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DOOR CRASHWORTHINESS CRITERIA

Highway Safety Research Institute
The University of Michigan
Huron Parkway and Baxter Road
Ann Arbor, Michigan 48105

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16. Abstract

A series of side impacts to the head and body were conducted up to the lethal level with infra-human primates whose anatomical and physiological relationship are most like man. The mechanical responses were then correlated with the degree of injury determined by gross autopsy. Dimensional analysis techniques and extrapolation were made from the infra-human primate data to estimate human tolerance for side impact. The threshold of brain injury was determined from these scaling relations to be 56 G's peak acceleration with a triangular pulse of 7.5 milliseconds. A tolerable contact pressure of 19 psi was established when impacted in the side by an arm rest-like striker.

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1. INTRODUCTION

This report describes the work performed for the National Highway Traffic Safety Administration under Contract No. FH-11-7288 entitled, "Door Crashworthiness Criteria."

In the performance of this study the Contractor, within the limits of time and funds available, was required to perform the following tasks:

1. Modify existing two-dimensional computer models for simulation of vehicle impacts to include the side impact situation and from the associated kinematics, identify those areas of the body which show greatest likelihood of impact with side structure. Identify the structural elements in side systems associated with the impact. Relate second collision impact velocities with crash velocity. Compare results of study with accident analyses which were to have been made available to contractor by NHTSA.

2. By suitable animal* and cadaver experimentation and literature analysis, develop curves relating intensity of body impact with probability of injury to man for each subject involved for the variety of realistic impact configurations determined from study under (1).

3. Conduct a series of idealized impact tests for side directed situations with animal and cadaver subjects to develop relationships between level of impact, contact area, body area and type and degree of injury to man.

1.1 CURRENT RESEARCH KNOWLEDGE

Knowledge of human response to lateral ($\pm G_y$) acceleration forces is very limited. In contrast to studies of impact tolerance involving vertical,

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*The animals used in this study were handled in accordance with the "Principles of Laboratory Animal Care" established by the National Academy of Science/National Research Council and National Society for Medical Research.

forward, or rearward-facing body orientations, to date few studies have been conducted with either human or animal subjects facing sideward. Most previous studies, furthermore, have been conducted under conditions of maximum restraint, offering considerably greater protection to the body than does the lap belt only. No studies are known that have been conducted in respect to side impact with unrestrained animal or human subjects.

1.1.1 Tolerance to Side Impacts

To date, animal tests have been primarily conducted relative to aerospace programs. In support of Apollo tests, one American black bear, wearing full Apollo restraint, except for the helmet, was exposed to a peak lateral acceleration of 46 G with a velocity change of 32 ft/sec and onset rate of 4180 G per second, without reported injury (Clarke, unpublished data, 1962). A second bear, in a single experiment in which the animal was restrained in a B-58 capsule, survived 8.5 G at four hertz without post-mortem evidence of trauma (Clarke, unpublished data, 1962).

Robinson, et al. (1963) have exposed rhesus monkeys to repeated lateral impacts of up to 75 G at 32 ft/sec while restrained in half-body mass. He found electrocardiographic evidence of transient abnormalities in both conduction and rhythm following impacts at accelerations higher than 55 G. Comparison of radiographs taken pre- and post-impact revealed an increase in the percent of the total heart shadow on the dependent side of the midline following the test. Abnormalities of the heart occurred twice as often in those monkeys receiving left lateral impacts as those impacted on their right side.

Stapp reported no injuries to five chipmanzees decelerated on the Holloman rocket track at 20.8 to 47 (calculated) input lateral accelerations (right, $+G_y$) at 929 to 1180 G/sec for 0.118 to 0.170 seconds duration (1952; 1955). Lombard, et al., exposed guinea pigs to 240 G for 0.033 seconds at 100,000 G/sec rate of onset in a fully contoured rigid support system (1964).

More recent tests utilizing baboon subjects have resulted in findings which indicate that significantly greater injury occurs in lateral ($+G_y$) impact, relative to either forward or rearward facing exposures, at every level of impact studies from 15 to 44 G (Snyder, et al., 1967). These tests, contrary to the bear, chimpanzee, and rhesus tests noted, were conducted with minimal restraint of a lap belt only, and may be of greater significance to the lap-belted human automobile occupant than the previous tests of full body support. The combination of lateral flexion of the thorax, plus torquing, places unusual stress on the abdominal and back musculature and viscera. Injuries fell into several categories. Five animals received ruptured bladders, an injury which only occurred in the lateral impacts. Contusions, tears, or lacerations, and a complete severance of the uterus also occurred in five cases. In three instances, cervical fractures occurred with complete atlanto-occipital separation and transection of the spinal cord occurring in one 30 G impact. Such cervical trauma did not occur in either rear-facing or forward-facing impacts. The most significant finding, and quite unexpected, was that of pancreatic hemorrhage in all lateral cases autopsied. Subsequent investigations were conducted of baboon subjects exposed to lateral impact wearing 3-point, Y-yoke, and a (European type) upper torso single diagonal belt only (Snyder, et al., 1968b; 1967a). Ninety degree side impacts at 22 G, with the 3-point system, resulted in severe dural and urinary bladder hemorrhage, and fatal dislocation of the atlanto-occipital joint at 30 G. These tests indicate that in any future side-impact studies particular attention should be paid to kidney, dural, and myocardial trauma, injuries found in these experiments and since noted in at least one study of side-impact automotive collisions et al.

Human lateral impact tests in support of Apollo have been conducted under conditions of maximum restraint protection including use of a 3-inch lap belt, a thigh strap, leg restraints, full torso restraint vest with integrated shoulder straps, a pressure suit helmet with restraining straps, and full body support by a contoured microballon mattress backed by 0.25 inch aluminum plate (Clarke, et al., 1963). Sixteen volunteer subjects were impacted in a series of 32 tests. No adverse subjective reactions were reported to peak accelerations of up to 22 G produced with velocity changes of up to 19.3 ft/sec., at a maximum onset rate up to 1350 G/sec. However, in view of the fact that these were young healthy male subjects in superb physical condition, utilizing the most sophisticated restraint protection yet tested, the relevance of these findings to the general population and to the automotive side-impact is not known. A subsequent study by Brown, Rothstein and Foster (1966) of 11 human tests, using a 3-inch lap belt, double shoulder harness, inverted "V" pelvic straps, and head restraint, found no significant injury from lateral impact at forces to 14 G on the sled, although effects reported by subjects included extended chest pain, muscle spasms, shoulder or abdominal pain.

Human tests with subjects protected by Project Mercury restraint and helmets were conducted in 15 right 90° lateral impacts and 17 left 90° lateral impacts to 21.5 peak G units (1350 G/sec at 0.036 sec). Only transient injuries were reported without reaching a tolerance endpoint for this system (Weis, et al., 1963).

Lateral impact tests have been conducted on 64 Air Force volunteers protected by various military aircraft and spacecraft restraint systems at up to 18.7 sled G at 20 ft/sec entrance velocity, without significant injury (Chandler, 1966).

Royal Air Force tests of the F-111 restraint (both GD F111 and RAF 1AM versions) involved 18 lateral impacts to five human subjects up to 17.7 G at 390 G/sec. Subject symptoms ranged from chest, groin, throat and collar bone discomfort to eye blood vessels ruptures, faintness, and breathing difficulties, but no irreversible injury (Reader, 1967).

In tests of the impact attenuators of the B-58 escape capsule, ten human male subjects were exposed, without reported injury, to impact forces associated with combined velocity changes of up to 25 ft/sec in the X axis and up to 34 ft/sec in the Y axis. Due to tumbling and skidding of the capsule, extrapolation of these findings to other conditions is difficult (Payne, 1961). Zaborowski on the Holloman "bopper" performed 87 tests on 52 male Air Force subjects at impact up to 11.59 G and durations of 0.22 to 0.09 sec while restrained with both lap belt and shoulder harness and side restraint panel. No permanent physiological changes were noted. Minor subjective physical complaints were reported by more than 60% of the subjects when exposed to 8.8 average G's or greater. The possibility of cardiovascular trauma halted the experiments after two subjects were exposed to 11.59 average G's at 13.3 and 14.6 ft/sec entrance velocities. Whitehouse in 1966 reported finding no pulmonary damage in 18 lateral ($-G_y$) impacts conducted on nine human subjects impacted at 15 G, using head and torso restraint. Other tests in support of the B-58 capsule, Mercury, Gemini, Apollo, F-111 and other advanced experimental systems have also employed maximum restraint systems, not comparable to that of minimal lap-belt-only restraint.

There apparently has been only one published study involving impact tolerances of the human while restrained by lap belt only. Zaborowski.

Rothstein, and Brown in 1963 published the first medical investigation on humans (restrained by lap belt only) in lateral impact and these had to be discontinued at 9 G (with impact durations of 0.1 sec) due "to subject discomfort with prolonged stiffness and soreness in the neck musculature." Fifty percent of the subjects complained of physical discomfort at 6 G.

A more recent study of over 100 lateral impacts from 9.2 to 10.0 sled G (12 to 14 chest G) to 32.6 ft/sec entrance velocity is still unpublished (Sonntag, 1966). One subject fainted and another subject received severe neck muscle strain. In other tests of human voluntary tolerance in side-impact, from 18 to 92° body orientation (from the forward facing position), Beeding has reported effects of chest pains, headaches up to 18 hours, brief disorientation, or difficult breathing; also a single case of mile ischemia, hyoid dislocation, shock, albuminucia. Other clinical findings have included no blood pressure immediately post run in one subject (1958).

Another source of information concerning human tolerance to lateral forces is found in studies of free-fall survivals. Although forces must be estimated through calculation, selected cases often have produced valuable data relative to extreme limits of human survivability not obtainable in the laboratory (Snyder, 1969a; 1968a; 1966b; 1966c; 1965; 1964; 1963a; 1963b). In eight cases reported in 1963, a considerably different distribution of injuries was found as compared to other body orientations (Snyder, 1963a; p. 669). In lateral human free-fall impacts into water surface, the highest velocity survived was 87 ft/sec which probably represents a near-maximum value for the human (Snyder, 1965; Snyder and Snow, 1967).

The physiological effects of lateral impact as found from both human and animal impact tolerance research studies have been summarized by Eiband (1965), Snyder (1966; 1969b), and by Stapp (1968; 1969). Results to date document that the human body is less able to tolerate accelerative forces in the $\pm G_y$ axis, than $\pm G_x$ or $\pm G_z$ axis.

Clinical reports of human lateral impact occurring in automotive accidents occasionally have included useful injury data, although usually the physician has no objective environmental information about the accident. A recent medical report of side-impact collisions in the Detroit area has resulted in the finding of pancreatic trauma in occupants.

In four automotive side-collision accident cases investigated by Huelke and reported by Yost (1967) the occupants were unrestrained. Extensive compartment invasion occurred in each case, with the occupants suffering moderate to fatal injuries.

States and States (1968) found in a study of 48 lateral automotive accidents that fractures of the acetabulum with intrapelvic protrusion of the hip and fractures are characteristic. The vehicle door was the structure producing the most injuries in such cases. They also noted that head injuries in lateral impact were the most common and also the most common cause of fatality.

Friedberg, et al., studied data from 1490 automotive side collisions, concluding that the frequency of dangerous or fatal injury is twice as great for occupants seated on the side of the car impacted, as for those away from the impact (1969). Subsequently, Lister and Neilson, studying automotive side impacts in the United Kingdom, reported that such collisions account for about 13% of all accidents involving cars in which some occupant was seriously or fatally injured (1969).

Head injuries in side-impact collisions have also been found to be the most common cause of fatal injury in studies by Huelke (1958 - 1969, data) and by Siegel and Nahum (1967-1969).

Side impact in automotive collisions also has long been studied through analysis of data involving actual crash tests with instrumented dummies. The literature is abundant with the results of such tests, and a continuing series of side impact design studies have recently been conducted by General Motors, Chrysler, and Ford Motor Company.

Such work has included review of 415 ACIR car-to-car side impacts with the conclusion that the 90° side impact is the most frequent side collision configuration.

Sled tests (90°) relating occupant chest and head accelerations to the distance from the inner panel and to glass position (up or down) have been conducted with dummies. Without glass, such tests indicate that the acceleration at the windowsill is about 90 G on a 20 millisecond base, plus an initial 100 - 150 G pulse on a 5 millisecond base. Little change in magnitude occurs until the dummy is 12 inches from the door. From such information mathematical modeling has advanced as a most useful tool in the assessment of improved design.

Yet, despite the technological advances in mathematical modeling and in obtaining objective data in experimental crash impacts from vehicle structures, the lack of knowledge of human lateral impact tolerances remains the weakest point in the design loop. Few animal or human experimental studies have been conducted with the subject restrained solely by a lap belt, and none have been conducted to date with unrestrained subjects. Clinical data from collisions and experimental data from the laboratory both indicate that the automobile occupant is less able to tolerate impact from the side. However, survivable and lethal levels for the restrained occupant are still little understood, and remain completely unknown for the unrestrained occupant.

1.1.2 Experimental Biomechanics and Modeling

The Biomechanics literature available in the field of human tolerance to acceleration effects is based upon data derived from four different types of experimental studies. These have involved the use of three types of test subjects and/or attempts to correlate injuries to mechanical inputs where they are known. The three types of test subjects have been human volunteers, cadavers, and experimental animals. The fourth type of data is derived from accident evaluation.

