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Standards for Athletic Helmets -- State of the Art and Recommendations

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Consumer Product Systems Section
Measurement Engineering Division
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Final Report

Prepared for

Consumer Product Safety Commission
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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Abstract

The literature concerning impact-induced head injuries was surveyed for information on types of head injuries, their relative severity, and injury threshold values. The search revealed that threshold values are either questionable or not available.

A review of standards for helmets revealed that there are no satisfactory performance standards for athletic helmets and that performance criteria and testing procedures used to evaluate other helmets may be neither appropriate nor adequate for testing athletic helmets.

Necessary information is suggested for developing performance criteria and test procedures for athletic helmets. Studies to acquire such information are recommended. Since some of these are complex and may take a long time to complete, interim performance standards for athletic helmets should be developed using current information, and these standards should be revised as the state of the art advances.

Standards for Athletic Helmets -- State of the Art and Recommendations

Introduction

Wearing helmets to prevent or mitigate head injury is not new. Protective headgear has been in use since ancient times, principally in war. Recently, protective helmets have found wide general use, especially in athletic games such as football, hockey, and baseball. In responding to increased participation by both children and adults in body-contact games, manufacturers have produced many protective helmets whose effectiveness may be questionable. Protective helmets are virtually mandatory in body-contact athletics, but performance standards for the protection offered by such helmets are almost non-existent. The National Commission on Product Safety indicates that football players in the United States suffer annually 250 000 to 500 000 brain concussions during play [62], emphasizing the need for performance criteria and test methods to evaluate athletic headgear.

To develop performance criteria and test methods, one should know the maximum acceptable impacts transmitted to the head through the helmet and the impact conditions that are generated by athletic mishaps. The maximum acceptable impacts transmitted to the head depend on the type and severity of head injuries which are acceptable. Information on impact-induced head injuries is essential. This information includes: (1) the type, mechanism, and relative severity of head injury likely to result when the human head is subjected to impact loads, and (2) the various criteria which are used to define impact tolerance limits, or injury threshold values, and the injury threshold values for different head injuries.

It is the purpose of this report to survey the literature concerning impact-induced head injuries, to review existing performance criteria and test methods for headgear, and to recommend studies which will supply the base for developing effective performance criteria and test procedures for athletic helmets.

Impact-Induced Head Injuries*

General

During the past three decades much research has concentrated on injuries to the human body subjected to impact loads. Head injuries have received more attention than injuries to any other part of the body, probably because of the vulnerability of the head to impact injuries and a high correlation between head injury and death.

Some of the factors known to influence head injury due to impact are the geometry and mechanical properties of the impacted surface, biophysical properties of scalp and skull, amount of hair on the head, region of the head, impact direction and intensity (velocity, momentum, or energy), the magnitude, distribution, direction, and duration of the resulting force, and the whole body orientation. In addition, physiological factors such as age, sex, and physical and mental condition of the individual are thought to affect the outcome of accidents, although the manner of their influence is not completely understood.

Several techniques have been used to explore the mechanism of head injuries, including experiments with cadavers, experiments with animals, and experiments with inanimate forms simulating human and subhuman heads. Different researchers have reached different conclusions concerning head injury mechanisms, especially for internal head injuries [1] to [20]. However, most researchers agree that head injuries are usually caused by a combination of mechanisms and that, depending primarily upon the impacting conditions, any one mechanism may contribute more to the overall damage than the others [21]. A discussion of head injury mechanisms and a list of references can be found in [5].

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*The information presented in this section is obtained from the literature pertaining to impact injuries. Over 150 articles and papers were consulted; only the more appropriate ones are cited.

Impact tolerance has been variously defined, and different investigators have used different criteria to establish injury threshold values [22] to [43]. Mechanical quantities used in these criteria to define tolerance limits or injury threshold values include impact velocity, momentum and energy, energy absorbed, impact force, effective contact area, impact duration, impulse, impulse divided by head mass (specific impulse), weighted impulse (Severity Index [24]), acceleration (both translational and rotational), change in head momentum or velocity, jerk, and induced pressure or pressure gradient.

Most of the critiera developed so far have limited application because of the great variety of head injuries, the variability of skull shape and other properties of the head from person to person, and the large number of probable impact conditions. There are some criteria, however, such as the WSU - Tolerance Curve [39], [28] and Severity Index, which have found widespread use despite all these limiting factors.

The data used in most of these developments came from clinical reports of accidents and the laboratory experiments mentioned above. Tolerance limits and threshold values so established may always be questionable, because (1) the data from clinical reports, estimated after the event, may not be reliable and (2) the experimental models (cadavers, living animals, and inanimate forms) do not have the same biophysical and physiological characteristics as those of the live human. At the present state of the art, it is not feasible to establish tolerance limits and threshold values using live humans.

