Energy Transmission from Bullet Impact onto Head or Neck through Structures of the Protective Ballistic helmet – Tests and Evaluation

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INTRODUCTION

It appears from studies of the topography of vital human organs and from evaluation of gunshot wounds in various anatomical areas that head protection is a very important issue [1-9].

The data, acquired during military conflicts in Dagestan and Chechnya (from 1999 through 2001), included a total number of 6053 wounded and 2037 killed subjects, while the ratio of killed to wounded was 1:3. Regarding the affected parts of the body, the injuries experienced by involved soldiers concerned the head – 21%, the chest -10%, the abdomen – 10.8% or the limbs – 57.5%.

Considering the character of wounds, one should notice that 45% of them accounted for shots with bullets and resulted in death of 56.6% of victims, while the prevalence of wounds from splinters was 55%, being death cause in case of 43.4% of affected subjects.

Regarding wound localisation, bullet wounds involved: the head - 50%, the chest - 40%, and the abdomen - 10%. The prevalence of fatal hits in the head was comparable with the number of fatal shots into chest and abdomen together, what – keeping in mind that the head stands for 8% of whole body surface indicates how important is protection of this body part.

The main goal of ballistic head protections, i.e., splinter- and bullet-resistant helmets, is the protection of human health and life against detrimental effects of traumas, resulting from hitting splinters or bullets. The introduction of more and more effective helmets has reduced the extent of traumas associated with bullet effects (explosion driven splinters, gunshot bullets). The introduction of modern materials (paraaramides, highly-resistant polyethylene, titanium, etc.,) minimised the possibility of helmet cover penetration by bullets, what significantly reduced the number of contact injuries (epicranial lesions, cranial bone fractures or cerebral injuries by a penetrating bullet). Together with higher resistance of the used protection covers to penetration, a still unsolved problem has occurred, regarding the, so-called, behind armour blunt trauma – BABT).

ENERGY TRANSMISSION ONTO HELMET USER'S HEAD

The benefits from stopping high-speed bullets by helmets are truly unquestionable. However, even if a bullet is stopped, a deformation of helmet's body, resulting from impact, may be at the base of BABT, while applying a certain linear and/or angular acceleration onto the head may cause inertial injury of the brain and/or of the cervical spine [10-18].

The above-mentioned phenomena have revealed their influences and are still a serious problem, especially since the introduction of light, composite materials for ballistic head protections, characterised by higher deformation under impact.

Evaluation methods of the effectiveness of helmet penetration by bullets are relatively simple and were defined in several documents, such as: NIJ 1981; MIL-H-44099A1986;H.P.White Laboratory1995;NATO1996; MIL-STD-662F 1997, being also at the base of defining the classes of helmet protection effectiveness.

PN-V-87001:1999 Standard "Light ballistic covers. Protective, splinter- and bullet-resistant helmets. General requirements and tests" is valid in Poland, defining helmet structure and its basic features of protection and use.

The most important helmet parameters, which should be determined acc. to the above-mentioned standards:

- resistance to puncture by bullet or splinter,
- the size of helmet body deformation at the time and place of bullet location.

A broader approach to evaluation of helmet protective features is represented in NIJ STANDARD 0106.01. The described methodology includes measurements of head dummy's acceleration during shot. The measurement is obtained by an accelerometer, mounted exactly in the middle of the dummy. The standard allows acceleration at the level of 400g.

No helmet puncture does not guarantee full protection of helmet user's health and life as found in studies on BABT. Helmet body deformation, resulting from bullet impact, may be the source of the behind-armour blunt trauma, manifested b contact or inertial injuries.

The results of an interesting experiment have been published, the experiment having been performed by researchers from the University of Virginia, the Uniformed Services University of the Health Science, the U.S. Army Natick Soldier Center and the Armed Forces Institute of Pathology, the end point of which was definition of head injury criteria during ballistic loads exerted onto protective helmets. The tests were done on human corpses. Helmets, placed on heads of the corpses, were shot with 9 mm bullets with impact energy from 620 J to 800 J. In five, out of nine cases, cranial fractures and brain injuries were noted.