Each choice of experimental program and subject has involved limitations on the use of the resulting information. Volunteers provide the most realistic simulation; however, their use is so restricted by the necessity of avoiding any acute or chronic injury that volunteer thresholds are well below the tolerance levels for minimal injury. For the case of side impact, structure design and the development of tolerance curves, the use of volunteers would have to be ruled out as appropriate experimental tools (McHenry, 1966).

Both cadavers and experimental animals have been suggested as suitable subjects for this research program. Since neither one is a complete or accurate representation of man their advantages and limitations based upon other previously reported research should be considered. Human cadavers have been used to any significant extent by only one research organization in this country. The early work of Gurdjian and Lissner (1965) regarding the tolerance of the head to impact followed by Patrick's studies of femoral and thoracic fractures constitute the bulk of the literature available. These studies are consistent in that embalmed cadaver material is only used to define skeletal injury and not associated soft tissue damage. In the case of studies of head impact tolerance, the shape of the curve and much of its underlying philosophy was derived from the pressure studies of canine concussion rather than from human cadaver experiments.

Cadavers are theoretically available in either the embalmed or unembalmed condition. Availability of cadavers is so limited that no group of investigators have been able to utilize the unembalmed material to any appreciable extent. The combined legal, esthetic and storage problems are such that embalmed material will undoubtedly continue to be used in the foreseeable future except under certain special circumstances. With this thought in mind, the effects of embalming must be considered in terms of how the tissues are affected and consequently how useful the ultimate results of the research will be.

Embalming is the basic process of replacing body fluids with a formalin solution to stop the autolytic processes associated with death. The effect is to preserve a human body which looks, weighs, and is constructed exactly like the living human. The chemical reactions involved have been shown to have widely varying effects on the mechanical behavior of the various tissues involved. The general structural behavior of the entire body remains essentially the same with approximately a 10% increase in mechanical stiffness. Kinematically, the body will respond in a highly variable manner depending upon the previous history of use, storage and efficiency of the embalming process.

Basically, since dead tissue does not recover when over extended as do living tissues, embalmed cadavers tend to become increasingly flexible until they are capable of contortions which no living subject would withstand. To date, no quantitative basis exists for determining when an embalmed subject

is no longer a suitable representation of the living body's kinematic response.

The skeletal system, however, appears to retain its fracture properties with little decrement as long as adequate precautions are taken to minimize drying. The physical properties of embalmed bone are not known well enough to make meaningful extrapolations to fresh bone.

Aside from the problem of increasing flexibility of an undefined nature, the greatest limitation of the human cadaver, aside from the obvious fact that it is not a functional system, is the totally unrealistic nature of its soft tissues in terms of their consistency and mechanical properties. The changes are the greatest in the brain followed by the vascular system and the abdominal viscera. This is probably the most significant limitation of the cadaver in terms of a side impact study. The fracture tolerance of the elements of the skeletal system which will be involved, the femur, pelvis, rib cage, humerus and skull, does not appear to be the limiting factor in terms of defining tolerance, but rather the associated soft tissues of the body appear to have the lowest thresholds for injury. The brain, vascular system and certain abdominal organs, namely the pancreas, kidney and spleen, are more vital to life and will probably play the major role as the weakest links in the system. Yet it is precisely these organs which are practically useless in cadaver impacts. If accurate and meaningful tolerance data are to be developed then it would appear that appropriate animal experimentation should play the major role. Unfortunately, the limited amount of research results available for this direction of loading provides only the most general of guidelines to be used in defining the research program (Thompson, 1968).

It follows, therefore, that as a model the cadaver is the least satisfactory of the four models mentioned. Although geometrically similar to a particular human being, it frequently falls outside the range of human norms. Its joint characteristics are quite different from the living human and unlike the dummy are not controllable. Therefore, the accuracy of kinematic and kinetic studies is reduced. The soft tissue responses are greatly altered and of course biologically there is no similarity. Thus, while the cadaver represents the best compromise for the most responses, in any given set of responses, i.e. kinematic or biological, it does not do as well as a more specific model chosen to match that set.

In this connection, it is convenient to divide human impact response into two classes. The first is a kinematic and kinetic response that is purely mechanical and in a first approximation independent of the deformation mechanisms of the structures involved. This is essentially the rigid body mechanics of the problem. Anthropomorphic dummies provide an appropriate method for the study of this type of response.

The experimental animal provides an excellent model to study injury mechanisms and tolerance. The model is both biologically and mechanically similar and with suitable scaling should provide reasonable estimates of human impact responses.

Since experimental animals, particularly primates, represent the best biological model of the human the development of a suitable scaling law is of major concern. Ommaya (1966) has reported the essential features of a scaling law for cerebral concussion of primates.

Dimensional Analysis and the theory of modeling is well founded in mathematical theory (i.e. Langhaar, 1951). However, the application of dimensional analysis to any particular problem requires the clear identification of the independent variables and their dimensions. The complexity of the scaling

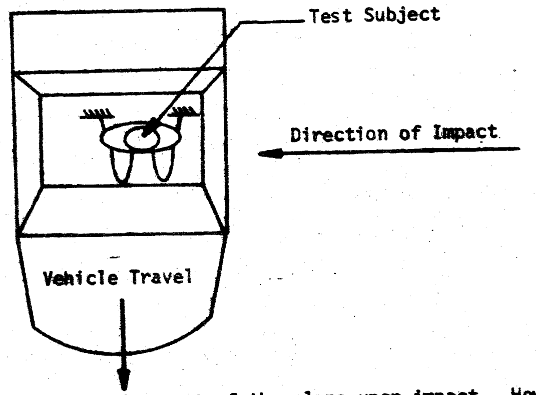
problem considered here makes this step intractable and therefore a combined experimental, theoretical approach is required. This approach should utilize as much modeling theory as is feasible coupled to data from experiments on various size primates and cadavers. The development of suitable scaling relationships that allows the prediction of impact tolerance levels in man from animal data would represent a significant step forward.

1.1.3 Mathematical Modeling

The study of the interaction between an occupant and the interior of a vehicle using analytical techniques can be used to develop an understanding of the relation between the physical variables describing the occupant and his protective or injury-producing environment. The four major parameter groups which have been used to describe a seated occupant are the seat, the vehicle interior consisting of restraint devices as well as the occupant compartment, the deceleration profile, and the occupant. Each of the parameters has a geometric relationship to the other parameters which, in total, define the configuration of an occupant seated in a vehicle. In addition, the parameters can interact with one another to produce motions, forces, acceleration, etc.

An analytical computer study of occupant kinematics consists of input information, computer program, and output display. Input information is gathered from experimental engineering observations of the geometry and material of the auto-occupant system. The computer program is based on the laws of physics governing the force and motion interaction of moving bodies possessing mass. The analysis can be formulated in either two- or three-dimensional space. A two-dimensional study restricts all motion to be in a plane whereas a three-dimensional analysis is not subject to this restriction and can represent adequately occupant kinematics in asymmetric collisions such as with asymmetric restraint systems, oblique collision, and side impact. The output of a mathematical model consists of tables, graphs, or pictorial displays of occupant motions, forces, velocities, etc.

The shortcomings of a two-dimensional analysis can be seen in the example of a side impact shown below. The view is looking down onto a restrained occupant. The plane of vehicle travel and the collision is horizontal (in the plane of this sheet of paper). First, the collision itself causes the vehicle to roll out of this plane due to tipping. Second, the head, shoulders, and upper torso will rotate down out of the plane upon impact. However, the leg mass will rotate about a vertical axis and remain in the plane, unless seat hop-up causes the legs to rise in passing up out of the seat. In the event of an oblique collision, rather than the direct side collision just illustrated, the situation is much more complex with large motions in and around all the three coordinates of real space. It is difficult to conceive a realistic two-dimensional model simulating side impact.



Large scale two-dimensional models have been developed by several research groups (Aldman and Appoldt 1964), the most sophisticated publicly available model being in use at HSRI (Robbins and Becker 1968). Most large models have eight masses representing body parts. Other models using fewer masses have been developed here and elsewhere. The only known published reports discussing three-dimensional models are by Roberts (1969) and Thompson (1968). Both of these papers report progress only.

2. COMPUTER SIMULATIONS

2.1 GENERAL

This section concerns the development and use of the HSRI Three-Dimensional Vehicle Occupant Model (Robbins, et al., 1970) for side impact descriptions and development of mathematical models of door structures.

The methods used may be divided into two separate phases:

Phase 1. Identification of the structural elements associated with side impacts, those areas of the occupant's body most likely to impact the car interior, and the impact velocities. In this phase, it was necessary to define the following:

1. a standard car interior,
2. a standard occupant,
3. standard vehicle dynamics.

The 3-D Model was exercised under a variety of combinations of input parameters, and the results were compared with accident investigation reports of side impacts.

Phase 2. Modifications of the standard car interior were made with the aim of optimizing crash worthiness. These modifications included padding the car interior, using softer spring constants for the door structure and varying the location of the arm rest. The geometry of the occupant and the crash profiles were changed as new information became available.

Two door models were developed to study the side penetration of the door. Current door structures were evaluated and compared with older type unreinforced doors. The effect of the location of the reinforcing member was also investigated.

2.2 PHASE 1. IDENTIFICATION

2.2.1 Standard Car Interior

A standard car interior was required in the development of appropriate geometry and mechanical properties of representative side panels, doors, arm rests and windows for the computer simulation. Measurements of 15 medium-priced cars were made and analyzed, resulting in a composite car interior shown in Figure 1.

This information was used to set limits of motions, to identify critical areas of the car interior and to relate second collision impact velocities with the primary crash velocity.

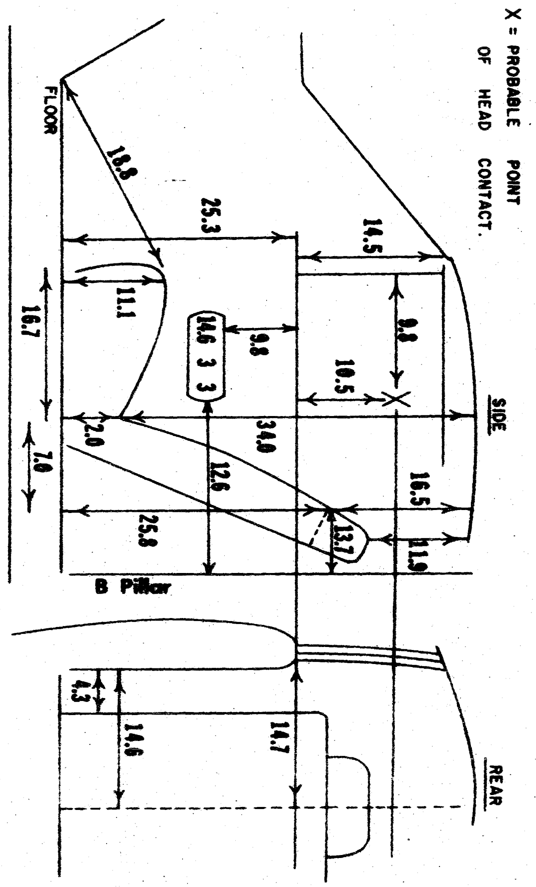
The mechanical properties of side structures were collected from the literature (Brink, 1955). They include load-deflection characteristics of side panels, seat cushion and back, window and seat belts.

Important elements in the geometry of the side structure which were studied include the location and size of the arm rest, the recess of the glass window, and the seat type. These were varied and the parts of the occupant body most likely to hit the car interior, where the hit occurred, the frequency of these impacts, and the impacts' velocities determined.

The restraint system used by the occupant was also varied in these simulations. The restraint systems considered were:

1. No restraint
2. Lap belt only
3. Lap belt and single diagonal shoulder belt
4. Y-yoke belts

The seat type was also varied from a standard bucket to a full bench seat resulting in eight different seat restraint systems.



ALL MEASUREMENTS MADE WITH SEAT IN FULL-FORWARD POSITION

FIGURE 1. H.S.R.I. COMPOSITE AUTOMOBILE INTERIOR

2.2.2 The Standard Occupant

The second type of information required in phase 1 of the Computer Simulations was that dealing with thé occupant. Anthropometric measures suitable for computer inputs were obtained from (D. H. Robbins, et al., 1970). A complete study of the effect of the previously mentioned seat-restraint system variables was made for the 50th percentile male and the six-year old child while only selected studies utilizing the 95th percentile male and the 5th percentile female were made.

Perhaps the most critical category of information required for computer simulation is the passenger compartment's deceleration profiles. The 3-D Model can accept six of these profiles: longitudinal, lateral and vertical linear deceleration pulses, and those of yawing, pitching and rolling of the vehicle. Two sets of data were obtained from the literature. One was a 30 mph side collision conducted by D. H. Severy (1959) (Figures 2, 3 and 4) and the other was a series of side impacts conducted by R. P. Mayor and K. H. Naad (1969). (Figure 5)

2.2.3 Results of Phase 1 of Computer Simulation

Two types of information of particular interest for each data set were computed:

1. The number of times (frequency) each part of the occupant impacted various locations of the vehicle side structure.

2. The average velocity of impacts at these locations.

In order to understand the effects of each restraint configuration, a qualitative description of the results is presented first, followed by a quantitative presentation.

