BIOMECHANICAL ASPECTS OF BLUNT AND PENENTRATING HEAD INJURIES

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Abstract. The objective of this presentation is to discuss certain biomechanical aspects of head injuries due to blunt and penetrating impacts. Emphasis is given to fundamental data leading to injury criteria used in the United States (US) regulations for motor vehicle safety. Full-scale and component tests done under US Federal Motor Vehicle Safety Standards (FMVSS) are described. In addition, results providing occupant safety and vehicle crashworthiness information to the consumer from frontal and lateral impact crash tests are discussed with an emphasis on head injury assessment and mitigation. Recent advancements are presented in angular acceleration thresholds for quantifying brain trauma. In the area of penetrating impact, newer experimental techniques are described for a better understanding of head injury secondary to penetrating impacts, with specific reference to the civilian population.

Key words: Head injury criteria, Federal Motor Vehicle Safety Standards (FMVSS), brain injury, skull fracture, penetrating trauma, linear and rotational accelerations

1. PURPOSE

Head injuries to the civilian population occur due to blunt or penetrating impacts. Motor vehicle crashes are a major source of blunt impact-induced head injuries. Biomechanical techniques used to establish injury criteria are helpful for assessing occupant safety and design user-friendly vehicular components. This presentation describes developments in this area along with current US standards. In the area of penetrating head trauma, a significant majority of the literature is from the military domain [1,2]. Recently, the focus has shifted toward the civilian domain, and because of technological improvements, it is possible to conduct tests to describe biomechanical aspects of injury from this type of external insult.

2. BLUNT IMPACT – FUNDAMENTAL DATA USED IN INJURY ASSESSMENT

Quantifications of head injuries were reported in the 1930-60 literature, although limited fundamental biomechanical studies were conducted earlier [3-7]. Linear and angular accelerations were considered governing variables to describe mechanisms of trauma and define tolerance limits [8,9]. Translational acceleration-time histories were related to skull fracture, using tests from four isolated embalmed cadaver heads and two full-body cadavers subjected to forehead impacts on flat unyielding surfaces. The specimens were dropped from predetermined heights and resulting linear accelerations were recorded at the occiput using an accelerometer. Pulses were of short duration because of the rigid end condition at the instant of impact. Association of linear skull fracture with brain injury, i.e., concussion (80% correlation from clinical cases) was based on previous studies [3,5]. Peak accelerations were used from three isolated and two intact whole-body cadaver tests, and mean acceleration data was used from the other isolated head to develop the original tolerance curve that had durations of up to 6 msec [8]. This curve and corrected data are shown in figure 1. Animal experiments were used to extrapolate to longer duration acceleration-time impacts. The final response, termed Wayne State University Tolerance Curve (WSTC) using effective accelerations as the ordinate, was obtained from animal, volunteer, human cadaver, and clinical research data [10,11]. While WSTC is applicable to the adult population, no efforts were made to develop age-dependent tolerance curves. Versace in 1971 argued that because WSTC curve was developed for average accelerations, comparisons should be made using the mean pulse of interest [12]. He proposed the head injury criterion (HIC), which was modified by NHTSA to provide a better comparison to longer duration human volunteer data [12,13]. This criterion was adopted by FMVSS in 1972 and is still used worldwide for head injury assessment in various areas of impact biomechanics [14]. The criterion is given in equation (1).

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \tag{1}$$

Where t_2 and t_1, arbitrary final and initial times during the acceleration pulse, are chosen to maximize HIC and a(t) is the resultant acceleration at the center of gravity of the head. NHTSA chose a value of 1000 as the threshold in 1972. In October 1986, the interval over which HIC was computed was limited to 36 msec (HIC_{36}) with the same threshold of 1000 for the 50th percentile Hybrid III anthropomorphic dummy. From a theoretical perspective, Backaitis stated that "the HIC formulation contains the peak power term or the rate of change of energy as seen by the head during the impact process" [15]. Eppinger interpreted HIC "as a measure of the change of specific kinetic energy modulated by the square root of the average acceleration over the time interval," and further remarked that, "if the 2.5 power in HIC equation were instead 2, the function would represent the peak average specific power delivered to the head [16]."

