Results of a Round Robin Ballistic Load Sensing Headform Test Series

M.M.G.M. Philippens[1], B. Anctil[2], K.C. Markwardt [3]

[1]*TNO Defence Security and Safety, P.O. Box 45, 2280 AA, The Netherlands*
mat.philippens@tno.nl
[2]*Biokinetics and Associates Ltd, 2470 Don Reid Dr., Ottawa, Ontario, K1H 1E1, Canada*
[3]*US Army Aberdeen Test Centre, Protective Equipment Division, 400 Colleran Road, Aberdeen Proving Ground, MD 21005-5059, USA*

Abstract.
The majority of methods to assess the behind armour blunt trauma (BABT) risk for ballistic helmets is based on plastic deformable headforms. An alternative, the Ballistic Load Sensing Headform (BLSH) can record the dynamic contact force between helmet back face and the skull. Helmet BABT methods are still under development and outcomes are highly sensitive to test procedures. A test method for the BLSH has been developed, as there was no method available, and evaluated in a round robin series performed by three laboratories, using the same procedure and their own headform, data acquisition and processing. Helmets were tested three times at front, rear and both lateral sides. Peak contact force is used as performance criterion. The peak force varies between 3.536 kN and 10.110 kN depending on location. This is to a large extend caused by a significant variation in stand-off which occurs despite the strict positioning procedure of the helmet. Results become more consistent by statistically correlating peak force and stand-off. However a significant spread within each laboratory remains, which needs further exploration. It is expected that peak force is too sensitive as it is a high frequency phenomena and the tested helmets are not designed to control nor optimize the BABT contact force. It appears that there is systematic difference between laboratories which is not understood. The helmet BABT risk assessment method needs further development to allow inter laboratory comparison and is therefore not acceptable for a test standard. However it is very useful for research purposes and helmet optimisation knowing the vulnerable and sensitive aspects. The scattered response requires a statistical approach and consequently multiple helmet test are required to allow for meaningful conclusions.

Keywords: Helmet, BABT, Test Method, BLSH, Round Robin.

Results of a Round Robin Ballistic Load Sensing Headform Test Series

M.M.G.M. Philippens[1], B. Anctil[2], K.C. Markwardt[3]

[1]*TNO Defence Security and Safety, P.O. Box 45, 2280 AA, The Netherlands*
mat.philippens@tno.nl
[2]*Biokinetics and Associates Ltd, 2470 Don Reid Dr., Ottawa, Ontario, K1H 1E1, Canada*
[3]*Aberdeen Test Centre, Protective Equipment Division, 400 Colleran Road, Aberdeen Proving Ground, MD 21005-5059, USA*

1. INTRODUCTION

The protective performance assessment of ballistic helmets has traditionally focused on quantifying the capability to stop high velocity projectiles. New fibre reinforced composites do enhance this capability significantly but at the cost of larger back face deformations. Helmet back face contact with the skull can lead to so called behind armour blunt trauma (BABT). Borrowing from the approach used in body armour test standards, headforms [1] with deformable clay witness material are used to measure back face deformation. These headforms are simple and provide a direct assessment of the local helmet deformation behind the impact location. However, testing is labour intensive and detailed calibration procedures are required to ensure that clay deformation characteristics are within tolerance. In addition, the clay does not simulate head skull stiffness and relationship between back face deformation and head injury is unknown. The Peep Site Headform [1] was developed recently to overcome practical issues but the lack of correlation with injury remains a major drawback. Sensor based headforms have been proposed as an alternative. The UVA headform [1][2] is a 50th percentile Hybrid III headform equipped with PVDF sensors to quantify the back face contact pressure between helmet and skull. An injury risk curve was developed to predict the occurrence of skull fracture from contact pressure measurements [2]. The Ballistic Load Sensing Headform (BLSH) [3][4][5] is another sensor based headform that is commercially available. It is equipped with a force sensor array which allows measurement of the back face contact forces at seven distinct locations on the skull. A fracture risk curve for the BLSH was derived from previous work by Bass et.al. [2] and confirmed by Raymond [6][7] who also verified the biofidelity of the skull compliance and attenuation. The BLSH is used by different laboratories but there is no general accepted test method. Using the approach presented by Bolduc et.al. [9], a test method for BABT risk assessment was developed for the BLSH [8]. A round robin series was performed by three laboratories to verify the robustness of proposed method. Each laboratory was required to perform the BABT evaluation according to the same test procedure using their BLSH, data acquisition system and processing algorithm. All three headforms are of the same make, version and use the same load sensors. The outcome of this round robin is presented herein.