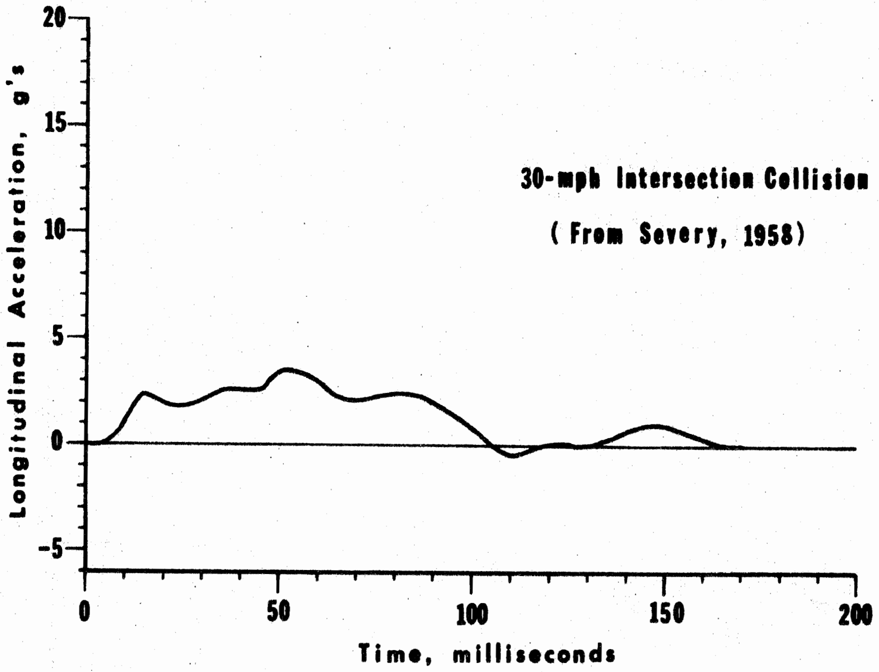


FIGURE 3. ACCELERATION OF VEHICLE COMPARTMENT

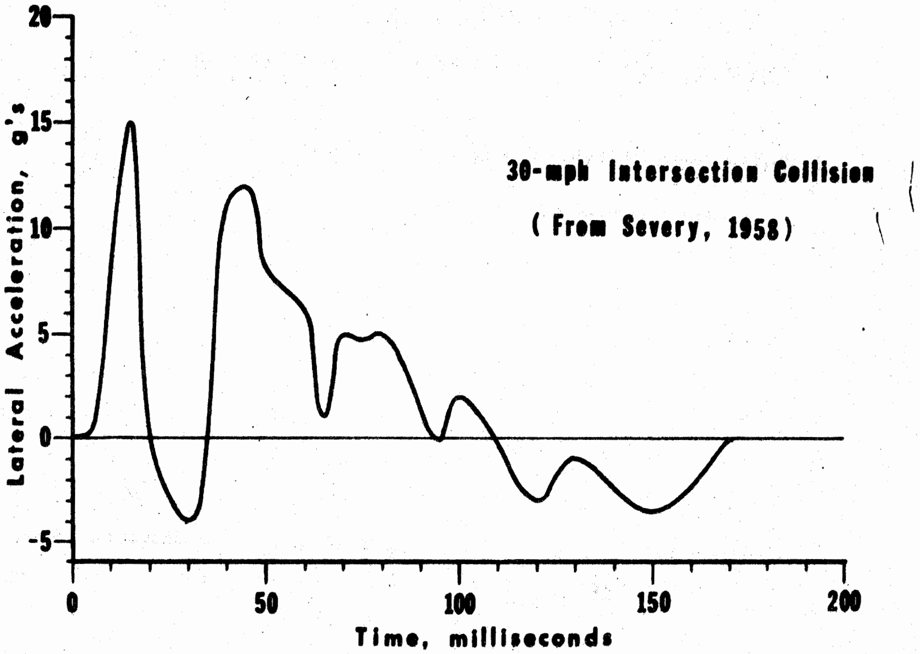


FIGURE 2. ACCELERATION OF VEHICLE COMPARTMENT

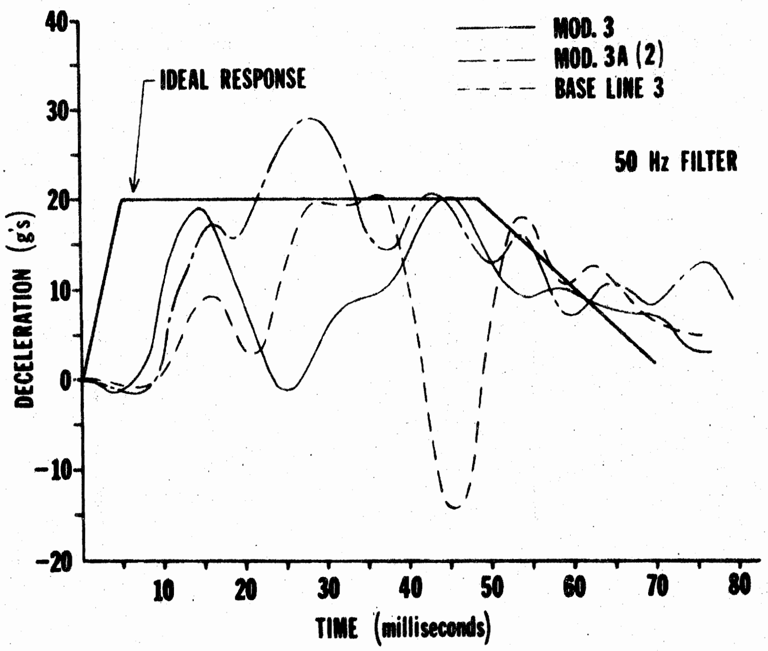


FIGURE 5. COMPARISON OF DECELERATION RESPONSES WITH IDEALIZED WAVEFORM from Mayor, R.P. and Naab, K.N., CAL Report No. YB-2684-V-3.

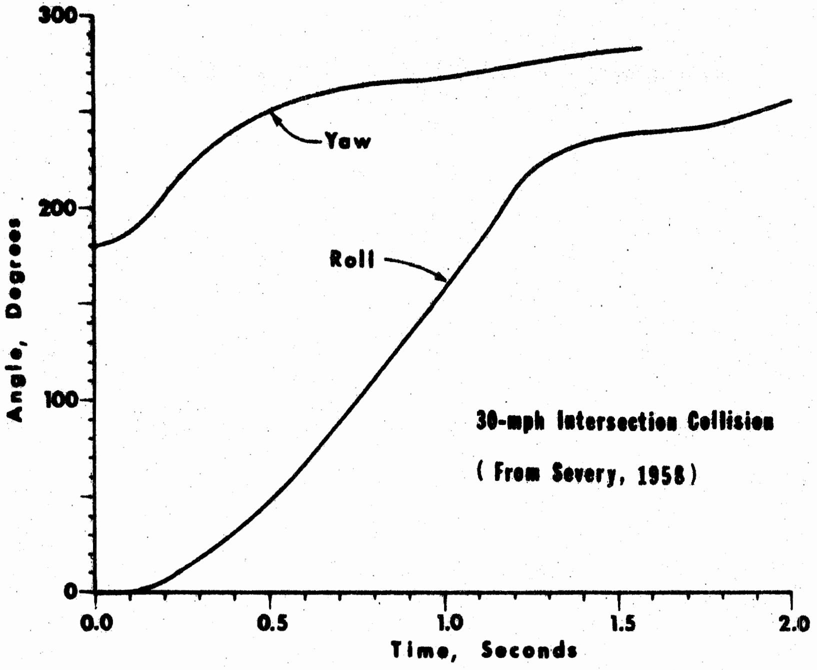


FIGURE 4. ANGULAR MOTION OF VEHICLE COMPARTMENT

2.2.3.1 Qualitative Results

There were 16 simulations for two sizes of occupant and two types of seat:

1. 50th percentile male - bench type seat
2. 50th percentile male - bucket seat
3. 6-year child - bench seat
4. 6-year child - bucket seat

For each combination, four different restraint systems were used: no restraint, lap belt only, diagonal shoulder harness and Y-yoke belts.

50th Percentile Male - Bench Seat

No Restraint - Almost all parts of the body impacted various regions of the door. The most severe impacts were to the head at the window, the middle torso at the arm rest, and the leg below and in front of the arm rest.

Lap Belt - Again all parts of the body impacted the side structure, but at lesser velocities. The improvement was most significant for the middle and lower torsos.

Shoulder Belts - As suspected, the upper torso and shoulder behavior was improved. The head velocity was not improved appreciably.

Y-Yoke Belts - A definite improvement for the head and the middle torso was obtained. The upper and lower leg velocities increased significantly over the unrestrained run.

50th Percentile Male - Bucket Seat

No Restraint - There was a slight improvement over the bench seat for the middle torso, lower torso, and upper leg, that is their impact velocity was reduced. The head, however, hit the window with a slightly higher velocity.

Lap Belt - The middle torso did not strike the arm rest, and the head velocity at the window was slightly reduced. Overall, impact was less severe than the non-belted run in both bucket and bench type seats.

Shoulder Harness - The overall behavior of the occupant was improved, but the head did hit the window, though at a lesser velocity than previously.

Y-Yoke Belts - A definite improvement over all three other restraint systems as far as the head is concerned. The head did not hit the window. The velocity of all three parts of the torso was reduced.

Six-Year Child - Bench Seat

No Restraint - The head impacted the window, the torso hit the door at the arm rest and the upper torso and shoulder hit the door below the window. The impact velocities were higher than that of the unrestrained male on a bench seat.

Lap Belt - The torso was restrained from hitting the door. The arm and shoulder hit the arm rest with a higher velocity than the unrestrained run.

Shoulder Harness - Performance was similar to that with lap belt only, but there was a decrease in the impact velocity of the shoulder and arm.

Y-Yoke Belts - Similar to the run with the shoulder harness, except the velocity of impact of the arm was not significantly reduced over the unrestrained run.

Six-Year Child - Bucket Seat

No Restraint - Generally, the same behavior was observed here as in the bench non-belted child run. The head and torso velocities were reduced slightly in comparison with the unrestrained bench seat.

Lap Belt - Slightly better performance than the bench seat.

Shoulder Harness - No interaction with the door.

Y-Yoke Belts - Same as above. No impact of the child with the door.

2.2.3.2 Quantitative Results

To simplify the presentation of these results, the occupants body was divided into six parts. Similarly, the door was divided into six corresponding general areas where respective body parts are likely to impact. Table 1 and Figure 6 show these major divisions. The frequency of impacts of the occupants members at various locations is the number of times a body part impacted certain regions of the door, without regard to the velocity of impact. The numbers of impacts are shown in Table 2 for all restraint systems, occupant sizes and seat types. In this table, the first number represents the frequency of impact for the 50th percentile male, the second number that for the six-year child. If one body part impacted a certain door region in every simulation, the number of hits would be eight for the 50th percentile male, and eight for the six-year child. Thus, the head of the 50th percentile male hit six times the window (out of possible eight) and that of the six-year dummy hit the window twice out of a possible eight.

The impact velocities of the body members at various door regions are summarized in Tables 3 and 4.

The frequency and location of impacts are also presented in three-dimensional histograms where the height of each "column" represents number of impacts at the region where this column is anchored. (Figures 7 and 8)

2.2.4 Comparison Model Predictions

The total number of accidents investigated and fairly well documented was 23 side impacts involving 33 occupants of which 31 were injured. There were nine fatalities, eight of which involved head injuries. A breakdown of injuries and fatalities is shown in Table 5.

