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The RID2 biofidelic rear impact dummy: a validation study using human subjects in low speed rear impact full scale crash tests. Neck injury criterion (NIC).

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ABSTRACT

Human subjects and the recently developed RID2 rear impact crash test dummy were exposed to a series of full scale, vehicle-to-vehicle crash tests to evaluate the biofidelity of the RID2 anthropometric test dummy on the basis of calculated neck injury criterion (NIC) values. Volunteer subjects, including a 50^{th} percentile male, a 95^{th} percentile male, and a 50^{th} percentile female, were placed in the driver's seat of a vehicle and subjected to a series of three low speed rear impact crashes each. Both subjects and dummy were fully instrumented and acceleration-time histories were recorded. From this data, velocities of the heads and torsos were integrated and used to calculate the NIC values for both crash test subjects and the RID2. The RID2 dummy is designed to represent a 50^{th} male. The overall performance and biofidelity of the RID2 compared most favorably to the human subject who was, himself, a 50^{th} percentile male. Although the number of tests was small, the biofidelity of the RID2, in the context of the smaller female and larger male, was limited. The overall performance and biofidelity of the RID2 was reasonable when compared to the 50^{th} percentile male volunteer. It is possible that under real world crash conditions, in which the occupant of the target vehicle is exposed to an unexpected impact, that their NIC values might be more comparable to those of the RID2, suggesting that its biofidelity could have been underestimated as a result of the alerted status of the crash test volunteers.

INTRODUCTION

Whiplash injury has become recognized as a significant public health problem in recent years (Spitzer et al., 1995). Some authors describe the minor neck or cervical spine injury resulting from any motor vehicle crash as *whiplash*. However, the risk for injury from the rear impact vector crash has been widely reported as being higher than for other vector crashes (Bylund and Bjornstig, 1998, Borchgrevink et al., 1996, Borchgrevink et al., 1997, Krafft, 1998, Richter et al., 2000). The outcomes in rear impact crashes at low speeds have also been reported to be less favorable than those of frontal or other crash vectors (Krafft, 1998), and long-term disability, a term which has not been operationally defined in most studies, has been variously reported to be 2% (Gargan et al., 1997), 5% (Borchgrevink et al., 1996), 7% (Radanov et al., 1993, Gozzard et al., 2001), 8% (Pettersson et al., 1997), 10% (Nygren, 1984), 12% (Gargan and Bannister, 1990, Kasch et al., 2001a, Kasch et al., 2001b), 16% (Bylund and Bjornstig, 1998), and 24% (Ettlin et al., 1992). The incidence of whiplash injury and disability have been increasing in recent years (Richter et al., 2000, Holm et al., 1999, Richter et al., 1999, Galasko et al., 2000).

Although rear impact crashes represent a minority of crash types, accounting for only about 25% of all crashes, they represent a disproportionate risk for injury (Holm et al., 1999). This differential risk may be explained through human subject crash testing. In one study, the subjects' head linear accelerations were found to be markedly higher in rear impacts vs. frontal impact crashes with crash speeds and other variables held constant, and subjects rated these crashes markedly less tolerable than frontal crashes (Croft et al., 2002a). The fact that the largest group exposed to this form of trauma are persons between the ages of 20-40 years of age and disability in this group results in a high loss of productive years of life, and the fact that this is potentially a preventable injury (or at least one in which the risk can be greatly reduced) make research in this area a high public health priority.

In order to better understand the forces imposed during low speed rear impact crashes (LOSRIC), human subjects have been placed in vehicles under full scale crash conditions (Croft et al., 2002a, Severy et al., 1955, West et al., 1993, Szabo et al., 1994, McConnell et al., 1993b, McConnell et al., 1995b, Szabo and Welcher, 1996, Siegmund et al., 1997, Brault et al., 1998, Croft et al., 2002b, Croft et al., 2002c). As in the case of higher speed crash tests, crash test dummies would be the preferable test subjects in low speed crashes. Unfortunately, the modern Hybrid III anthropometric test device (ATD) lacks adequate biofidelity to serve as a valid proxy for human subjects in the special application of LOSRIC and this has lead to the development of a series of specialized rear impact dummies (RID) (Svensson et al., 1993, Davidsson et al., 2001, Philippens et al., 2002, Cappon et al., 2000). Early attempts were simply to modify existing Hybrid III dummies by substituting a more supple neck, but the Hybrid III's rigid thoracic spine rendered such configurations impractical. It is clear from observation of human subject crash testing that, under direct loading from the seat back, the thoracic curve, which is normally kyphotic in humans, will be flattened. This was first observed by McConnell et al. (McConnell et al., 1993a, McConnell et al., 1995a) who reported the resulting vertical motion of the head (which is partially contributed to by a ramping up the seat back) to be as much as 3.5 inches. This flattening of the thoracic spine and vertical rise of the head is also associated with compression of the spine (Bertholon et al., 2000). It has been postulated that this type of loading can fracture cervical vertebral end plates and may be factor in some cases of chronic pain (Freeman et al., 2001). Vertical motion of the head will also alter the relative head restraint geometry by increasing the topset, **Figure 1**. Thus, a flexible thoracic spine is necessary in the rear impact dummy in order to improve its biofidelity by allowing some degree of torso flattening.

