Biofidelity of Rear Impact Dummies in Low-Speed Rear-end Impact - Comparison of rigid seat and mass-production car seat with human volunteers -

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ABSTRACT

Rear impact dynamic test methodologies for reducing minor neck injuries have recently been examined internationally by EEVC, GTR, NCAP (Europe, Japan), and others. In these test methodologies, the biofidelity of the dummies is of utmost importance, so this study evaluated the biofidelity of rear impact dummies (BioRID-II, RID3D and Hybrid-III) and compared the results with those of human volunteer tests.

To evaluate the biofidelity of rear impact dummies, two test series were conducted under the same conditions as with the human volunteer tests at the impact velocity of 8 km/h: the deceleration sled test and the acceleration sled test. In the deceleration sled test, a wooden rigid seat without headrest was mounted to a sled which was moved on ramped rails and collided into a damper. In the acceleration sled test, a mass-production car seat with headrest was mounted to a sled which was accelerated horizontally. In both test series, five tests were conducted for each dummy.

In the two test series, the behavior of BioRID-II was very similar to that of the volunteers. In addition, BioRID-II showed good biofidelity for the head angle with respect to T1 (the first thoracic spine), which is considered to be an important characteristic of a rear impact dummy. These results were possible due to the spine structure flexibility of BioRID-II. On the other hand, RID3D, which has flexibility in the neck, needs flexibility between the torso and the lower neck to improve its biofidelity. For Hybrid-III, the dummy showed a very different behavioral response compared to the human volunteers; its biofidelity was lower than that of the rear impact dummies.

Keywords: REAR IMPACT, BIOFIDELITY, MINI SLED, BACK IMPACT

WHIPLASH INJURY DURING A REAR END COLLISION causes serious damage and social cost, so multiple countries are collaborating to reduce neck injuries (Hynd et al. 2005). One method of evaluating the safety performance of the headrest, namely dynamic test methodologies using a rear impact dummy, is being examined by EEVC, GTR, and NCAP (Europe, Japan) (Avery et al. 2006, Bortenschlager et al. 2007). Although such examinations cover many topics like the testing conditions and evaluation method, the dummy is the most important measurement apparatus in the test and has attracted the most research attention.

Currently, BioRID-II and RID3D have been suggested as suitable candidates as rear impact dummies in addition to Hybrid-III for frontal crashes (Davidsson 1999a, Cappon et al. 2003, Foster et al. 2003). Several validations and improvements to these dummies have been made under various testing conditions. Philippens et al. (2002) compared the responses of BioRID-II, RID2 (the previous version of RID3D) and Hybrid-III in tests conducted under the same test conditions as the original tests used to develop and validate the rear impact dummies, and concluded that Hybrid-III should not be used for rear impact tests because its biofidelity was lower than that of BioRID-II and RID2. Willis et al. (2005) conducted sled tests using BioRID-II, RID3D and Thor-Alfa, and evaluated the biofidelity of these dummies by comparing the results with those of human volunteer tests. Their report concluded that the responses of BioRID-II and RID3D approximated the volunteers' responses but did not completely satisfy the range of their responses, and the response of Thor-Alfa was not close to that of human volunteers. Yaguchi et al. (2006) evaluated five types of dummies (BioRID-II, RID2, Hybrid-III, Thor-NT and Thor-FT) by comparing the results with those of mini-sled tests using human volunteers and the results of back impact tests using PMHS, and reported that BioRID-II was most similar to human volunteers and PMHS in terms of its response to low-speed rear impacts.

However, there is insufficient objective data to evaluate the biofidelity of the latest version of each dummy. Especially, there are few reports on the comparison between rear impact dummies and human volunteers for mass-production seats.

In this study, mini-sled tests using a rigid seat and a mass-production seat for three types of dummies (BioRID-II, RID3D and Hybrid-III) were conducted under the same conditions as human volunteer tests. By comparing the responses of the dummies with those of human volunteers, we evaluated the biofidelity of dummies in order to identify the most suitable dummy for use in low-speed rear impact tests.

METHODS AND MATERIALS

DUMMIES EVALUATED IN THIS STUDY: The dummies evaluated in this study were BioRID-II version g, RID3D version of December 2006 and Hybrid-III. BioRID-II and RID3D were developed for low-speed rear impacts. BioRID-II has a segmented spinal structure consisting of the same number of vertebrae as that of a human, i.e. 7 cervical, 12 thoracic and 5 lumbar vertebrae. The thoracic spine has a kyphosis and the lumbar spine is straight as in a human in the seated posture (Davidsson 1999b). RID3D basically has a rigid spinal structure, but it also has flexible elements in the thoracic and lumbar regions and a fully flexible neck design (Cappon et al. 2005). Hybrid-III was developed for high-speed frontal impacts, and basically has a rigid spinal structure except for the cervical part and the lumbar part (Foster et al. 1977).

MINI-SLED TEST: To evaluate the biofidelity of rear impact dummies, two test series were conducted under the same conditions as with the human volunteer tests: the deceleration sled test and the acceleration sled test. In both test series, five tests were conducted for each dummy. Dummies were positioned in the following states: (1) the bottom of the skull cup was kept horizontal, (2) The upper torso was pushed against the seat back as much as possible, and (3) hands were put on the handle (deceleration sled tests) or were put on the knees (acceleration sled tests) as well as the volunteer tests. The coordinates of the head and hip point were measured and checked to maintain the same seating posture in each test that used the same dummy.

In the deceleration sled test, a wooden rigid seat without headrest was mounted to a sled which was moved on ramped rails and collided into a damper at the impact velocity of 8 km/h (Figure 1). By using the rigid seat, the inherent impact response of the dummies can be evaluated without the influence of the mechanical properties of the seat.

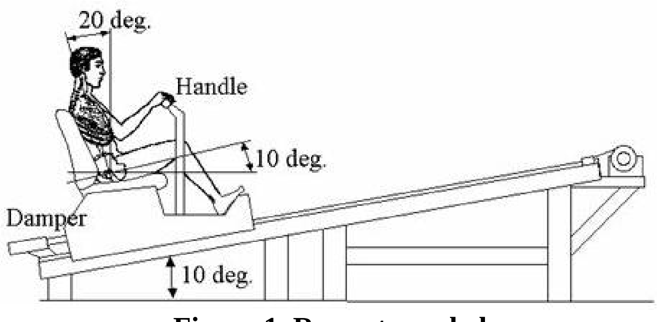

Figure 1. Ramp type sled

In the acceleration sled test, a mass-production car seat with headrest was mounted to a sled which was accelerated on horizontal rails by an electric motor. The change in velocity of the sled was 8 km/h (Figure 2). The objective of this test series was to evaluate the biofidelity of the dummies using a mass-production seat in consideration of accident conditions.