2. MATERIALS AND METHODS

2.1. Samples

The helmets for all laboratories were provided by the Clothing and Personal Equipment department of the Dutch MoD, were manufactured in 1996-1997 but not restricted to one lot, batch etc. For better consistency, the helmets were hand-picked and visually inspected for unacceptable damage, wear and tear. Medium size combat helmets were selected to fit the ISO J shape of the BLSH. Helmets, suspension and retention systems were of the same type and brand

Figure 1. Shell Only

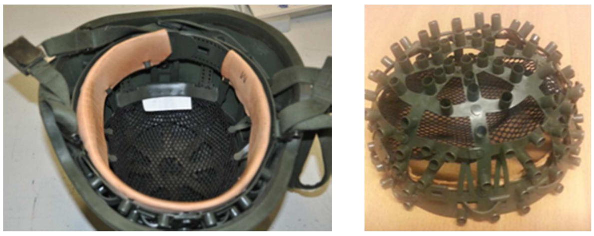

Figure 2. Complete Helmet and Suspension System

The round robin series was performed in two test configurations:

1) Shell only, with retention system and stand-off holders, Figure 1;
2) Helmet system with standard suspension and retention system, Figure 2.

The test with only the shell were performed to provide an better defined stand-off compared to the full helmet system and omit the influence of the suspension system on the force response.

2.2. Equipment

The general description of the BLSH can be found in earlier publications, [5][9]. The front-rear and left-right (lateral) headforms were used for the round robin test series. The centre off the middle load cell was aligned with the line of fire. The headform's impact pad surface was oriented perpendicular to the line of fire, Figure 3.

Figure 3. BLSH Alignment

The load cells were covered with a polyurethane skin pad to provide compliance similar to the skull-skin of a human cadaver [6]. The BLSH impact response was verified for consistency using a 2.2 kg pendulum (100 mm dia., 3.9 m/s), setup illustrated in Figure 4.

Figure 4. Pendulum Setup

2.3. Data Acquisition and Post-Processing

The force gauge signals were recorded at a sampling rate of 100 kHz with a 10 kHz anti-aliasing filter. The recorded force data was filtered digitally with a phase less 2nd order cascade Butterworth low-pass filter having a cut-off frequency of 4.5 kHz. The total force was calculated by adding the seven filtered signals. The maximum of the resulting total force time trace (peak total force) is the response parameter correlated to the BABT injury risk.

2.4 Test Procedure

The tests were performed at ambient conditions (18-22 ºC, 30-50% relative humidity). Helmet samples and test equipment were kept at these conditions for at least 4 hours prior to testing. 9 mm full metal jacketed (FMJ) bullets (124 gr, Remington Part No. REM 23558), as defined in NIJ 0101.06, were fired at 415 m/s ± 10 m/s. The projectiles were launched from the 9 mm Luger rifled barrel (1 in 250 mm twist).

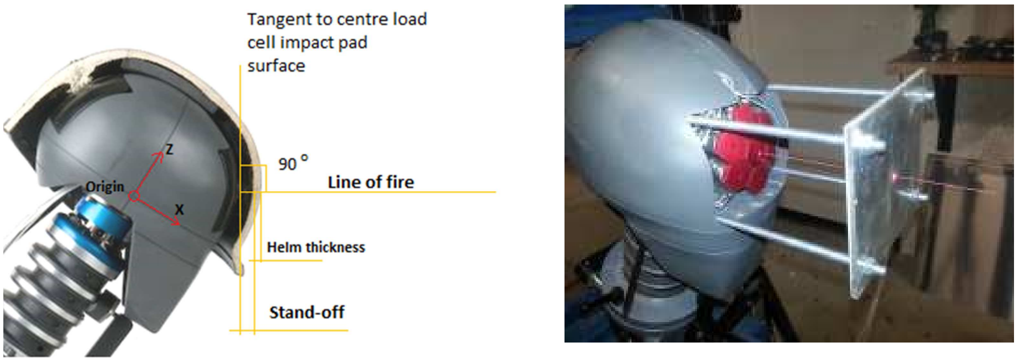

Figure 5. Definition off stand-off, line off fire (l.o.f.) alignment and origin for 3D measurement system

The line of fire (l.o.f.) alignment is performed by a laser bore in the weapon and an alignment tool. A small hole in the plate aligns perpendicular with the centre load cell. Stand-off was measured with two methods, a 3D measuring tool and a laser distance gauge. The 3D measuring arm was not available for the whole test series. After alignment of the headform and the line of fire, the skin pad is replaced over the load cells. The intersection of the line of fire and the skin pad is marked by the laser bore. In case of the laser gauge method, the laser gauge is aligned with the line l.o.f.

