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Evaluation of the Head Trauma Safety For Low and High Cut Composite Ballistic Helmets Design

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ABSTRACT

The subject of the study was to assess the risk of internal injuries to the head protected by ballistic helmets varying in design and material composition. For the study, the two design of the ballistic head protector: high- and lowcut helmets were applied, for which the safety was verified using FMJ 9 mm parabellum projectile. The user's safety of ballistic helmets was evaluated using a ballistic impact attenuation test as well as by estimating the Head Injury Criterion (HIC). In this study, a HIC value of >800 was assumed as an acceptability criterion, which is a more critical approach in relation to the AIS scale, where a value of >1000 was assumed. The aim of the study was to identify the risk of cranial trauma and Traumatic Brain Injuries (TBI) as well as to estimate its level for various types of composite ballistic helmets tested in conditions similar to those in real life. The adopted research methodology made it possible to identify and estimate the risk associated with cranial injuries and/or TBI of the user when protected by ballistic helmets differing in material composition (quantitatively and qualitatively) and design. Low-cut helmets achieved a significantly lower HIC coefficient than helmets with a lower protection surface area. Data from the research process carried out in laboratory conditions indicated that the side of the head protector subjected to FMJ 9 mm parabellum projectile is also important, considering the risk of TBI.

Keywords: Safety risk of ballistic helmet estimation; HIC testing; Ballistic impact attenuation test

NOMENCLATURE

AIS	:	Abbreviated injury scale
BHBT	:	Behind blunt trauma
BFD	:	Back face deformation
TBI	:	Injury to the brain
HIC	:	Head Injury Criterion
a(t)	:	Resulting acceleration, in g, measured in the gravity center of the head
T_0	:	Simulation start time in seconds
T_E	:	Simulation end time in seconds
t_1, t_2	:	Initial and final instant of a time interval, expressed in seconds, during which the HIC assumes the maximum value; the width of this interval is conventionally equal to 36 ms.
FMJ	:	Full metal jacket
RN	:	Round nose
M	:	Areal density of the flat composites [g/mm^2]
m	:	Mass of the flat composite [g]
A	:	Area of the tested sample [mm^2]

1. INTRODUCTION

Modern combat helmets made from advanced composites provide good protection against penetrating head injuries from ballistic and shrapnel threats and have saved lives of many soldiers. In recent years, the development of technology and material engineering has contributed to the creation of modern, composite ballistic helmets, which are designed to provide users with maximum protection against the effects of impacts and penetration. New materials with unique mechanical properties, such as Kevlar®, p-aramids or carbon fibers, allow the design of durable ballistic helmets. The introduction of innovative composite materials, such as aramid PPTA fibers or Ultra High Molecular Weight Polyethylene (UHMWPE), allowed the creation of light and effective ballistic helmets. The use of advanced production technologies, such as vacuum forming and lamination techniques, enables the production of helmets with a precisely designed structure, ensuring maximum protection. The development of detection and monitoring systems allows modern ballistic helmets to be equipped with detection and monitoring systems that can track impact forces and provide information about possible injuries[1-6].

There are many researches in the literature that describe experiments using skull models and various research tools, such as falls on platforms, impact simulations and ballistics tests. These tests allow for the assessment of the strength of the skull structure and the identification of factors influencing the risk of injuries. Computer simulations are an increasingly used tool for assessing the risk of cranial injuries. Analyses of Finite Element Models and Finite Element Method enable the simulation of various injury scenarios, which allows the identification of areas most at risk of injury[7-13].

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Although Behind Blunt Trauma (BHBT) has emerged as a serious injury type experienced by soldiers in battlefields. BHBT has been found to range from skin lacerations to brain damage and extensive skull fracture. Head protection against cranial trauma and TBI (injury to the brain) is a key safety aspect both in the sphere of military operations and in other areas where there is a risk of exposure to ballistic injuries. Therefore, continued efforts to develop more advanced protection technologies for soldiers re-quire a full understanding of the research being conducted. Although TBI is the subject of a wide range of specialties, there is still little information about the mechanism of TBI[5].