Figure 2. Horizontal type sled

DATA ANALYSIS: In each of the two test series, the motion of the head/neck/torso during low-speed rear impacts was recorded with a high-speed video camera. Based on the movement of target marks attached to the dummies, relative displacements and rotations of their head, neck, and torso were measured and analyzed. In addition, accelerations of head C.G. and T1 and the force/moment of the upper neck were measured by accelerometers and load cells attached to the dummy. The acceleration of the head C.G. (center of gravity) and upper neck loads of the volunteer were calculated using the six-degree freedom component measuring method (Ono and Kanno 1993). The T1 linear and angular displacements of the volunteer were calculated as a weighted average value from the film target data on the T1 and on the sternum. The method of measuring volunteer data is described in detail in the reference (Davidsson et al. 1999a).

Two categories of parameters were used to compare the dummy response with the human volunteers. One category of parameters concerned the external behavior obtained by video analysis, and the other concerned the impact response measured by sensors (Table 1). For parameters of the external behavior, changes of the head angle with respect to the neck (HA-NA), the neck angle with respect to T1 (NA-TA), the head angle with respect to T1 (HA-TA), the T1 x coordinate relative to the sled (T1-X-disp), the T1 z coordinate relative to the sled (T1-Z-disp) and the T1 angle with respect to the sled (Sled-TA) were used (Figure 3). For parameters of the impact response, accelerations of head C.G. in the x direction (Head Ax) and T1 in the x direction (T1 Ax), and shear force (Upper Neck Fx), axial force (Upper Neck Fz) and moment (Upper Neck My) were also used. Figure 4 shows the polarities of the impact response parameters.

Table 1. Evaluated parameters

Behavior	HA-NA	Change of head angle with respect to neck angle
	NA-TA	Change of neck angle with respect to T1 angle
	HA-TA	Change of head angle with respect to T1 angle
	T1-X-disp	Change of T1 X coordinate relative to sled
	T1-Z-disp	Change of T1 Z coordinate relative to sled
	Sled-TA	Change of T1 angle with respect to sled plane
Impact response	Head Ax	Head center of gravity acceleration in x direction
	T1 Ax	T1 (First thoracic vertebra) acceleration in x direction
	Upper Neck Fx	Upper neck shear force in x direction (Fx)
	Upper Neck Fz	Upper neck axial force in z direction (Fz)
	Upper Neck My	Upper neck moment about y axis (My)

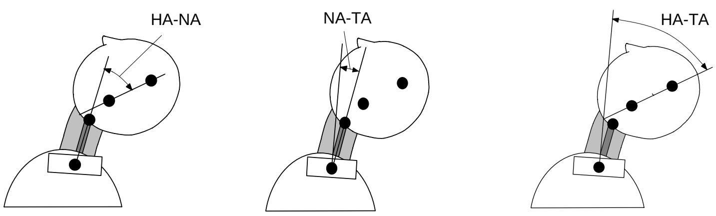

Figure 3. Explanation of evaluated parameters for behavior

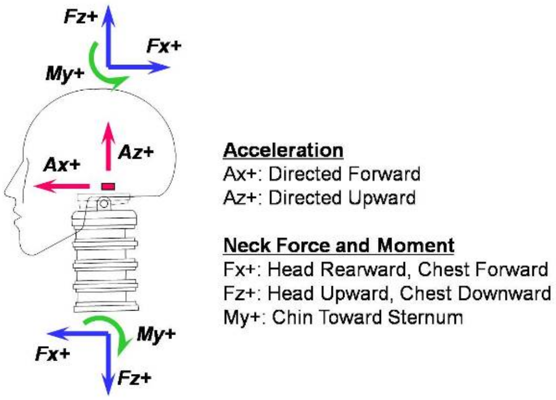

Figure 4. Polarities of responses

VOLUNTEER TEST DATA: The human volunteer test data of this study were obtained from the following two low-speed rear impact experiments:

(1) Deceleration sled test: Experiments on nine tests by seven volunteers using a ramp type sled with a rigid seat without headrest (Davidsson et al. 1999).

(2) Acceleration sled test: Experiments on six human volunteers using a horizontal type sled with a mass-production car seat with headrest (Pramudita et al. 2007).

From these experiments, human volunteers' corridors for parameters of external behavior and impact response were provided. These corridors were derived from the average value and standard deviation of volunteers' responses. In this study, these corridors were used to evaluate the biofidelity of the dummies.

RESULTS

DECELERATION SLED TEST: Figure 5 shows the sled acceleration pulse and the sled velocity pulse in the deceleration sled test. In this graph, each curve shows the average response of five tests conducted for each dummy. The shape of the acceleration pulse and duration showed a similar response to the volunteer test though some differences were seen in the peak acceleration of the installed dummy. Therefore, it is confirmed that the test conditions of each dummy were almost the same as those of the volunteer test.

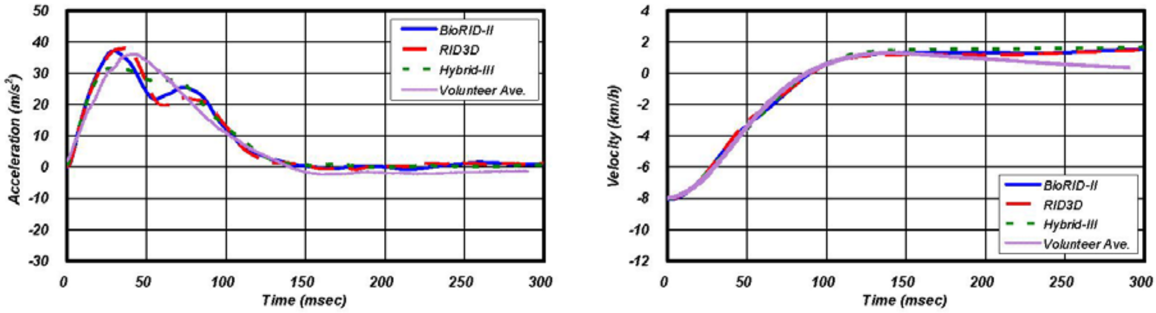

Figure 5. Sled acceleration and velocity (Deceleration sled tests)

<u>External behavior of dummies</u> – Figures 6 and 7 compare the external behavior of each part of the dummy (average response of five tests) with the volunteers' behavior. As for the sign of HA-NA, NA-TA and HA-TA, a plus value shows the flexion behavior and a minus value shows the extension behavior.