Figure 6. 3D measuring tool

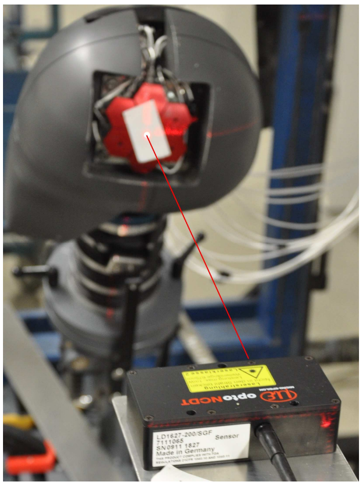

Figure 7. Laser gauge l.o.f. alignment

The stand-off measuring procedure for both methods:

	3D measuring tool	Laser distance gauges
1	Measure skinpad-l.o.f. intersection: SP(x,y,z)	Measure distance skinpad-l.o.f. intersection: D
2	Position the helmet on the headform	
3	Mark the intersection of the helmet shell and l.o.f	
4	Remove helmet from headform	
5	Measure the thickness of the helmet at the helmet-l.o.f. intersection: Ht	
6	Reposition the helmet – helmet-l.o.f. mark aligned with l.o.f.	
7	Measure the helmet-l.o.f. intersection: H(x,y,z)	Measure distance to helmet- l.o.f. mark :H
8	Stand-off = $\lvert SP(x,y,z)-H(x,y,z)\rvert$- Ht	Stand-off = D-H-Ht

The (laser) procedure is illustrated in Figure 8.

a) Measure distance to skin pad – l.o.f. intersection.
b) Position helmet and mark shell - l.o.f. intersection.
c) Measure shell thickness at l.o.f. mark
d) Reposition helmet
e) Measure distance shell-l.o.f. mark prior to test

Figure 8. Illustration of the laser gauge stand-off measuring procedure

Shell only tests were performed for the frontal location only. Custom made holders located over the lateral and rear load cell areas were used to control the stand-off distance between the helmet backface and the surface of the skin pad. A piece of foam in the crown area was attached using Velcro$^{(TM)}$. Three M6 bolts and nuts with a plastic washer were mounted in the holes originaly used for attachment of the retention system, Figure 9.

Full helmet system tests were performed for the three locations on the helmet corresponding to the BLSH front, left and right sensing positions. The adjustable band strap and height adjust band of knob band helmet were set to a predefined position, Figure 10.

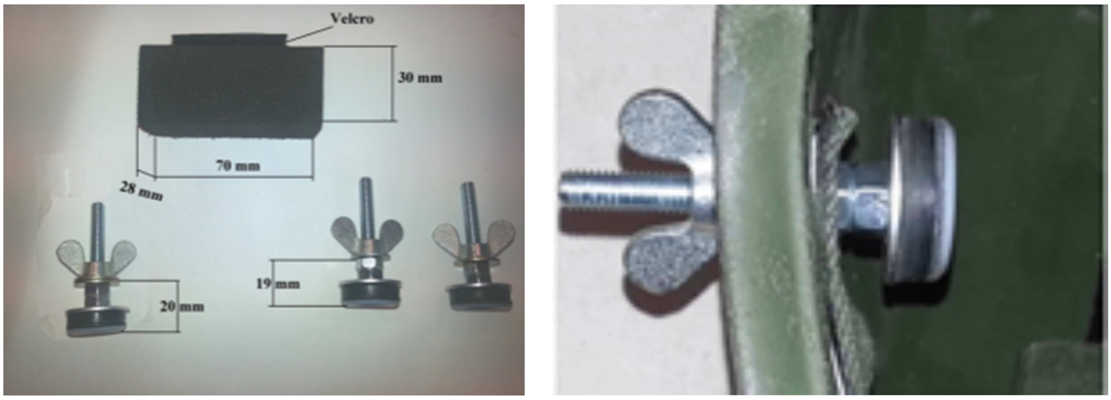

Figure 9. Foam and Bolt Kit

Figure 10. Band Strap Settings

Helmet samples were positioned using the headforms' reference lines. The helmet mid sagittal plane was aligned with the mid sagittal line on the headform, Figure 11. Shell only and complete helmet systems ended up in a similar position on the headform.