The helmet's body, together with its internal accessories, make a structure which, during bullet impact, absorbs its kinetic energy, thus protecting against helmet cover puncture.

Results of theoretical studies and practical experiments indicate that not all energy of the bullet is absorbed by the helmet's body and internal structure. A considerable amount of this energy is transferred on the head-neck system of helmet's user.

It is assumed that bullet's kinetic energy, during penetration into an obstacle, changes into:

- bullet deformation energy,
- obstacle deformation and damage energy,
- heat, generated during bullet impact and penetration into obstacle,
- impact energy, i.e., the energy transferred onto the body (a group of bodies) behind the protective cover.

The energy of hitting bullet is partially absorbed by the helmet, the deformation of which may be at the base of contact injuries. However, much of this energy is transfer red onto the head, applying linear and/or angular acceleration to it, what may be the direct cause of inertial trauma.

Behind armour blunt head traumas, induced despite the lack of helmet puncture, may be considered in the following three aspects:

1. primary and secondary brain injuries resulting from rapid accelerations and decelerations,
2. traumatic injuries of the spine and of the vertebral canal in the cervical section, associated with exceeding physiological mobility limits,
3. contact injuries caused by helmet body deformation.

The mechanism of the injuries, presented in item 1 above, is associated with accelerations and/or decelerations, the immediate consequence of which is relative brain motion vs. the skull. This brain shift may induce various negative outcomes. First of all, the brain is at risk of hitting inward protruding bone and meningeal elements. Acceleration-deceleration injuries may also lead to excessive stretching, dislocations, parenchymal tensions within the brain and the vascular bed, becoming an immediate cause of diffuse axonal injury.

The risk of cervical spine traumas is another significant aspect of energy transfer from the bullet impact, which is partially absorbed by the helmet but is also broadly delivered onto the head and neck of affected subject, inducing their linear and/or angular acceleration. The forces which act onto the head are transmitted to the cervical spine and if spine movement, exerted by the applied energy, exceeds physiological limits, serious injuries may occur.

In case of contact injuries, direct, structural tissue damage is observed, resulting from impact of an outer physical factor. In the course of the behind armour blunt trauma, practically all the tissues, protected by a given ballistic cover, are at risk of injury.

Contact brain injuries result from two main mechanisms. The first one is associated with penetration of bone fragments, while the second one with dynamic cranial deformation. The transfer of energy from helmet onto the epicrania and then, onto the skull, causes its deformation and transmission of the energy further down onto the brain.

Research on BABT is underway all over the world, including, among others, organisations which are subject to the U.S. Army, the University of Virginia in the U.S.A., the Royal Institute of Technology in Sweden, the University of Southern Denmark, JVC

NII Stali in Moscow and in many other research organisations.

Evaluation of the effectiveness of ballistic protection covers employs, via experiments, various study methods, in which the following materials are used: technical – plasticine, soap, gelatine blocks of different density; biological - experimental animals, human tissue fragments, human and animal corps, analogues of live tissues.

In the entire, historical course of gun shot injury evaluation, various biological materials were experimentally used: human and animal corpses, corpse fragments, pigs, goats, sheep, dogs, rabbits, rats and guinea pigs. During use of these materials, evaluation is performed by medical researchers, following the protocols, approved for this type of studies. Evaluation of results is performed after detailed, medical studies of tissues, what leads to elongated processing periods of the results.

Beside biological materials, analogues of live tissues are also used in these experiments. A dummy object, corresponding to a given biological structure, is made in such a way as to simulate skin tissues, muscles and bones, with a possibility to register physical processes which occur during dynamic impact. This increases the reliability of obtained experimental data, while the experiment itself as well as the analysis of recorded data becomes much simpler.

Finite element method (FEM) is applied for the simulation of processes which occur during bullet impact. Examples of calculations, referring to head or trunk dummies, together with ballistic protections, are available in Literature [19-20].

