CHARACTERIZATION OF HELMET ENERGY ABSORBING LINER MATERIALS

Matthew Keown[1], Ed Fournier[1], Kevin Williams[2], Dave Tack[3], and Benoît Anctil[1]

[1]Biokinetics and Associates Ltd., Ottawa, Ontario, Canada
[2]Defence R&D Canada - Valcartier (DRDC Valcartier)
[3]Humansystems Inc., Guelph, Ontario, Canada

keown@biokinetics.com

Summary

Tests conducted at Defence Research and Development Canada (DRDC) Valcartier have shown that an efficient helmet liner system may be most responsible for reducing potentially serious head injuries from blast induced head accelerations. Although combat helmets are typically designed to protect against ballistic type threats, blast type weapons and low velocity impact on rigid objects present additional hazards to the soldier. It has been speculated that a helmet's ability to protect against blunt impact may be indicative of its ability to protect against blast loading. To investigate this hypothesis a series of energy attenuating systems were tested under impact drop conditions and blast loads with instrumented headforms. Experimental results were compared to establish correlation between blast and blunt impact tests. While a good correlation was found for the top performing liner system, the ranking order of other systems varied according to the test method. As such, it becomes difficult to predict the blast performance of a helmet based on the outcome of the blunt testing. Further analysis could determine whether a better approach for developing a correlation can be found in peak values of acceleration or injury criteria.

1. Introduction

Combat helmets are designed to protect against ballistic threats such as shrapnel from explosive devices and even small arms fire. It is recognized that soldiers often face a number of other threats including those from blast weapons and blunt impacts. A blast wave from an explosive weapon can present a significant threat. The severity of blunt loading, which can result from a fall or impact with a low velocity heavy object, can vary greatly depending on the situation. Ballistic performance aside, a combat helmet is likely capable of providing a reasonable level of protection against both the blunt impact and blast wave threat. Furthermore, it is speculated that performance of a helmet against these two threats is related and blunt impact testing may be used to estimate mitigation performance of blast wave threats.

Previous work by DRDC Valcartier has suggested that the helmet liner system will play a key role in the mitigation of head accelerations, and consequently head injuries, during a blast. To investigate the relationship between protection levels for blunt and blast loading, a number of different helmet liner systems were evaluated. Initially, the liner systems were screened through the completion of simple drop testing. Top performing systems were then subjected to blast testing to determine if the system performance ranking was similar between the two test methods.

2. Materials and Methods

Testing consisted of two separate and independent test methods. The first method which was for impact testing comprised of fitting the helmet onto an instrumented Hybrid III head and neck system that was dropped using a monorail [1]. A typical set-up for a rear impact is shown in Figure 1. From five different drop heights, the head and helmet were allowed to impact a rigid flat steel plate. To assess helmet liner performance over a range of impact severities, the five drop heights were selected to represent impact energies of 30 J, 60 J, 90 J, 120 J and 150 J. These values were selected based on a review of expected energies resulting from a variety of impacts, for example a brick falling from a building or a person falling from a standing position. In addition to the energy levels, the helmet was also impacted at five different locations and these were the front, rear, left and right side and crown.

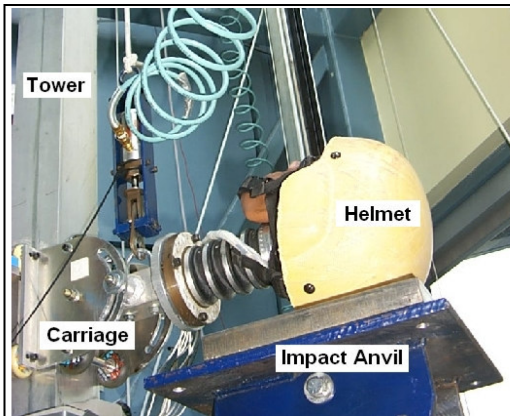

Figure 1: Test set-up.

The second test method was for the performance evaluation under blast loading [2]. As with the impact testing, the blast testing made use of an instrumented Hybrid III head and neck system. Instead of a drop test, these heads were exposed to a free field blast resulting from a 5 kg C4 explosive charge suspended 1.5 m above the ground. The headform was also at a height of 1.5 m and was positioned facing the charge at either 3.5 m or 5.0 m from the charge. For the blast testing, all helmets were fitted with a Med-Eng VBS-250 visor to mitigate direct loading on the dummy face and to prevent the blast wave from propagating directly up into the helmet shell.