Type, Mechanism, and Relative Severity of Head Injuries

Possible head injuries resulting from impact loads are scalp injuries, skull fractures, and internal head or brain injuries. (Figure 1 shows the schematic anatomy of the human head.)

Scalp injuries can be divided into five types, described below in increasing order of severity:

1. A bruise (contusion) is damage to the soft tissue and small blood vessels that does not break the skin. It occurs when a compressive impact causes the small blood vessels beneath the skin to force (extravasate) blood into the surrounding tissue under the intact skin.

2. An abrasion is caused by a blunt object sliding over the scalp with sufficient force to remove the superficial layers of the skin.

3. A <u>puncture</u> occurs when a sharp (pointed) object impacts the skin with sufficient force to penetrate it.

4. A <u>laceration</u> is an incised wound which usually occurs when a sharp object (a sharp edge or a sharp point) pressing against the skin is pulled across it.

5. An <u>avulsion</u> results when the peeling action of an impacting object rips off a portion of the scalp from the skull.

Scalp injuries are quite common, especially when the head is bare when impacted, and may result in severe hemorrhage, infection, or disfigurement. Even so, they are not as potentially lethal as are skull and brain injuries.

<u>Skull fractures</u> may be either closed or open. A closed fracture is a break in the skull with no apparent break in the overlying scalp. In an open fracture both the skull and the overlying scalp are broken. Open fractures are more serious than closed ones because the open fractures may become infected, and infection may complicate the healing process.

Skull fractures are of four major types: linear, indented, depressed, and crushed. The first three types are not life threatening if not accompanied by brain damage.

1. A <u>linear fracture</u> usually results from head impact with a relatively blunt object (contact area in the range of two square inches or larger) [32]. It occurs when the applied load, acting on a section of the skull, produces a large enough bending moment to crack the bone. Because of the biological variations in skulls, the exact configuration of the crack cannot be predicted with certainty. Usually it appears as a single line emanating from the area of impact and may involve either the inner or outer skull surface or both [1]. Sometimes, however, linear fracture appears as a stellate fracture, a group of cracks in a star shape radiating from the central impact point. Another form of linear fracture is the basal fracture which results when the impact energy from a blow to the cranial vault is transmitted around the skull to cause fracture in the area of the foramen magnum.

   Sometimes a linear fracture perpendicular to the path of a meningeal artery may rupture the artery and cause a blood clot on the main surface (epidural hematoma), a life-threatening injury.

2. In an <u>indented fracture</u> the skull is displaced inwardly

without a fracture line being visible. It occurs mainly in children whose skull bones are thin and flexible. Complications may include brain compression and disfigurement.

3. Depressed fractures are of two kinds, penetrating and comminuted.

   Penetration-type depressed fractures are the result of highly localized loading of the skull by an insulting object with an impact area less than one square inch [32]. The failure appears directly under the impactor on the outer surface of the skull, usually as the impactor punches out, by shearing action, that portion of the skull directly under it, with little or no disturbance of the surrounding skull [1], [32].

   Comminuted depressed fracture generally occurs when an impactor, having an impact area in the range of one to two square inches, causes a localized indentation of the skull and breaks the depressed bone into several pieces [32]. The larger impact area generally precludes skull penetration; instead, the skull in the vicinity of the impacted region deforms as a structural unit, producing a concentrated bending moment in the skull directly under the load region causing the bone to fail. Broken fragments of the bone may be driven into the interior of the head causing internal injuries.

4. A crush fracture occurs when the head is caught in a vise-like action, such as when a car rolls over a victim's head. Crush fractures usually result in death. This type of fracture is not likely to result from foreseeable athletic mishaps.

In general, skull fracture is an indication of severe impact. There are conditions, however, under which fatal impacts to the human head may not cause skull fracture. For example, if the impact loading is distributed over the skull (a desirable condition for fracture mitigation, and one of the functions of a protective helmet), a fatal internal head injury can result without skull fracture [5].

Internal Head or Brain Injuries

Internal head or brain injuries are much more serious than scalp and skull injuries [1] and consequently are the most important to be protected against. The types of brain injuries to be discussed are cerebral concussion, and brain contusion, laceration, and intracranial bleeding, of which concussion is the most common.

The mechanisms of brain injury have been a subject of controversy among researchers, who have concentrated on different mechanical causes, including: linear and rotational acceleration, deceleration, compression, changes in intracranial pressure, cavitation in the area opposite to the site of impact (countrecoup), and relative motion of the brain with respect to the skull.