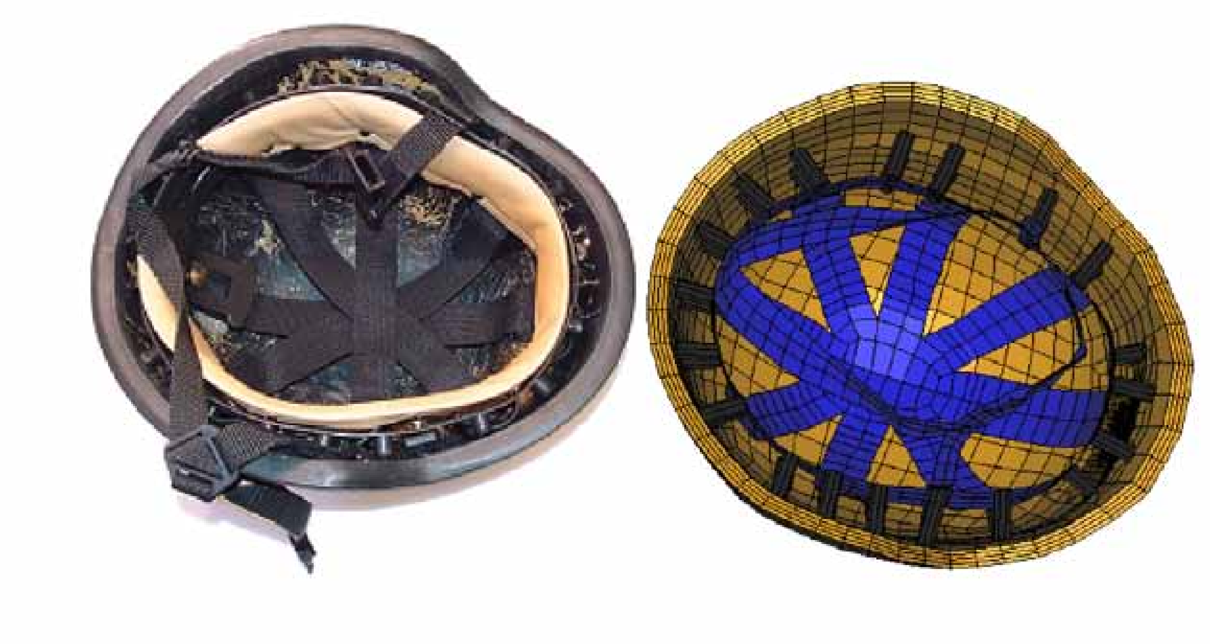

Fig. 1. Helmet's interior and its FEM model, used for simulations [19].

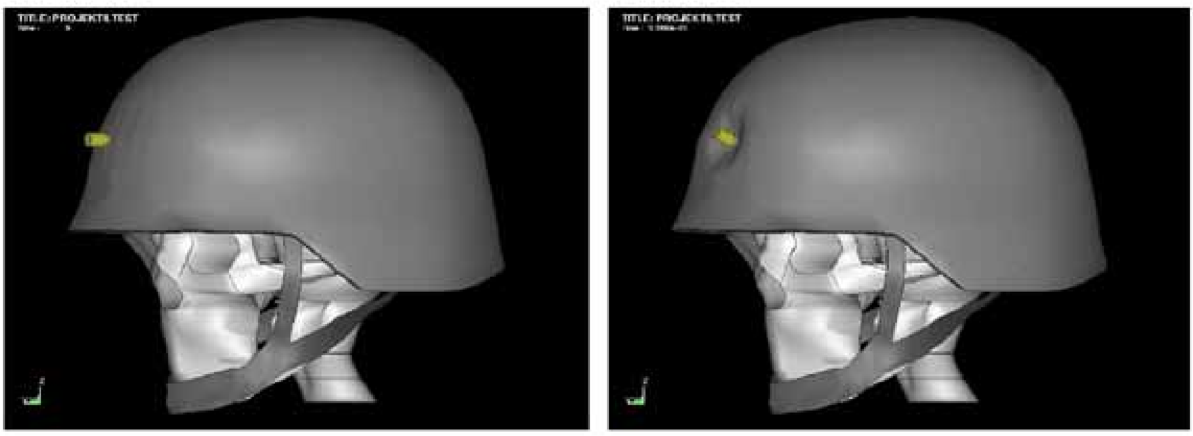

Fig. 2. A model of human head with a ballistic helmet before and during bullet impact [19]

A cranial bone injury, resulting from frontal bullet impact, is presented in Fig, 3. Various stresses occur which may induce various consequences.