While the test method was different, the instrumentation inside the Hybrid III head was similar for the blast and impact loading. Both heads consisted of a nine accelerometer package oriented parallel to the axis system of the headform. The nine signals allow for the measurement and computation of linear and angular acceleration about the head centre of gravity. The sampling rates required for the impact and blast testing were 10 kHz and 500 kHz, respectively. Acceleration signals were filtered with a passive CFC 1000 low pass filter according to SAE J211 recommended practice [3].

The response of the instrumented head was evaluated using a number of available injury prediction tools, each based on the measurement of acceleration inside the headform. First, the acceleration itself was used by determining the peak value. Second is the Severity Index (SI) which was developed for the automotive industry [4] but is also used for the performance evaluation of sports helmets. SI is computed using an integration of the linear acceleration. The third measure was the Head Injury Criterion (HIC). HIC was also developed for the automotive industry to predict the occurrence of skull fracture based on linear acceleration [5]. It is still commonly used in automotive safety research where, for a frontal car crash, an allowable HIC of 700 is specified for a 50th percentile male Hybrid III crash test dummy [6]. Similar to SI, HIC is also based on the time integration of the resultant linear acceleration measured at the head centre of gravity. The difference is that HIC uses a 15 ms integration limit [7]. The last measure is Head Impact Power (HIP). This criterion combines both linear and angular acceleration signals to compute a time history of power imparted to the head [8]. Developed to study injuries resulting from head-to-head contact in American football, HIP was shown to have a better correlation to mild traumatic brain injury than other available measurements.

Considering these four predictors of head injury, it is recognized that each was developed for a specific loading condition under a particular environment, like football or car crashes. To immediately adopt any one of these to predict injury in the current work would require appropriate validation. The loading conditions or even the use of a combat helmet can influence the correlation the response has to the predicted risk of injury. However, it is not the intention at this time to predict injury. Instead, these four injury criteria will be used independently to simply rank one liner system against another based on a reduction of peak acceleration, SI, HIC or HIP.

Table 1: Liner Materials

Liner System	Material	Density (pcf)	Thickness (in)	Description
1	EPS	2.53	3/4	Liner cut to match ACH pads
2	EPS	4.51	3/4	Liner cut to match ACH pads
3	EPP	2.66	3/4	Liner cut to match ACH pads
4	EPP	4.82	3/4	Liner cut to match ACH pads
5	ACH Pad	n/a	3/4	Manufacturer 1
6	ACH Pad	n/a	3/4	Manufacturer 2
7	ACH Pad	n/a	3/4	Manufacturer 3
8	ACH Pad	n/a	3/4	Manufacturer 4
9	ACH Pad	n/a	13/16	Manufacturer 5
10	EPP	3	3/4	9/16” EPP + 3/16” Comfort Foam
11	XPE	2.1	3/4	9/16” XPE + 3/16” Comfort Foam
12	EPP	dual	11/16	3/16” EPP (5.5 pcf) + 1/2" PE (2.7 pcf)
13	Vinyl Nitrile	dual	3/4	3/8” NX210 + 3/8” 405S
14	Vinyl Nitrile	n/a	3/4	3/8” VN600 (2 layers)
15	Vinyl Nitrile	n/a	3/4	3/8” VN740 (2 layers)
16	Suspension	n/a	n/a	Generic suspension/retention system.

The MSA Advanced Combat Helmet (ACH) shell was selected to evaluate the liner systems. Sixteen liner systems were then selected and prepared for use inside the ACH (see Table 1). These systems included different types of foams as well as different densities of similar foams. Some liner systems were products developed for the ACH and consisted of seven individual pads for the sides (two each), the front, back and crown. A typical system of pads is shown in Figure 2. Additional liner systems were cut from flat stock and from shaped EPS and EPP liners using the same pad geometry.