TABLE 1. DESIGNATION OF BODY AREAS AND DOOR REGIONS

Human Body Areas	Door's Regions
1. Head	1. Window
2. Upper torso-arm	2. Between window and arm rest
3. Middle torso-arm	3. Arm rest and vicinity
4. Lower torso	4. Directly below arm rest
5. Upper leg	5. Above and in front of arm rest
6. Lower leg	6. Below and in front of arm rest

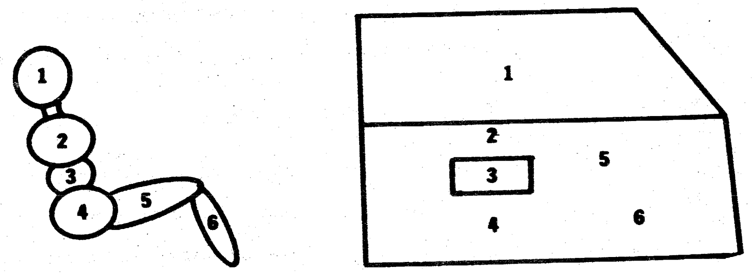


FIGURE 6. DESIGNATION OF BODY AREAS AND DOOR REGIONS

TABLE 2. FREQUENCY OF IMPACTS OF BODY AREAS AT DOOR REGIONS

Body Parts	Region #1	Region #2	Region #3	Region #4	Region #5	Region #6
Area #1	6,2*					
Area #2		11,3				
Area #3			12,6		6,2	
Area #4			8,0	1,1		
Area #5					4,0	0,2
Area #6						6,1

***50th Percentile Male**, 6-Year Old Child

TABLE 3. IMPACT VELOCITIES (MPH) - 50th PERCENTILE MALE

30 mph Computer Simulations of Intersection Collision

Body Part #	Door Region #	No Belts		Lap Belt		Shoulder Belt		Y-Yoke Belts	
1	1	8.9	7.4	3.5	6.0	3.9	6.0	-	-
2	2	7.9	6.4	6.5	4.8	6.5	3.5	6.0	3.8
3	3	8.0	4.0	4.7	-	4.7	-	4.5	-
4	3	7.8	5.4	6.6	3.5	6.5	3.5	6.8	4.2
4	4	2.1	-	-	-	-	-	-	-
5	5	8.2	-	1.4	-	-	-	-	5.0
6	6	12.2	13.8	-	11.9	-	11.4	2.6	12.8

TABLE 4. IMPACT VELOCITIES (MPH) - 6-YEAR CHILD

30 mph Computer Simulations of Intersection Collision

Body Part #	Door Region #	No Belts		Lap Belt		Shoulder Belt		Y-Yoke Belts	
1	1	7.0	7.9	-	-	-	-	-	-
2	2	7.4	5.8	-	-	-	-	-	-
3	3	7.0	11.1	6.9	-	6.1	-	3.4	-
4	3	8.7	-	-	-	-	-	-	-
5	3	9.0	2.1	-	-	-	-	-	-
6	5	-	16.0	-	-	-	-	-	-

FIGURE 8. SUMMARY OF COMPUTER SIMULATION WITH VARIABLE RESTRAINT AND SEATING GEOMETRY

CENTER SIDE IMPACT, SIX YEAR OLD CHILD

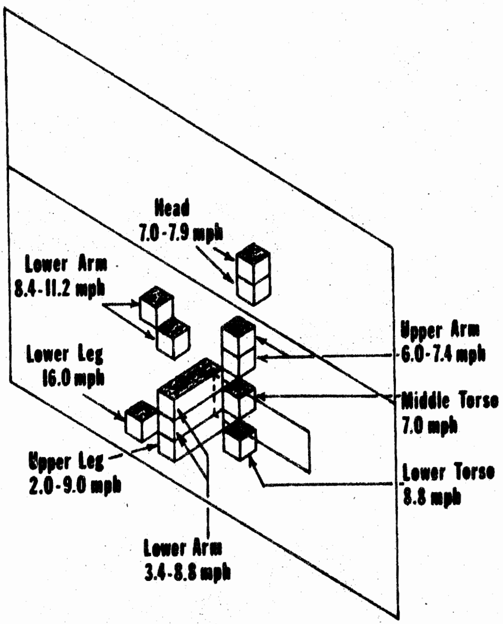


FIGURE 7. SUMMARY OF COMPUTER SIMULATION WITH VARIABLE RESTRAINT AND SEATING GEOMETRY

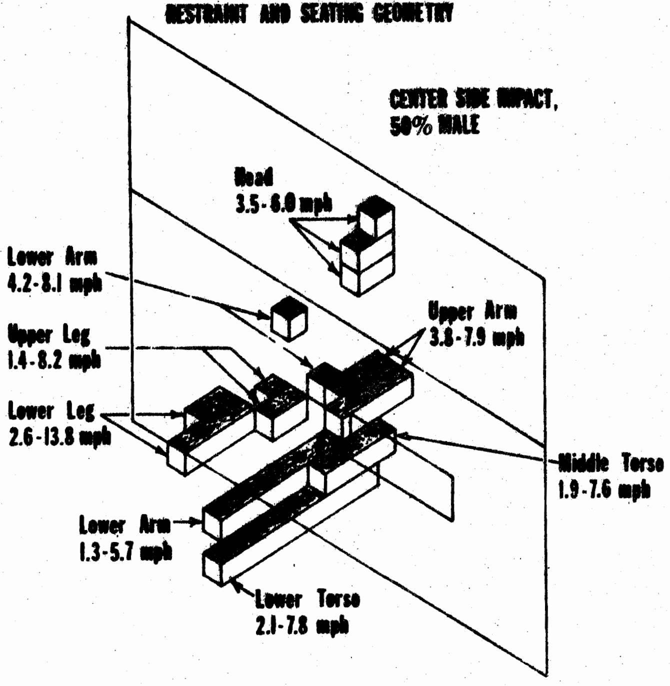


TABLE 5. ACCIDENT INVESTIGATION OF SIDE IMPACTS

I. Statistics:		
1. Total Number of Accidents		23
2. Total Number of People Involved		33
3. Total Number of People Injured		31
4. Total Number of People Ejected from Vehicles		1
5. Total Number of Fatalities		9
II. Total Injury Breakdown: (NOTE: Each injury, as with multiples, is counted.)		
1. Head and Neck Injuries		
a) Skull Fracture		9
b) Concussions		4
c) Intracranial Hematomas or Necrosis		9
d) External Contusions or Lacerations		16
e) Blindness or Deafness		1
2. Thoracic and Abdominal Injuries		
a) Fracture or Internal Injuries		8
b) External Laceration or Contusions		6
3. Extremities		
a) Fractures		2
b) Lacerations		3
c) Contusions or Abrasions		11
III. Fatality Breakdown: (NOTE: Each fatal injury, as with multiples, is counted.)		
1. Head	8	
a) Fracture or Head Opening		5
b) Intracranial Hematoma or Contusions		7
2. Trunk	1	
a) Thoracic Internal Lacerations or Hematoma		4
b) Abdominal Internal Lacerations or Hematoma		3

The injury patterns generally observed compare well with the 3-D computer simulations. The model, for instance, predicted that an unbelted six-year old child would hit the side window just above the window-door interface. In the accident reports, a five-year old child impacted the window-door interface in a 15 mph side collision, and was knocked unconscious, but otherwise unhurt.

In an intersection-type side impact, the change in velocity in the lateral direction of the struck car tends to be small, approximately 6 mph for a 30 mph collision. Consequently, the occupant is involved in a secondary collision of 6-10 mph from which he can be protected if there is minimal intrusion.

2.2.5 Comparison with Accident Investigation

A comparison of the impact velocities of the occupant, as predicted by the model, with accident investigation reports is not directly possible. What has been compared is the locations of injuries and their severities. The location of impact on the door by the occupant was determined by careful examination of the vehicle. The type of injury was determined from the medical records. Tables 2 and 5 provide a convenient summary of these findings. The computer simulation predicts similar involvements of body parts and vehicle components. Of course a quantitative comparison cannot be made because precise numerical information is not generated by accident investigations. However, there are evident similarities between Table 6, the accident investigations, and Tables 2, 3 and 4, the computer simulations.

2.3 PHASE 2. OPTIMIZATION AND MODIFICATION

The accident investigations together with computer simulations indicated that most of the injuries were due to the second impact of the occupant with

TABLE 6. LOCATION OF OCCUPANT IMPACT WITH DOOR
23 Accidents Involving 33 Occupants

Location of Impact	Frequency	
1. Window	Head	12
2. Window-arm rest interface	Shoulder	8
3. Arm rest and vicinity	Thorax & Abdomen	8
4. Region below arm rest	Hip & Thigh	3
5. Side panel, front of arm rest	Arm	7

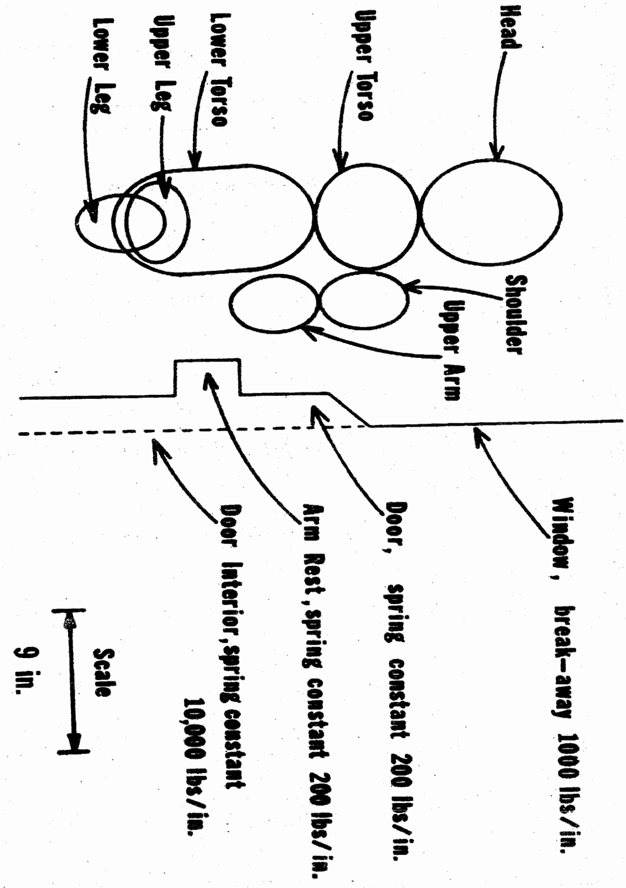


FIGURE 9. 3-D MODEL for SIDE IMPACT of 50% MAN

the door. Modifications of the door structures were therefore explored in order to reduce intrusion and attenuate the impact forces. (Figure 9)

2.3.1 Vehicle Deceleration Profiles

Four deceleration profiles were used in this part of the study. They were obtained from Cornell Aeronautical Laboratory Report CAL No. 4B-2684-V-6. They are:

1. Base line 3,
2. Mod 3,
3. Mod 3-A(2),
4. Ideal-response profile

Base line 3 was obtained from a crash of a 1966 Ford into a pole on the passenger side at 20 mph. Mod 3 was the car deceleration profile recorded in a repeat of the Base line 3 test, except the passenger door was reinforced. Mod 3-A(2) was also a repeat of the base line, except the reinforcement was this time along the whole right side of the car. The Ideal-Response deceleration profile was determined from Cornell's experience. Researchers at Cornell argued that a uniform deceleration waveform achieve two desirable design goals; namely limitation of peak G's and minimization of displacement for a given G limit.

The three actual profiles are similar in overall shape but differ in the timings and magnitudes of their peaks as well as in their durations. The two extremes are the Base line 3 profile (BL-3) and the Mod 3-2(A) profile (M3-2A). (Figure 5) Table 7 shows the occupant body part velocity at the coordinates of the undeformed door assembly for the various deceleration pulses described above. The stiffer the side of the vehicle becomes the greater will be the occupants velocity during the second collision. However, injury is related

SECONDARY COLLISION VELOCITY (MPH)

OCCUPANT WITH LAP BELT AND BENCH SEAT

TABLE 7.

	IMPACTED PORTION OF THE DOOR			
Body Sections	Window	Door Edge	Door	Arm Rest Side
Head	1* NC 2* NC 3* NC 4* NC			
Upper Torso				
Lower Torso				1* 11.7 mph 2* 11.8 3* 16.3 4* 17.5
Shoulder	1* 9.75 mph 2* 10.5 3* 15.9 4* 17.9	1* 9.75 mph 2* 8.50 3* 11.8 4* 17.9		
Upper Arm			1* 11.7 mph 2* 11.8 3* 16.4 4* 17.5	
Upper Leg			1* 11.55 mph 2* 12.30 3* 17.15 4* 19.35	
Lower Leg			1* 17.4 mph 2* 18.6 3* 25.1 4* 28.1	

1* Base line 3
2* Mod 3
3* Mod 3A(2)
4* Ideal Response

to the relative velocity and the intruding velocity of the door must be considered.

2.3.2 Door Stiffness and Padding

A proper design of automobile doors with reinforcing member is essential to minimize the intrusion into the passenger compartment in the event of a side impact. The reinforcing member can either be located close to the interior surface of the door (Case I) or close to the exterior surface of the door (Case II) or anywhere in between.