Detailed descriptions of brain injuries and brain-injury mechanisms can be found in references [5] and [18]. The following are simplified descriptions of the brain injuries mentioned above.

1. Cerebral concussion may be described as an immediate post-traumatic brain dysfunction characterized by unconsciousness and blindness or inability to focus which is usually reversible but may be fatal [5]. In closed-head injury, concussion is generally considered to be due to the stretching of the brain stem. [A direct blow to the head causes the skull and brain to move in a direction determined primarily by the location and direction of the blow. The brain lags behind the skull, causing a relative motion between the skull and brain which allows the main cerebral mass to move (translate or rotate) with respect to the brain stem. The relative motion between the brain and brain stem produces stretching of the brain stem.]

   However, the mechanisms responsible for long periods of unconsciousness, which accompany severe concussion, have not been definitely established. In severe concussion, extensive diffuse cerebral damage is usually found; thus stretching of the brain stem may not be solely responsible. Furthermore, direct impact of the head is not the only way in which a concussion is produced. It is known that a concussion may also be produced by a whiplash [1], [16].

   A concussion with loss of consciousness for up to 30 minutes is considered to be serious but not life-threatening; a concussion with unconsciousness lasting more than 30 minutes is considered to be life-threatening.

2. Relative movements of the brain with respect to the skull are due to different rates of acceleration of the skull and brain following impacts. These movements are the usual cause of brain contusion. Brain contusions occur not only in the site-of-impact (coup) and opposite-to-the-impact (contrecoup) regions, but may be sufficiently widespread to constitute a form of diffuse brain damage.

   The relative motion between the skull and brain produces injury to the brain as well as tearing of the blood vessels that connect the brain to its overlying membranes, causing intracranial bleeding (subdural hematoma). Subdural bleeding following a head injury in sports is potentially lethal [5], [7], [9].

   In the region of the impact, pressure from the blow may cause the small blood vessels to burst and force (extravasate) blood into the surrounding tissue.

   In the region opposite the impact site, the mechanism of injury is more complex. One theory holds that the skull being more rigid than the brain, is driven in the direction of the blow with the contrecoup point traveling nearly as fast as the coup point, while the brain deforms and lags behind the skull. Under these conditions a positive pressure at the coup point and a negative pressure at the contrecoup region are developed. The negative pressure causes the formation of bubbles in and on the brain substance; brain damage results during both formation and collapse of the bubbles [5].

   Subdural and subarachnoid hemmorhages (see Fig. 1) have been observed in athletes who have suffered severe head injuries during baseball and football. In many cases of fatal boxing injuries, large subdural hematomas are seen [7]. A frequent pathological finding is the presence of hemmorhages in the brain stem. These may be secondary to pressure against or other injury to the brain stem or to primary lesions caused at the time of impact by shear strains in the brain stem which result from pressure gradients [5].

   Brain laceration occurs when the brain is subjected to a force of sufficient intensity to cause tearing of the brain substance. Brain laceration, when accompanied by skull fracture, can be produced by broken bone fragments that are driven into the brain substance.

   These injuries (brain contusion, brain laceration, and intracranial bleeding), based on clinical prognosis, may be different levels of severity. However, all of them are life-threatening, and for the purpose of this report they are placed at the same level of severity.

Table 1 shows in summary form the various types of impact-induced head injuries and their relative severity.

Injury Criteria and Threshold Limits

Some of the criteria that have been used to define or establish threshold limits for the three major categories of head injuries are given below.

Scalp injuries have received the least attention of all the head injuries, and relatively little has been done to establish scalp injury threshold limits. Gadd et al. [23] obtained limited data for the laceration and crushing of the scalp and related their data to impact force and the geometry of the impacting object. Others [44] to [46], studying the resistance of skin to puncture and laceration under mostly static loading, also used the applied force and the geometry of the insulting object in their analysis.

From the limited data of references [23], [44], [45], and [46], the following injury threshold values can be estimated: The scalp contusion threshold is approximately 500 lbf/in^2 ($3.5 \times 10^6 N/m^2$). The scalp puncture and/or laceration threshold ranges from 1300 lbf/in^2 to 10 000 lbf/in^2 (9×10^6 to 69×10^6 N/m^2), depending upon the geometry of the injuring object and the biophysical properties of the scalp.

No data have been found on abrading and avulsion of the scalp.

Some of the criteria or combinations of different physical factors which have been used to establish skull fracture tolerance or threshold values are: (1) peak impact force and effective contact area, (2) peak impact force and the geometric description of the impacting object, (3) energy absorbed, (4) acceleration (peak or average) and effective contact area, (5) average or effective acceleration and time duration, as in the Wayne State University acceleration-time tolerance curve (WSU-curve) [28], (6) Severity Index (S.I.), and (7) Effective Displacement Index (EDI). The last three of these, however, were originally proposed for life-threatening cerebral concussion.