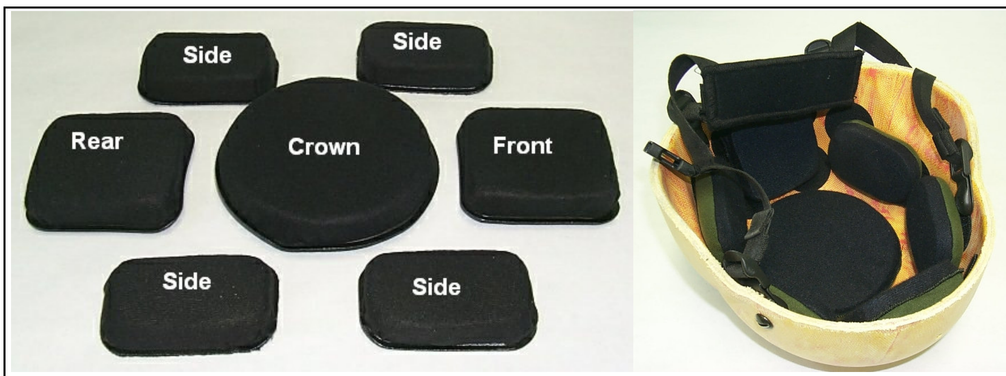

Figure 2: Standard seven pad system for the ACH.

For each test, the centre of the helmet was aligned with the centreline of the test headform. The fore-aft tilt of the helmet was positioned in a repeatable manner using an indexing tool, a device that measures the distance from the headform's nose to the brim of the helmet shell. With the exception of the generic suspension system (shown in Figure 3), the helmet was then secured to the headform using the standard ACH retention system. In all cases, the retention system was tightened to provide a snug fit around the chin of the headform. For repeatability within a given test series, the same technician was responsible for fitting the helmet. Resilient foams were given a minimum of ten minutes to recover before subsequent tests while consumable foams, such as polystyrene, were replaced after each test.

Figure 3: Generic suspension system.

3. Results

The impact tests and blast loading evaluations were completed in sequence with one another. The impact testing was completed first and the subsequent analysis revealed a subset of materials for inclusion in the blast evaluation. As such, only those materials that were subjected to both impact and blast testing will be discussed further.

Two sample traces of resultant linear head acceleration are shown in Figure 4. The impact test was conducted at the 120 J test height on the front impact site while the blast test corresponds to a 5 kg charge at a 5 m stand-off distance. These sample signals are typical with respect to the shape but the magnitude, or peak, of each test was dependant on the impact energy (i.e. drop height) or blast severity (i.e. stand-off distance).

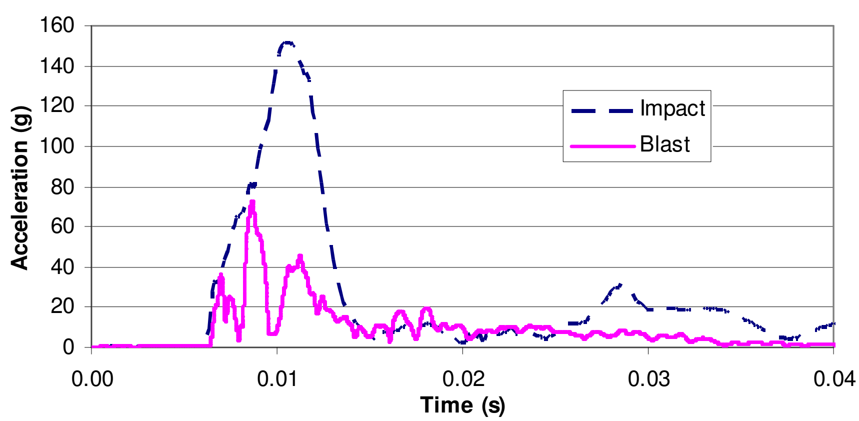

Figure 4: Resultant Linear Head Acceleration (Sample).

For the analysis of the impact testing, the goal was to consider the results of the five impact sites at the five energy levels and produce a list of materials that ranked the best to the worst. For example, the peak resultant acceleration from the front impact site was averaged for the five different impact energy levels. The liner systems were then ranked from lowest to highest average peak acceleration and awarded a score (from 1 to 16). This was repeated for the other impact sites of the helmet, as shown in Table 2. The sum of the individual scores for each liner system resulted in an overall ranking based on acceleration. The same approach was used for the other head injury criteria, namely HIC, SI and HIP.