Each test was performed on an undamaged (not tested before) helmet. Each condition was repeated three times. A total of 12 tests (3 on shells only, 9 on complete helmet systems) were performed by each laboratory for the round robin series.

Figure 11 Alignment of helmet with headform

3. RESULTS

3.1 Pendulum Verification Testing

Changes in skin pad during the round robin series could only be verified by one laboratory (Lab 2) with the pendulum verification test procedure. An average peak total force of 4390 N was measured. The largest difference between the pre and post values (134 N, 3%) was observed for the front location while the lowest difference was obtained for the left side (16 N, 0.4%). All post-test values were lower than pre-test values. However the difference is well within the variations for the round robin results.

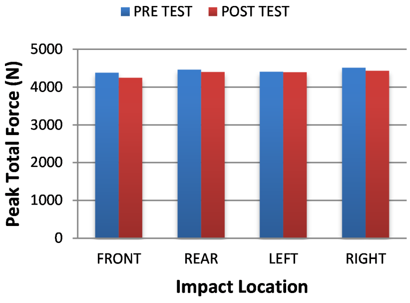

Figure 12. Pendulum Test Results

3.2 Loading Conditions

The measured bullet velocities were all within requirements (415 ± 10 m/s) but more variability was noticed for Lab 2 as shown in Figure 13. Stand-off distances were measured before each test. It is a parameter used to characterize input loading conditions. A lower stand-off distance will result in a higher impact force for a given bullet velocity. Rather large stand-off differences were observed between Lab 1 and Lab 2 for the front shell only condition (no data available from Lab 3). More variability was noticed for the two side locations in comparison with front and rear locations (Figure 14).

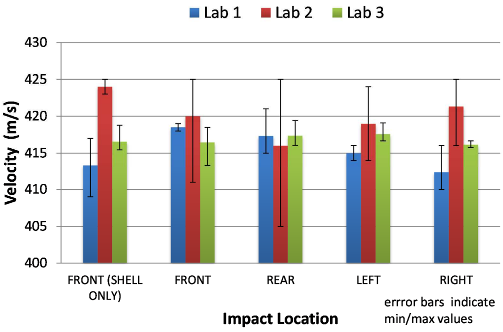

Figure 13. Bullet Velocity.

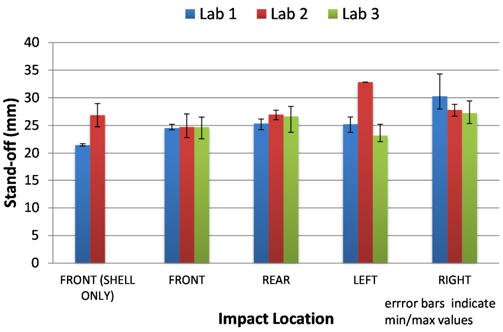

Figure 14. Helmet Stand-off

Figure 13, Figure 14show results for the shell only and for all four locations for the full helmet system: helmet fitted with retention and original suspension system.

3.3 Impact Force

Filtered force signals for the front location are compared in Figure 15 to Figure 17 to illustrate the responses recorded by the three laboratories. Impact force was focused on the centre load cell (Load Cell 1) but significant contribution was registered from the remaining 6 load cells. The total force is the sum of the force time history of all seven load cells.