Various mechanisms that lead to TBI have been described in the literature, such as rotational and linear impact forces that can cause crushing, displacement, and other structural injuries within the skull[14]. Biomechanical research allows us to understand how external forces act on the structure of the skull and the brain, leading to injury. These mechanisms include displacement of brain tissue, changes in intracranial pressure, and structural damage. Scientific papers also discuss the effects of cranial trauma at the neurobiological level, pointing to chemical and neurological changes in the brain that can lead to long-term health consequences. The criteria for the resistance of the human head to dynamic injuries used in applicable standards are based on the so-called WSUTC (Wayne State University Tolerance Curve). Its course indicates the dependence of the head tolerance to dynamic loads - contact loads resulting from a collision with another body, on the duration and value of linear acceleration. This curve determines the limit below which the human head can tolerate dynamic loads and above which there is a high probability of head injury[15].

The US National Highway Traffic Safety Administration (NHTSA) proposed the Head Injurympact Criteriona (HIC). Head Injury Criterion (HIC) is the most important parameter in terms of human survival; it is indicative of brain injuries due to the impact of the head in numerous cases, with a vehicle. This index can be estimated by integrating the resulting acceleration of the head (measured in its gravity center) in a time window according to the following definitione[16]:

$$HIC = \max_{T_0 \le t_1 \le t_2 \le T_E} \left[\left(\frac{\int_{t_1}^{t_2} a(t)dt}{t_2 - t_1} \right)^{2,5} (t_2 - t_1) \right] \le 1000 \tag{1}$$

The use of quantitative criteria by medical practitioners to describe injuries in clinical practice turned out to be quite troublesome, as a result of which the medical community proposed the use of the so-called anatomical and is also used for comparative and statistical purposes. This scale allows you to determine the degree of injuries in individual systems and organs, i.e. head and neck, chest, abdominal cavity, pelvis and limbs. The Abbreviated Injury Scale (AIS) is a classification system that anatomically measures severity of injury on a scale of 0 to 6, where 0 signifies no injury, and 6 denotes an injury that is fatal[18]. A critical limitation with HIC is that it does not in-corporate head rotation that is known to be important to cause brain shear deformation responsible for concussive injury, diffuse axonal injury (DAI), and subdural hematoma[19]. Therefore, more recent injury metrics now explicitly include head rotational acceleration or velocity to assess the injury risk. Some of them are combinations of linear and rotational acceleration, and some are entirely based on head rotation e.g., the rotational injury criterion (RIC)[20] and the brain injury criterion (BrIC),[21-22] Power Rotational Head Injury Criterion (PRHIC)[23].

The aim of the study was to identify and estimate, through the use of modern research and analytical tools, in conditions similar to the reality risk of cranial injuries and TBI of users protected by advanced, composite ballistic helmets. In the conceptual process, we assumed that the tests in laboratory conditions would allow for a comprehensive identification and analysis of risks associated with the use of composite ballistic helmets in the area of cranial injuries and TBI related to the non-penetrating impact of the projectile.

2. METHODOLOGY

2.1 Materials

Ballistics tests were carried out for two types of composites helmets with confirmed ballistic resistance according NIJ Std. 0106.01 p.5.2., level II[24], against 9 mm FMJ projectile (Table 1) within the same batch of helmets used (not included in this study). Only after such verification of the tested samples were allowed testing ballistic helmets within the described in NIJ Std. 0106.01 p. 5.3 as shown in Fig. 2.