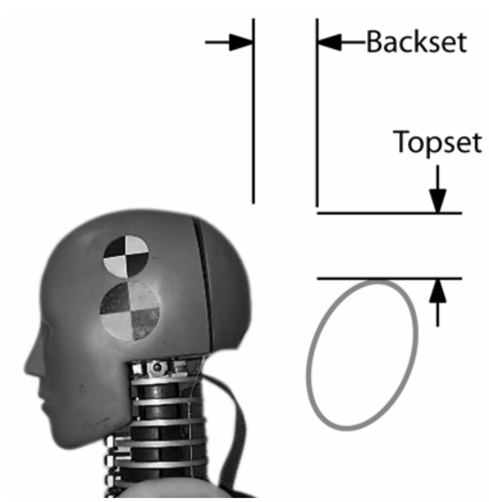

Figure 1. Critical head restraint geometry are described in terms of the horizontal distance between the head and restraint, *backset*, and the vertical distance from the top of the head to the top of the restraint, *topset*.

Svensson and Lövsund (Svensson and Lovsund, 1992) developed a new neck for use with the Hybrid III dummy—the RID neck—and validated it with previous human studies and impact testing. They tested three different neck stiffnesses and compared these to tests with the original Hybrid III neck, which was markedly more stiff. The purpose of this work by TNO (TNO Crash-Safety Research Centre, The Netherlands) was to develop a neck for the 50th percentile Hybrid III dummy to be used in rear impact simulations of up to 25.8 km/h. The TNO Rear Impact Dummy (TRID) Neck was an improvement, but still lacked a flexible thoracic spine, as the TRID neck was a replacement for the Hybrid III neck only.

The RID2 (First Technology Safety Systems, Plymouth, Michigan) has a fully mobile neck in all ranges, and a flexible thoracic spine with motion possible at one joint. Tests comparing the Hybrid III, BioRID, and RID2 have been conducted (Philippens et al., 2002, Zellmer et al., 2002, Cappon et al., 2000) and have generally found the BioRID and RID2 dummies to be comparable to each other and significantly more biofidelic than the Hybrid III for testing under LOSRIC conditions. However, these studies have not been conducted under real world boundary conditions (i.e., full scale low velocity vehicle-to-vehicle crash tests) with living human subjects and RID2 side-by-side.

A potential limitation to some of the validation studies that have been completed to date is that, in many case, seats and seat backs are sometimes purpose-built for the tests and might not be representative of real production car seats in terms of seat back stiffness, compliance, and overall restitutional behavior. One of the ultimate goals in crash testing is to develop a surrogate or proxy for human subjects which will allow testing under conditions which are not suitable for human subject testing (e.g., a high frequency of tests and/or high acceleration pulses) because of the health risks imposed. In order to develop such a device, it is necessary to validate the ATD against living human subjects within the boundary conditions for which the ATD is intended, and that was the goal of this study. Main Section