For the theoretical analyses we use the following two models representing Case I and Case II shown in Figures 9 and 10. The symbols designate the following qualities:

M: Mass of the impacting vehicle
V: Velocity of the impacting vehicle
k_1, k_1': Spring constant of the exterior sheel metal of the door
k_2, k_2': Spring constant of the door without the reinforcing member
k_1'', k_2'': Spring constant of the reinforcing member
k_3: Spring constant of the interior padding
M_1: Mass of the door
M_2: Mass of the impacted vehicle
M_3: Mass of the vehicle occupant
f: Sideward resistance force of impacted vehicle
x_1, x_2, x_3, x_4: Absolute displacements

Let us assume that vehicle occupant is impacted after x_2 attains a certain value, say, $x_2=d$, and corresponding time is t_d. The equations of motion for Case I for $t<t_d$ are:

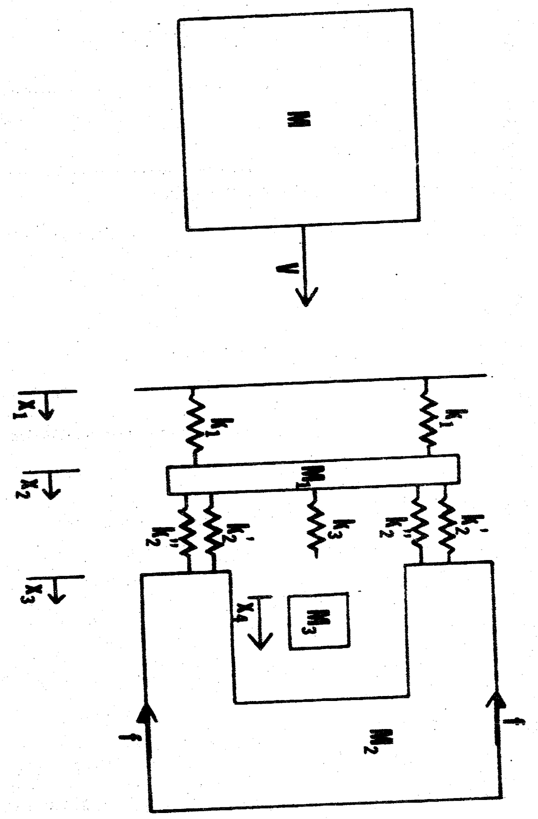


FIGURE 10. THEORETICAL MODELLING of SIDE-IMPACT, CASE I

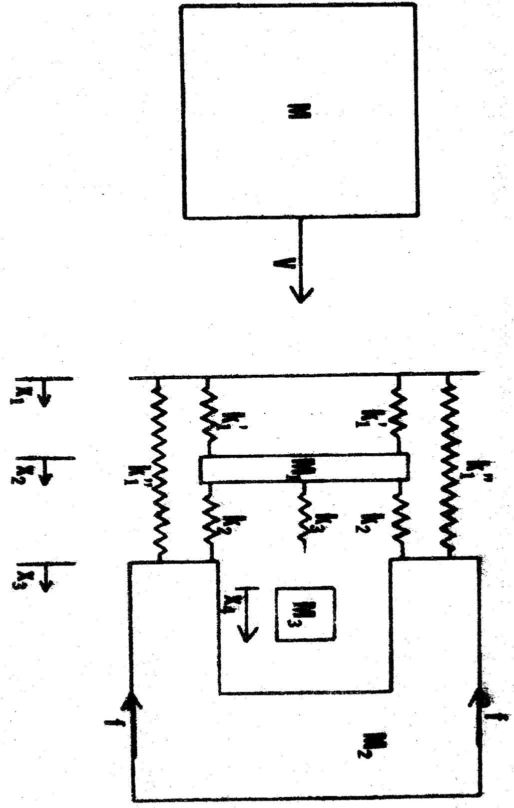


FIGURE 11. THEORETICAL MODELLING of SIDE-IMPACT, CASE II

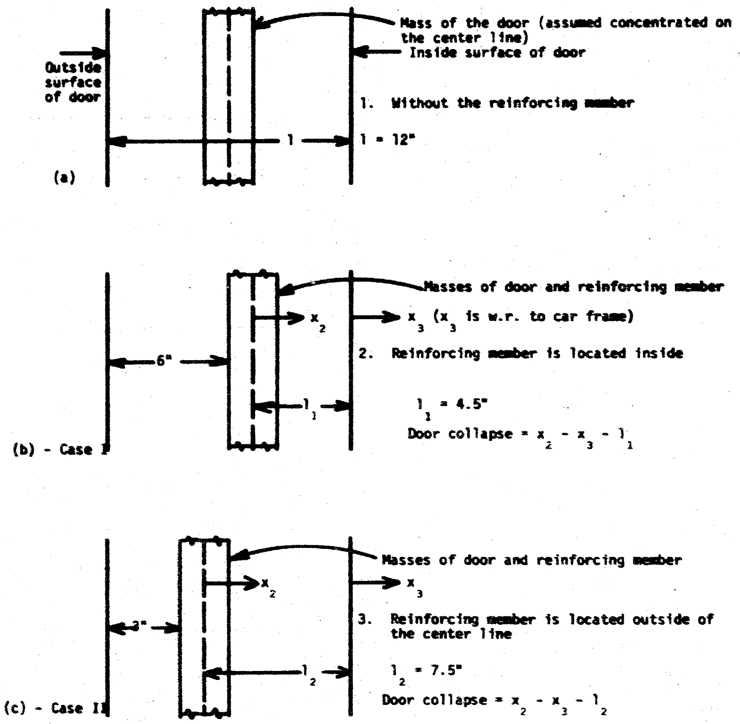


Figure 12

DOOR MODEL FOR SIDE IMPACT

$$M\ddot{x}_1 + k_1 (x_1-x_2) = 0 \tag{1}$$

$$M_1\ddot{x}_2 - k_1 (x_1-x_2) + (k_2'+k_2'')(x_2-x_3) = 0 \tag{2}$$

$$M_2\ddot{x}_3 + (k_2'+k_2'')(x_3-x_2) = -f \tag{3}$$

and after time t_d a fourth equation is introduced to the above equations

$$M_3\ddot{x}_4 - k_3(x_2-x_4-d) = 0 \tag{4}$$

also the term $k_3(x_2-d-x_4)$ is added on the left side of Equation 2. The initial conditions for these equations are:

$$\begin{array}{llll} x_1(0) = 0 & x_2(0) = 0 & x_3(0) = 0 & x_4(0) = 0 \\ \dot{x}_1(0) = V & \dot{x}_2(0) = 0 & \dot{x}_3(0) = 0 & \dot{x}_4(0) = 0 \end{array} \tag{5}$$

Equations (I) are first transformed to first order differential equations, then integrated on the computer according to the following steps:

1. Equations (1) - (3) are integrated starting with the initial conditions (5) until $x_1(t)$ becomes a particular value. This value corresponds to the distance between the exterior sheet metal and the reinforcing member. (In the numerical analysis this value of x_1 was chosen to be ≈6", see Figure 12-(b)).

2. Integration of Equations (1) - (3) is continued with the values of x_2, $\dot{x}_2$, x_3 and $\dot{x}_3$ obtained at the end of step 1 except the value of $\dot{x}_1$* is equated to the value of x_2 and the spring constant k_1 is raised to a very high value (such as 10^6 in/lb). This procedure accomplishes elastic behavior of the exterior sheet metal for a predetermined distance and after that metal to metal crushing type of behavior. In fact for the rest of the integration x_1 and x_2 values remain very close to each other. The integration process is

---

*The value of $\dot{x}_1$ at step 1 is kept the same for the beginning of step 2.

continued until x_2 attains a certain value, x_2=d, at time t_d (d is the distance between occupant and door).

3. After time t_d, Equation (4) is also added to the integration process. The initial conditions for this step are the values obtained at the end of step 2 with the exception of course $x_4(0)=\dot{x}_4(0)=0$. The integration of the simultaneous differential equations is continued until x_2-x_3 and x_4 attain maximum values. Since x_2 and x_3 represent the motion of door mass and the vehicle motion respectively, x_2-x_3 represents, with a constant, the door collapse or door intrusion into the occupant compartment. More precise value of this collapse is $x_2-x_3-l_1$ for Case I. (Figure 12-b). The value of the occupant force is obtained from $F=k_3(x_2-x_4-d)$.

The equations of motion for Case II for $t>t_d$ are:

$$M\ddot{x}_1 + k_1' (x_1-x_2) + k_1'' (x_1-x_3) = 0 \tag{6}$$

$$M_1\ddot{x}_2 - k_1' (x_1-x_2) + k_2 (x_2-x_3) = 0 \tag{7}$$

$$M_2\ddot{x}_3 + k_2 (x_3-x_2) + k_1'' (x_3-x_1) = -f \tag{8}$$

and after time t_d, a fourth equation, Equation 4, is introduced to Equations (6) - (8) and the term $k_3(x_2-d-x_4)$ is added to the left side of Equation 7. The integration procedure followed for Case II is similar to that used for Case I. The basic difference between the two cases are:

1. In the first step the limiting value for x_1 is 3" instead of 6" as shown in Figure 12.

2. At the end of step 1 $k_1''(x_1-x_3)$ term in Equation (6) is changed to (x_1+c-x_3) and $k_1''(x_3-x_1)$ term in Equation (8) is changed to $k_1''(x_3-x_1-c)$. The procedure followed at the second step of the previous case is repeated here and for the value of c 3 in. is used.

3. Procedure at this step is identical to that of Case I except the door collapse and the occupant force are obtained from $x_2-x_3-l_2$ (see Figure 12-c) for l_2 and $F=k_3(x_2-x_4-d-c)$.

2.3.2.1 Results of Door Stiffness and Padding

The numerical values used in obtaining Figures (13-15) are as follows:

k_1 = 1000 lbs/in.

k_2 (or k_2') = 1000 lbs/in.

k_3 = 200 lbs/in.

$M = M_2$ = 3860 lbs.

M_1 = 50 lbs.

M_3 = 175 lbs.

f = 3040 lbs.

V = 528 in/sec.

The value of k_1'' (or k_2'') is raised from 1000 lb/in. to 13000 lbs/in.

A theoretical model of a side impact with two configurations has been developed. Case I considers the reinforcing member close to the interior surface of the door, while Case II has the reinforcing member close to the exterior surface of the door (Figures 10 and 11). This model was specifically developed to show the effect of varying the location of reinforcement on the severity of impacts under similar conditions.

A plot of the reinforcing member stiffness vs. maximum occupant force is given in Figure 13. This curve shows that the stiffer the reinforcing member, the lower the occupant forces with a leveling off at a constant force for the very rigid members. The curve also shows that a 28% reduction in maximum

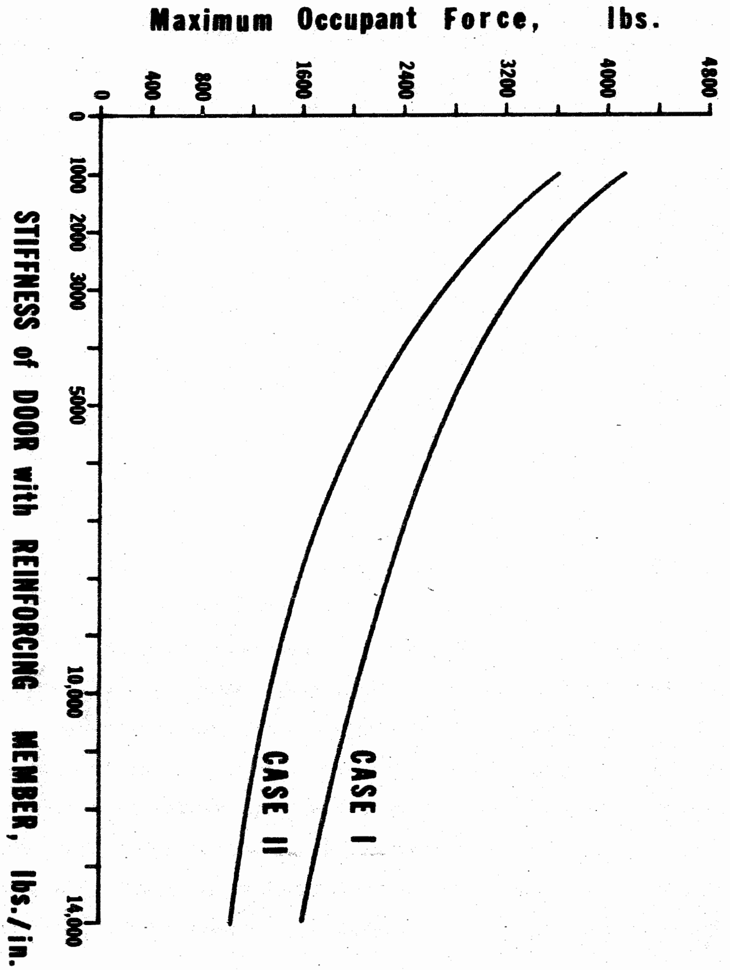


Figure 13

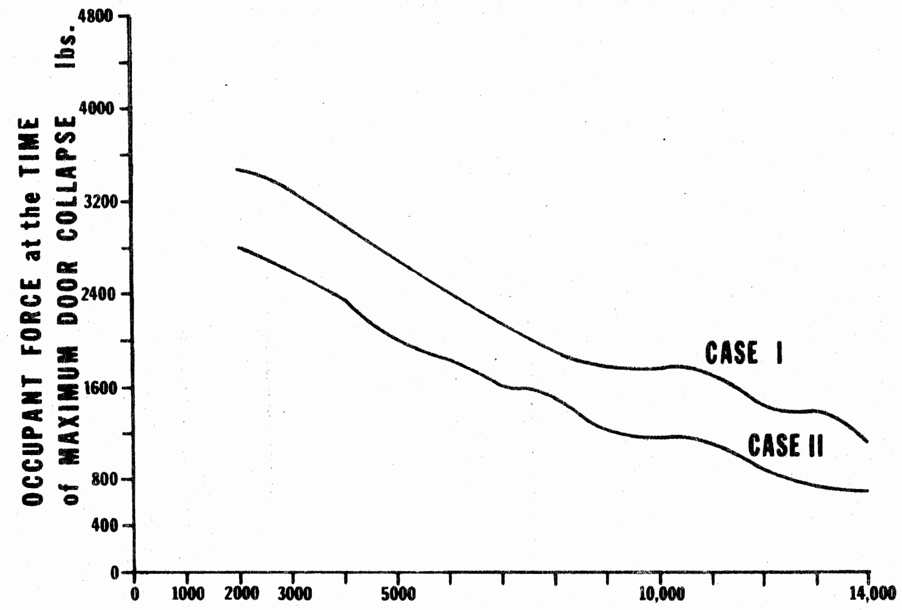


FIGURE 15. STIFFNESS of DOOR with REINFORCING MEMBER, lbs./in.