The response of HA-NA (the head rotation angle with respect to the neck) in human volunteers showed flexion before around 150 msec, and the angle change was comparatively small. The response of

HA-NA was quite different between the three dummies. RID3D showed flexion before 100 msec and showed extension afterwards while BioRID-II showed only flexion. Hybrid-III did not show flexion at all, but showed only extension.

As regards NA-TA (the neck rotation angle with respect to T1), the human volunteers' response showed slight flexion before around 80 msec, and showed gradual extension behavior that reached the range from –25 to –45 degrees at 250 msec. The response of NA-TA was different between the three dummies though extension behavior was indicated in each dummy. BioRID-II showed flexion at an early timing and showed extension after 100 msec. The extension behavior of the dummy was close to the lower limit of the volunteers' corridor. RID3D showed extension behavior after 50 msec and showed the same behavior as BioRID-II between 140 to 200 msec. Hybrid-III showed extension behavior that peaked at 130 msec, and returned forward quickly. Therefore, the extension behavior of Hybrid-III was obviously different from the response of the human volunteers.

HA-TA (the head rotation angle with respect to T1) means the sum of HA-NA and NA-TA. The response of HA-TA in the human volunteer tests showed flexion behavior at around 80 msec, and showed extension behavior that reached from –35 to –45 degrees at 250 msec. BioRID-II showed similar behavior to the human volunteers in terms of flexion at around 80 msec and extension until 250 msec. RID3D and Hybrid-III did not show flexion behavior at an early stage. RID3D reached a peak extension angle of –55 degree at 180 msec, and Hybrid-III reached a peak extension angle of –30 degree at 140 msec. Therefore, RID3D and Hybrid-III showed different behaviors to the human volunteers.

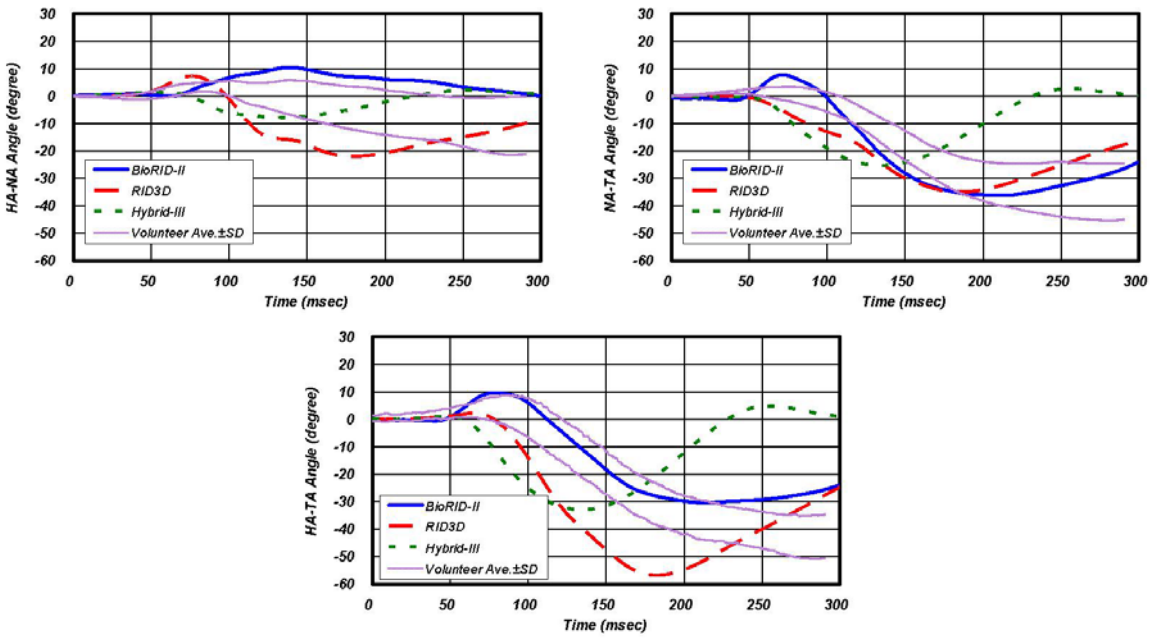

Figure 6. HA-NA, NA-TA and HA-TA (Deceleration sled tests)

Displacements and the angle change of T1 were influenced by the interaction between the back of the dummy and the seat back. For T1-X-disp and Sled-TA, the responses of BioRID-II were close to the lower limit of the volunteers' corridors, whereas those of RID3D were close to the upper limit of the corridors. As regards T1-Z-disp, the responses of both BioRID-II and RID3D were close to the lower limit of the corridor. The responses of Hybrid-III for T1-X-disp, T1-Z-disp and Sled-TA were different from volunteers' corridors.

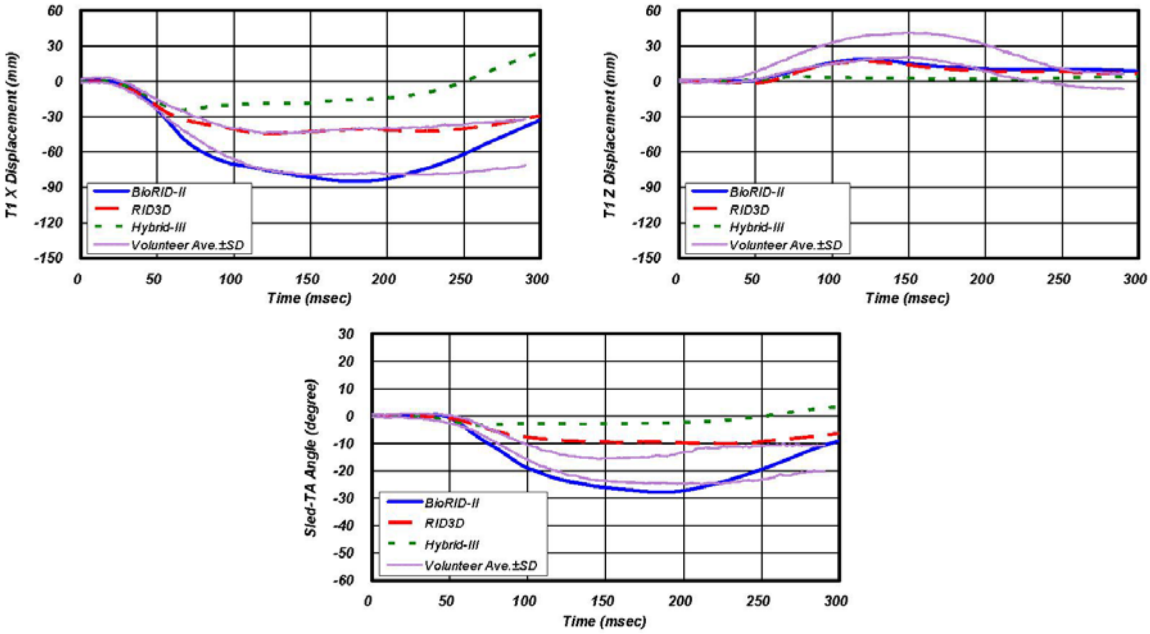

Figure 7. T1-X-disp, T1-Z-disp and Sled-TA (Deceleration sled tests)

Impact response of dummies – Figures 8 to 10 compare the impact responses of each part of the dummy (average response of five tests) with volunteers.