MATERIALS AND METHODS

All human subjects and the RID2 were instrumented for every test. Crash test vehicles were also instrumented. The subject's headgear array consisted of three triaxial blocks of IC Sensors 3031-050 (50 g) accelerometers tightly affixed to the head via a lightweight headband. Peripheral head acceleration measurements were resolved to the approximate head static center of gravity via an algorithm which utilized the locations of each triaxial block relative to known anatomical landmarks. A low profile triaxial block of thoracic accelerometers was constructed using two Entran EGAXT-50 (50 g) accelerometers and one IC Sensors 3031-050 (50 g) accelerometer. The accelerometers were affixed to the subjects with medical adhesive and tightly fitted straps at the approximate level of C7-T1 on the anterior torso. For the lumbar measurements, a lightweight uniaxial IC Sensors 3031-050 (50 g) accelerometer was affixed with medical adhesive to the base of the subjects' lumbar spines at approximately the level of L5-S1. Target and bullet vehicle accelerometers consisted of a triaxial block of 3031-050 (gain adjusted to ± 15 g full scale) accelerometers affixed with sheet metal screws to each vehicle's chassis at the approximate static center of gravity. Analog to digital conversion was performed by a 12-bit A/D converter operating with a maximum conversion rate of 330,000 samples per second. All data were collected following the general theory of Society of Automotive Engineers (SAE) Recommended Practice: Instrumentation for Impact Test—Part 1—Electronic Instrumentation—J211/1 Mar95. (SAE, 1996). All accelerometer data was collected at 1000 Hz. Vehicle accelerations were filtered using an SAE Class 60 filter. Vehicle changes in velocity were calculated from vehicle acceleration data filtered with an SAE Class 180 filter. Occupant accelerometer data was filtered with and SAE Class 60 filter. Vehicle speeds were also measured using an MEA 5th wheel (MacInnis Engineering Associates, Richmond, BC Canada) attached to each vehicle. Data were acquired at 128 Hz simultaneously for both vehicles for the period 1 sec before to 4 sec after impacts. Time traps for recording vehicle impact speed consisted of custom built Timer Interval Meter with internal clock calibrated to an NIST traceable source. The pressure sensitive tape switches were Tape Switch Corporation Type 102A, requiring 40 ounce pressure for activation. RID2 instrumentation consisted of triaxial head cg linear accelerometers, skull cap force transducer, a 6 component upper neck load cell, a 6 component lower neck load cell, T1-level triaxial linear accelerometers, T12-level triaxial accelerometers, triaxial pelvis linear accelerometers, and 6 inclinometers used for static positioning.

A total of 9 tests, consisting of three tests each with the RID2 as front seat passenger and a human volunteer as driver, were performed, **Table 1**. In each of the three tests series, accurate rear impact test speeds were facilitated using a trunk lid-mounted speedometer on the bullet vehicle which was fed by an MEA 5th wheel. The bullet vehicle was pushed by a practiced push team capable of speeds in excess of 16.2 km/h with reproducibility of +/- 0.3 km/h. In all 9 crash tests the bullet vehicle was a 1994 Ford Crown Victoria (1727 kg) and the target vehicle was a 1989 Chrysler Le Baron (1290 kg). Both vehicles were inspected for damage prior to and after each test. Neither vehicle sustained any significant residual structural damage in these 9 tests and no repairs were necessary to guarantee repeatability or reproducibility of crash conditions. In all tests, the human subject was instructed to place his/her foot on the brake using the same force as he/she would normally use in traffic, and were all allowed to assume their relaxed, normal seating posture. They were also instructed to keep their eyes open and to place their hands lightly on the steering wheel and not to grip it.

Summary of crashes			
Crash #	Subj-ects *	V_c (km/h)	delta V (km/h)
1	DV	8.4	6.0
2	DV	12.4	8.7
3	DV	16.3	11.0
4	AF	9.0	6.6
5	AF	11.9	8.4
6	AF	15.0	10.3
7	RC	8.7	5.5
8	RC	11.1	7.9
9	RC	15.3	9.0

* Human subjects were seated in driver's seat. RID2 ATD was in passenger seat in all tests.
Subject DV: 27-year-old male, 1.8 m in height, 81 kg (50th percentile male)
Subject AF: 24-year-old female, 1.6 m in height, 56 kg (50th percentile female)
Subject RC: 19-year-old male, 1.9 m in height, 109 kg (95th percentile male)
In all cases the bullet vehicle was a 1994 Ford Crown Victoria and the target vehicle was a 1989 Chrysler Le Baron.
V_c: closing velocity
delta V: change in velocity

Table 1.

The stationary target vehicle was placed in neutral with the motor turned off.

Selection/exclusion criteria for human subjects included a willingness to participate in low speed crash tests, no history of significant spinal pain or headaches, and no prior significant injuries to the spine. Each volunteer also was examined by a licensed physician to ensure their fitness for participation, and cervical spine range of motion was measured using a CROM device and recorded before and after the tests were completed. Radiographic studies were undertaken before and after all crash tests to insure volunteer safety.