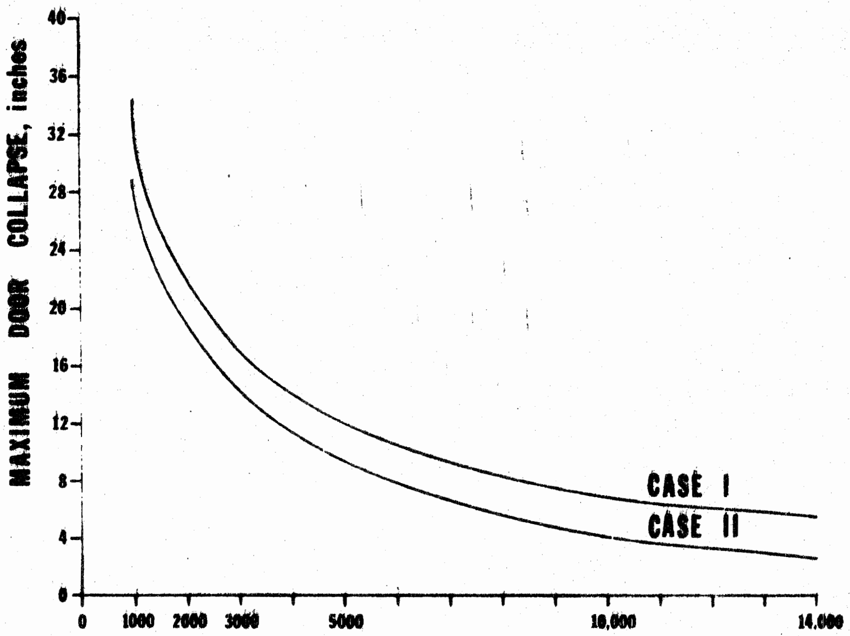


FIGURE 14. STIFFNESS of DOOR with REINFORCING MEMBER, lbs./in.

occupant force at 8000 in/lb can be obtained by implementing Case II, that is with the reinforcing member closest to the exterior surface of the door.

In Figure 14 the door collapse distance is reduced as the reinforcing member is stiffened, and as before, the door collapse distance can be cut by 35% at 8000 in/lb by implementing Case II. Case II starts slowing down the impacting car immediately upon contact, therefore the entire width of the impacting car is used to slow the impacting car. In Case I the crush to the exterior of the reinforcing member is not put to efficient use in decelerating the impacting car.

3.1 INTRODUCTION

The results of the 3-D computer crash simulator exercises and the accident investigations from the previous section indicated critical regions of the body and the door. The frequency with which each body region impacted the door from the computer simulations are given below:

BODY REGION	PERCENTAGE OF IMPACTS
Head	50%
Thorax	63%
Upper Abdomen	81%
Lower Abdomen	56%

The accident investigation data indicated the regions of the body most vulnerable to major injuries in automobile side impacts. The percentages of serious injury for the four regions of the body listed above for the accidents investigated are given below:

BODY REGION	PERCENTAGE OF SERIOUS INJURY
Head	45%
Thorax	11%
Upper Abdomen	21%
Lower Abdomen	0%

An ordering of the body regions most likely to be injured in a side impact car crash was obtained by multiplying the frequency of the impact by the percentage of serious injuries. This ordering is listed below.

ORDER OF IMPORTANCE	SEVERITY INDEX	
First most likely	Head	2250
Second most likely	Upper Abdomen	1700
Third most likely	Thorax	700
Fourth most likely	Lower Abdomen	0

The above indicates that the head is the most critical region followed by the upper abdomen with the thorax third.

A series of head and torso impacts were conducted up to the lethal level with infra-human primates whose anatomical and physiological relationship are most like man. Through scaling techniques similar to the one developed by Hirsch and Ommaya (1967) extrapolation of the results to man was accomplished.

3.2 EXPERIMENTAL METHODS

Five primates were considered for these tests:

1. (Saimiri sciurius) squirrel monkey [sm]
2. (Macaca fascicularis) cynomolgus [cyn]
3. (Macaca mulatta) rhesus monkey [rh]
4. (Papio cynocephalus) baboon [ba]
5. (Pan satyrus) chimpanzee [ch]

The baboons were not used in the head side impact portion of this project because of the marked differences in shape and dynamic response of the baboon head to those of the other primates used in the study. The baboon has a very large face in comparison to his cranium. (Figure 16) This leads to large differences between the response of baboons head and the other types of primate heads under impact conditions.

Mechanical impedance of the living heads for all primates used in the head impact portion of the project are given in Figure 17. All of the head

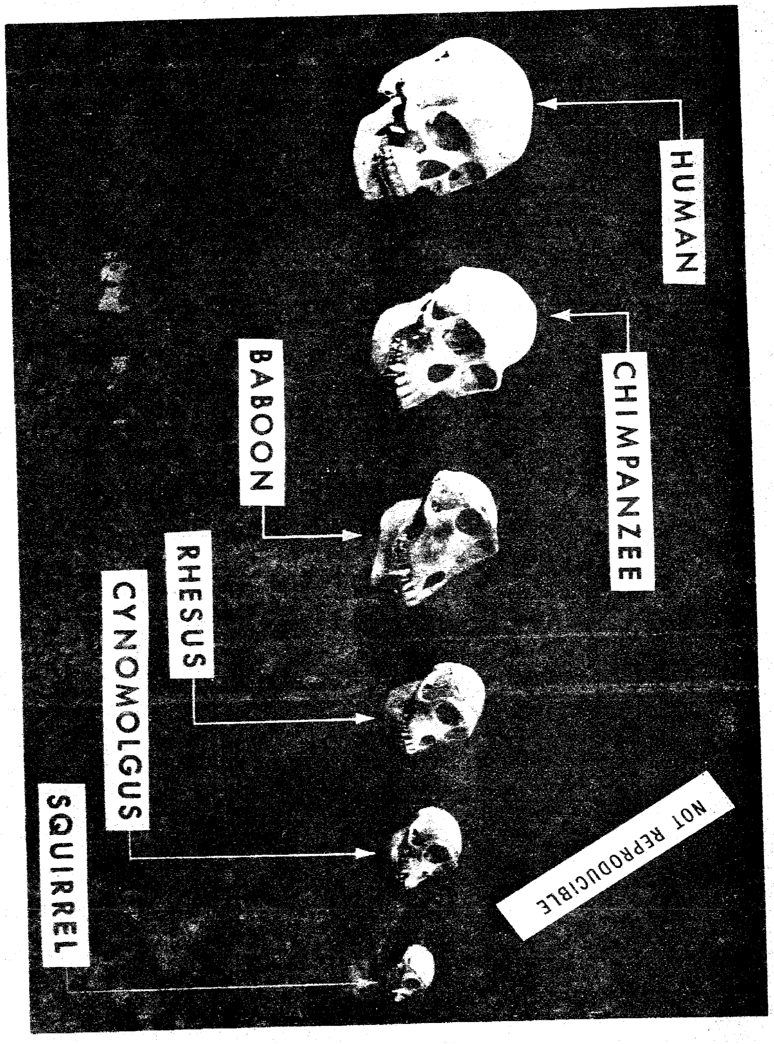
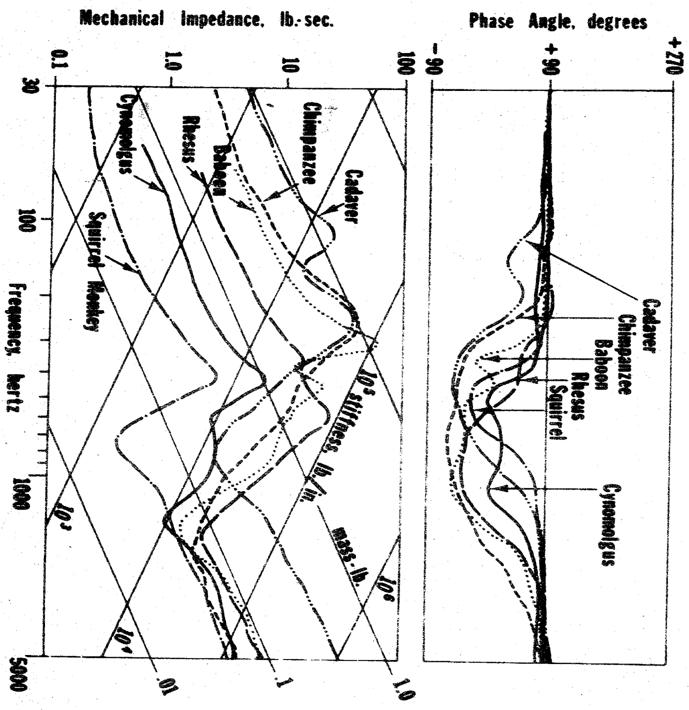


FIGURE 16. SKULLS OF PRIMATES



MECHANICAL IMPEDANCE FOR THE SIDE OF PRIMATE HEADS

FIGURE 17.

oped by Stalnaker and McElhaney (1970, 1971).

The same five species were considered for the side torso impact portion of this project. Because of the small number of chimpanzees available to the project (4) it was decided to use the chimpanzees only in the head impact study and use baboons for the torso side impact study.

The test animals were housed in the Biomedical Laboratory's vivarium of Highway Safety Research Institute for a minimum of two days. During this time the animals were examined and their physical condition recorded. This pre-impact physical was then compared to the post-impact physical and used in evaluating the extent of injury.

The animal to be tested was anesthetized with 30 mg/kg of ketalar [dl 2-(0-chlorophenyl)-2-(methylamino) cyclohexanone Hydrochloride)]. This drug is a rapid-acting general anesthetic producing an anesthetic state characterized by profound analgesia, normal pharyngeal-laryngeal reflexes and normal or slightly enhanced skeletal muscle tone. With this drug the post-impact state of consciousness can be determined. The good muscle tone provided by this drug made the test conditions more realistic and representative of the responses of the alert animal.

Pre-impact radiographic films were taken to ensure that no pre-existing anomaly would influence the experiment. The Radiographic Laboratory is located directly adjoining the Vivarium with the test impact facility, on one side, and the Operating Surgery and Autopsy Laboratories on the other. This facilitated movement of animals from the Vivarium preparation area. A hospital type Picker radiographic unit with a capacity of 300 MA and 140 RvP was utilized.

After the animal was fully anesthetized, he was shaved and targeted for high speed photographic analysis. The animal was then taken to the impact room where EKG, respiratory rate and reflex state were recorded. A complete set of anthropometric measurements were then made of each test animal. The test animal was seated for the impact tests on a bench type seat and supported by surgical thread through the ears. This method of support makes the animal essentially a free body. It was found to provide reproducible results and eliminated the complicated boundary conditions of a seat or sling.

All impacts were carried out by a pneumatically operated testing machine especially constructed for impact studies. (Figure 18) The machine consists of an air reservoir, and a ground and honed cylinder with two carefully fitted pistons. One, the transfer piston, is propelled by compressed air through the cylinder and transfers its momentum to the impact piston. A striker plate, attached to the impact piston, travels a distance of about four inches, when an inversion tube absorbs the energy of the impact piston and halts its movement. The stroke of the impactor was controlled by its initial positioning and its velocity was controlled by the reservoir pressure. The impactor was instrumented with an accelerometer and an inertia compensated force transducer. (Figure 19) High speed motion pictures at 5000 fps were taken for photometric analysis.