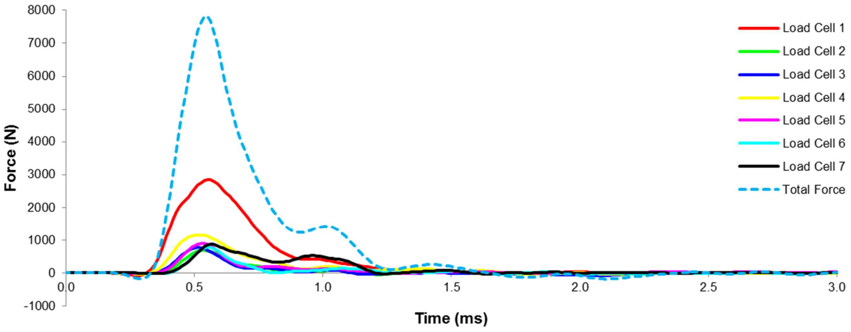

Figure 15. Force Signals (Lab 1, Front, Velocity=419m/s, Stand-off=24.2mm)

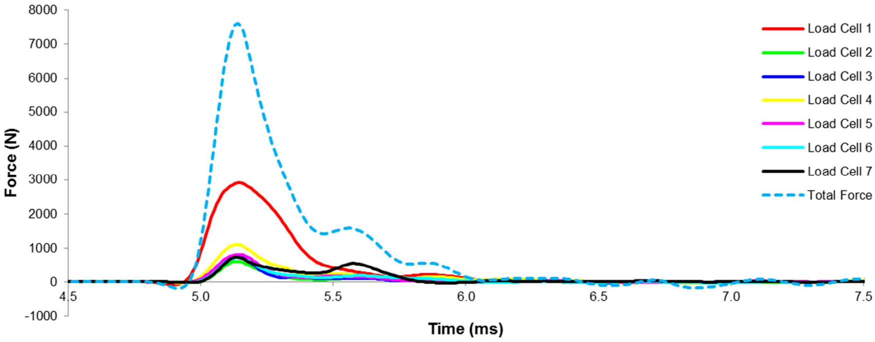

Figure 16. Force Signals (Lab 2, Front, Velocity=424m/s, Stand-off=22.8mm)

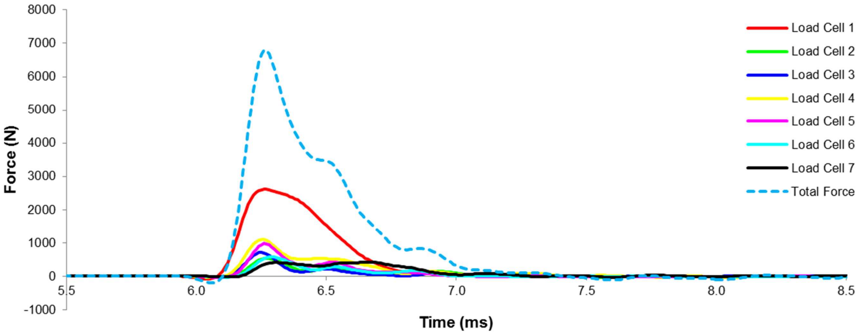

Figure 17. Force Signals (Lab 3, Front, Velocity=419m/s, Stand-off=26.5mm)

The peak total force values recorded for each location are summarized in Figure 18. Results varied between 10110 N and 3534 N for all laboratories and all locations. The largest difference in averages between laboratories for the same impact location is 2813 N for left lateral, see Figure 18 fourth data set, labeled left. The ranges of peak total forces (difference between maximum and minimum values) for all results are for

shell only	3066 N
front	2058 N
rear	4080 N
left	5367 N
right	4601 N

Maximum difference between laboratories is 5367 N for the left lateral location.

Range in peak total force for one location for each lab, see Figure 19, is for:

- Lab 1: maximum 1760 N and minimum 592 N
- Lab 2: maximum 4601 N and minimum 238 N
- Lab 3: maximum 2462 N and minimum 489 N

As expected, inverse relationships were observed between the stand-off values and peak total force. Lower stand-off values corresponded generally to higher peak total force measurements. Figure 22 and Figure 21 illustrate the findings between peak total force and stand-off as derived from the results of the three laboratories combined for, respectively, all front location tests and combined left and right lateral tests.