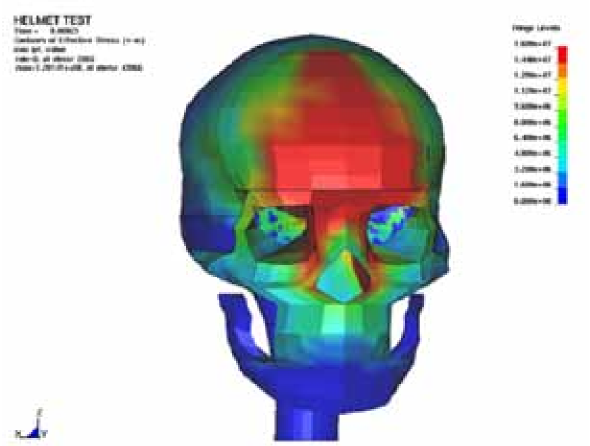

Fig. 3. Stress distribution during frontal bullet impact (range from 0 MPa – blue colour to 144 MPa – red colour) [19].

A prototype head dummy (modified Hybrid III dummy – see Fig, 4) with special tooling for measurements with the use of load cells, may be model example for experimental studies at ballistic station, especially in the motor sector.

Fig. 4. Hybrid III dummy [21].

It was purchased by the „MORATEX" Institute of Security Technology within the research Project: „Modelling of protective features of bullet- and splinter-protective helmets in the aspect of the minimal injury risk of the helmet user's head and neck." The dummy is equipped with a 6-axis force and torque transducer, attached to the upper part of the dummy's neck. This dummy fulfils the criteria of the Code of Federal Regulations, Title 49, Part 572, Subpart E and Federal Motor Vehicle Safety Standards and Regulations, Standard No. 208.

The applied 6-channel transducer allows for measuring forces and torques in three axes and within ranges of minimum 10 kN for forces and 3400 Nm for torques. The display from the transducer provides data on generalised force components (3 forces and 3 torques), acting onto the cervical spine, as well as onto any cranial site (measurement by an ultra-fast camera).

The mathematical model, shown below, allows for evaluation of:

- cross-sectional forces at any cross-section of analysed spine section;
- deflection of any part of the cervical spine;
- angle of deflection of any part of the cervical spine;
- acceleration of any part of the cervical spine;
- angular acceleration of any part of the cervical spine .

These possibilities are provided by the mathematical model, employing the differential line of beam deflection, including corrections in case of extensive deflections (Fig. 5b) or without corrections in case of small deflections (Fig. 5a).

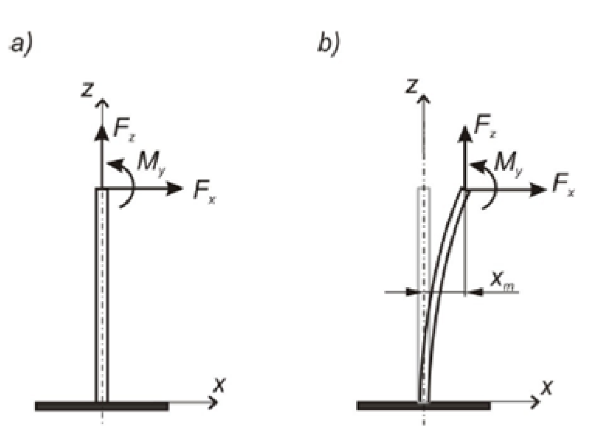

Fig. 5. Mathematical model of the cervical spine.