3.2.1 Head Impacts Set Up

The head impacts were carried out using three flat rigid impactors. Each impacting surface was larger than the head to be impacted. (Figure 20) The test animal was placed with his head a predetermined distance from the impactor to prevent the impactor from contacting the lower part of the neck. (Figure 21)

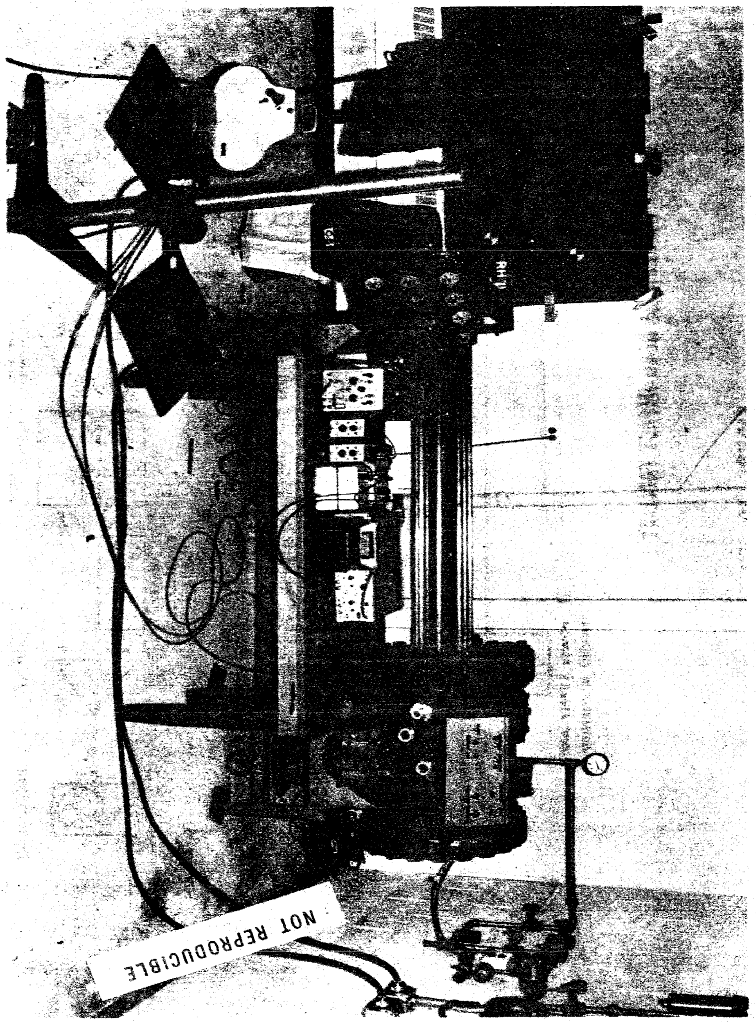


FIGURE 18. OVER-ALL SET-UP OF PNEUMATIC IMPACTING FACILITY

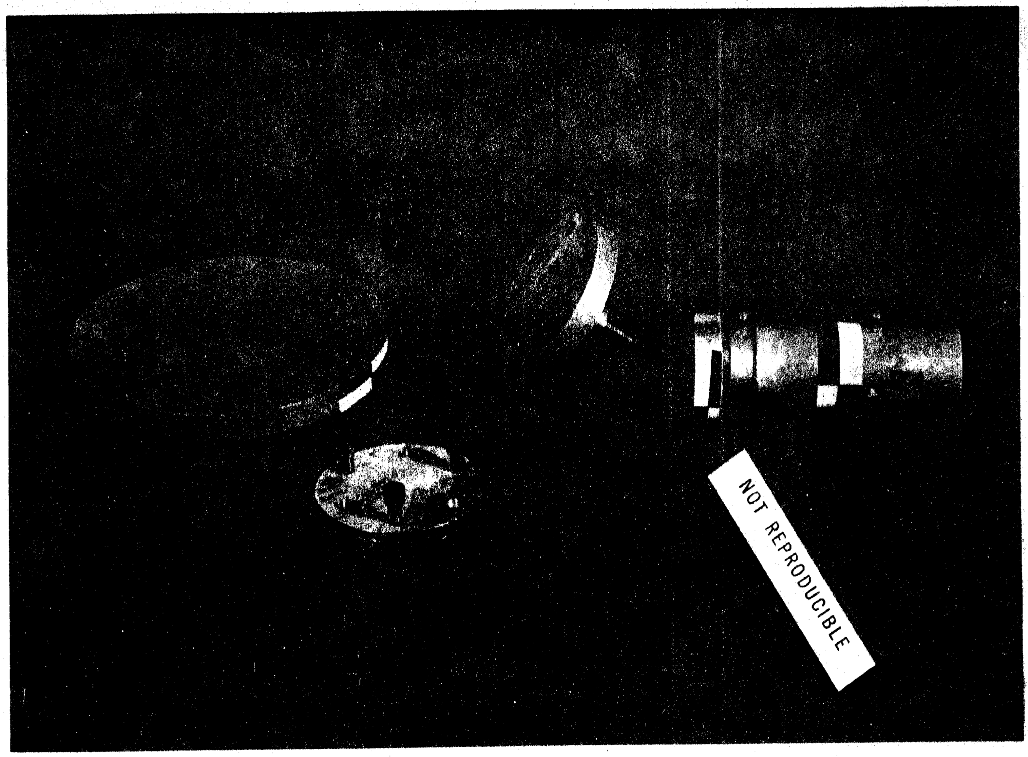
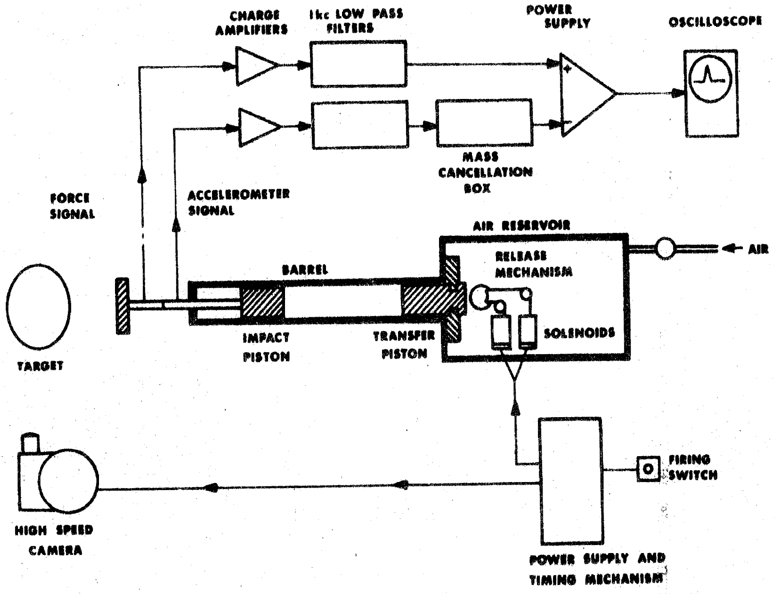


FIGURE 20. FLAT RIGID IMPACTORS AND TRANSDUCERS



BLOCK DIAGRAM of HEAD IMPACT FACILITY

FIGURE 19

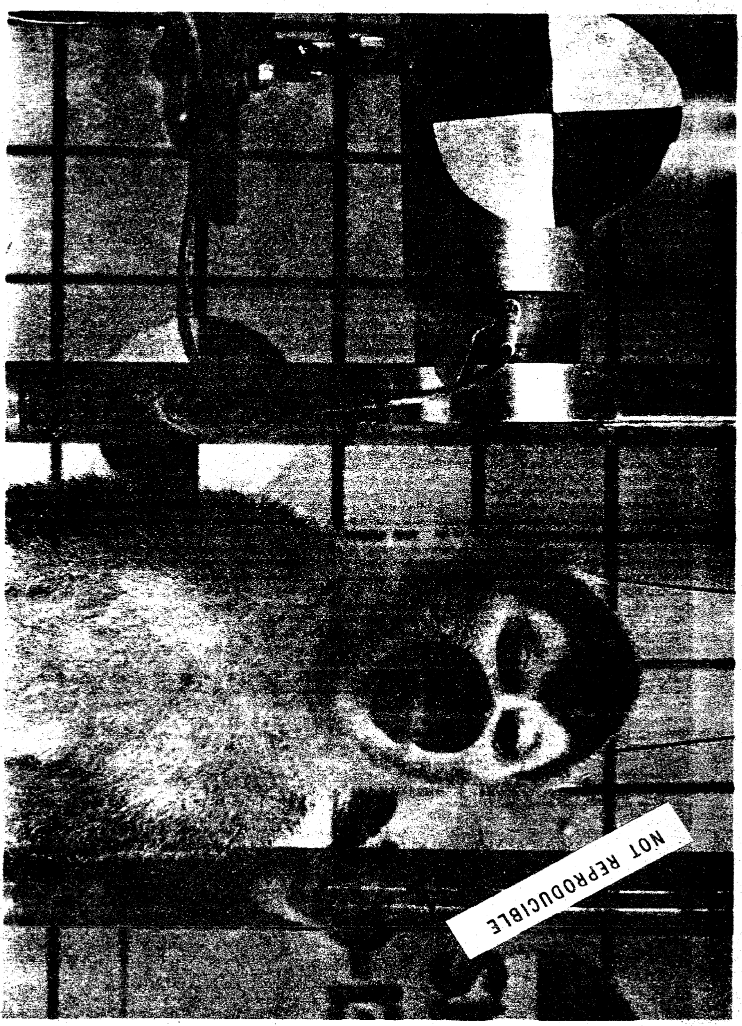


FIGURE 21. TEST SET-UP FOR HEAD SIDE IMPACT

The weight of the impactor was 22 pounds, at least five times the weight of the largest head to be impacted. This was designed to assure an essentially constant velocity impact for all head impacts.

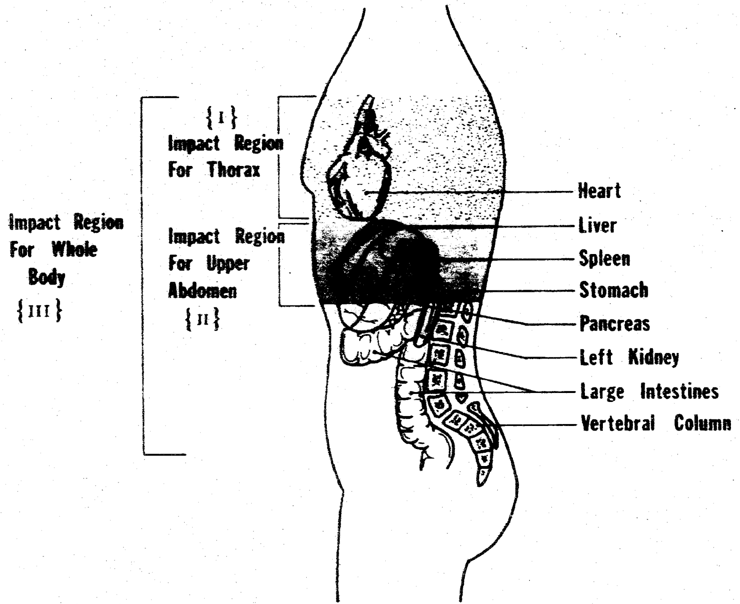
The contact force-time plot was obtained from oscilloscope traces. The peak forces, shape, pulse duration and impulse were taken from these oscilloscope traces.

The high speed movies of each test was analyzed and processed on a Van Guard film analyzer utilizing differentiation and smoothing techniques to determine the linear and angular velocity and acceleration of the impacted animals head. The vector sum of the x and y components for both the acceleration and velocity were also determined.

A second series of head impacts were conducted using a padded impactor to distribute the load and increase the pulse duration for comparative purposes.

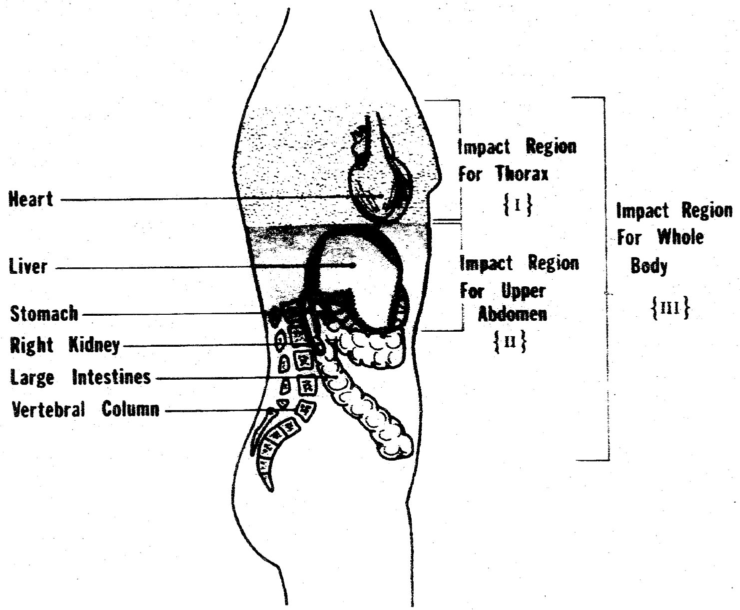
3.2.2 Body Impacts

The thorax and abdominal body areas were divided into three major impact regions. Region I consisted of the thorax as located between the jugular notch of the sternum and the diaphragm. Region II was defined as including the area between the diaphragm (9th rib) and a horizontal plane transisting the abdomen along the inferior margin of the liver and stomach, and located approximately 1-3 cm superior to the umbilicus on the surface. Region III included the entire thorax and abdominal area, from the jugular notch to the iliac chest. All body impacts to Region I were carried out midway between the superior mediastinum and the diaphragm. The impacts to Region II were carried out in the transverse plane, and all impacts to Region III enclosed all of Region III. All of these points were located as accurately as possible on the subhuman primates before each test. The body regions are illustrated



BODY IMPACT REGIONS FOR LEFT SIDE

FIGURE 22



BODY IMPACT REGIONS FOR RIGHT SIDE

FIGURE 23

for the left and right side views in Figures 22 and 23.

All impacts made to Regions I and II use a 20-pound impactor with a scaled arm rest for a contacting surface. This contacting surface was made from a 9 lb/ft^3 high density polyethylene foam to distribute the contact load. (Figure 24) The scaled arm rest was replaced by a scaled flat rigid plate for all impacts to Region III.

The animals were positioned to limit the depth of penetration to approximately 50% of body width, and a one-foot thick soft foam pad was arranged to prevent injury after impact.

The same testing procedure was used for each test sequence. The animal was impacted on the right side, and the injury evaluated. If the injury was not serious, then the next animal was impacted at a higher velocity. The procedure was continued until a serious injury was obtained. The next sequence of impact would be for the left side in the same region as just completed.

The engineering parameters recorded for these tests were force-time history from an oscilloscope trace, and impact velocity, and depth of penetration from the high speed photography.