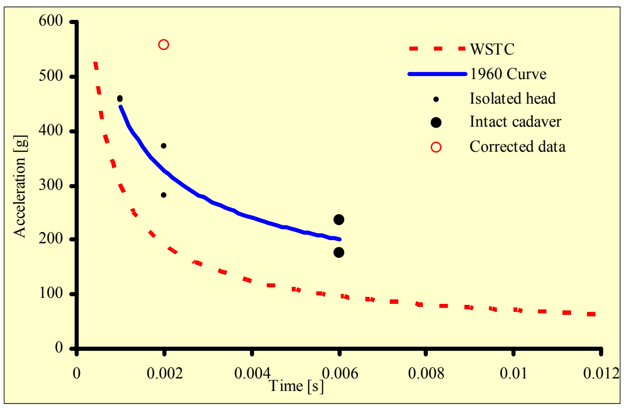

Figure 1. Acceleration responses from embalmed human cadaver tests and the original and revised tolerance curves. The 280 g data (at 0.002 sec, below the 1960 curve) was incorrectly plotted in the original publication [8]; corrected data is shown, open circle (0.001 sec, 557 g).

2.1 Adult occupant protection in frontal impact – FMVSS 208

The principal purpose of the standard is to decrease the number of injuries and fatalities by specifying crashworthiness of vehicles in terms of biomechanical variables measured in dummies tested in simulated environments. The federalized Hybrid III dummy is the anthropomorphic test device. The FMVSS 208 standard specifies the injury metric in terms of HIC for different dummies for head impact protection. The frontal impact standard calls for full-scale vehicle-to-barrier tests at a velocity of 48 km/h and 40 km/h with outboard belted and unbelted dummies in the front seat for the 50th percentile male dummy. While the same fixed rigid barrier tests are specified for the 5th percentile female dummy, tests include an additional

40% left offset frontal deformable barrier test with belted driver and passenger dummies for the 5th percentile female anthropometry (Figure 2). In the case of the unbelted test with the 50th percentile adult male dummy, the vehicle is required to impact the rigid fixed barrier perpendicular to its line of travel and at any angle up to 30 degrees in either direction from the traveling line. In all tests and for both anthropometries (except offset test), the impact is always perpendicular to the path of the vehicle. For certain vehicles, an alternative unbelted test is done to evaluate airbags by sled testing at 48 km/h such that the sled acceleration falls within the corridors shown in figure 3. HIC, determined using the resultant acceleration at the center of gravity of the dummy head, is computed over a 15-msec interval. The injury criterion is based on linear head acceleration data gathered for a period of 300 msec after the vehicle strikes the rigid barrier. HIC limit is chosen as 700 for both adult anthropometries, with no gender bias. For child dummies, HIC_{15} values are as follows: 12-month-old CRABI (Child Dummy AirBag Interaction) is 390, 3-year-old is 570, and 6-year-old is 700. It should be noted that the 95th percentile dummy is not specifically included in the current 208 standards, although the HIC value of 700 was suggested during rulemaking processes.

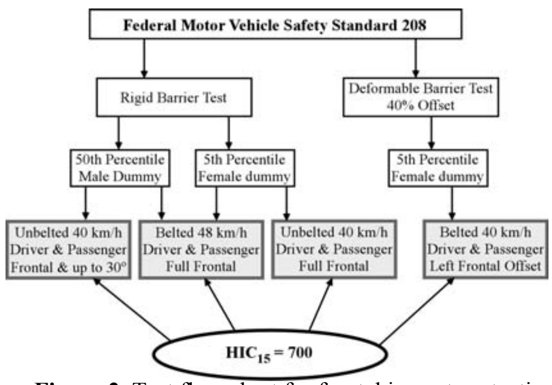

Figure 2. Test flow chart for frontal impact protection.

