, 2001). The threshold for injury levels based on N_{km} is 1. Schmitt *et al.* (2001) has shown that N_{km} varies depending on the dummy used in the test.

The lower neck moment is sensitive to seat design parameters (Prasad et al.,1997; Song et al., 1996). Lower neck loads are also consistent with the facet-based injury mechanism supported by the works of Yoganandan et al. (2000), Ono et al. (1997) and Deng et al. (2000). Heitplatz et al. (2003) presented the Lower Neck Load – Index (LNL). It incorporates a combination of neck loads at T1-level. Indications of LNL correlation to injury risk were reported but the need for a more extensive evaluation of the LNL was also emphasised (Heitplatz et al.; 2003)

$$LNL-index(t) = \left| \frac{\sqrt{My_{lower}(t)^2 + Mx_{lower}(t)^2}}{C_{moment}} \right| + \left| \frac{\sqrt{Fx_{lower}(t)^2 + Fy_{lower}(t)^2}}{C_{shear}} \right| + \left| \frac{Fz_{lower}(t)}{C_{tension}} \right| \quad (3)$$

The IV-NIC criterion developed by Panjabi *et al.* (1999) is based on the hypothesis that a neck injury occurs when an intervertebral extension-flexion angle exceeds its physiological limits. It is defined as the ratio of the intervertebral motion T_{trauma} under traumatic loading and the physiological range of motion $T_{physiological}$. The IV-NIC is calculated by:

$$IV-NIC_i = \frac{\Theta_{trauma,i}}{\Theta_{physiological,i}} \quad (4)$$

This criterion still lacks a threshold. Using the IV-NIC requires a dummy neck capable of simulating intervertebral motion. At present, only the neck of the BioRID has this capacity in the sagittal plane. The biofidelity of the angular motion of the individual BioRID spinal units has however not been evaluated.

The NDC, proposed by Viano and Davidsson (2001), is based on the angular and linear displacement response of the head relative to T1, from volunteer tests. The criteria are given as corridors of the z versus angular and x versus angular displacement of the occipital condyle of the head relative to the T1. Working performance guidelines for NDC in the Hybrid III and the BioRID P3 for low speed rear impacts are proposed in four different categories: Excellent, Good, Acceptable and Poor. For the Hybrid III, the requirements for Excellent are:

- The head relative to T1 angle should be < 20 degrees.
- The x displacement of the head relative to the T1 < 30 mm.
- The z displacement of the head relative to the T1 < -15 mm.

The requirements for Good are:

- The head relative to T1 angle should be < 35 degrees.
- The x displacement of the head relative to the T1 < 50mm.
- The z displacement of the head relative to the T1 < -25mm.

The requirements for Acceptable are:

- The head relative to T1 angle should be < 50 degrees.
- The x displacement of the head relative to the T1 < 70mm.

- The z displacement of the head relative to the T1 < -35mm.

The requirements for Poor are:

- The head relative to T1 angle is > 50 degrees.
- The x displacement of the head relative to the T1 > 70mm.
- The z displacement of the head relative to the T1 > -35mm.

In addition, a response outside the corridor places the response in the category “Poor”. For the BioRID, the guidelines were 5 degrees higher for the head relative to T1 angle, 5mm more for the x displacement of the head relative to the T1 and the same as for the Hybrid III for the z displacement of the head relative to the T1 (Viano and Davidsson, 2001). The correlation between these three injury criteria and the risk of long term soft tissue neck injury has not yet been established.

The Neck Injury Criterion (NIC) (Boström et al., 2000) uses differential horizontal acceleration between the head and the T1 vertebra to assess the neck injury risk. The NIC was initially based on experimental injury findings summarised by Svensson et al. (2000). NIC would also function as a predictor of other types of injury mechanisms and indications of correlation between NIC and long term neck injury risk have been presented (Boström et al., 2000).

$$\mathrm{NIC} = 0.2 \times a_{\mathrm{rel}} + v_{\mathrm{rel}}^2 \qquad (5)$$

a_{rel} is the relative horizontal acceleration between T1 and the occipital joint,
v_{rel} is the relative horizontal velocity between T1 and the occipital joint.

In rebound, the rebound velocity or the seat belt load may be used as injury criteria.
The Nij, Nkm, NIC, NDC and lower neck moment can be applied to current rear impact dummies. Reference values have to be adapted to the chosen dummy. The validity of all these criteria, in predicting the injury risk, needs to be established.