Table 1. 9 mm FMJ projectile specification acc. NIJ Std. 0106.01 p. 5.2., level II

Projectile type	Projectile mass [g]	Impact velocity [m/s]	Kinetic energy [J]	Shots required [number]
9 mm FMJ RN (brass jacket)	8.0 ± 0.1	358 ± 15	513 ± 42	4

The designs of low-cut and high-cut ballistic helmets were taken for testing. The testing objects were varied in a design and shape and had slight difference in areal density as well as external protection surface (Table 2). The design of the fixation system was similar differing in the geometry of the mounting to the helmet due to the design of the helmets. The specification and methodologies used of the tested composite ballistic helmets was presented in Table 2.

Two helmets were tested according NIJ Std. 0106.01 p. 5.3., ballistic impact attenuation test and three helmets acc. NATO Std. AEP-55, vol. 3, annex E p. 6.3.1 (HIC) using ammunition specified in Table 1, manufacturer: Winchester.

In order to determine the manufacturing parameters of the ballistic helmets, as well as the surface density, it was necessary to determine the surface area of the helmet shells. For this purpose, low- and high-cut helmets were scanned using an ATOS Compact Scan (Zeiss/Germany) with an the value of uncertainty up to 0.2 mm. Than the model mesh was smoothed to remove paint roughness. On the finished models,

Table 2. Characterisation of the ballistic helmets in study used

Variant of the advanced, composite ballistic helmet	Compounds	Average areal density of the composite [g/m^2]	External surface of the helmet [cm^2]	Bullet proofness level II p. 5.2 acc. NIJ Std. 0106.01	Methodology of the tests	
					NIJ Std 0106.01 p. 5.3 (Ballistic impact attenuation test) [number of helmets]	NATO Std. AEP-55, vol. 3, annex E p. 6.3.1 (HIC) [number of helmets]
Low-cut helmet	p-aramid woven fabric	8930 ± 15	1125.3	passed	2	3
High-cut helmet	p-aramid woven fabric/ UHMWPE unwoven fabric (hybrid design)	8750 ± 15	1107.7	passed	2	3

a freeform surface was created to replicate the geometry of the outer part of the ballistic helmet shells.

The areal density of the composites used for the fabrication of the ballistic helmets was determined using the flat samples with size 30 cm x 30 cm. The process of flat composites fabrication was identical to that used for ballistic helmets manufacture.

Areal density of the flat composites were determined based on the below-presented equations:

$$M = \frac{m \times 10^6}{A} \quad (2)$$

Before testing samples were acclimatized and tested in conditions specified in accordance with PN-EN ISO 139:2006+A1:2012 standard (at temperature of 20 °C and relative humidity of 65 %).

2.2 Ballistic Test Methodology

Majority of the Testing Standards defining ballistic resistance of helmets only by determining penetration of a projectile into ballistic protectors and deformation of shell. The energy of shot is partially absorbed by helmet, but it is mostly transmitted to a head, giving it a linear and/or angular acceleration. An important component of the protective properties of a helmet is the value of kinetic energy, which is transferred to the user's body (head and cervical spine) during the process of penetration of a striking projectile into ballistic protection (ballistic helmet). Transferring too much energy to the head may result in skull fracture, brain and spine injuries. The mechanism of this type of injury is related to the action of accelerations and/or decelerations, which result in a relative displacement of the brain within the skull.

2.2.1 Infrastructure

In order to the determine the transferred energy the following devices were used for testing:

Projectile Yaw Measurement System (Prototypa/Czech Republic) dedicated to projectile velocity (up to 2500 m/s) and yaw measurements before impact on the target according AEP-55 Std.[25], consisting of two light screens (gates) LS-01L enabling measurement or calculation of impact velocity with an expanded uncertainty [U] not exceeding 0.2 % (PYAWMS – 2019) (Fig. 1).

System is equipped with a headform mounted on a rail that allowing movement while shooting (Fig. 2), developed by Beatronic Supply (Netherlands). It consists SLICE PRO/

Figure 1. Projectile Yaw Measurement System (PYAWMS - 2019; Prototypa/Czech Republic).

