The Development of a Ballistic Helmet Test Standard

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Abstract

With the results of recent impact biomechanics research and the latest progress in ballistic resistant composite materials, it became important to address the deficiencies of performance evaluation methods for ballistic helmets. Current procedures were not based on scientific studies and were not systematically updated to address the evolution of ballistic materials.

Since February 2006, a CSA Technical Committee (Z613) has been working on the preparation of an updated performance standard for ballistic helmets. In addition to the three types of ballistic tests considered (penetrating impact assessment (V_{proof}), Behind Armour Blunt Trauma (BABT) assessment, and ballistic limit (V_{50})), other important aspects were included. Helmets will also be evaluated for retention system strength, helmet stability, and non-ballistic impact attenuation. Ballistic performance levels were also reviewed to include relevant threats to corrections, law enforcement, and military personnel.

The proposed approach is thorough and addresses a wider range of threats. The outcomes should lead to improved helmet designs providing better protection for the users.

Introduction

The need to update ballistic helmet test performance standards arose when recent impact biomechanics research [1] concluded that existing test methods were not suitable to evaluate the risk of Behind Armour Blunt Trauma (BABT). Modernization of ballistic helmet standards became also more relevant with the introduction of lightweight composite materials that are particularly compliant under impact. While these new lightweight helmets have increased protection against penetration, large backface deformation having the potential of causing serious head injuries can be observed under non-penetrating handgun bullet impacts conditions as shown in Figure 1.

Figure 1: Shell deformation from a defeated handgun bullet.

Current ballistic helmet test methods [2, 3, 4, 5] were developed several years ago. They were not based on ballistic impact biomechanics, and were not regularly updated to take into account the technical progress in ballistic resistant composite materials.

The National Institute of Justice (NIJ) Standard 0106.01 (1981) for ballistic helmets [2] includes procedures to evaluate penetration resistance and transmitted force. Penetration resistance is evaluated using 2 helmet samples per test ammunition. The first helmet is tested at ambient condition while the second sample is evaluated after wet conditioning. Helmets are positioned on headforms (Figure 2) and shot at four impact locations: rear, front, left, right. Penetration at any location constitutes a failure. The impact force transmitted to the head is evaluated using a headform assembly free to translate in the same direction as the bullet trajectory (Figure 3). One helmet is tested at ambient condition and shot at four impact locations: rear, front, left, right. The peak linear acceleration must not exceed 400 g's to meet the requirement of the standard. The correlation between this approach and head injury is unknown.

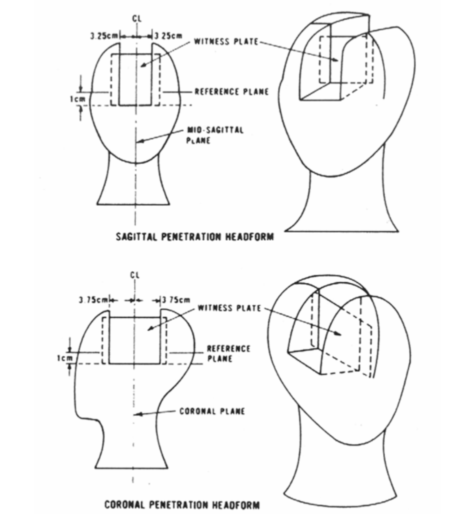

Figure 2: Penetration headforms [2].

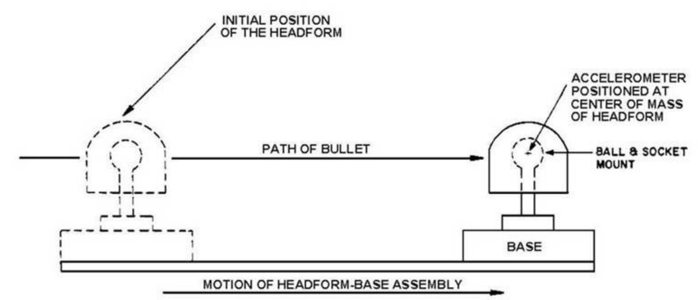

Figure 3: Transmitted force evaluation device [2].

Another method was developed by H.P. White Laboratories [4] which uses a similar approach to NIJ 0106.01 for assessing penetration resistance with a modified version of the headform shown in Figure 2. For non-penetrating impacts, the headform cavities are filled with clay and helmet performance is evaluated by measuring the maximum indentation but no pass/fail criteria are proposed in this method. This approach has also no direct correlation with head injury assessment.