Table 2: Liner Ranking Based on Linear Acceleration

Score	Front	Rear	Left	Right	Crown
1	EPS 2.53	EPP 4.82	EPP 4.82	VN740	ACH Mfr. 3
2	EPS 4.51	VN740	EPP 2.66	EPP 4.82	EPP 2.66
3	VN600	EPP 2.66	VN600	VN600	VN600
4	VN740	EPS 2.53	ACH Mfr. 3	EPS 2.53	EPP 4.82
5	EPP 2.66	EPS 4.51	EPS 2.53	EPS 4.51	EPS 2.53
6	ACH Mfr. 3	VN600	VN740	VN dual	EPP 3.0
7	VN dual	ACH Mfr. 3	ACH Mfr. 2	ACH Mfr. 3	ACH Mfr. 4
8	EPP 4.82	ACH Mfr. 4	EPP 3.0	ACH Mfr. 2	EPS 4.51
9	ACH Mfr. 2	VN dual	EPS 4.51	EPP 2.66	EPP Dual
10	ACH Mfr. 4	EPP 3.0	ACH Mfr. 4	ACH Mfr. 4	VN740
11	XPE 2.1	EPP Dual	XPE 2.1	ACH Mfr. 1	VN dual
12	EPP 3.0	ACH Mfr. 2	ACH Mfr. 5	XPE 2.1	ACH Mfr. 2
13	ACH Mfr. 5	ACH Mfr. 5	VN dual	EPP Dual	ACH Mfr. 1
14	EPP Dual	ACH Mfr. 1	EPP Dual	ACH Mfr. 5	XPE 2.1
15	ACH Mfr. 1	XPE 2.1	ACH Mfr. 1	EPP 3.0	ACH Mfr. 5
16	Suspension	Suspension	Suspension	Suspension	Suspension *

* Impacts to the crown were not completed due to damage incurred during testing at other impact sites.

Five liner systems were selected to advance to the blast testing as listed in Table 3. The rationale for the selection of each material includes the combined ranking scheme of the different injury criteria with representative samples from each material type.

Table 3: Selected Liner Systems

Ranking	Liner System	Type	Rationale
1	14	VN600	Best performing of the vinyl nitrile materials tested.
2	1	EPS 2.53	Best performing of the expanded polystyrene materials tested.
3	4	EPP 4.82	Best performing of the polypropylene materials tested.
4	7	ACH Mfr. 3	Best performing off-the-shelf pad system available for the ACH.
5	16	Suspension	Helmet without padding for a worst-case baseline.

These five liner systems, with the addition of a bare head configuration, were evaluated against the blast loading. At the stand-off distances of 3.5 m and 5.0 m, each configuration was tested twice, against two different blasts. Given the variability between blast effects with the same mass of C4, the resultant acceleration and other injury criteria computations were normalized using the blast impulse. For a blast, the impulse is defined as the integral of the pressure pulse as a function of time. The normalized peak values were averaged for the different pad systems and stand-off distances. While it is recognized that the number of tests may not provide statistically significant data, restrictions in time and budget limited the number of repeated tests to only two.

Using the normalized results, the liner systems were ranked in order of performance for peak resultant acceleration, HIC, SI and HIP for each stand-off distance of 3.5 m and 5 m. Each liner system was awarded a ranking score (from 1 to 6) for each combination of injury criteria and stand-off distance. The sum of these scores provided an overall ranking for the liner systems, with the lowest scores representing the best performance.

The liner system ranking from both the blast and impact tests are shown in Table 4. Liner system 14, the VN 600, was found to perform the best under both loading situations. The remainder of the liner systems did not show any correlation to one another as the order is significantly different. The suspension system and bare head configurations were the poorest performing in both the blast and impact tests. It is noted that while the bare head was not actually evaluated during the impact tests, it would have certainly been rated the worst as compared to any of the other helmet liners.

Table 4: Liner System Ranking Based on Blast and Impact

Liner System	Ranking Based on: Blast Results	Impact Results
14	1	1
7	2	4
4	3	3
1	4	2
Bare	5	6*
16	6	5

* - not tested

Several important observations were noted during the trials. For the blast trials, post blast rotation of the helmet and visor was observed for some tests and it was found that this rotation resulted in higher peak acceleration values when compared to a helmet that did not rotate. The effect of this rotation was not studied with respect to the type of helmet liner because in high-speed video, the headform was often obscured by the fireball and smoke. Since some materials were cut from flat stock, comfort and fit was not a consideration and concern is raised as to whether or not the fit affected the amount of helmet rotation.

In the drop testing, the highest drop height was not completed for all the liner systems due to risk of instrumentation damage as accelerations exceeded acceptable levels. In the previous ranking based of blunt impact performance, the 150 J impacts were not considered. For the impacts to the left and right sides of the helmet, different impact points were selected. On the left side, the impact point was above the raised ear portion while on the right side, the contact patch on the anvil included a point on the raised ear portion and a point on the curvature above. The response was different between the impact sides due to the proximity of the impact point to the padding behind the shell. This directional effect was not considered with the blast loading, which was applied only from the front.