The basic equation, describing the case in Fig. 5a:

$$EJ \cdot \frac{d^2 x}{dz^2} = F_X \cdot z - M_Y$$

Its solution (bilateral integration) allows determining deflection value and deflection angle at any part of the cervical spine in time:

$$EJ \cdot \frac{dx}{dz} = \frac{1}{2} F_X \cdot z^2 - M_Y \cdot z + C$$

$$EJ \cdot x = \frac{1}{6} F_X \cdot z^3 - M_Y \cdot z^2 + C \cdot z + D$$

where C and D are integration constants, determined from the boundary values (the way of spine fixing at the base of the test stand). Then, by differentiation after time, it is possible to determine the values of speed (the first deflection derivative after time) and of acceleration (the second deflection derivative after time). The procedure is analogous for tests with large deflections, adding only appropriate corrections, accounting for the fact that at each time point, the generalised forces exert different effects on the spine model.

A differential deflection equation with corrections has the following formula:

$$EJ \cdot \frac{d^2 X}{dz^2} = F_X \cdot z - M_Y - F_Z \cdot x_m$$

This equation has been introduced for the case of experimental system loading by bullet impact, applied onto the frontal part of the helmet – frontal part of the head. In all the equations, the values of Fx, Fz, My and xm are the measured values (Fig. 5). In the above equations, EJ rigidity (E – Young's module, J = moment of inertia) should be approached as a substitute parameter which will be determined as constant or variable value in time from the measurement of the cervical spine end dislocation.

CONCLUSIONS

1. High ballistic armour protection levels do not guarantee complete protection of helmet user's health and life.
2. It is compulsory to design study protocols and evaluation criteria of helmets in consideration of the BABT effects (e.g., medically allowed energy levels which can be delivered by impacting bullet and transferred via ballistic head protection onto the head-neck system.)
3. Head and neck injuries, resulting from shots, are highly differentiated and rather complex because of different force values, application sites and directions. An extended evaluation of helmets, regarding energy transmission onto users will provide the base, allowing detailed definition of physical trauma characteristics and accurate estimation of protection levels required for design of optimal ballistic covers.
4. Design of ballistic head protection systems has to take into consideration energy levels, transmitted onto cervical neck and head.
5. Studies on BABT with regards to head injuries may undoubtedly contribute to higher life and health safety of soldiers, better head protection systems but also to deeper understanding of the biomechanical aspects of head and cervical neck injuries, while targeting at their improved therapy.

Literature

1. *M.B. Tiurin, I.N. Sapronienkowa; „Analiza doświadczenia zdobytego w czasie eksploatacji ogólnowojskowych ochronnych hełmów balistycznych"; 4 Rosyjska Naukowo Praktyczna Konferencja, Sankt Petrsburg 2001, materiały konferencyjne.*
2. *S.M. Logamkin, L.B. Ozierenkowski, P.A. Alusow; „Topograficzno-anatomiczne przesłanki doskonalenia kamizelek kuloodpornych"; 4 Rosyjska Naukowo Praktyczna Konferencja, Sankt Petrsburg 2001, materiały konferencyjne.*
3. *T.A. Mierzeabasow, D.O. Biełow, I.A.Klaus, M.W. Tiurin, I.N. Sapronienkowa; „Kompleks ekspertyz tarcz-system do badań kamizelek kuloodpornych"; 4 Rosyjska Naukowo Praktyczna Konferencja, Sankt Petrsburg 2001, materiały konferencyjne.*
4. *M.W. Tiurin, I.N. Sapronienkowa „Ogólne metodyczne sposoby podejścia do badań w zakresie urazów spowodowanych środkami balistycznymi"; 4 Rosyjska Naukowo Praktyczna Konferencja, Sankt Petrsburg 2001, materiały konferencyjne.*
5. *J. Crowley, J. Persson, "Injury Data on the Nature of Head and Neck Injuries Occurring in Military Helicopter Crashes", Proceedings of the RTO AVT/HFM Specialists' Meeting on Equipment for Personal Protection (AVT-097) and Personal Protection: Bio-Mechanical Issues and Associated Physio-Pathological Risks (HFM-102) (2003), materiały konferencyjne.*
6. *J.A. Pellettiere, „Helmet-Induced Tensile Neck Loading", Proceedings of the RTO AVT/HFM Specia-*

lists' Meeting on Equipment for Personal Protection (AVT-097) and Personal Protection: Bio-Mechanical Issues and Associated Physio-Pathological Risks (HFM-102) (2003), materiały konferencyjne.