The NATO standard on personal armour and combat clothing, STANAG 2920 [5] addresses the ballistic penetration resistance of helmets but there is no requirement for non-penetrating impacts. When describing the requirements to purchase large helmet quantities, product specifications typically refer to the above test procedures to define performance criteria. Current combat helmet specifications, for example, only state a maximum indentation in clay to assess the non-penetrating impact performance.

The deficiencies of these methods were recognized many years ago when the NATO behind armour blunt trauma TG001 specialist group was formed to study the effects of non-penetrating ballistic impact to the head and thorax. Further research in this area was led by Defence R&D Canada-Valcartier [6, 7, 8], US Army Natick Soldier Center [9, 10, 1] and the Délégation Générale pour l'Armement (DGA) [11, 12] in France.

In the research program conducted by Bass *et al.* at the University of Virginia [9, 1] for the US Army Natick Soldier Center, the physical response of a helmeted surrogate head (modified Hybrid III headform) was characterized for a series of ballistic impacts. Experimental setup and test conditions were reproduced with Post Mortem Human Subjects (PMHS) to identify the most suitable biomechanical parameter for predicting the risk of injury. The results showed that the dynamic peak force measured at the surface of the skull correlates well with the occurrence of skull fracture [10]. The outcomes of this work were used to develop a transfer function to transpose the injury risk curve from the PMHS to a head surrogate for non-penetrating ballistic impact tests.

Following efforts by Anctil *et al.* at Biokinetics and Associates Ltd. [6, 7, 8] for Defence R&D Canada-Valcartier produced a ballistic load sensing headform (Figure 4) capable of measuring helmet backface loading. The availability of this tool set the basis to update ballistic helmet test performance standards.

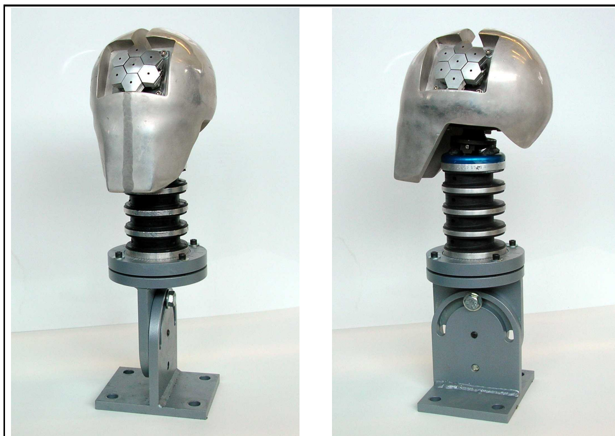

Figure 4: Load sensing headforms (fore-aft, side).

In February 2006, the first meeting of the Technical Committee (TC) on Ballistic Helmets (Z613) of the Canadian Standards Association (CSA) was held to define the objectives of the new standard. The TC consists of voluntary members representing the user community, helmet manufacturers, regulatory authorities, and the R&D sector. Members come from Canada principally but also from the United States, United Kingdom and The Netherlands.

Through the development of this CSA standard, in addition to BABT, other important aspects were considered to ensure that ballistic helmet users are protected against a variety of hazards. Requirements to evaluate retention system strength, helmet stability, and non-ballistic impact attenuation were added to the ballistic resistance evaluation tests. A revision of the ballistic threats was also conducted to actualize the protection levels. In the definition of the scope, it was decided to limit the application of the future standard to personal apparel intended to provide protection to the head of corrections, law enforcement, and military personnel from the impact effects (penetration and blunt trauma) of ballistic threats (i.e. small caliber bullets and fragments from explosive devices) and low-velocity blunt impacts (e.g. fall on the ground).

The objective of this paper is to present an overview of the requirements defined for the CSA Ballistic Helmet Standard. The proposed performance evaluation procedures summarized in the following sections were established from previous R&D work, helmet test standards, and based on the experience of TC members.

Ballistic Protection Levels

Four types of ballistic threats were considered: fragments, handgun bullets, rifle bullets, and shotgun slug to encompass a range of the hazards to military and law enforcement personnel. When establishing the requirements, users and designers would be able to select one or multiple protection levels, depending on the application. For example, a police organization may need handgun and shotgun protection while military would require only fragment protection. Projectile test velocities proposed were based on experimental trials conducted with current helmet models or on the last update to the body armour Standards of NIJ [13] and the Home Office Scientific Development Branch (HOSDB) [14]. Up to four distinct performance levels are considered for each type of threat. Three categories of tests are proposed namely, penetrating impact assessment (V_{proof}), behind armour blunt trauma assessment (BABT), and ballistic limit (V_{50}). The proposed series of protection levels is presented in Table 1.