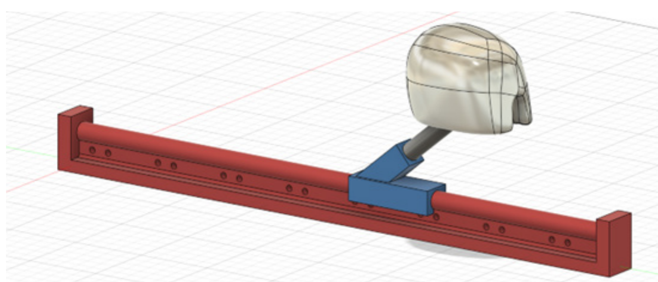

Figure 2. Scheme of test set up for ballistic impact attenuation test acc. NIJ Std. 0106.01, p. 5.3.[24]

SLICE PRO LAB Sensor and registering device DTS SliceWare (Diversified Technical Systems, Inc./USA). Sensor measurement range up to 2000 g. Sensitivity of the piezoelectric sensor is equal 0.2 mV/g. System registering the values of accelerations torques occurring in direction x complied with NIJ Std. 0106.01, p. 5.3[24] and with SAE Recommended Practice J211b requirements for Channel Frequency Class 1000 (CFC 1000)[26].

Test set up for measuring the risk of Head Injury Criterion (HIC). Hybrid III 50th Male Dummy (Humanetics/USA) complied with Code of Federal Regulations, Title 49, Part 572, Subpart E and federal motor vehicle safety standards,

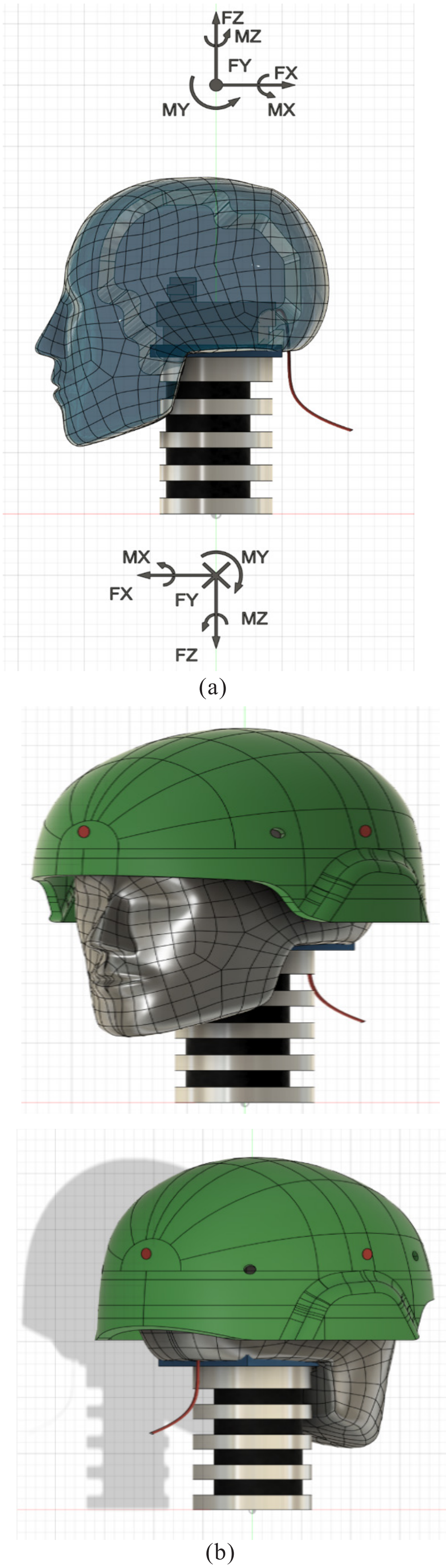

Figure 3. Scheme of (a) test set up for measuring the risk of Head Injury Criterion (HIC) and (b) location of shot points on head-neck system.

regulations, Standard No. 208 and National Highway Traffic Safety Administration (NHTSA)[27], NATO AEP-55[25].