7. A.K. Ommaya, „Traumatic Brain Injury Past, Present and Future", Proceedings of the RTO AVT/HFM Specialists' Meeting on Equipment for Personal Protection (AVT-097) and Personal Protection: Bio-Mechanical Issues and Associated Physio -Pathological Risks (HFM-102) (2003), materiały konferencyjne.
8. R. Bass, B. Bogges, B. Bush, M. Davis, R. Harris, S. Rountree, S. Campman, J. Eklund, W. Monacci, G. Ling, G. Holborrow, E. Sanderson and S. Waclawik, „Helmet behind armor blunt trauma", Proceedings of the RTO AVT/HFM Specialists' Meeting on Equipment for Personal Protection (AVT-097) and Personal Protection: Bio-Mechanical Issues and Associated Physio-Pathological Risks (HFM-102) (2003), materiały konferencyjne.
9. B. Anctil, D. Bourget, G. Pageau, K. Rice, J. Lesko; "Ewaluacja systemów pomiaru siły uderzeniowej w celu oceny urazów podpancerzowych powstających pod nieprzebitymi hełmami"; Proceedings PASS 2004, materiały konferencyjne.
10. J.R. Stone, D.O. Okonkwo, A.O. Dialo, D.G. Rubin, L.K. Mutlu, J.T. Povlishock, G.A. Helm, Exp. Neurol. 190 (2004) 59.
11. R.H. Singleton, J.T. Povlishock, J Neurosci. 24 (2004) 3543.
12. J.E. Pittella, S.N. Gusmao, J Forensic Sci. 48 (2003) 626.
13. A. Hamberger, Y.L Huang, H. Zhu, F. Bao, M. Ding, K. Blennow, A. Olsson, H.A. Hansson, D. Viano, K.G. Haglid, J Neurotrauma 20 (2003) 169.
14. C. Niess, U. Grauel, S.W. Toennes, H. Bratzke, Acta Neuropathol (Berl) 104 (2002) 79.
15. W.C. Hanigan, C., Neurosurgical FOCUS 16(1) (2004) E4.
16. M.R. Coakwell, D.S. Bloswick, R. Moser, Aviation, Space, and Environmental Medicine 75 (2004) 68.
17. J.V. Rosenfeld, J Clin Neurosci 9(1) (2002) 9.
18. J.T. Youman's Neurological Surgery ed. 4, Philadelphia, W.B. Saunders Co. 1996.
19. M. Aare, S. Kleiven, International Journal of Impact Engineering 34 (2007) 596.
20. J. Hopkins, Apl. Technical Digest 26(1) (2005) 84.
21. First Technology, Hybrid III 50th Male Dummy.

Materiały dziewiarskie do zastosowania na odzieżowe wyroby ochronne przed gorącymi czynnikami termicznymi

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1. Wprowadzenie

Specjalne funkcje użytkowe materiałów tekstylnych o przeznaczeniu na odzież ochronną kształtowane są zależnie od grupy zagrożeń występujących w określonych warunkach pracy oraz planowanego asortymentu wyrobów [1]. Znaczną grupę wśród odzieży ochronnej stanowi odzież chroniąca przed czynnikami gorącymi tj. płomień, promieniowanie cieplne, iskry, rozpryski płynnego metalu, gorące przedmioty. Do grup zawodowych narażonych na działanie tej grupy czynników termicznych należą m.in. strażacy, hutnicy, odlewnicy, spawacze, hartownicy i pracownicy przemysłu metalurgicznego. Materiały przeznaczone na odzież ochronną przed czynnikami gorącymi powinny wykazywać określone właściwości, do których należą m.in.[2]:

- odporność na działanie wysokiej temperatury (nie powinny się topić, nadmiernie kurczyć, ulegać destrukcji),
- odporność na zapalenie, żarzenie i podtrzymywanie płomienia,