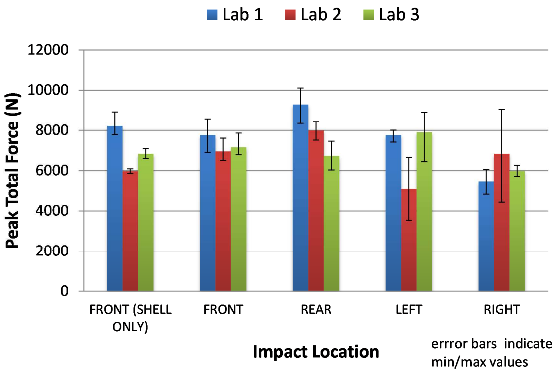

Figure 18. Peak Total Force

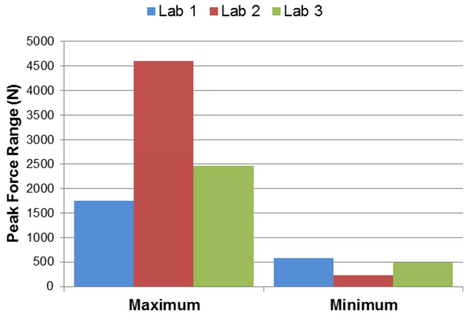

Figure 19. Maximum and Minimum Ranges

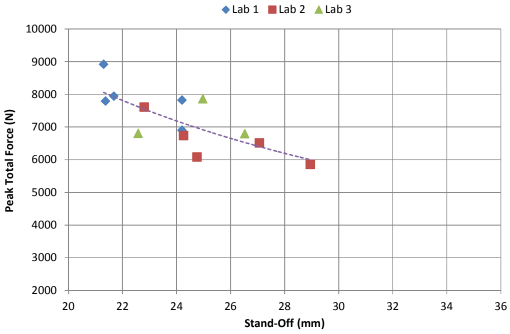

Figure 20. Peak Total Force – stand-off, front

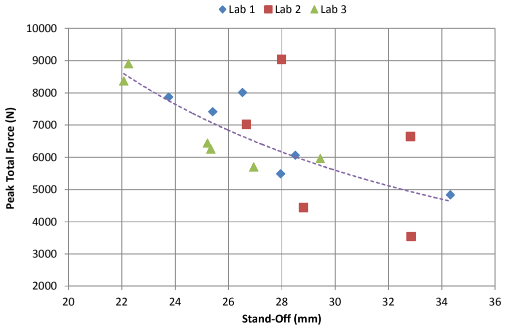

Figure 21. Peak Total Force – stand-off, lateral

The three smallest lateral stand-offs were recorded for the left hand side for Lab 1 and Lab 3. These correspond with the highest peak forces compared to the peak forces for the lateral side. Results of Lab 2 are more scattered and less consistent in the peak force / stand-off correlation.

4. DISCUSSION

These findings highlighted the complexity of ballistic helmet evaluation and the need to control experimental parameters (Figure 22) to achieve repeatable and reproducible results. Possible sources of error associated with the present study are reviewed hereafter.

Bullet product number was specified to ensure that the laboratories used the same projectile built according to the manufacturer's tolerance. Bullet speed was controlled but variation corresponding to a maximum of 5% of the target velocity was allowed. These parameters, in addition to yaw angle and impact location may have affected the results but the requirements were comparable to existing methodology for personal ballistic protection systems. Wear of the barrel rifles can also effect the break up of the projectile. More stringent control on bullet characteristics should be considered but is less practical and less cost effective in the context of standard testing.