As regards Head Ax (anterior-posterior acceleration of the center of gravity of the head), the impact response of the human volunteers showed low posterior acceleration before around 80 msec, and showed anterior acceleration that reached from 10 to 50 m/s^2 at around 140 msec. Although the maximum anterior accelerations of Head Ax of the three dummies were almost the same as the upper limit of the volunteers' corridor, the timings of maximum accelerations differed among the dummies. The maximum acceleration of Hybrid-III occurred at 120 msec while those of BioRID-II and RID3D occurred from 170 to 190 msec. Only BioRID-II showed posterior acceleration before 80 msec, which was also seen in the volunteer's response.

Whereas T1 Ax of the human volunteers reached from 30 to 40 m/s^2 at around 70 msec, the three dummies showed around twice the acceleration compared with the human volunteers. T1 Ax of BioRID-II showed posterior acceleration at 40 msec, then showed anterior acceleration that reached a maximum at 70 msec. On the other hand, T1 Ax of RID3D and Hybrid-III showed a similar response, with anterior acceleration reaching a maximum at 60 msec without posterior acceleration initially.

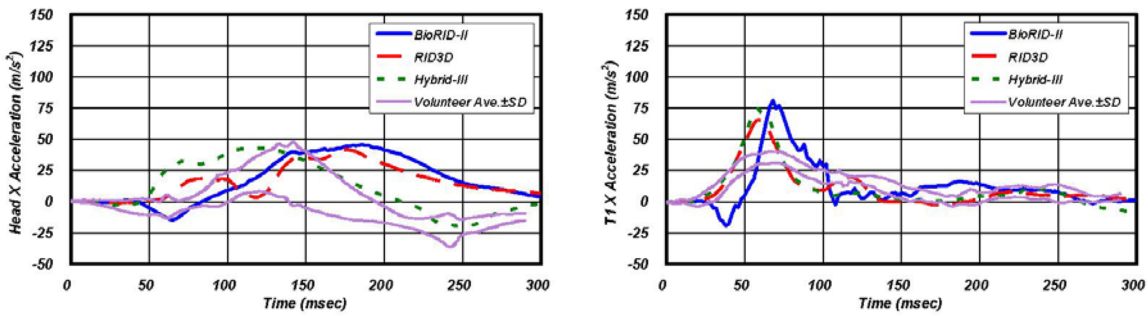

Figure 8. Head Ax and T1 Ax (Deceleration sled tests)

The response of upper neck Fx (upper neck shear force) in the volunteer tests showed a negative value before 140 ms, and changed to a positive value gradually. Only BioRID-II showed a negative value at an early timing in the three dummies. The tendency of the difference in the three dummies was the same as their Head Ax responses.

The response of upper neck Fz (upper neck axial force) in the volunteer tests showed compression before 110 ms, and then changed to tension. The three dummies were the same as the human volunteers in terms of the change in direction of force, although its peak value and timing were different. In addition, responses of BioRID-II and RID3D were comparatively similar to the volunteers' corridor.

The response of upper neck My (upper neck moment) in the volunteer tests showed flexion before 100 msec, and changed to extension gradually. The three dummies were the same as the human volunteers in terms of the change in direction of moment. However, the maximum values of the flexion of BioRID and RID3D were two or three times higher than that of the human volunteers. It was thought that the rigidity of the joint of the head and the neck in BioRID-II and RID3D was higher than that of the human volunteers though the dummies had flexibility in the neck. Although Hybrid-III indicated the same level of flexion as the volunteers, the change from flexion to extension was rapid and the maximum extension was three times higher than that of the volunteers. In Hybrid-III, it was thought that there was hardly any flexion behavior since the rigidity of the entire spine was higher than that of the other dummies, and the flexion moment was low.

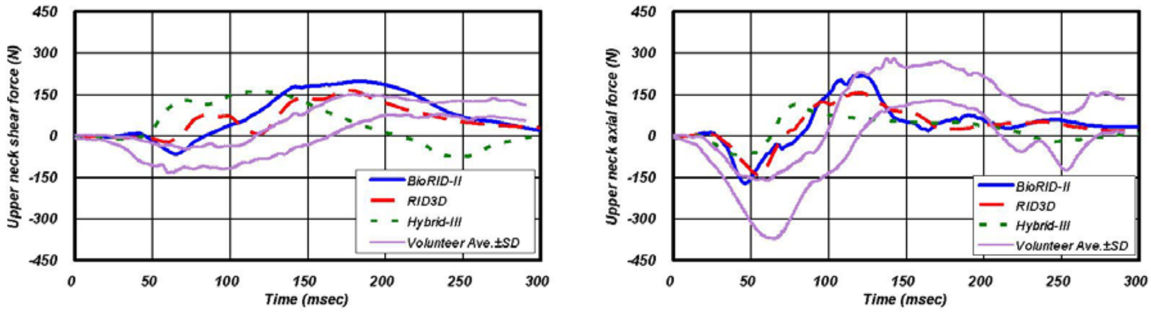

Figure 9. Upper neck shear force Fx and axial force Fz (Deceleration sled tests)

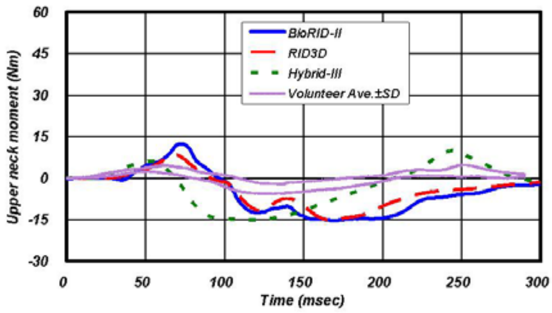

Figure 10. Upper neck moment My (Deceleration sled tests)

ACCELERATION SLED TEST: Figure 11 shows the sled acceleration pulse and the sled velocity pulse in the acceleration sled test. In this figure, each curve shows the average response of five tests conducted for each dummy. The shape of the acceleration pulse and duration showed a similar response to the volunteer test though some differences were seen after 120 msec depending on the installed dummy. Therefore, it is confirmed that the test conditions of each dummy were almost the same as those of the volunteer test.