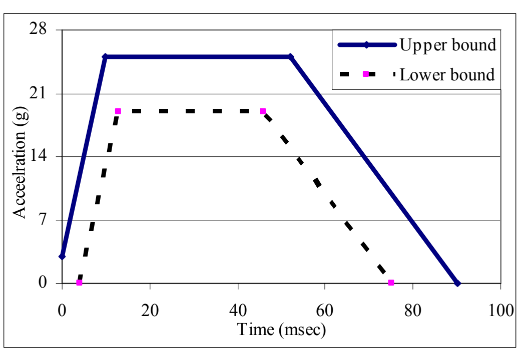

Figure 3. Deceleration pulse corridors for alternative sled tests with unbelted dummies.

The New Car Assessment Program (NCAP) referred to as consumer information tests for relative crashworthiness of vehicles, was initiated by NHTSA in 1978 [17]. The ultimate goal of NCAP is to improve safety by providing market incentives for vehicle manufacturers to voluntarily implement improved crashworthiness in vehicles, rather than through only regulations, i.e., compliance tests such as 208 and 214 standards. For frontal impacts, procedures similar to 208 are followed with the speed raised from 48 to 56 km/h. This increased speed differentiates the performance of vehicles as the energy in the NCAP test is 36% higher than the compliance 48 km/h test. Another measure of severity is the change in velocity (ΔV) of the occupant: 64 km/h (accounting for rebound) in the NCAP compared to 53 km/h in the compliance test. The NCAP currently computes HIC over a 36-msec interval compared to the 15-msec interval used in 208. However, in a recent Request for Comments (RFC) regarding the frontal program, NHTSA gave indication of its intent to begin using HIC_{15} as part of any potential upgrade. By combining injury numbers from the head and chest, a star-rating and a probability of injury are computed (Table 1). NHTSA published an RFC for establishing a high-speed regulation in 2001; it does not have a high-speed frontal offset test in the current standards. Figure 4 shows the probability of injury (AIS 4+) as a function of HIC. The head injury risk from real-world data (National Automotive Sampling System, NASS database) at the two speeds falls on the probability curve.

Table 1: Star-rating in rigid barrier frontal impact NCAP test

Star-rating	Probability of injury
5 stars	10% or less chance of serious head/chest injury
4 stars	11-20% chance of serious injury
3 stars	21-35% chance of serious injury
2 stars	36-45% chance of serious injury
1 star	46% or greater chance of serious injury

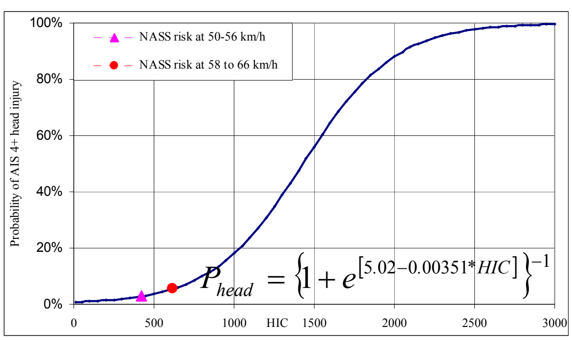

Figure 4. Probability of head injury as measured by HIC for MAIS $\geq$ 4 in frontal impacts. Solid circle and triangular symbols show the risk of head injury based on NASS analyses.

2.2 Occupant protection in side impact - FMVSS 214

The FMVSS 214 standard uses the side impact dummy (SID) designed for lateral impact crashworthiness evaluations. However, a newer dummy, ES-2re, is being considered for future crashworthiness tests because of its enhanced biofidelity compared to SID [18]. Specific limits for head injury assessment do not exist in the current version; thoracic and pelvic regions are covered by respective injury metrics. Like the frontal NCAP, the lateral impact test, LINCAP, uses a higher speed for the moving deformable barrier (62 km/h instead of 54 km/h in the compliance 214) test. These tests also use a star-rating, but the probabilities are different because the side star-rating is calculated only from injury metrics recorded in the chest/torso compared to the frontal impact that uses metrics from both the head and chest. However, since April 2002, NHTSA has noted safety concerns not reflected in the star-rating. One of those is specific to head injuries in LINCAP crash test. A safety concern remark is introduced informing the consumer about the potential for head injury in tests with HIC_{36} exceeding 1000. It should be noted that the same threshold of 1000 is chosen based on the FMVSS 201 pole test. Figure 5 shows the warning scheme that incorporates head injury measure in LINCAP tests, although probabilities are not attached with respect to specific HIC values.