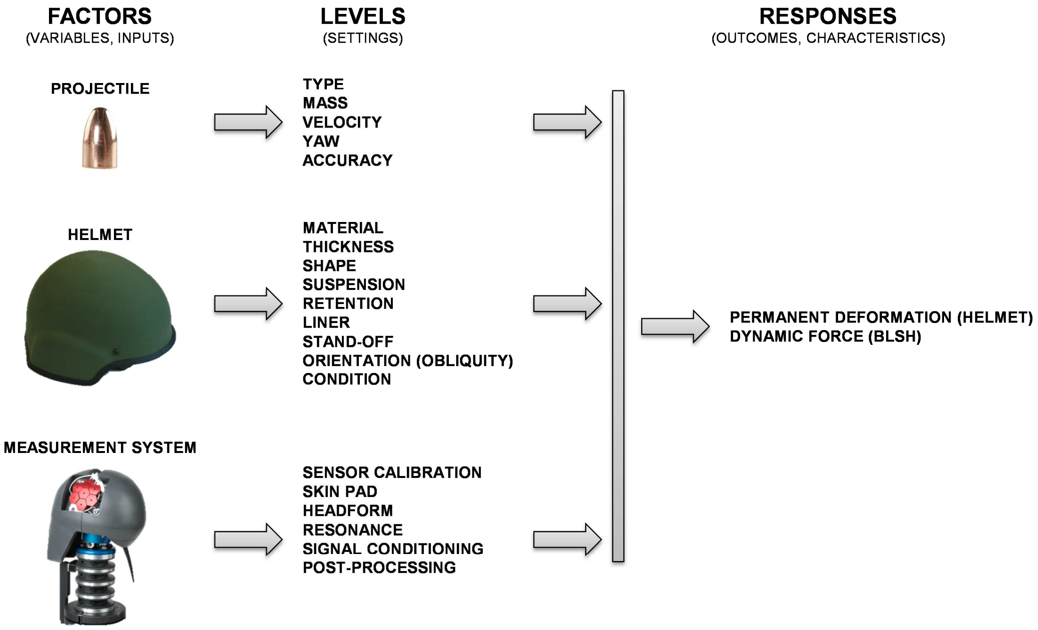

Figure 22. Experimental Parameters

Test samples (helmets) were previously used for training by soldiers. In some cases, helmet shells were deformed (not symmetrical) as shown in Figure 23. It is not known how the degradation of shell material, suspension or retention systems could have affected the force measurements but it can only be quantified by comparing the results obtained with new combat helmets of similar construction.

Figure 23. Deformed Helmet Shell

However, the FSP V_{50} did not change over the years as shown in Figure 24 . Note that these helmets are not designed to control back face contact force. BABT requirement for these helmets is a maximum backface deformation of 20 mm for a 1.1 non penetrating FSP.

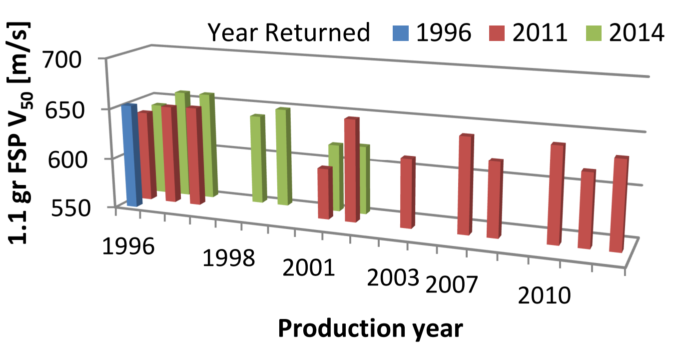

Figure 24. 1.1 FSP V_{50} for different production years and period in use.

Delamination of the helmet runs close to, or into, the rim of the helmets. In previous tests it was found that different composite fibre webbing densities were used, which does not affect the penetration resistance but resulted in significant differences for the back face deformation. The helmet type tested has a hole at the rear for attachment of the retention system which was over the area of the rear load cell array.

The pendulum test results suggest that the BLSH response was not affected by the ballistic loadings. Unfortunately, only one laboratory was able to perform such evaluation. The pendulum system was designed to reproduce the momentum of behind armour loading but it does not replicate the loading rate experienced during helmet backface deformation. A pendulum is a practical tool for laboratory testing but it is a compromise between repeatability and accurate representation of field conditions. To further investigate the measurement system response under dynamic loading, additional tests were performed with a cylindrical 37 mm diameter, 0.093 kg projectile launched with an air cannon (Figure 25). The distance between the headform and the barrels end was less than the projectiles length. This creates a guided impact to control target location and yaw angle. Headforms from Lab 1 and Lab2 were evaluated at the same laboratory.

Figure 25 Air Cannon Test Setup

Figure 26 shows the peak total force as a function of the projectile velocity for the right and left locations. Results between the two headforms are similar at velocities lower than 30 m/s but a significant gap exists for the right location at 30 m/s. The higher peak force response for Lab 1 is in line with the higher peak forces found for the right lateral helmet test. However, it appears that the smaller stand-off for the right hand side dominates over the difference found in this air cannon test.