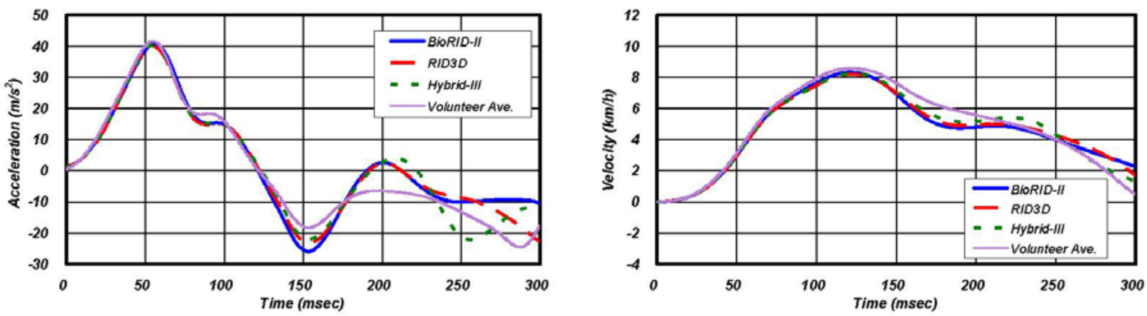

Figure 11. Sled acceleration and velocity (Acceleration sled tests)

External behavior of dummies – Table 2 lists the time at which the head made contact with the headrest for each test. Figures 12 to 13 compare the external behavior of each part of the dummy (average response of five tests) with the volunteers' behavior.

The response of HA-NA in the volunteer tests shows flexion between 100 and 150 msec. BioRID-II and RID3D showed flexion of around the lower limit of volunteers' corridor though the timings were around 30 msec later. The behavior of BioRID and RID3D regarding HA-NA was similar to that of the human volunteers, taking into consideration the fact that the headrest contact time of the dummies was later than that of the volunteers. On the other hand, Hybrid-III did not show flexion at all, unlike the other rear impact dummies.

The response of NA-TA in the volunteer tests showed flexion behavior in which the angle increased after the head made contact with the headrest. BioRID-II showed flexion except a small extension at 160 msec. RID3D showed extension before the head and headrest made contact, and changed from extension to flexion at 160 msec, then extension occurred again. Hybrid-III also showed extension behavior before the head and headrest made contact, and changed from extension to flexion after 240 msec when the dummy's back moved away from the seat back.

The response of HA-TA in the volunteer tests showed almost constant flexion after the head and headrest made contact. The response of BioRID-II was similar to that of the human volunteers, taking into consideration the fact that the head and headrest made contact 20 msec later than that of the volunteers, though the angle was small. The response of RID3D showed that flexion occurred later than BioRID-II, and changed to extension at 240 msec. Hybrid-III showed completely different behavior to the volunteers; the dummy showed extension only before the head and headrest made contact.

Table 2. Head restraint contact time

Unit :msec

	Volunteer	BioRID-II	RID3D	Hybrid-III
	n=6	n=5	n=5	n=5
Earliest	*74*	*112*	*114*	*124*
Latest	*112*	*116*	*120*	*128*
Average	*94*	*114*	*117*	*126*
S.D.	*14.2*	*1.7*	*2.3*	*2.0*

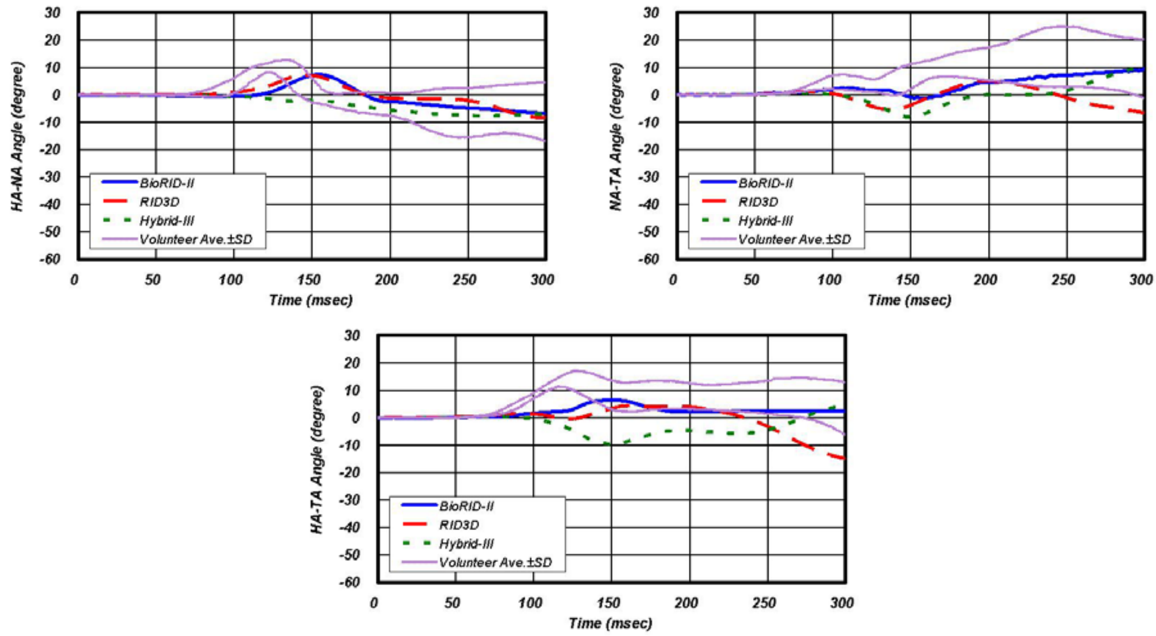

Figure 12. HA-NA, NA-TA and HA-TA (Acceleration sled tests)

For T1-X-disp, the responses of the three dummies were close to the upper limit of the volunteers' corridor. For T1-Z-disp, the response of BioRID-II was almost within the range of corridors before 150 msec. As regards Sled-TA, the response of BioRID-II was almost within the range of corridors.