For the fragment threat, the 17 gr FSP and the 11.5 mm diameter steel sphere (96 gr) were selected. The 17 gr FSP is a chisel-nose steel cylinder. It is probably the most common projectile currently used in ballistic testing to simulate bomb or shell fragments for evaluating the performance of fragment resistant body armour and helmets [15]. The 96 gr steel sphere was selected to represent heavier fragments for assessing BABT. It is easy to launch, there is no issue with flight stability (no yaw), and it is readily available at low cost. The first performance level (FG-A) was defined to correspond to helmet designs requiring only a minimum level of protection. The second level (FG-B) matches the protection capabilities of current helmet designs while the third level (FG-C) represents a 20% performance increase over FG-B.

The selected handgun bullets are: 9 mm FMJ, 0.357 SIG, 44 Magnum SJHP, and the 9 mm Penetrator. The first two bullets have similar characteristics but the 0.357 SIG is fired at a velocity 50 m/s faster than the 9 mm FMJ bullet. The third projectile represents heavy handgun bullets. These three projectiles were identified as relevant threat to law enforcement personnel in the draft body armour standard NIJ 0101.06 [13]. The 9 mm Penetrator was selected to represent high penetrating performance bullets. The results of ballistic limit (V_{50}) test series showed that the “Penetrator” (109 gr, tin coated solid brass - round nose manufactured by Ruag) was the most severe threat among the 9 mm bullet tested.

A series of rifle bullet protection levels is also proposed even if current ballistic helmet designs offer only limited protection against this threat. For the first level (RF-A), the 7.62 mm FMJ-SP at a reduced velocity (630-650 m/s) is selected to meet the performance of current helmet designs. The three higher performance levels are defined with the anticipation of future helmet development. The second (RF-B) and third (RF-C) levels uses the standard 7.62 mm NATO FMJ at 45^{o} and 0^{o} obliquity, respectively. The 5.56 mm SS109 with higher penetrating performance is defined for the fourth level (RF-D).

The last category introduces the shotgun slug threat because it is commonly encountered in law enforcement and corrections environments. The impact velocity selected (415-455 m/s) is based on the HOSDB standard [14]. Current helmet designs were found to defeat the 12-Gauge shotgun rifled slug at muzzle velocity but, because of the mass of the projectile (28.4 g), the anticipated risk of injury from behind armour loads is extremely high.

Table 1: Ballistic protection levels.

Type	Protection level	Test projectile		V_{50} (m/s)	V_{proof} (m/s)	BABT	Notes
		Description	Mass (g)				
Fragment	FG-A	FSP	1.10	450	390-410	-	Lightweight design with minimum protection
		Steel sphere	6.74	-	240-260	✓	
	FG-B	FSP	1.10	630	570-590	-	Current helmet design
		Steel sphere	6.74	-	390-410	✓	
	FG-C	FSP	1.10	730	670-690	-	20% increased protection over FG-B
		Steel sphere	6.74	-	490-510	✓	
Handgun	HG-A	9 mm FMJ RN	8.04	-	389-409	✓	NIJ 0101.06 Level II [13]
	HG-B	.357 SIG	8.10	-	439-459	✓	NIJ 0101.06 Level IIIA [13]
	HG-C	44 Mag SJHP	15.55	-	427-447	✓	NIJ 0101.06 Level IIIA [13]
	HG-D	9 mm Penetrator	7.06	-	357-377	-	High penetrating performance handgun bullet
Rifle	RF-A	7.62 FMJ-SP	8.10	-	630-650	✓	Corresponds approximately to FG-B and HG-B, i.e. current helmet designs
	RF-B	7.62 NATO FMJ (45 degrees)	9.59	-	838-858	✓	NIJ 0101.06 Level III at 45° obliquity
	RF-C	7.62 NATO FMJ	9.59	-	838-858	✓	NIJ 0101.06 Level III at 0° obliquity [13]
	RF-D	5.56 mm SS109	3.95	-	900-920	✓	High penetrating performance rifle bullet
Shotgun	SG-A	12-GA rifled slug	28.40	-	415-455	✓	HOSDB level SG1 [14]

Testing Sequence

It was proposed to conduct the ballistic helmet evaluation in five consecutive phases as listed below. The testing process may stop after a failure; i.e. it will not be required to complete the subsequent tests when a failure occurs. Basic helmet performance evaluation is to be conducted initially such that more demanding ballistic tests would not have to be performed if the minimum requirements are not met.