The numerical values obtained for skull fracture threshold limits range widely, primarily because the outcome of impact depends upon the region of skull impacted, the geometry of the impacting object and the biophysical properties of the skull and overlying scalp, which vary from individual to individual.

Threshold values for skull fracture and other injuries and the appropriate references are presented in Table 2.

The most frequently used criteria for defining the threshold values for internal head injury are the following: WSU-curve [28], S.I. [24], EDI [22], Maximum Strain Criterion Tolerance Curve (MSC) [40], J-Tolerance Value of the Vienna Institute of Technology [38], and the National Highway Traffic Safety Administration's Head Injury Criterion (HIC) [48].

The WSU-curve , for cerebral concussion due to frontal impacts, was constructed by combining data from intracranial pressure studies, cadaver skull fracture tests, and volunteer sled riders [7], [28]. The tolerance data are presented as a curve on rectilinear graph paper with effective acceleration (area under the computed acceleration pulse divided by the pulse duration) as abscissa and pulse duration as ordinate. From this curve, cerebral concussion threshold limits can be obtained in terms of effective acceleration of the head and pulse duration (See table 2).

The severity index is defined as

$$\text{S.I.} = \int_{t_o}^{t_f} (a/g_n)^m dt \qquad \text{(seconds)} \qquad (1)$$

where: g_n = 9.806 65 meters per second squared.

a = acceleration in the units used for g_n .

m = weighting factor greater than one (2.5 has been used for internal head injury).

t_o = starting time of the acceleration pulse in seconds.

t_f = final time of the acceleration pulse in seconds.

The method for computing the S.I. from the acceleration-time record of any pulse is found in references [39] and [47]. A value of S.I. = 1 000 seconds has been proposed as the threshold value for life-threatening internal head injury.*

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*Although the units of S.I. and HIC are seconds, the units are almost always omitted in the literature.

The EDI tolerance values are obtained by computing the maximum displacement of the mass in a mathematical head-damage model, when the model is excited by an impulse applied to its base. The model is a single-degree-of-freedom, damped spring-mass system represented by a second-order differential equation which is uniquely specified by a natural frequency and damping factor. By adjusting the natural frequency and damping factor, and assuming a maximum permissible displacement, the best fit to the acceleration-time tolerance curve is obtained.

Since the MSC and J-Tolerance criteria are both very similar to EDI, they are not discussed here.

The HIC, essentially a modification of the S.I., is given by

$$\mathrm{HIC} = (t_2 - t_1)\left[\frac{1}{(t_2-t_1)} \int_{t_1}^{t_2} (a/g_n)\, dt\right]^{2.5} \quad \text{(seconds)} \qquad (2)$$

where t_1 and t_2 are two points in time whose selection rules are specified [48].

All of the above mentioned criteria are for impact-induced translational acceleration. As discussed earlier, impact-induced rotational motion may be one of the causes of internal head injury. Moreover, unless the line of impact passes through the center of rotation of the head, all impacts would cause the head to rotate. Although some investigators [2] and [16], experimenting with animals to study the mechanism of internal head injury, have shown that under certain conditions an injury may be produced by impact-induced rotation alone, yet relatively little has been done to establish tolerance limits for rotational acceleration.

Ommaya et al. [36] obtained a rotational acceleration-time tolerance curve for whiplash injury and cerebral concussion for monkeys. They also obtained a scaling relationship between sub-human primates and man for concussive levels of rotational acceleration, and concluded that the human should have greater than a 99% probability of concussion at an angular acceleration of 7500 rad/s^2 with impact pulse duration exceeding 6.5 milliseconds.

Suggested threshold values for life-threatening concussions or internal head injury are given in Table 2. Threshold values for other internal head injuries and non-life threatening concussion have not been found.

Present Standards for Helmets

The first performance standard for crash helmets for racing drivers was published by Snell Memorial Foundation in 1959. It was revised and made more stringent in 1962, and again in 1968, as the state-of-the-art of helmet manufacture advanced. The Foundation published a newer Standard for Protective Headgear which became effective July 1, 1970. This Standard is even more demanding in its test requirements [49]. It specifies methods to test the impact energy attenuation properties of the helmet assembly, shell penetration resistance, and the strength of the retention system and its attachment. The impact energy attenuating (shock-absorbing) properties of the helmet assembly are tested as follows: The helmet to be tested is placed on a standard headform containing an acceleration transducer at its center of gravity and the headform assembly is dropped from a specified height, in a specified orientation, onto a steel anvil. The transducer output is recorded as a function of time. If the recorded acceleration is less than specified limits for a specified time duration, the helmet is assumed to be adequate. Details of the test equipment and test procedures are found in the Standard [49].