Head and neck headform equipped with a 3-channel accelerations torque transducer (Fig. 3). The headform is equipped with a Slice Pro/Slice Pro Lab Sensor (Diversified Technical Systems Inc/USA) and registering device DTS SLICEWare (Diversified Technical Systems Inc/USA). All above allows registering the values of accelerations torques occurring in three directions: x, y, z axis. Sensor measurement range up to 2000 g. Sensitivity of the piezoelectric sensor: 0.02 mV/g (a_x – acceleration component in the direction of the x axis; a_y – acceleration component in the direction of the y axis; a_z – acceleration component in the direction of the z axis; x direction – determined by the axis passing through the forehead and occiput of the headform; y direction – determined by the axis passing through the headform ears; z direction – is determined by the axis passing through the headform neck).

2.2.2 Head Injury from Ballistic Impact Testing

A bullet resistance test of the ballistic helmets was performed in accordance to NIJStd. 0106.01, p.5.2., 5.3. Figure 2 and using Hybrid III 50th Male Dummy (Humanetics/ USA) (Fig. 3) with 4 shots fired at an angle of incidence of 0 ± 5° and in the velocity range of 358 ± 15 m/s using 9 mm FMJ RN projectile (brass jacket; 8.0 g ± 0.1 g). Before the tests above, helmets were air-conditioned at a temperature of 20 ± 2 °C at a relative humidity of 65 ± 5% for 24 h. After removing the tested helmet masking cover and other additional equipment marked four hit points on the outer surface of the helmet. Location should be on the forehead, back and both sides. All points was designed so that no more than 9 cm above the basic plane and no more than 5 cm from the mid-sagittal plane. The velocity of the projectile, including the determination of the effect of the shot (partial or complete penetration), was measured at each shot. For each helmet, 4 shots were performed in accordance with the conditions specified in[24]. Only after such verification of the tested samples were allowed to test the ballistic helmet mounted on the layout of the head as described in[24] (Fig. 2).

2.2.2.1. Ballistic Impact Attenuation Test acc. NIJ Std. 0106.01 p.5.3.

A simple translational head acceleration limit of 400 g was used in[24]. The tested helmet has to positioned strictly on the head form and secure it by its chin strap or other means, which will not interfere with the test. Instrumented test head form-base assembly was positioned in the line of fire so that the axis of the accelerometer and the line of fire are colinear within 5°. During these tests performed four test rounds at the helmet, one at each of the 4 sites as described in 2.1 (Tabel 1) and 2.2.1 (Fig. 2) Measured velocity of each fair hit and the head form acceleration produced in the center of the head form mass were determined. Accelerations were filtered in accordance with CFC 1650, SAEJ211[26].

2.2.2.2 Determination the Risk of Head Injury Criterion (HIC)

Determination the risk of Head Injury Criterion (HIC) was carried out according to NATO Std. AEP-55 vol. 3, annex E, p. 6.3.1.[25]

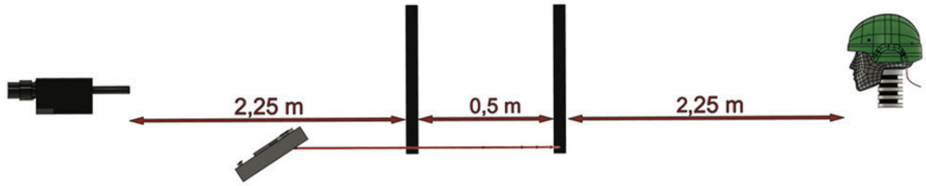

Figure 4. Scheme for ballistic set up test according NIJ Std. 0106.01[24].

Head Injury Criteria (HIC) is an IARV for injury risk to the skull and brain. That value is the standardized maximum integral value of head acceleration. The length of Δt interval is maximum 15 ms (HIC15). Due to the duration phenomena of energy transfer at the projectile - helmet interface at the weakest area, where 3 technological holes for night vision holder are placed, a HIC15 parameter was rationally selected for the research .