International Insurance Whiplash Prevention Group (IIWPG) recently presented performance assessment values that are expected to be used in their insurance rating programmes. These assessment values are based on various hypotheses on injury mechanisms and injury criteria. They are intended to be simple and robust measurements that reflect the key concepts of the earlier proposed criteria.

The seats and head restraints first have to meet minimum geometric criteria. Seats that get geometric approval are then exposed to a sled test using a generic crash pulse and a BioRID II dummy. The dynamic test criteria are divided into two groups — seat design parameters and test dummy response parameters (Table C). The seat design parameters are time to head restraint contact (max 70 ms) and T1 acceleration (max 9g) of which at least one has to be met. The dummy response parameters are the neck forces, shear (max 130N) and tension (max 600N) and neck distortion (retraction of the head relative to first thoracic vertebra, T1).

Table C: IIWPG rating matrix

<table>
<tr><th rowspan="2">Initial Geometry</th><th colspan="5">Dynamic Test Results</th><th rowspan="2">FINAL RATING</th></tr>
<tr><th>HR Contact Time T_{HRC}</th><th>Torso Acceleration T1g</th><th>Neck Shear Fx</th><th>Neck Tension Fz</th><th>Summary Dynamic Performance</th></tr>
<tr><td rowspan="3">Good

Height = -6 cm
Backset = 7 cm</td><td>= 70 ms</td><td>any value</td><td rowspan="2">= 130 N</td><td rowspan="2">= 600 N</td><td rowspan="2">Pass</td><td rowspan="2">GOOD</td></tr>
<tr><td>any value</td><td>= 9 g</td></tr>
<tr><td>> 70 ms</td><td>> 9 g</td><td>any value</td><td>any value</td><td>Fail</td><td>ACCEPTABLE</td></tr>
</table>

	any value	any value	> 130 N	any value		
	any value	any value	any value	> 600 N		
Acceptable Height = -8 cm Backset = 9 cm	**= 70 ms**	**Any T1g**	**= 130 N**	**= 600 N**	**Pass**	
	Any T_{HRC}	**= 9 g**				
	> 70 ms	**> 9 g**	any value	any value	**Fail**	**MARGINAL**
	any value	any value	**> 130 N**	any value		
	any value	any value	any value	**> 600 N**		
Marginal Height = -10 cm Backset = 11 cm	**No Dynamic Test**					
Poor Height = -10 cm Backset > 11 cm						**POOR**

A rear impact test program was recently launched as collaboration between the Swedish National Road Administration (SNRA) and the Swedish insurance company Folksam to give car buyers information about the crash performance of recent car models on the market (Krafft et al., 2004). This programme uses a BioRID II dummy on an accelerating sled and includes3 test conditions at different velocity and acceleration (Table D).

Table D. Test speed and acceleration

Test	Speed	Mean acceleration
1 – Low severity	16 km/h	4,5 g
2 – Mid severity	16 km/h	5,5 g
3 – High severity	24 km/h	6,5 g

The SNRA/FOLKSAM procedure uses three assessment parameters, NIC, Nkm and rebound speed with limits according to Table E. The overall rating is based on point scores. In the calculation of points, the seats got points if each measured parameter exceeded critical limits as described in Table 6. Two limits per injury criteria were used and maximum 2 points for NIC_{max} and N_{km} and were given, while maximum 1 point was given for head rebound velocity. High point scores indicate poor protection levels.

Table E. Critical limits and points.

Criterion	Lower limit	Upper limit	Green Low risk	Yellow Medium risk	Red High risk
NIC_{max}	> 15 m^2/s^2	> 18 m^2/s^2	= 15 m^2/s^2	15 < NIC_{max} = 18	> 18
N_{km}	> 0,3	> 0,4	= 0,3	0,3 < N_{km} = 0,4	> 0,4
Rebound velocity	> 4,5 m/s	> 6,0 m/s	= 4,5 m/s	4,5 < Vel. = 6,0	> 6,0

ADAC (2004) has launched a similar test programme in Germany. The tests are carried out using a BioRID II dummy on a decelerating sled at three delta-v levels, 10, 16 and 25 km/h. One additional seat integrity test is done with a 95th percentile Hybrid III dummy at 30 km/h delta-v. The assessment parameters and score system is not yet published.

Table F: Required dummy instrumentation

NIC	Head x-acc T1 x-acc
Nij	Occipital Fz Occipital My
Nkm	Occipital Fx Occipital My
NDC	Head angular displacement relative T1 Head horizontal and vertical displacement relative T1
LNL	T1 Fz T1 Fx T1 My
IIWPG Rebound	Occipital Fz Occipital Fx T1 x-acc Scull cap contact foil Neck retraction measurement (e.g. high speed camera) Seat belt load cell High speed film analysis Appropriate transducers for NICmin, Nkm, Nij, NDC etc.