Institutional review board approval was obtained. In all cases, participants were fully informed of the potential risks of crash testing, and consent for participation was obtained in full accordance with the Office for Protection from Research Risks (OPRR) of the Department of Health and Human Services, and the recommended *Belmont Report*. Subjects were interviewed after each test and were given the opportunity to terminate their participation at any time without penalty. The RID2 ATD was calibrated and repositioned prior to each test in accordance with the manufacturer's recommendations. In this paper, the SAE right hand coordinate system is used to represent vectors and motion paths. The proposed neck injury criterion considers the relative acceleration and velocity between the top and bottom of the spine and is given as (Croft et al., 2002c):

$$\text{NIC}=a_{rel}x0.2+v_{rel}^2 \quad \text{Eq. (1)}$$

where a_{rel} and v_{rel} are the relative horizontal acceleration and velocity between the bottom (T1) and top (C1) of the cervical spine. The constant, 0.2, represents the approximate length of the neck in meters. This equation accounts for what is now widely held to be one of the most important risk factors in LOSRIC injury—the retraction of the head (head lag) during the first 100 or so milliseconds of the crash sequence (Siegmund et al., 1997, Brault et al., 1998). The equation for NIC is calculated as follows:

$$\text{NIC}(t)=a_{rel}(t)x0.2+\left[V_{rel}(t)\right]^2$$
$$\text{where } a_{rel}(t)=a_x^{T1}(t)-a_x^{Head}(t), \quad \text{Eq. (2-3)}$$
$$\text{and } V_{rel}(t)=\int a_x^{T1}(t)dt-\int a_x^{Head}(t)dt$$

where a_x^{T1} = the acceleration-time history measured in the antero-posterior (x) direction at the level of the first thoracic vertebra in units of g. Likewise, a_x^{Head} = the acceleration-time history measured in the antero-posterior (x) direction at the location of the center of gravity of the head in units of g.

The integration of the acceleration (converted to m/s^2) at the level of head center of gravity in the time domain, giving the velocity in the x-direction (resulting in units of m/s), is expressed by:

$$\int a_x^{Head}(t)dt \quad \text{Eq. (4)}$$

The integration of the acceleration (converted to m/s^2) of the first thoracic vertebra in the time domain, giving the velocity in the x-direction (resulting in units of m/s), is expressed by:

$$\int a_x^{T1}(t)dt \quad \text{Eq. (5)}$$

RESULTS

No serious injuries were reported by the subjects and all subjects completed all three of their crash tests and all post-crash examinations. One female subject, however, did report mild neck discomfort and headache following the third test.

Overall, the comparison of the RID2 and 50th percentile human subjects' head linear (x) acceleration-time histories are quite good, **Figure 2**. In all cases, the RID2's acceleration was somewhat greater in both phases, but the morphology of the acceleration pulses was found to be generally good in this study. The NIC values of the RID2 and human subjects of the current study are provided in **Table 2**. These values are also plotted in **Figure 3**.

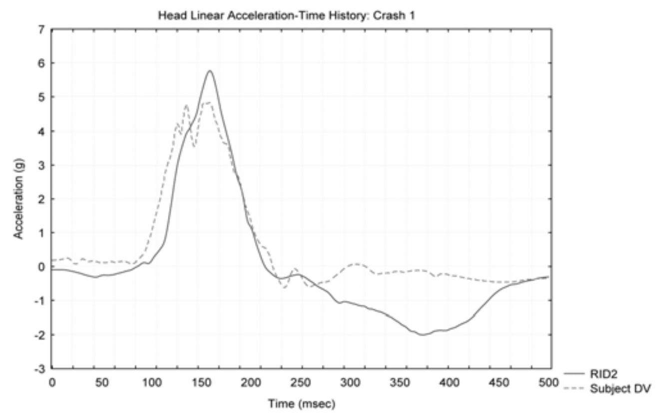

Figure 2. Exemplar acceleration time history comparison between RID2 and human subject. Both are 50th percentile males. The multiple peaks seen in the curve of the human subject are likely minor artifacts induced during the time of head contact with the head restraint resulting from relative motion between head and headgear. The lower negative acceleration of the human subject during the period between 250 and 450 msec is the result of muscle activation.

Neck Injury Criterion (NIC) (m^2/s^2)			
Crash #	RID2	Human subject	Variation (%)
1	5.6	6.6	17.9
2	6.8	10.3	51.5
3	8.0	8.2	2.5
4	5.4	0.8	-85.2
5	9.1	3.2	-64.8
6	7.6	1.6	-79.0
7	5.2	3.0	-42.3
8	6.3	3.6	-42.9
9	8.1	4.7	-42.0

Table 2.