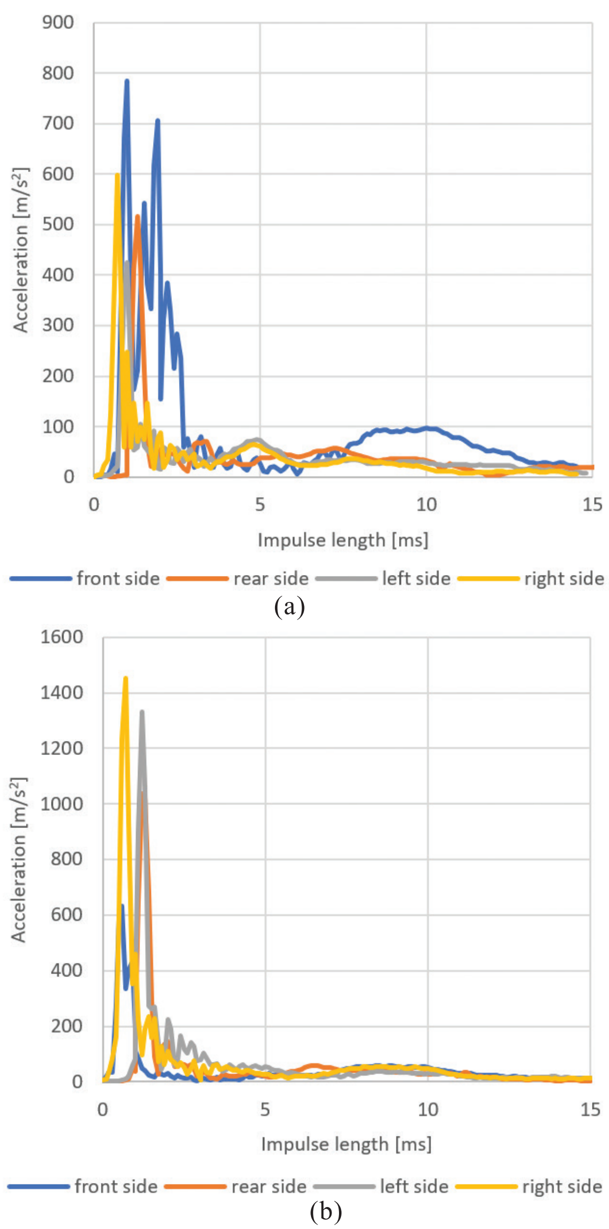

Figure 5. An example of resultant acceleration a [m/s²] registered for: (a) low-cut; (b) high-cut ballitic helmets.

Calculation of these parameter is given on the following Eqn.[16]:

$$HIC_{\Delta t_{\max}} = \max_{t_1,t_2}\left[\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2,5}(t_2-t_1)\right] \quad (3)$$

$$t_2 - t_1 \leq \Delta t_{\max} \quad (4)$$

$$a = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (5)$$

where:

- a-resultant acceleration of the center of gravity of the head in g = 9.81 m/s²;
- t_1 *and* t_2 - moments in time event, where HIC achieve the maximal value [*s*].

Examples of the relationship between the resulting acceleration a [m/s^2] and the pulse length for the four sides of the ballistic helmets tested are shown in Fig. 5.Ballistic tests were performed by shooting of 4 times in the tested helmet, one at each of the four sites as it is described in 2.2.2. The crucial item was registration of Hybrid III 50th Male Dummy accelerations signals at the moment of the impact of the projectile into the helmet and shortly after hitting it till the time system helmet-head-neck will stabilize itself.

The registration of acceleration signals (ax, ay, az) was made by using the device DTS SLICEWare (Diversified Technical Systems Inc/USA) and the 3 channel sensors mounted in the headform.

Head accelerations were filtered by low-pass (digital) filter routine according Channel Frequency Class 1000 (CFC1000) in accordance with SAE J211[26]. HIC15 parameters were calculated for every each of tested helmets side: front, back and both sides.