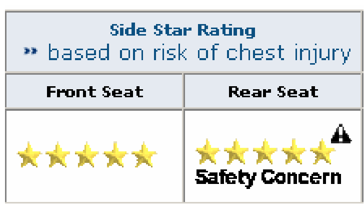

Figure 5. Rating scheme used in lateral impact NCAP tests wherein a warning indicating a higher likelihood of head injury is noted if the test results in a HIC_{36} value exceeding 1000.

2.3 Child occupant protection in frontal impact - FMVSS 213

The FMVSS 213 standard focuses on child restraint systems. Unlike other standards, different dummies are used representing the growing anthropometric characteristics of the human child; table 2 shows specific dummies used for tests. Similar to 208, this standard also uses HIC although the time interval is 36 msec, and the threshold value of 1000 is independent of dummy age. Specifically, depending on the type of restraint, newborn, 9-month old, 12-month, 3- and/or 6-year old dummies are subjected to a ΔV of 48 km/h in a sled environment. The newborn and 9-month old are not instrumented. The characteristic pulse shown in figure 6 has a peak acceleration of 23.5 g at 20 ms. For child seats manufactured after August 1, 2005, NHTSA added upper and lower bounds to the pulse (Figure 7).

Table 2: FMVSS 213. Parentheses refer to the subpart specification of the part 572 dummy.

Weight (kg)	Height (mm)	Dummy to be used in child seats manufactured before August 1, 2005
≤ 5	≤ 650 mm	Newborn (part 572 K)
> 5 and ≤ 10	> 650 and ≤ 850	Newborn (K) and 9-month-old (J)
> 10 and ≤ 18	> 850 and ≤ 1100	9-month-old (J) and 3-year-old (C)
> 18	> 1100	6-year-old (I)
Weight (kg)	Height (mm)	Dummy to be used in child seats manufactured on or after August 1, 2005
≤ 5	≤ 650 mm	Newborn (part 572 K)
> 5 and ≤ 10	> 650 and ≤ 850	Newborn (K) and 12-month-old (R)
> 10 and ≤ 18	> 850 and ≤ 1100	12-month-old (R) and 3-year-old (P)
> 18	> 1100	6-year-old (N)
> 22.7	> 1100	N dummy weighted to 28.2 kg

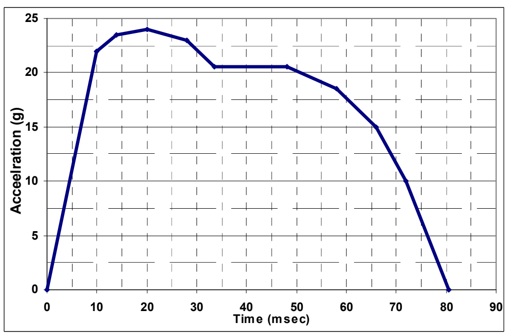

Figure 6. Acceleration-time history according to FMVSS 213 for vehicles manufactured before August 1, 2005.

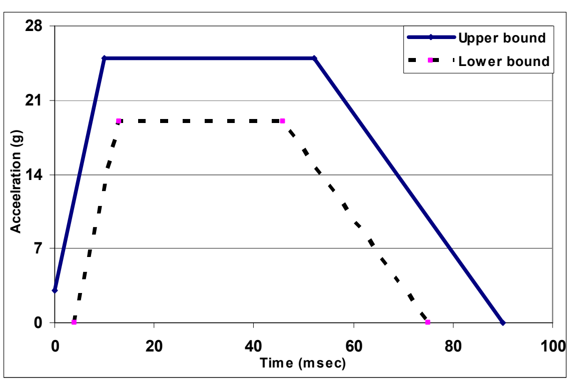

Figure 7. Acceleration-time history according to FMVSS 213 for vehicles manufactured on or after August 1, 2005.