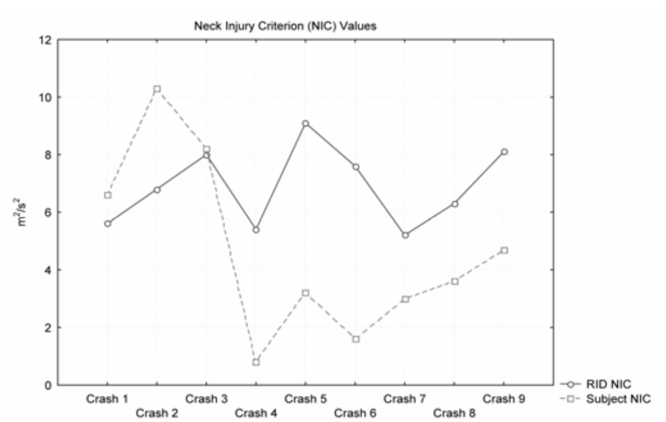

Figure 3. Plot of NIC values for RID2 and human subjects for all crash tests.

DISCUSION

The higher NIC values seen in subject DV in crashes 1-3, which averaged 24% higher than those of the RID2, may reflect the difference in compliance between the human and RID2 cervical spines. In crashes 4-6, subject AF had markedly lower NIC values than the RID2 (averaging 76.3% lower), probably as a function of her initially very low backset, which reduced the differential motion between the torso and head and which demonstrates how optimal head restraint geometry is a critical factor in reducing NIC values. In crashes 7-9, the 95th percentile male subject's (RC) NIC values parallel those of the RID2 but averaged 42.4 % lower, probably as a result of his larger mass. Generally, higher RID2 NIC values coincided with higher speed changes, with one exception. This is likely the result of subtle positioning variation of the RID2 between tests.

Overall, the RID2 performed adequately under crash conditions that are representative of real world crashes at low speeds. Peak linear x acceleration of the RID2 head was always higher than that of the human subjects, averaging 51% higher. The average RID2 head linear x acceleration was 31% higher than those of the 50th percentile male and female subjects. There are potential limitations with this kind of crash testing in terms of its external validity. Recent research has demonstrated that subject awareness alters the responses to staged crashes significantly, with later muscular activation recorded in both surprised male and female subject groups, higher amplitude muscular contraction in the male surprised group, and greater head retraction ranges in the female group compared to groups who were alerted to the impending event (Siegmund et al., 2003).

Thus, aware subjects of crash tests cannot be considered fully representative of the subgroup of real world crash victims who are unaware of the impending rear impact crash. Siegmund et al. (Siegmund et al., 2003) speculated that previous reports of clinical symptoms generated in crash test experiments may underestimate the risk of whiplash in real crashes. The scientific limitations of extrapolating risk estimates from these studies has been reported previously (Freeman et al., 1999). Taking these facts into consideration, the RID2's overall biofidelity might have been underestimated by the current study. It is noteworthy that persons who report having been caught unaware of the impending rear impact crash are at greater risk of injury (Dolinis, 1997, Sturzenegger et al., 1994) and have been reported to have a significantly worse prognosis (Ryan et al., 1994).

As a result of the small number of tests that volunteers can be exposed to for safety reasons, and as a result of the practical limitation on the total number of tests that can be run and the small number of volunteers used, it is not possible to apply meaningful statistical analysis to this set of data. Other factors also limit the external validity of these tests. Many of the variables present in real world crashes, such as offset crash conditions, bumper over- or under-ride, variations between relative masses of crashing vehicles, and the wide variety of seat back and head restraint designs and stiffnesses cannot be accounted for in small-scale crash test studies of this kind. Moreover, subjects were placed into ideal positions, with head restraints adjusted in their upright position, and all were healthy subjects who were both medically screened for known risk factors and were aware of the impending crash. Extrapolations regarding the risk for injury from this study to real world crashes cannot be made with any degree of reliability and should be discouraged..

CONCLUSION

The RID2 dummy is designed to represent a 50th male. The overall performance and biofidelity of the RID2 compared most favorably to the human subject who was, himself, a 50th percentile male. Its overall higher ranges of head acceleration and calculated NIC values compared to the human subjects were generally consistent and potentially explainable on the basis of pre-crash head restraint geometry and differences in body size between the RID2 and the three volunteers. It is possible that under real world crash conditions, in which the occupant of the target vehicle is exposed to an unexpected impact, their excursions and accelerations might be more comparable to those of the RID2, suggesting that its biofidelity could have been underestimated as a result of the alerted status of the crash test volunteers. This is a variable we cannot easily evaluate for practical and ethical reasons. Although the number of tests was small, the biofidelity of the RID2, in the context of the 50th percentile female and 95th percentile male, was limited.

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