3. RESULTS

3.1 Ballistic Impact Attenuation Test

The ballistic impact attenuation test results of the two variants of the ballistic helmets: high-cut and low-cut helmets are presented in Fig. 6. using projectile described in Table 1.

The high cut helmet is characterised by the high ballistic impact attenuation result if the test was carried out at front (203 ± 22) g and at right side (199 ± 23) g of the product. The test provided at rear and at left side yielded in the reduction in the ballistic impact attenuation by approximately 13% (rear) – 18 % (left side) in comparison to the test carried out at the front of the ballistic helmet. Moreover, the determined parameter remains the relatively high value. Despite this, received value remains at a safe level for the user.

For the low-cut variant, the highest ballistic impact attenuation was obtain if the test was conducted at the front of the ballistic helmet (181 ± 40) g. Then, the parameter was decreased from (100 ± 80) g (rear) to 36 ± 4 g (left side) and (40 ± 16) g (right side). The test confirmed that the design of the tested ballistic helmets influenced the safety of the use. Side cut-outs in the design of the helmet, which also reduce its protective surface, increase the evaluated parameter. In the case of a low-cut helmet variant, the amount of energy absorbed by the helmet shell is higher, which makes it safer to use.

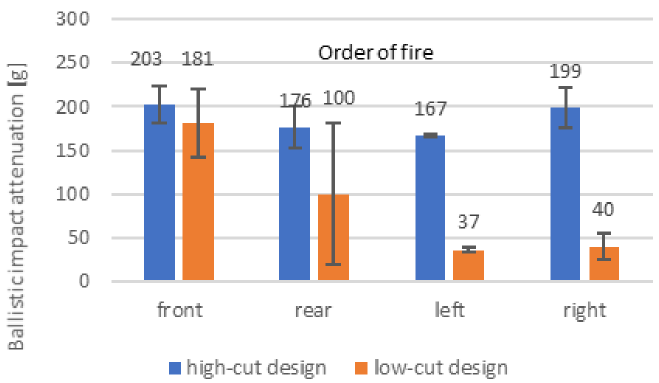

Figure 6. Ballistic impact attenuation test results of the two variants of the ballistic helmets: High-cut or low-cut helmets.

3.2 Determination the Risk of Head Injury Criterion (HIC)

HIC results determined for two designs of the helmets: low- or high-cut are shown in Fig. 7.

The FMJ 9mm projectile was selected due to rational effect of bullet impact and outcomes from battlefield. Energy of the .357MAG and .44MAG calibres are much higher than 9mm (around 500 J) and for the testing set-up (short distance from muzzle to the headform) will provide only fatal consequences for the user in the aspect of obtained HIC value.

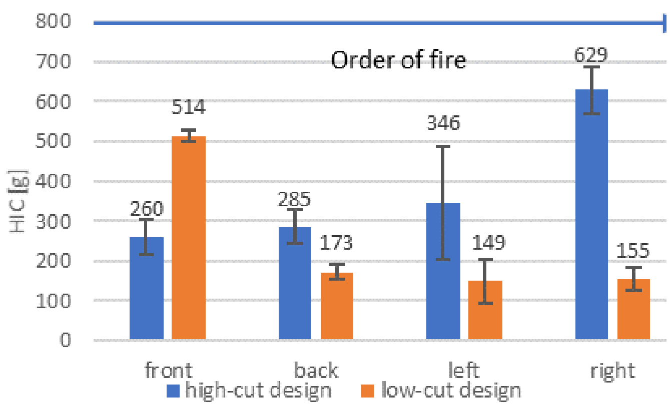

Figure 7. Head Injury Criterion (HIC) test results of the two variants of the ballistic helmets: High-cut or low-cut helmets.