2.4 Occupant protection in interior impact - FMVSS 201

The FMVSS 201 standard has two parts. One part focuses on interior structures (A- and B-pillars and instrument panels) and uses HIC as the injury metric, with a different time limit for its computation, using a head-form for testing. The other part is an optional test for dynamically deployed head protection systems and uses a pole test. For the head-form test, a 6.8 kg, 165-mm diameter, free motion head-form impacts various points inside the vehicle with a velocity of 24 km/h. For a vehicle to pass, the deceleration of the head cannot exceed 80 g for a time period of 3 ms. For evaluating dynamically deployed head protection systems, tests are done using a SID instrumented with a Hybrid III anthropomorphic head and neck and impacting the side of a full vehicle instrumented with a 254-mm diameter stationary rigid pole at a velocity between 24 and 29 km/h. The performance criterion is HIC_{36} threshold of 1000. Injury criteria formula for the free motion head-form is given in equation 2.

$$HIC = 0.75446\ (\text{free motion head-form } HIC_{36}) + 166.4 < 1000 \qquad (2)$$

2.5 Angular acceleration in head injury

As indicated earlier, rotational accelerations have been implicated as a mechanism of injury since the 1940s [9,19]. In a series of publications, Genenralli and co-workers studied the effects of pure angular acceleration, i.e., without direct impact to the head, on brain injuries [20-24]. Their exhaustive research using subhuman primates and physical models led to the development of rotational acceleration thresholds for varying levels of brain injury including concussion, diffuse axonal injury (DAI), and subdural hematoma. More recently, Genneralli et al. synthesized these data and proposed angular acceleration thresholds for diffuse brain injuries as a linear function of varying severities (equation 3, $R^2 = 0.99$), described by the Abbreviated Injury Scale [25,26].

$$\ddot{\omega} = 2.88 * AIS \qquad (3)$$

where, $\ddot{\omega}$ is the rotational acceleration (krad/sec^2) and AIS represents the injury severity values in the length of unconsciousness section according to AIS 1998 version. Using descriptors adapted from literature (Table 3) and the above equation, relationships between various grades of brain injury and AIS were derived (Figure 8). The proposed 10% and 20% decrease in tolerance due to the adverse effect of the epsilon 4 (e4) allele of the apoE genotype is also included in the figure. The profound adverse effect of the epsilon 4 allele of apoE on injury severity and outcome may reflect many factors including biomechanical changes in neuron or astrocyte cell membranes in the brain, and therefore, this genetic characteristic may affect brain injury tolerance [26].

Table 3: Diffuse brain injury categories. Concussion grades are according to ref ([27]).

Description	AIS	Concussion grade	Loss of consciousness
Mild concussion	1	1 to 3	None
Classical concussion	2	4	Less than 1 hour
Severe concussion	3	4	1- 6 hours
Mild diffuse axonal injury	4	5	6 - 24 hours
Moderate diffuse axonal injury	5	5	> 24 hours, no brain abnormality
Severe diffuse axonal injury	5	5	>24 hr, decerebration/decortication

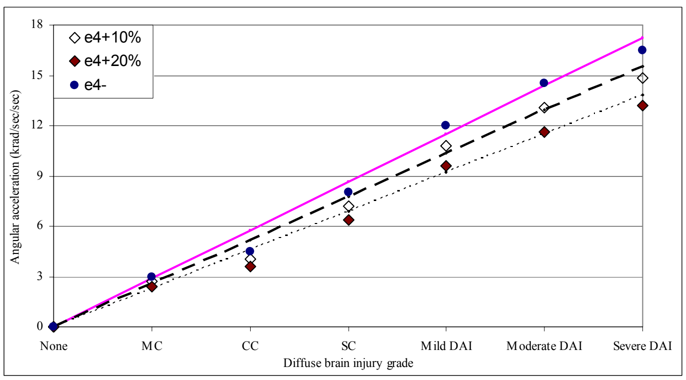

Figure 8. Angular acceleration (krad/sec/sec) as function of diffuse brain injury severity; e4- represents the normal population, and e4+10% and e4+20% correspond to the postulated decreases in tolerance values due to allele of the apoE genotype.