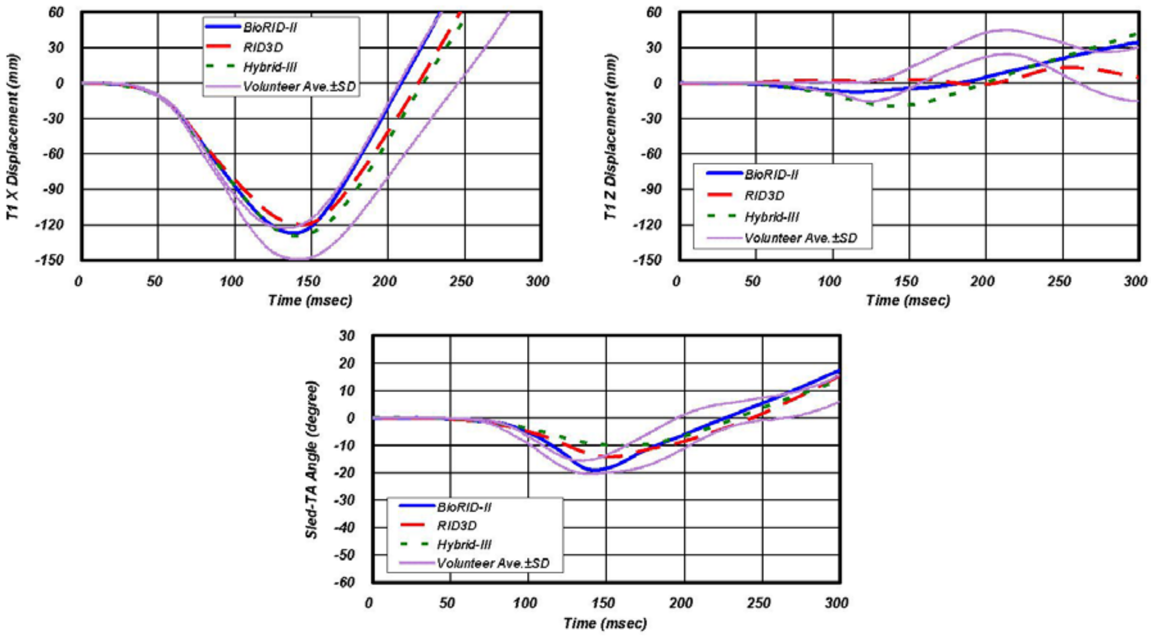

Figure 13. T1-X-disp, T1-Z-disp and Sled-TA (Acceleration sled tests)

Impact response of dummies – Figures 14 to 16 compare the impact responses of each part of the dummy (average response of five tests) with those of the volunteers.

As regards Head Ax, the impact response of the human volunteers showed anterior acceleration that reached from 40 to 80 m/s^2 between 100 and 150 msec. Although the three dummies showed around twice the acceleration compared with the human volunteers, the timing of the peak was similar to that of the volunteers taking into consideration the fact that the head and headrest made contact later.

The response of T1 Ax in the human volunteers showed anterior acceleration that reached from 35 to 50 m/s^2 between 70 and 170 msec. T1 Ax of the three dummies was close to the upper limit of the volunteers' corridor. For T1 Ax, RID3D was the most similar to the volunteers in terms of acceleration level, while BioRID-II was most similar in terms of the duration.

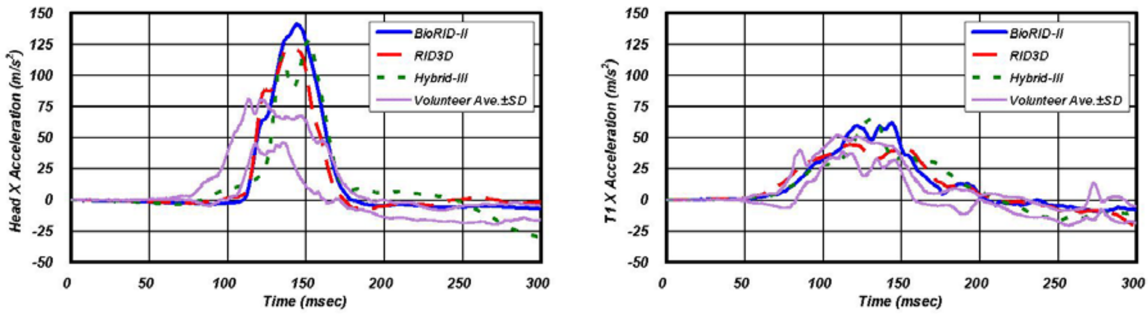

Figure 14. Head Ax and T1 Ax(Acceleration sled tests)

The response of upper neck Fx in the volunteer tests showed a negative value between 100 and 160 msec, which was the timing at which the head made contact with the headrest. The three dummies showed a different response to the volunteers. In BioRID-II, neck shear force did not occur. In RID3D, a slight shear force occurred, and the direction of the force changed at around 150 msec. In Hybrid-III, the shear force was positive while the head was in contact with the headrest.

The response of upper neck Fz in the volunteer tests showed tension between 100 and 160 msec and a similar tendency was seen in the three dummies. However, in BioRID-II the force was around twice that in the human volunteers. The responses of RID3D and Hybrid-III were almost the same as the upper limit of the volunteers' corridor.

As regards the upper neck My, the impact response of the volunteers showed flexion between 90 and 160 msec due to the contact between the head and headrest. The three dummies also showed flexion, though the peaks were small. The timing of the peak in Hybrid-III was later than in the other dummies, and this tendency was the same as upper neck Fz.

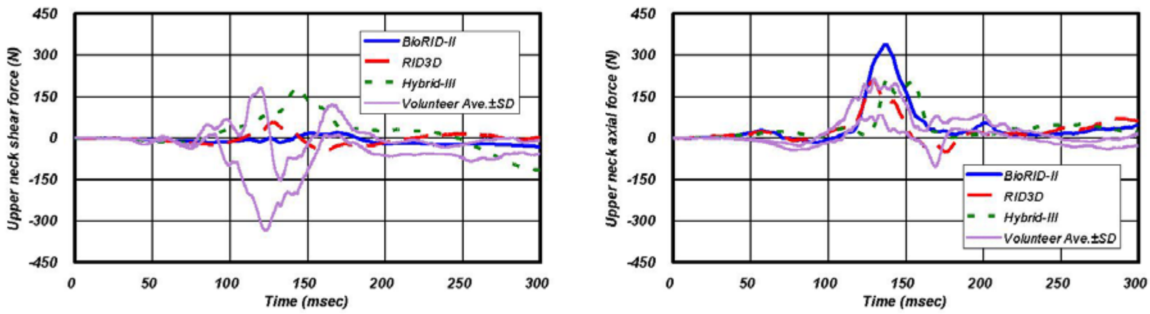

Figure 15. Upper neck shear force Fx and axial force Fz (Acceleration sled tests)

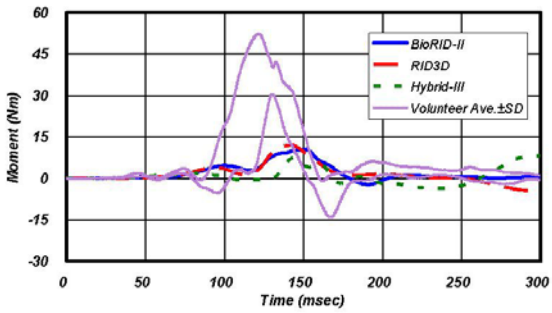

Figure 16. Upper neck moment My (Acceleration sled tests)

DISCUSSION

DECELERATION SLED TEST: Some differences were seen in the external behavior between two rear impact dummies. In BioRID-II, NA-TA showed flexion behavior first, and then shifted to extension behavior. The flexion behavior of HA-NA was caused by this NA-TA motion. On the other hand, in RID3D, the flexion behavior of HA-NA and the extension behavior of NA-TA were caused at the same time, and then HA-NA shifted to extension behavior.