Injury criteria and risk curves

Recently studies have shown predictability of some of the proposed whiplash injury criteria (Kullgren et al 2003, Eriksson and Kullgren 2003). Based on reconstruction of real-life crashes where the crash pulse was recorded, dummy readings have been compared with real-life injury outcome. The injuries were divided in duration of symptoms, less than one month and more than one month. The studies only involved 3 car models of the same make and the numbers of injured occupants were relatively low. In one study including 110 front seat occupants whereof 14 with symptoms more than one month, the crashes were reconstructed in computer simulations using a BioRID II Madymo model. In another including 45 front seat occupants whereof 9 with symptoms for more than one month, the crashes were reconstructed with sled tests using a BioRID II dummy. Despite the relatively low number of crashes it gives an indication of criteria possible to use and also injury reference values. It was found that both NIC_{max} and N_{km} predict whiplash injury risk, while NDC and lower neck moment were found to be less applicable using the BioRID II dummy. NIC_{max} of 15 and N_{km} of 0.3 corresponded to 10-20% risk of injury with symptoms for more than one month, see figures below. NIC_{max} of 15 and N_{km} of 0.3 also corresponded to 40%-50% risk of initial symptoms of whiplash injury. It was also indicated that both NIC_{max} and N_{km} separately influence the injury risk, why both are preferable to use to increase the predictability.

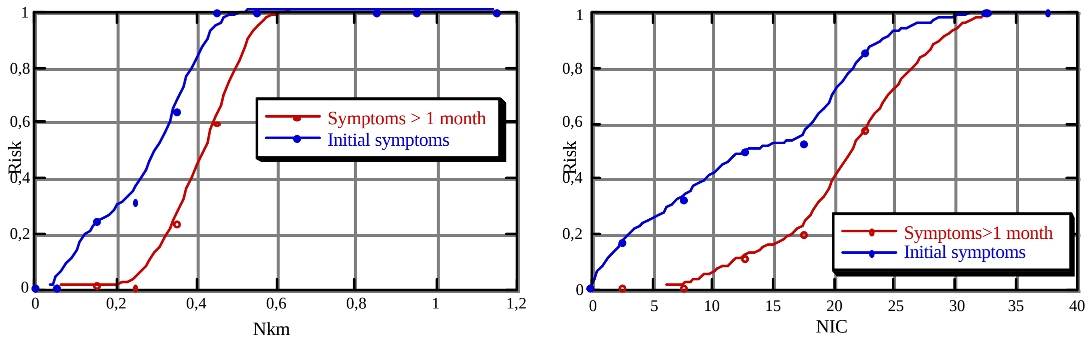

Figure 2: Schematic Neck injury risk curves…

Recent unpublished findings within EU-Whiplash2 (May 2004) give somewhat contradictory indications. The LNL in combination with the RID 3D dummy in sled tests appears to give the most consistent correlation with the injury risk of the so called “statistical performance list” (SPL). The SPL is based on the risk of long term WAD symptoms in six common European car models. These recent findings call for a thorough investigation of the methods used in these different injury criteria evaluation studies.

Conclusions of injury criteria

• The injury symptoms are well known both regarding type and duration.

• The injuries causing the acute symptoms are not known though several possibilities have been suggested in the literature. Several injuries may coexist and cause very similar symptoms. It is unknown if one or several of these injuries could cause chronic neck symptoms. The relation between acute injury and chronic pain is not known and the origin of the chronic pain is not known. Strong indications however exist for central nervous system pain sensitisation in the chronic stage.

• The head and neck kinematics during whiplash trauma is relatively well known.

• Several injury criteria have been suggested but in published studies only two of them, NIC and N_{km}, have been thoroughly evaluated.

• There are three ways that injury criteria could be verified:
1) By identification of the actual acute injury that causes chronic pain. This would probably tell us which injury mechanism is the cause.
2) Evaluation of proposed criteria against experimental data where certain injuries have been caused and where injury threshold levels can be identified (this will however leave an uncertainty about the relation between the observed injuries and the symptoms experienced by living patients)
3) By high quality evaluation against field accident data.

• An injury criterion with proven correlation to injury risk is a requirement for a future test procedure. Injury risk curves have been developed for NICmax and Nkm (Kullgren et al 2003; Eriksson and Kullgren 2003; Linder et al., 2004).

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