4. DISCUSSION

A research methodology was developed for the assessment of TBI of a helmet under ballistic impact. The effects of the shell structure, and impact direction on head injury risks are studied. The low-cut design of the helmet shell offer a better protection.

Additionally, the slightly larger helmet surface leads to a significant reduction in head injury risks. An impact on the front and back parts of the tested helmet results in a more severe injury than an impact on left and right parts. Various types of ballistic helmets are marketed and their protection level varies from one to the other. Abbreviated Injury Scale (AIS) is a scoring system for the severity of injury based on anatomic location to classify each injured body region in a 6-point scale[17]. AIS is a useful tool for evaluating injury severities according to the specific anatomic sites of trauma.

The main effect of research was focused on the identification of the relationship of head injury severities for two designs of ballistic helmets protections in ballistic impact. The both tested helmets were characterised by slight reduction of areal density for high-cut helmet (difference in value of approx. 180 g/m^2; Table 2) and varying in the design (low or high-cut) and outer surface (differing in 17.6 cm^2; Table 2), that effected in the HIC characteristic.

There are many head injuries caused by high-cut design helmets which provide less protection to the head during ballistic fire. The average HIC value yielded in 380 is corresponded to level 1 of AIS scale and indicates the risk of mild injury. However, it should be noted that for a frontally fired high-cut helmet, the HIC value achieved the highest value of 629, which relates to level 2 of the AIS scale (moderate injury).

The average HIC value for low-cut helmet remains 247, although the highest HIC value of 519 was recorded if test was performed at front of the tested helmet. Above phenomenon results in fewer and milder risk of head injuries associated with low-cut design helmets. Research showed that both designs of ballistic helmet: high-cut and low-cut helmet with equal surface density, provide ballistic protection. However, taking into the account HIC and related AIS level, the low-cut ballistic helmet undoubtedly ensures greater safety of use resulting from the helmet design, slightly higher outer surface as well as surface density. The larger surface of the helmet shell provides greater safety and reduces the probability of severe head injuries.

5. CONCLUSIONS

The design of a ballistic helmet clearly affects its safety, which has been clearly demonstrated in the conducted research. Selected models of ballistic helmets differing in design and material composition (homogeneous composite or hybrid composite) showed different properties in ballistic tests directly related to their safety, while respecting the requirements related to the tests according to NIJ Std. 0106.01, p. 5.3., level II, against 9mm FMJ projectile. The value of the ballistic impact attenuation increase for the high-cut variant during the more shelling while for the low-cut one is characterized by the reduction of described parameter. When the both variant of helmets were tested for the HIC estimation, the highest average value of HIC was found if the high-cut variant were tested. In the case of the low-cut ballistic helmet, the highest value of the HIC coefficient was observed if the firing was carried out from the front of the tested object, while in other cases significantly lower values of the coefficient were found compared to the high-cut helmets.HIC allows us to assess the risk of potential injury. Moreover, in the case of our research, it reflects the impact of the helmet design – the helmet surface and design reduce the risk of brain injury and trauma.

The design of ballistic helmets cannot focus only on demonstrating the fulfilment of basic ballistic requirements qualifying the possibility of projectile penetration or not, but should also take into account safety aspects related to the measurable assessment of the acceptability of residual risk associated with potential damage to the skull and brain (TBI) of the user.

Research related to the comprehensive assessment of the ballistic helmet properties, linking them to the design process, selection of materials and composition should constitute the basic designer's workshop enabling both the design of a functional product and a product that is safe for its user. The ballistic helmet design and even slight changes in the protective surface as well as surface density contribute to increasing the safety of the user, especially in terms of its reduction in the TBI area.

Aspects of ballistic tests related to the assessment of BFD (Back Face Deformation) constituting an additional indicator of TBI risk assessment in terms similar to the real conditions of use of ballistic helmets and, finally, an attempt to develop a simulation model of a projectile impact on ballistic helmets of different design and construction, as a tool generating output data for design and material ballistic helmet optimisation, will be the subject of subsequent publications.

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