These differences in behavior between BioRID-II and RID3D in the deceleration sled test were considered to be caused by the structural difference of their spines. The test results showed that RID3D has local flexibility in the upper part of the neck while BioRID-II has flexibility in the entire spine including the neck. These differences appeared clearly in HA-TA, which showed the entire change of angle between the head and the neck. As for HA-TA, only the behavior of BioRID-II was almost the same as the human volunteers' corridor. For Hybrid-III, the dummy showed a big difference in most of the parameters for evaluating external behavior compared to human volunteers.

The impact response of BioRID-II concerning Head Ax, Upper Neck Fx, and Fz was similar to that of the human volunteers. A response opposite to that of the human volunteers was seen in Head Ax and Upper Neck Fx of RID3D at an early time (before 100 msec). It was thought that these responses were due to the influence of the rigidity of the entire spine. The response of Head Ax and Upper Neck Fx of Hybrid-III was markedly earlier than that of the human volunteers.

The coefficient of variation (CV) for peak values of the evaluated parameters was calculated to evaluate the repeatability of the dummies. CV was expressed as a percentage after dividing the standard deviation of the peak measurement values of each dummy by the average value.

$$CV = \text{standard deviation of the peak values} / \text{average value of the peak values} \times 100\ [\%]$$

Tables 3 to 6 show the CV in the deceleration sled test results. All three dummies showed good repeatability for HA-NA. For T1-Z-disp and Sled-TA, values of CV were large since average values were small. As for T1-X-disp, values of SD were almost the same in the three dummies. As regards impact response parameters, values of CV of the three dummies were within 10% except Fz of Hybrid-III.

Table 3. CV (Deceleration sled tests): BioRID-II

BioRID-II	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-30.4	-85.0	18.9	-27.8
S.D. of Max.	0.7	5.2	1.2	0.8
C.V. of Max.	2.3	6.1	6.3	2.7

BioRID-II	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	48.7	84.7	199.0	231.2	12.5	-15.5
S.D. of Max.	1.8	7.1	1.3	5.0	0.6	0.1
C.V. of Max.	3.7	8.4	0.6	2.1	4.9	0.8

Table 4. CV (Deceleration sled tests): RID3D

RID3D	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-56.9	-44.9	17.0	-10.2
S.D. of Max.	1.2	5.7	2.0	0.8
C.V. of Max.	2.1	12.7	11.9	7.8

RID3D	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	43.0	67.2	168.8	167.4	9.1	-15.2
S.D. of Max.	2.0	1.5	7.6	7.1	0.2	0.7
C.V. of Max.	4.7	2.3	4.5	4.2	2.6	4.5

Table 5. CV (Deceleration sled tests): Hybrid-III

Hybrid-III	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-32.9	-25.3	4.7	-3.3
S.D. of Max.	0.9	5.2	0.6	0.9
C.V. of Max.	2.7	20.6	13.0	27.0

Hybrid-III	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	44.6	80.2	163.3	127.4	10.2	-15.2
S.D. of Max.	2.3	5.7	4.3	12.8	0.4	0.8
C.V. of Max.	5.1	7.1	2.6	10.1	3.7	5.5

ACCELERATION SLED TEST: A difference was seen between two rear impact dummies in NA-TA for external behavior. In BioRID-II, both HA-NA and NA-TA showed flexion behavior. On the other hand, in RID3D, HA-NA showed flexion behavior and NA-TA showed extension behavior. The difference in NA-TA caused the difference of the timing of the flexion behavior of HA-TA. HA-TA of BioRID-II showed better correlation with the volunteers than RID3D, though the angle was smaller and the time of contact with the headrest was around 20 msec slower than that of the human volunteers. In Hybrid-III, HA-TA showed extension behavior before the head came into contact with the headrest, and showed behavior opposite to that of the human volunteers.

As for the impact response, all three dummies showed about twice the peak value for Head Ax compared to the human volunteers though they showed a similar response for T1 Ax. There was a possibility that the impact velocity of the head with the headrest increased since the impact timing of the head and the headrest was slower than that of the human volunteers in the dummy. Hybrid-III showed a response of the opposite direction compared to the human volunteers in Upper Neck Fx before the head came into contact with the headrest.

Tables 6 to 8 show CV in the acceleration sled test results. For BioRID-II, the value of CV for HA-NA was large since the average value was small. For RID3D, CV for HA-TA was large because the maximum value for extension was measured in the rebound phase. As regards Head Ax and T1 Ax, all three dummies showed good repeatability.

Table 6. CV (acceleration sled tests): BioRID-II

BioRID-II	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-0.1	-127.0	34.5	-19.1
S.D. of Max.	0.1	2.6	1.6	0.6
C.V. of Max.	116.7	2.1	4.8	2.9

BioRID-II	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	143.8	66.6	20.5	344.5	10.7	-2.4
S.D. of Max.	4.5	3.0	4.5	9.5	0.9	0.4
C.V. of Max.	3.1	4.6	22.0	2.8	8.0	15.6

Table 7. CV (acceleration sled tests): RID3D

RID3D	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-14.8	-120.0	13.5	-14.2
S.D. of Max.	3.8	2.1	3.2	0.2
C.V. of Max.	26.0	1.7	23.3	1.5

RID3D	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	124.6	47.5	61.5	223.7	12.4	-0.1
S.D. of Max.	4.2	1.9	8.0	18.1	0.9	0.0
C.V. of Max.	3.4	4.0	13.0	8.1	7.2	30.7

Table 8. CV (acceleration sled tests): Hybrid-III

Hybrid-III	HA-TA	T1-X-disp	T1-Z-disp	Sled-TA
	extension	rearward	upward	extension
Average of Max.	-9.9	-129.6	42.4	-10.2
S.D. of Max.	1.1	5.0	2.6	0.6
C.V. of Max.	11.2	3.8	6.2	5.9