The American Standards Association, in 1966, published the ASA Z90.1-1966 standard requiring the same level of protection against impact as required in the 1962 Snell Memorial Foundation standard. The test equipment and the test procedures specified in the present form of this standard, known as ANSI Z90.1-1971 American National Standard Specifications for Headgear for Vehicular Users [50], are identical to those of the Snell Memorial Foundation 1970 standard. However, the performance requirements of the ANSI Z90.1-1971 standard, especially with respect to the energy-absorbing capability of the helmet, are less demanding, because the tests are conducted with lower impact energies and greater induced accelerations are acceptable.

The safety standard proposed by the National Highway Traffic Safety Administration for motorcycle helmets [51] is a modification of the ANSI Z90.1-1971 standard. The major difference is the criterion for adequate energy-absorbing performance. Instead of peak acceleration and time duration above a specified acceleration, the criterion used in this standard is a specified value of HIC (equation 2), calculated from characteristics of the acceleration pulse obtained from the drop test. If the calculated HIC is less than 1000 seconds the test helmet is assumed to be satisfactory. Details are given in reference [51].

Rayne and Maslen [52] in 1969, suggested methods to evaluate buffet helmets, i.e. helmets used to protect against repeated low-energy impacts. Their suggested test method, similar to that specified in the ANSI Z90.1-1971 standard, is conducted with an impact energy of 22.5 foot-pounds-force (30.6 joules); the maximum acceleration acceptable is 120 g_n .

The preliminary standard for hockey helmets, published in January 1973 by the Canadian Standards Association [53], is a modified version of the American National Standard Safety Requirements for Industrial Head Protection (ANSI Z89.1-1969), which was published on December 17, 1969 [54]. The test equipment and test procedures do not appear to be applicable to athletic helmets.

The Law Enforcement Standards Laboratory of the National Bureau of Standards is developing safety standards for riot police helmets, and Committee F-8 of the American Society for Testing and Materials (ASTM) is developing safety standards for football helmets. The test methods proposed by both of these organizations are similar to those described in the ANSI Z90.1-1971 Standard. However, certain changes in the test equipment, the impact energy at which the tests are conducted, and the performance criteria are all under review [55].

A major change considered by ASTM is a change in the test headform. Instead of the metallic headform described in the ANSI Z90.1-1971 Standard, a resilient headform designed and developed at Wayne State University was considered. However, ASTM decided not to use the resilient headform at this time and to continue using the metallic headform because the resilient headform has not given reproducible results during a round robin test, it is thought to be fragile, thereby limiting the impact energy that can be used in drops, and it is still under development [55].

Each of the present standards specifies a solid headform without a simulated neck attachment and therefore cannot provide information regarding impact-induced rotation of the head. Impact-induced rotation has been identified as one of the major causes of internal head injuries [14], [16]. It may also cause injuries to the neck area, including damage to the spinal cord, blood vessels, and muscles and ligaments of the neck [5], [6]. Moreover, a poorly designed helmet system may actually increase the likelihood of impact-induced head rotation, thereby increasing the danger of neck and internal head injuries. For example, Schneider et al. [56] claim that the use of face protection devices which are part of the helmet system has increased the number of injuries of the neck and spinal cord.

Although helmets are not designed to protect against neck injuries, an effective evaluation of the overall helmet system should include a measurement of impact-induced rotation, in order that any additional danger of neck injuries created by the helmet system could be verified. Obviously, protection of one part of the body at the expense of another may not be desirable.

The performance criteria in most of the standards are based upon life-threatening head injury. These criteria may be adequate for crash helmets, designed to protect against a single strong impact. In athletic events, however, the athlete should also be protected from injury that can result from repeated moderate or intermediate impacts. Therefore, the performance criteria and test conditions developed for crash helmets may not be appropriate for athletic helmets.

Performance Criteria for Athletic Helmets

To develop effective performance criteria, one should have a clear understanding of the type and severity of head injuries which are unacceptable. From impact tolerance curves and injury threshold data, one could then determine the maximum acceptable impacts that may be received by the head. Unfortunately, injury threshold data for sub-fatal internal head injuries are not available, yet such injuries, including sub-fatal concussion, are among the most common head injuries suffered by helmeted athletes.

The other important information required for helmet performance criteria concerns the impact conditions that are generated in athletic accidents, such as the ranges of impact energy and velocity, regions of the head impacted, geometry of the object contacted. Although some investigations have been conducted in the past to study head injuries occurring in certain sports [56], [57], [58], [59], and to determine the translational accelerations experienced by football players during competition [60], [61], systematic assessment of impact conditions has received little attention. Impact conditions differ from one sport to another. To be effective, performance criteria and test procedires must be specific for the impact conditions of each sport.