Although rotational acceleration thresholds are established from non-contact-induced experiments (e.g., [28]), studies have examined the importance of head contact to induce the necessary angular acceleration magnitudes. For example, Meaney et al., using computer models, emphasized head contact to develop inertial loading conditions to induce diffuse brain injuries in minor to moderate collisions; ΔV of 74 km/h was needed to exceed the tolerance for concussion and "yet higher velocities for mild to severe DAI" [29]. Their conclusions on the significance of head contact were supported by real-world epidemiological studies of Morris et al. [30]. Backaitis, from an analysis of 755 cases of AIS 3+ injuries in motor vehicle crashes, reported only one injury was associated with no contact [15]. In another analysis of 414 fatal cases of road users in Australia, McLean found no cases of brain injury in the absence of evidence of head impact [31]. Our-to-be-published review of cases from the CIREN database also shows head contact associated with brain injuries (with or without skull fracture) in motor vehicle occupants, thus, reinforcing the role of contact-induced dynamic force application to the human head.

3. PENETRATING IMPACT

The majority of studies in this area is focused on the military domain and used gelatin as the simulant for injury/wound quantification, typically determined as the residual deformation following projectile penetration [1,2]. In addition, the shape of the model is primarily confined to rectangular cross sections. Therefore, their applicability to human head trauma is limited. Recent tests from our laboratories have focused on civilian projectiles, used a more realistic brain simulant, and employed high-frequency pressure transducers coupled with very high-speed digital videography to capture the sequence of temporary cavities, and adopted a model better approximating the shape and boundary conditions of the head.

Briefly, two agents of a silicone dielectric gel, Sylgard 527 A and B were mixed and poured into a diameter globe. A hole in the center of the globe approximated the foramen magnum. A layer of neutral density reference lines was embedded in the "mid-sagittal plane" of the globe to monitor temporal movements of the projectile and gel material. Four pressure sensors were inserted into the globe through predrilled symmetrical holes. Two transducers were close to the entry, and two were close to the exit of the projectile. These pairs were referred to as entry- and exit-transducers for data interpretation. All transducers were approximately at the mid-height of the globe. They were inserted 3.5 cm from the outer surface of the globe so that all sensors were mutually orthogonal to each other. Nine-mm and 25-caliber projectiles were discharged to ensure penetration at the mid-diameter of the globe. The test was photographed using a digital video camera at 20,000 frames/sec. A digital data acquisition system was used to capture the transducer signals at 308 kHz. A fresh globe was used for each test. Parallel tests were conducted by replacing the Sylgard gel with gelatin. Pressure data are summarized in table 4.

Table 4: Peak average pressures (kPa) comparing responses from two brain simulants for two projectiles. Averages were computed from the two entry- and two exit-transducer sets.

Projectile	25 caliber		9 mm	
Simulant	Entry-transducers	Exit-transducers	Entry-transducers	Exit-transducers
Gelatin	245	151	569	484
Sylgard gel	179	242	645	630

In general, results from both simulants indicated significantly higher energy and wounding power for the 9-mm than the 25-caliber projectile; this was determined by the formation and collapse of the temporary cavities and pressure distributions. The 9-mm and 25-caliber projectiles had entry velocities of 378 and 238 m/s. The Sylgard gel responded with higher changes in pressures than the gelatin (e.g., entry: 466 versus 324 kPa) for the 9-mm projectile, demonstrating its greater sensitivity. Because material properties of the gel are closer to the human brain, i.e., increasing dynamic modulus with increasing loading frequency, and because this simulant responded with more differentiable responses compared to the gelatin, the gel may be the most appropriate simulant for brain injury penetrating trauma studies. Temporal pressure distributions at various locations can be used to validate computer models aimed to delineate stress analysis-related variables for brain injury quantifications. Numerical models using the finite element technique are being pursued in our laboratories.

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