- Phase 1: Retention System and Helmet Stability
- Phase 2: Impact Attenuation
- Phase 3: Ballistic Penetration Resistance (V_{proof})
- Phase 4: BABT Resistance (V_{proof})
- Phase 5: Ballistic Limit (V_{50})

An overview of the different phases of testing is described in the following sections. Sample conditioning under ambient, high, and low temperature, water immersion, and for artificial aging is also considered to represent environmental situations under which the helmets are expected to be used.

Ballistic Impact Tests

Three types of ballistic tests were considered. The capacity of the helmet to stop the projectile is assessed initially. If no penetration occurred, the level of force applied by the helmet's backface during non-penetrating impact is evaluated. An optional evaluation of the ballistic limit can be performed if required. Further details on the proposed test procedures are provided below.

Ballistic Penetration Resistance (V_{proof})

Ballistic penetration resistance is evaluated using 3 helmet samples per test ammunition. All samples are tested at ambient condition and any size of helmet may be used. Helmets are positioned on a penetration headform and shot at four impact locations: rear, front, left, right. Penetration at any location constitutes a failure.

The penetration headform (Figure 5) is constructed from a lower half cast in urethane elastomer and a upper half of soft silicone material. While the lower portion fits on a surrogate neck, the upper half is secured to the base. The silicone part can capture penetrating threats and it is disposable after several penetrations occurred.

It was proposed to use the "Army Criterion" to assess complete penetration [18]. This criterion states that for a complete penetration the projectile can be seen from the rear of the target or a hole or crack permits the passage of light through it.

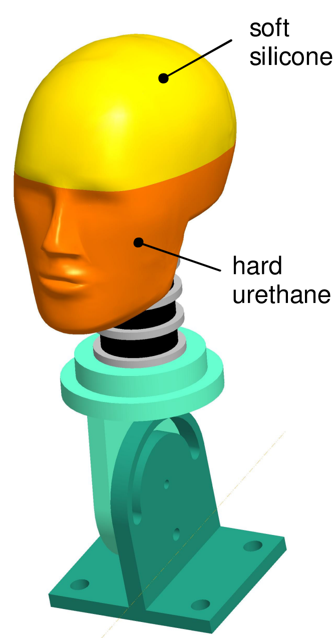

Figure 5: Penetration headform.

BABT Resistance

Evaluation of behind armour blunt trauma resistance is conducted with three helmet samples per test ammunition. Each test sample is subjected to a total of 4 accepted hits. A peak force exceeding the specified value by any single accepted hit constitutes failure. A given helmet has to first comply with the ballistic penetration requirement before BABT resistance testing is initiated to ensure that the risk of instrumentation damage is minimized. Helmet samples are positioned on the load sensing headforms shown in Figure 4 and shot at four impact locations: rear, front, left, right with the target location centred on the load cell array. An artificial skin cover is placed over the load cells to obtain a more realistic load distribution. Pressure sensitive film may be placed between the skin cover and the load cells to confirm that the impact occurred within the sensing area.

It was proposed to test samples at ambient condition and only the appropriate helmet size to fit an ISO J headform is used.

Ballistic Limit (V_{50})

Ballistic limit tests are optional. They are conducted to quantify the performance of the protective helmet for the fragment threat and/or to provide a baseline for quality assurance purposes.

The total number of shots is unknown with the proposed procedure. The firing continues until the confidence interval on the V_{50} reaches ± 10 m/s for 90% or 95% confidence level to ensure statistically significant results. The recommended firing procedure was based on the Bruceton method (Up and Down). This method has the advantage of providing a better estimate of the variance since tests are conducted within and outside the velocity zone of mixed results. Ballistic limit value and associated standard deviation are obtained by fitting a Probit curve to the experimental data.