To determine the types and severities of head injuries which are unacceptable, to assure the adequacy and reproducibility of test equipment and to obtain other needed information, the studies indicated below are recommended.

1. Consensus. Determining the types and severities of head injuries which are unacceptable is extremely difficult,

primarily because many subjective questions must be resolved. For a conclusive settlement of this problem, a consensus of medical experts, parents, athletes, coaches, trainers, and team physicians, should be obtained by means of a carefully planned survey.

2. <u>Case and field studies</u>. An in-depth study should be made of athletic accidents that have resulted in head injuries. These studies should investigate factors such as the cause of the accident, state of mind of the athletes involved prior to the accident, type and severity of injuries inflicted, impact conditions of the accident, and the objects contacted. In addition to the accident itself, environmental conditions to which the athletes are subjected during the competition should also be studied.

   Tools to accomplish these objectives may include motion pictures of games, and interviews with athletes, coaches, and team physicians. Such studies will require the cooperation of the coaches and trainers, physicians, and sport organizers.

3. <u>Threshold values for sub-fatal internal head injuries</u>. Investigations are needed to establish the threshold values for sub-fatal internal head injuries. Such studies may require a team consisting of neurologists, pathologists, neurosurgeons, and engineers and adequate laboratory facilities for experiments with live animals and human cadavers. Investigators such as Hodgson [13] and Ommaya [16] did obtain data for impact-induced sub-fatal internal head injuries sustained by experimental animals. Further investigations would yield additional information, which when combined with the presently available data could determine the threshold values for sub-fatal internal head injuries in humans.

4. <u>Calibration of test headform with respect to injury</u>. Research should be undertaken to calibrate the test headform and to establish the relationships between the response of the headform to impact and probable human injury due to similar impact. A team of investigators and laboratory facilities similar to those required for study 3, above, would be needed.

   A procedure for development of the desired relationships is as follows: The headform and the intact cadaver head should be subjected to a series of identical impacts with impactors having a range of masses and geometric characteristics, and using a range of impact velocities. The data will consist of the mechanical responses of the test headform and the cadaver head, and appraisal of the damage to the cadaver head for each impact. Mechanical quantities of interest are impulse, acceleration-time history, and peak force.

The data obtained from impact experiments should be used to develop the relationships between the responses to impact of the test headform and of the cadaver head. A second relationship between the cadaver head response and live human injury should be developed. The data obtained in the impact experiments, injury data in the literature, and data collected for sub-fatal internal head injuries in study 3, may be useful for developing the second relationship.

These two relationships would then be combined to yield the correspondence between test headform response and probable human injury. Thereafter, similar test headforms could be calibrated using the data already developed.

5. Test Equipment

   A round robin test program should be designed and undertaken to make certain that participants interested in helmets are capable of obtaining equivalent results.

   Before launching a program to develop new test headforms the possibility of using the ANSI Z90.1 headform, with or without modifications, or the resilient headform developed at Wayne State University, or the resilient head-neck system developed at the Highway Safety Research Institute, University of Michigan, should be thoroughly explored.

6. Interim standards. The efforts essential for effective standards for athletic helmets are involved and may take a long time to complete. However, helmet safety standards, especially for amateur athletes and children, are badly needed. By making the best use of current information, an interim performance standard for athletic helmets should be developed. As the state of the art advances, the interim standard can be appropriately revised.

Concluding Remarks

It is difficult, at present, to establish effective performance criteria for athletic helmets because most of the needed information is not yet available. Vital information, such as threshold values for sub-fatal head injuries, is hard to obtain because humans are complex and variable, and techniques for testing live humans are limited. Nevertheless, by careful use of available information, interim performance criteria and standards for evaluating athletic helmets can be developed. An interim standard will have to suffice until the essential information becomes available.

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TABLE 1. IMPACT-INDUCED HEAD INJURIES AND THEIR RELATIVE SEVERITY*

Head Part Injured	Injury Type and Relative Severity				
	Level 1 Minor	Level 2 Moderate	Level 3 Moderately severe	Level 4 Life-threatening	Level 5 Fatal
Scalp Injuries	Contusion, abrasion	Lacerating puncture, avulsion			
Skull Fractures			Linear skull fracture	Depressed skull fracture indented skull fracture	Crushed skull fracture
Brain Injuries - Concussion			Concussion with unconsciousness lasting up to 30 minutes	Concussion with unconsciousness lasting more than 30 minutes, brain contusion, brain laceration, and intracranial bleeding	Fatal concussion, brain stem severence

*References [1], [28], and [43].