4. Conclusions

The helmet liner system that was found to offer the greatest level of protection against blunt impact was also the best performing helmet in the C4 blast loading condition. This is an interesting and promising result for that particular liner system. For the current work, this result supports the notion that a correlation may exist when evaluating an impact attenuating material based on the performance of two different test methods, namely impact and blast wave loading. Similarly, the two worst performing systems were the suspension system and the bare head, neither of which offers any significant impact attenuation, and they both performed poorly in both test methods. However, the ranking system fails when considering the three remaining materials. In fact, the ranking order is completely opposite from the blast to the impact results. This suggests that ranking the systems may not be the most appropriate method for developing a performance correlation.

There are reasons why the ranking system may not have worked as well as it could have. First, the ranking in each of the test methods was based on a combination of resultant acceleration, HIC, SI and HIP. These injury criteria were all developed on the premise of a contact-type impact. While drop-test impacts certainly involved contact, the blast loading is considered a non-contact event. As such, the head response, as measured by linear acceleration, could falsely alter the outcome of one or more of the injury criteria. Impact duration could also affect the applicability of these injury criteria. Additional effort should focus on selecting the most appropriate injury criteria for the loading conditions. Then a correlation could possibly be developed to predict the outcome of the blast loading based on results from blunt impacts.

To accomplish this difficult task, further simplification is likely required. Another reason for the difficulties with the ranking system may be due to loading direction. The ranking based on the blunt loading response considered five different loading directions while the blast load was only frontal. It may be that a better correlation in the ranking against the two methods would have been possible if only the frontal blunt impacts were considered. If a correlation can be developed to predict the blast response for frontal loading, additional blast testing along the other loading directions can be evaluated against the different loading directions exercised in the blunt impact testing.

Throughout the current work, the ballistic protection level of the helmet has not been considered. It should not be ignored, however, as ballistic protection is often the primary design goal of a combat helmet. Work is ongoing to investigate how the ballistic protection of the ACH shell is affected by these six different helmet liners by evaluating the behind armour blunt shell loading. Future work will aim to further develop the performance correlation to include injury response against blunt impact, blast overpressure and ballistic threats.

5. Acknowledgement

The work presented here was supported by Defence R&D Canada – Valcartier. The authors are thankful to Mr. Doug Baines and Mr. David Sullivan of Biokinetics and Associates Ltd. for their support during the blunt impact testing. The authors would also like to acknowledge the support provided by the Munitions Experimental Test Centre (METC) during the blast trials.

6. References

1. Fournier, E., Keown, M. (2005). *Performance Assessment of Helmet Liner Material: Blunt Impact*. Report No. R05-06, Biokinetics and Associates Ltd., Ottawa, Canada, July 6, 2005.
2. Fournier, E. (2006). *Performance Assessment of Helmet Liner Material: Blast Loading.* Report No. R05-26, Biokinetics and Associates Ltd., Ottawa, Canada, January 27, 2006.
3. SAE (1995). *Instrumentation for Impact Test – Part 1 – Electronic Instrumentation.* J211-1, SAE International, Warrendale, Pennsylvania, March 1995
4. Gadd, C. W. (1966). *Use of a Weighted-Impulse Criterion for Estimating Injury Hazards.* Proceedings of the 10th Stapp Car Conference, Holloman Air Force Base, New Mexico, November 1966.
5. Versace, J. (1971). *A Review of the Severity Index.* Proceedings of the 15th Stapp Car Crash Conference, Los Angeles, California, November 1971.
6. NHTSA (2000). *Occupant Crash Protection,* Standard No. 208, Part 571, Federal Motor Vehicle Safety Standards, Department of Transportation, National Highway Traffic Safety Administration, Washington, D.C., May 2000.
7. SAE (1996). *Injury Calculations Guidelines*, J1727, SAE International, Warrendale, Pennsylvania, August 1996.
8. Newman, J. A., Shewchenko, N. and Welbourne, E. (2000). *A Proposed New Biomechanical Head Injury Assessment Function- The Maximum Power Index.* Proceedings of the 44th Stapp Car Crash Conference, Atlanta, Georgia, November 2000.