It was estimated that 20 to 35 shots will be necessary to obtain the selected confidence level, depending on the type of helmet shell material. It corresponds approximately to the number of shots required for three typical ballistic limit evaluations based on the MIL-662F procedure [19]. This estimation was based on Monte Carlo simulations and actual test data acquired to update the standard STANAG 2920 [5]. Multiple helmet samples are required to determine V_{50} as the total number of shots will most likely exceed the capacity of a single helmet shell considering that test shots have to be separated from each other by at least 100 mm and no closer than 50 mm from an edge. Ballistic limit tests are conducted for side and crown areas separately to quantify the difference in performance between these two zones. The need for two distinct evaluations is justified by the fact that typically, side and crown areas use different construction patterns.

The penetration headform (Figure 5) and the "Army Criterion" proposed to assess complete penetration for ballistic penetration resistance tests are also used for V_{50} evaluation.

Non-Ballistic Impact Tests

Retention System Strength and Helmet Stability

The dynamic test method outlined in the CSA Z611-02 standard (Riot Helmet) [16] was selected to evaluate the strength of retention systems. It consists of dropping a mass on a guide attached to the helmet's retention system, and measure the corresponding elongation (both maximum and residual). The mass and drop height were taken from the Canadian combat helmet specifications [17] (5 kg dropped from 350 mm). The performance requirements were kept the same as for the Canadian combat helmet, i.e. maximum of 25 mm transient elongation, with maximum residual elongation of 12 mm. The CSA standard required the helmet to be fitted on a complete headform, to ensure that the retention system is appropriately and realistically positioned, in an as-worn configuration, making this test more realistic.

The retention system test is carried out at only one condition (ambient), to limit the number of test and samples required. Both the smallest and largest helmet sizes are tested, assuming that the other intermediate sizes have performance values between those of the two extreme sizes.

The selected helmet stability test was also inspired from the CSA Z611-02 standard for Riot Helmets [16]. It consists of applying a load of 250 N at the edges of the helmet, both forward and backward, and measuring the resulting change in orientation of the helmet as the load is applied for 5 seconds. A pass grade was assigned if both changes in rotation are below 45 degrees. Only ambient conditioned samples are required, and the same two helmets used for the dynamic retention system test are used.

Impact Attenuation

For impact attenuation, testing is conducted using a drop tower (monorail or twin wire) and standard ISO rigid headforms. Each helmet is tested at two energy steps, to ensure that helmets perform appropriately in both the low and high ranges of blunt impact (not ending up with a helmet system designed for a specific threat, while underperforming against the other one). These two energy steps consist of 30 J and 60 J impacts. The 30 J value corresponds current energy requirement for combat helmets, while the 60 J impact is representative of more severe impacts. These two energy steps correspond to velocities at impact of 3.5 and 4.9 m/s respectively. The theoretical equivalent drop (or fall) heights associated with these velocities are respectively 0.61 m and 1.22 m. In addition to energy steps, two protection levels were proposed as indicated in Table 2.

Table 2: Acceleration thresholds for impact attenuation.

Energy Step		**Threshold Acceleration**	
		Level A	**Level B**
Low:	30 J (3.5 m/s – 0.61 m)	150 g’s	100 g’s
High:	60 J (4.9 m/s – 1.22 m)	300 g’s	200 g’s

Level A is meant to be the mandatory requirement at which current helmets would comply. These two acceleration threshold values are commonly encountered in various other helmet impact standards. Moreover, experimental head impact data obtained with current military helmets indicate that current helmets are indeed likely to pass the requirements of Level A for both energy steps.

A more severe level, labelled as Level B, was also defined, with accepted acceleration limits of respectively 100 and 200 g’s. It was ensured that the ratio of the acceleration thresholds for Level B were the same as for Level A (ratio of 2 to 1), given that experimentally, a linear relationship is known to exist between impact energy and measured acceleration. Moreover, these lower acceleration thresholds were selected to provide a more aggressive target for helmet manufacturers to aim at, if deemed necessary to increase blunt impact performance.

To maintain the number of samples within reasonable limit, three helmet conditions (ambient, hot, cold), two steel anvils (flat and hemispherical), and two sizes (smallest and largest) were selected. Each helmet is impacted at 5 locations, corresponding roughly to the front, back, right side, left side and crown. A total of twelve helmet samples is required for impact attenuation tests.

Conclusions

The proposed standard should lead to enhanced helmet designs that will improve protection against ballistic threats and low velocity impacts. The recommended procedures are based on recent R&D work and thus provide a sound scientific background.

The next step before the final implementation requires that the test procedure is evaluated experimentally by different laboratories. This final stage is essential:

- to validate methods and established performance requirements;
- to confirm and refine (if needed) the methodology, and
- to define the test parameters.

Acknowledgement

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