TABLE 2. Head Injury Threshold Values

Injury	Criterion	Threshold Value	Remarks	References
SCALP INJURIES				
Contusion	(Force divided by area) F/A	500 lbf/in^2 (3.5×10^6 N/m^2)	Experiment conducted with 1 in^2 (6.45 cm^2) contact area.	23
Abrasion			No data available.	
Puncture and laceration	F/A	1300-10,000 lbf/in^{2*} (9×10^6 - 69×10^6 N/m^2)	Varies with geometry of the injuring object and scalp properties.	23,44,45
Avalusion			No data available	
SKULL FRACTURES				
Linear (average)	(Energy absorbed) E_{ab}	400 - 900 in lb (45.2 - 101.7 J)	Intact cadaver head dropped onto steel block. Impact velocity range 15-19.3 ft/s (4.572 - 5.883 m/s).	8,32
Midfrontal region	E_{ab}	571 in lb (64.5 J)		
Midoccipital region	E_{ab}	571 in lb (58.4 J)		
Anterior Inter-panetal region	E_{ab}	710 in lb (80.2 J)		
Region above each ear	E_{ab}	615 in lb (69.5 J)		
Linear Frontal bone	(Force) F	940 lb (4180 N)	1 in^2 (6.45 cm^2) striker impacting the intact cadaver head with skin removed from skull. Striker weight 2.76 lb (1.252 kg), velocity 7.1 ft/s (2.264 m/s).	32
Linear Frontal bone	F	943-2050 lb (4195-9120 N)	5.2 in^2 (33.54 cm^2) padded striker surface, time duration 4-5 ms.	32
	F	940-1650 (4172-7340 N)	Intact cadaver head impacted by the curved surface of 1 in (2.54 cm) radius cylinderical striker. Striker assembly weight, 10 lb (4.536 kg) dropped on cadaver head from heights 5-20 in (12.7 50.8 cm).	11,32
	F	700-1730 lb (3114-7695 N)	Curved surface of 5/16 in (0.79 cm) radius striker dropped onto the cadaver head.	11,32

TABLE 2 continued

Linear 1/	Peak acceleration and time duration (a_p,t)	A_p (g) 337 344 724	t(ms) 11.25 4.88 3.38	Intact cadaver head dropped onto the instrumental panel of car with forehead impacting.	32
Linear	Effective acceleration and time duration (a_e,t)	A_e (g) 180 135 100 80	t(ms) 2.0 3.0 5.0 8.0	Frontal bone impact, intact cadaver head dropped on unyielding plane surface. Based upon the Wayne State curve.	17,37,38
Linear	Severity Index S.I. effective displacement index EDI.	565 s 0.12 in. (0.305 cm)		Intact cadaver head dropped onto a flat plate. Drop height 10-30 in (25.4-76.2 cm).	27
Indented Fracture				No data available	
Depressed Fracture Frontal bone	Force F	900 lb (4003N)		1 in^2 (6.45 cm^2) impactor surface.	32
Temporal area	F	450 lb (2002N)		impactor weight 2-10.6 lb (0.907-4.797 kg)	
Zygomatic area	F	200 lb (889.6N)		impactor drop height 2.5-9.5 ft (0.762-2.896 m)	
Depressed Penetration Fracture Frontal region	F	500 lb (2224N) with 0.432 in (1.1 cm) dia impactor		Skull caps from embalmed cadaver mounted in holding fixture were loaded statically and at 14 ft/s and 28 ft/s impactor velocity.	32,39
	F	1000 lb (4448N) with 0.5 in (1.27 cm) dia. impactor			
	F	1000 (4448N) with 0.612 in (1.55cm) dia. impactor			
Depressed penetration fracture Parietal region	F	140 lb (622.7N) with 0.432 in (1.1 cm) dia impactor			
	F	400 lb (1779N) with 0.5 in (1.27 cm) dia impactor			
	F	500 lb (2224N) with 0.612 in (1.55 cm) dia impactor			

TABLE 2 continued

Crushed Fracture			No data available
Brain Injuries			
Concussion	S.I. Linear acceleration and time duration	1000 Same as for linear fracture above.	Suggested value for life-threatening concussion.
	Rotational acceleration	7500 rad/s , for time duration 6.5 ms or longer.	Life-threatening ceregral concussion suggested by the scaling of animal data.
Other Internal Head or Brain Injuries.			No data available.

*Estimated from the data of the references cited.

1/ Type of fracture not given.