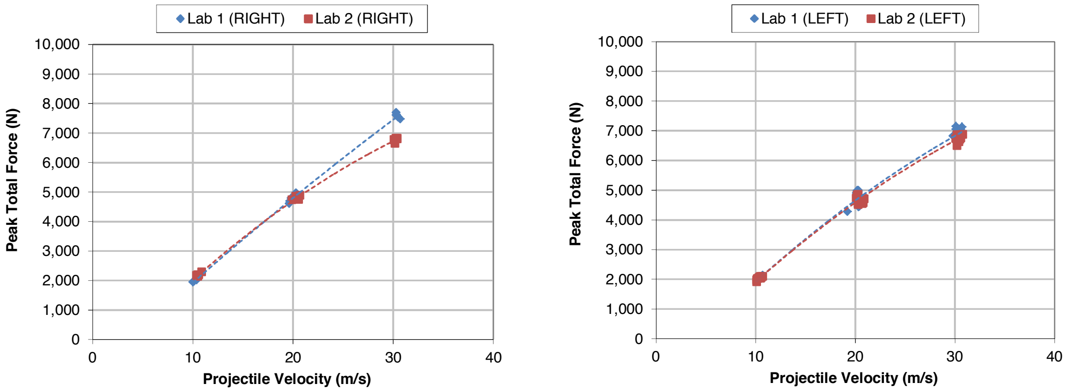

Figure 26. Air Cannon Test Results

Other parameters than the peak total force may be better suited to quantify the risk of BABT associated with combat helmets. A small variation in the force response has a significant effect on the peak force value because of the high frequency content of the signal. A combination of parameters such as force and time duration maybe less sensitive to small variation in loading conditions and represent the energy transfer which will more likely correlate to the mechanical response and injury risk. A force-time based injury assessment reference value is not available at this moment. This will need to be investigated further to select the most relevant force signal features.

5. CONCLUSION

Comparable trends were obtained between the three laboratories but the response variability is too high for the BLSH method to be used in a ballistic helmet standard. The BLSH response was found to be sensitive to helmet setup, i.e., stand-off, symmetry. Results are also sensitive to impact location. Helmet design can contribute to this but could not be isolated from the results. Based on the strong relationship between force and helmet stand-off, the stand-off needs to be incorporated in the data analysis and consequently measurement of stand-off should be performed accurately. An in-depth review of force signal features will help to identify a better suited parameter to quantify BABT injury risk. In the interim, the BLSH can be used as a research and development tool to evaluate helmet integral design, material technologies, geometry and components to help reduce head loading from backface deformation paying attention to the above discussed issues affecting the peak total force response.

Acknowledgement

The authors want to acknowledge the Clothing & Personal Equipment branch Defence Material organization of the Netherlands Ministry of Defence

References

[1] Testing of Body Armor Materials: Phase III, Committee on Testing of Body Armor Materials for Use by the U.S.Army--Phase III; Board on Army Science and Technology; Division on Engineering and Physical Sciences; National Research Council, ISBN 978-0-309-25599-8

[2] Bass C.R., Boggess B., Bush B., Davis M., Harris R., Rountree M.R., Campman S., Ecklund J., Monacci W., Ling G., Holborow G., Sanderson E., and Waclawik S. Helmet behind armor blunt trauma. Specialist Conference on Human Factors in Medicine, Koblenz, Germany 2003.

[3] Anctil B., Bourget D., Pageau G. Rice, K. and Lesko J. Evaluation of Impact Force Measurement Systems for Assessing Behind Armour Blunt Trauma for Undefeated Ballistic Helmets. Personal Armour Systems Symposium, The Hague, The Netherlands, 2004

[4] Anctil B., Keown M., Bourget D. and C. Pageau. A novel test methodology to assess the performance ballistic helmets. 22nd International. Symposium on Ballistics, Vancouver, Canada, 2005

[5] Anctil B., Keown M., Bourget D., Pageau G., Rice K. and Davis G. Performance Evaluation of Ballistic Helmet Technologies. Personal Armour Systems Symposium, Leeds, UK, 2006

[6] Raymond D.E., Biomechanics of Blunt Ballistic Temporo-Parietal Head Impact, PhD Dissertation, Wayne State University, Detroit, Michigan, 2008

[7] Raymond D.E., Van Ee C., Crawford G. and Bir A.C., Tolerance of the Skull to Blunt Ballistic Temporo-Parietal Impact, Journal of Biomechanics, vol. 42. Pp 2479-2485, 2009.

[8] Philippens M., BABT protection for composite ballistic helmets; Ballistic Load Sensing Headform & Suspension System; TNO report TNO2014 R10151, Technical Sciences, P.O. Box 2280 AA Rijswijk, The Netherlands, 2014

[9] Bolduc, M, Anctil, B. Improved Test Methods for Better Protection, a BABT Protocol, Proposal for STANAG 2920, Personal Armour Systems Symposium, Quebec, Canada, 2010