Hybrid-III	Head Ax	T1 Ax	Neck Up. Fx	Neck Up. Fz	Neck Up. My	
	forward	forward	positive	tension	flexion	extension
Average of Max.	131.5	67.4	189.2	249.9	11.3	-2.6
S.D. of Max.	4.1	4.2	2.6	10.4	1.0	0.3
C.V. of Max.	3.2	6.3	1.4	4.2	8.5	13.1

The cumulative variance ratio (CVR, Philippens et al. 2002) was calculated to evaluate the biofidelity of the dummies objectively. A lower CVR value indicates good biofidelity, as the variance of the dummy is more similar to corridor variance. A CVR value of over 5 means little or no correlation between the dummy response and the volunteer response. Therefore, CVR values of over 5 were set equal to 5 for calculating the average CVR in the same way as in previous literature.

$$CVR = \frac{\sum_{t=Tstart}^{t=Tend} \left(dummy(t) - volunteer\_ave(t) \right)^2}{\sum_{t=Tstart}^{t=Tend} \max\left(cor(t) - volunteer\_ave(t) \right)^2}$$

where, dummy(t) is the time response of the evaluated parameter of the dummy, volunteer_ave(t) is the average of the corresponding parameter of volunteers, and cor(t) is the volunteer corridor.

Since the CVR value is obtained by integration, it is affected by the end time of the calculation. Tables 9 and 10 show CVR values for external behavior parameters and impact response parameters until 150 msec (sled reached maximum velocity) and until 250 msec (end of response) respectively.

For external parameters, BioRID-II showed the smallest average value of CVR in the three kinds of dummies for all test and calculation conditions. As for impact response parameters, BioRID showed the smallest CVR in one case (deceleration sled test, calculation time of 150 msec), and RID3D showed the smallest CVR in the other three cases. However, the CVR value is calculated based on the difference from the average value of the volunteers. Therefore, to evaluate the biofidelity of the dummy, it is necessary to consider the shape of the time history of the response. For example, though values of CVR for HA-NA in the deceleration sled test were 2.8 in BioRID-II and Hybrid-III respectively, the shape of the response in BioRID-II was more similar to the volunteers' corridors (Figure 6).

Table 9. CVR (Deceleration sled tests)

[150ms]	BioRID-II	RID3D	Hybrid-III
HA-NA	2.8	5	2.8
NA-TA	2.9	5	5
HA-TA	0.4	5	5
T1-X-disp	1.5	0.8	5
T1-Z-disp	1.2	1.7	5
Sled-TA	3.0	4.8	5
Average	2.0	3.7	4.6

[250ms]	BioRID-II	RID3D	Hybrid-III
HA-NA	2.4	3.7	1.0
NA-TA	1.1	2.0	5
HA-TA	0.6	5	5
T1-X-disp	1.2	0.8	5
T1-Z-disp	1.1	1.5	4.3
Sled-TA	1.8	3.1	5
Average	1.4	2.7	4.2

[150ms]	BioRID-II	RID3D	Hybrid-III
HeadAx	0.4	0.8	3.2
T1Ax	5	5	5
Upper neck Fx	5	5	5
Upper neck Fz	2.8	2.7	4.0
Upper neck My	5	5	5
Average	3.6	3.7	4.4

[250ms]	BioRID-II	RID3D	Hybrid-III
HeadAx	5	4.6	2.4
T1Ax	5	4.1	5
Upper neck Fx	4.6	3.4	5
Upper neck Fz	2.5	2.5	3.3
Upper neck My	5	5	5
Average	4.4	3.9	4.1

Table 10. CVR (Acceleration sled tests)

[150ms]	BioRID-II	RID3D	Hybrid-III
HA-NA	2.8	1.5	5
NA-TA	1.0	5	5
HA-TA	5	5	5
T1-X-disp	1.2	3.1	1.0
T1-Z-disp	0.3	1.0	3.0
Sled-TA	1.6	5	5
Average	2.0	3.4	4.0

[250ms]	BioRID-II	RID3D	Hybrid-III
HA-NA	1.0	0.8	1.1
NA-TA	1.2	2.1	3.6
HA-TA	1.8	2.8	5
T1-X-disp	1.0	0.3	0.1
T1-Z-disp	3.1	4.3	5
Sled-TA	0.2	0.8	1.4
Average	1.4	1.9	2.7

[150ms]	BioRID-II	RID3D	Hybrid-III
HeadAx	5	5	4.0
T1Ax	1.8	0.5	1.7
Upper neck Fx	0.7	1.2	2.8
Upper neck Fz	4.6	0.6	2.2
Upper neck My	1.7	1.7	2.6
Average	2.8	1.8	2.6

[250ms]	BioRID-II	RID3D	Hybrid-III
HeadAx	5	4.1	5
T1Ax	2.1	1.7	3.1
Upper neck Fx	0.7	1.3	3.0
Upper neck Fz	3.3	0.9	2.9
Upper neck My	1.8	1.7	2.6
Average	2.6	1.9	3.3

In the above-mentioned result, the biofidelity of BioRID-II was slightly higher than that of RID3D in the study based on the results of two types of sled tests. Hybrid-III showed different behavior from the volunteers. Similar results were reported in the EEVC research report (EEVC 2007) and the presentation for UN ECE WP29 head restraint GTR informal group (Hynd 2007). Prasad et al. (1997) reported that Hybrid III was biofidelic when compared to the data from Mertz and Patrick (1967), however, the biofidelity evaluation was limited to head rotations only. The same studies also showed that Hybrid III was not biofidelic in consideration of seat interaction.

In this study, tests were conducted at 8 km/h in order to compare the response with that of human volunteers. Therefore, biofidelity evaluations of dummies were limited to low-speed impact. However, the biofidelity of BioRID at high-speed impact (16.5 km/h and 23.7 km/h) was confirmed by comparison with PMHS by back impact tests using a pendulum (Astrid el al. 2002, Yaguchi et al. 2006).

CONCLUSION

In the two test series, it was shown that the external behavior and the impact response of BioRID-II were very similar to those of the human volunteers. In the test using the rigid seat, the change of head angle with respect to T1, which is considered to be an important characteristic of a rear impact dummy, was almost the same as that of the human volunteers. BioRID-II also showed a similar response to the human volunteers in the test using a mass-production seat, considering the delay of the contact time of the head and the headrest. These results may have been due to the spine structure flexibility of BioRID-II.

The flexibility of the neck was observed from the change of angle in each part in the deceleration sled test for RID3D, but the flexibility was limited to the neck. To improve the biofidelity of RID3D, it is necessary to have flexibility between the torso and the lower neck.

For Hybrid-III, the dummy showed a very different behavioral response compared to the human volunteers. The biofidelity of Hybrid-III was lower than those of the other rear impact dummies; the dummy showed behavior different from that of the human volunteers in some evaluation parameters.

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