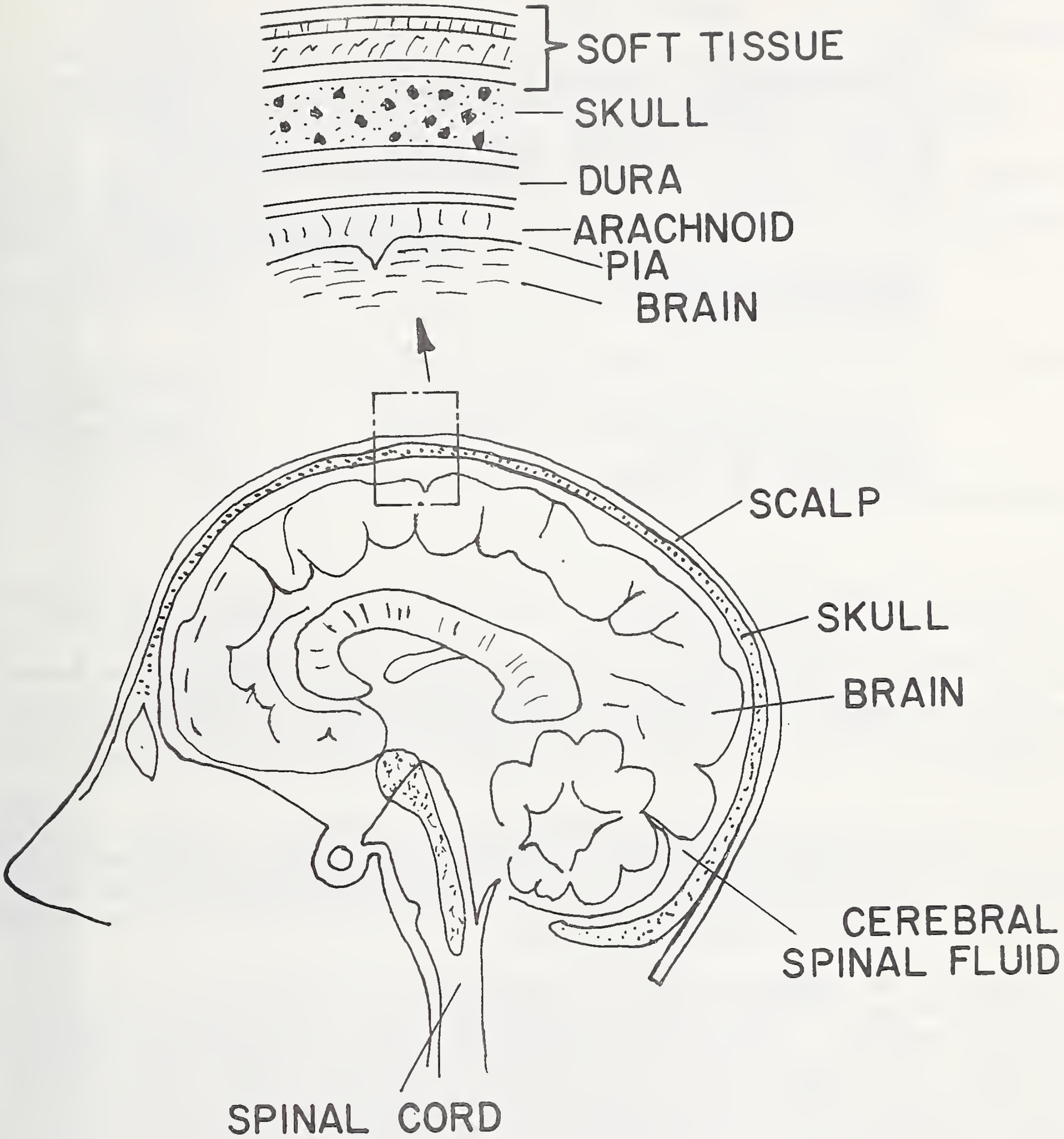

Figure 1. Schematic Anatomy of Human Head

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The literature pertaining to impact-induced head injuries was surveyed to collect information concerning various types of head injuries, their relative severity, and suggested threshold values for these injuries. The search revealed that such threshold values are either unavailable or questionable.

The review of the performance standards for helmets revealed that there are no satisfactory performance standards available for athletic helmets and that the performance criteria and testing procedures presently employed to evaluate helmets may be neither applicable to nor adequate for the testing of athletic helmets.

Information is suggested that is considered necessary for the development of performance criteria and test procedures for meaningful evaluation of athletic helmets. Pertinent studies required for the acquisition of such information are suggested. Since some of these studies are complex and may take a long time to complete, it is suggested that interim performance standards for athletic helmets be developed utilizing presently available information, and that these standards be revised as the state-of-the-art advances.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Athletic helmets; injury criteria; head injury; protective helmets; impact injury; cranial concussion

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