The contact force and acceleration time history were recorded on an oscilloscope. The impactor velocity and depth of body penetration was determined from high speed motion picture analyses.

3.2.3 Biomedical Data Collection

The impacted animal was taken from the impact room to the X-ray for post-impact x-rays. These x-rays proved to be particularly useful in locating fractures, determining whether a shoulder was dislocated or whether a fracture was involved, and alerting the investigators to hairline fractures which

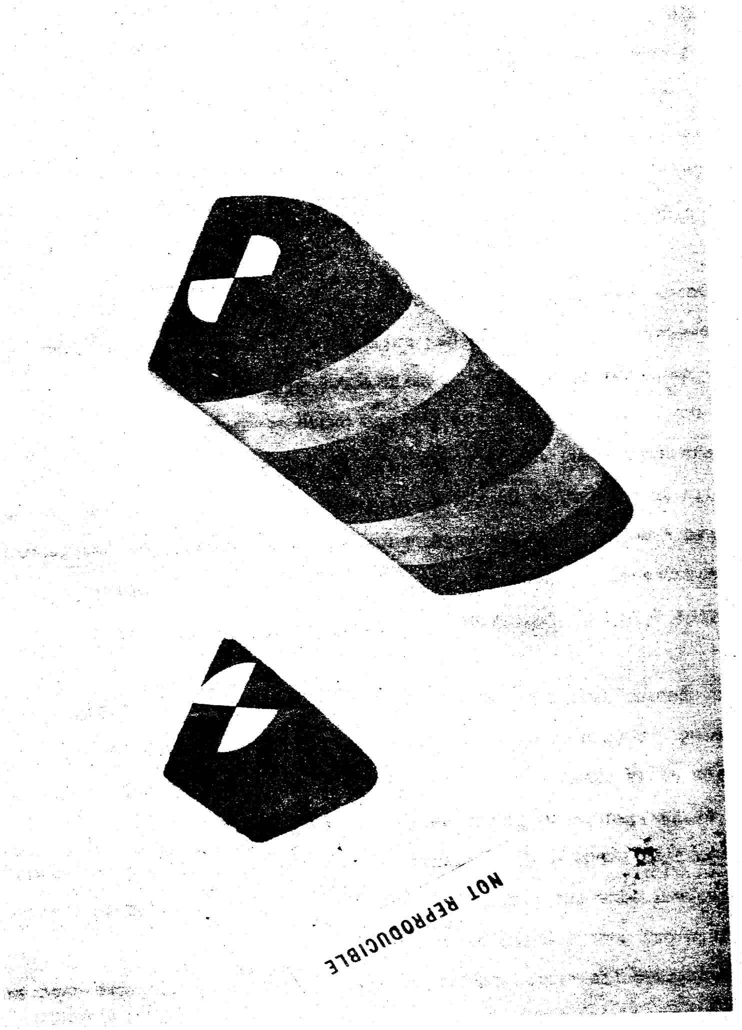


FIGURE 24 . BLUNT WEDGE HARD FOAM IMPACTORS

NOT REPRODUCIBLE

might have been overlooked in autopsy. However, some fractures, particularly in the smaller squirrel monkey, were not found to be evident upon radiological examination of post-impact x-rays. Previous clinical and experimental studies with both human patients and cadaver materials have shown that rib fractures and vertebral end-plate fractures often cannot be visualized as well. For this reason the skulls of the test animals were saved after autopsy and cleaned using an Antiformin technique for further reexamination. Several fractures were found which had been previously undetected either through careful dissection or x-ray.

Gross autopsy was conducted in the Autopsy Laboratory, specially equipped for dissection. Autopsies were conducted as a blind, according to accepted research procedure, with the investigator conducting the gross autopsy having no knowledge of physical data on the intensity, location of impact, or circumstances of each test. Careful anatomical dissection of the head, face and neck tissues, where head impacts occurred allowed discrete identification of many sites of vascular failure. When gross trauma was found it was photographically recorded using a specially modified Pentax camera with close-up lens, either in situ or as an isolated entity to provide a permanent record of the injury.

Tissues were saved from all major organs for further histopathologic examination. A typical copy of the autopsy report form used for each subject is included in Appendix A. Weights of major organs were obtained, including the heart, brain, lungs, liver, spleen, pancreas, adrenals, and kidneys. Each autopsy report includes gross and microscopic pathology, anthropometry, pre- and post-impact radiographs, color photographic documentation of dissections, injuries, and the animal test preparation. Isoenzyme determinations

information relative to the history, case, and any medication of the particular subject.

It should be noted that no animal carcass was destroyed post-autopsy without making an effort to more fully utilize the remains within the Medical School community. In this connection, some 12 departments received carcass materials which were of direct benefit to other medical research studies in progress. Some examples included the testis which were used by the Department of Gynecology and Obstetrics for hormone studies, thigns by the Department of Surgery for fascia graft experiments, and other 'discarded' materials were received by the Human Growth Center, Department of Anatomy, Department of Opthamology, Department of Otorhinolarynogy, Department of Pathology, Kresge Hearing Research Institute, Department of Anthropology, University of Michigan Museum, and hands and feet were used for a study of dermatoglyphics by School of Public Health investigators. Thus, the animal subjects were optimally utilized in respect to all animal utilization codes of ethics.

Tissue specimens were prepared in the HSRI Histology Laboratory for microscopic examination. Fixed in a solution of formalin, the specimens were dehydrated with alcohol, cleaned, infiltrated and finally imbedded in paraffin. The paraffin blocks were placed in the microtome and tissues were sectioned at a thickness of 5 microns, using an AO Sencer 820 microtome and mounted on a glass slide. Various stains were used, but in the case of brain tissue some slides for each subject were prepared with Gallocyamin stain for Nissl substance, since early dissolution of Nissl substance has been found to occur subsequent to nerve cell injury.

Microscopic examination and study of the tissue preparations was accomplished with an AO Spencer Series 10 microscope using 4X, 10X and 45X objectives with trinocular body, which permits the use of a Pentax H/a camera for microphotography. Histopathology was evaluated by specialists from the University School of Medicine. As a further check on interpretation, selected brain tissues were submitted for evaluation by two additional pathologists experienced in infra-human brain pathology, Dr. Weatherbee, Chief of the U.S. Veteran's Hospital Pathology Department at Ann Arbor, and Dr. G. T. Price, pathology consultant. A difference in brain histopathology observations as well as interpretation is not unusual among pathologists, and the submission of critical tissue specimens to more than one pathologist without the knowledge of the other was intended as a check to decrease the chances of missing any pertinent pathology, as well as alert us to any specific cases where there might be a difference of opinion as to pathological interpretation. A similar procedure was also followed in the final interpretation of injury severity related to both gross and microscopic findings, with separate ratings made by two researchers experienced in infra-human primate injury investigations. Interpretations and scoring was consistently within 1/2 scaling point out of 5, giving considerable confidence to our final scaling design. The following injury scale was used to rate the injury of all test animals.

1. No injury - minor injury
2. Recoverable injuries (these may be severe, but non-dangerous to life)
3. Marginal as to whether injury is irreversible (i.e., results in permanent disability of function or structure)
4. Serious injury, non-reversible, probably not survivable
5. Fatal trauma

3.2.4 Test Results

3.2.4.1 Results of Head Injuries

Two types of head injuries were seen in this study. The first was the open-brain injury. This is when the dura mater is penetrated by some type of intrusion. Because a large surface impactor was used in all tests, the only type of intrusion seen was from bone fragments that were pushed into the brain. Seven depressed fractures were encountered in the head study, all life-threatening. In each case the depressed fracture was easily diagnosed from x-rays and preliminary examination.

The second type of head injury seen was the closed brain injury. This type of injury occurs when the dura mater is intact but the brain is still damaged. One such closed brain injury is the contrecoup injury. Depressed fractures are coup injuries, that is, the injury is at the site of impact or of fracture, whereas the contrecoup is remote from the point of impact. The contrecoup type of injury was always found directly opposite the impact point. The injury varied in size and shape, but generally appeared to be made up of many tiny pin-point hemorrhages. (Figure 25) Because of the localized nature of these injuries, a cavitation mechanism is suspected.

3.2.4.2 Results of Body Injuries

The injuries to the body were mainly of one type, direct damage to an organ. A typical type of injury is shown in Figure 26 which depicts a fractured liver. Another common injury was to the kidney shown in Figure 27. This also was from direct pressure.

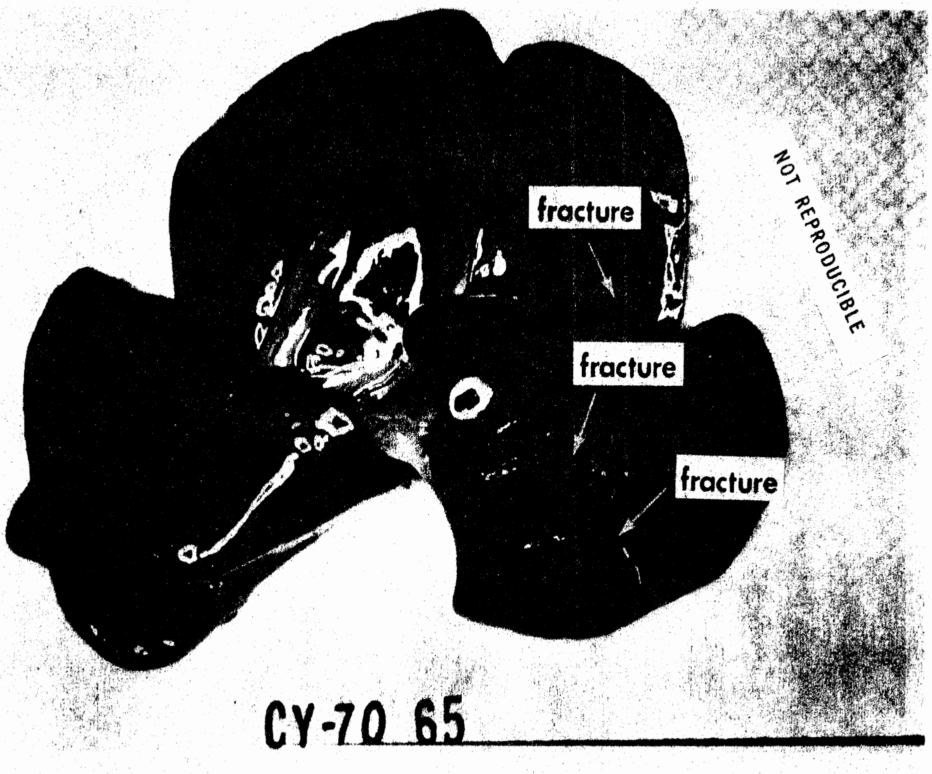


FIGURE 26. TYPICAL LIVER FRACTURES

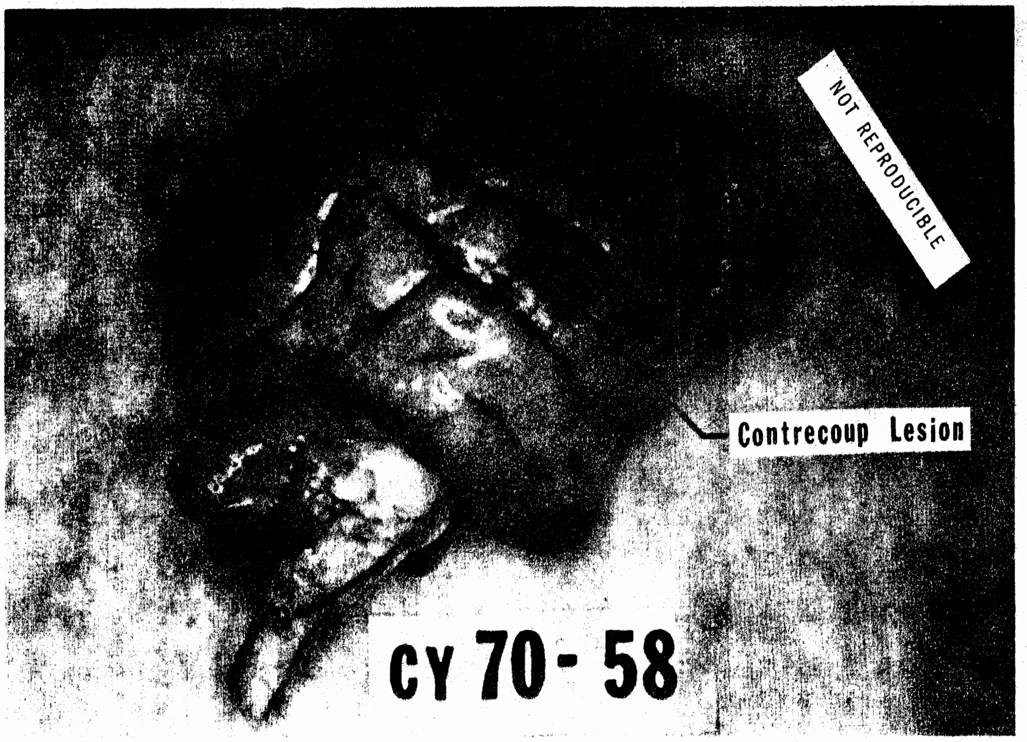


FIGURE 25 TYPICAL CONTRECOUP INJURY

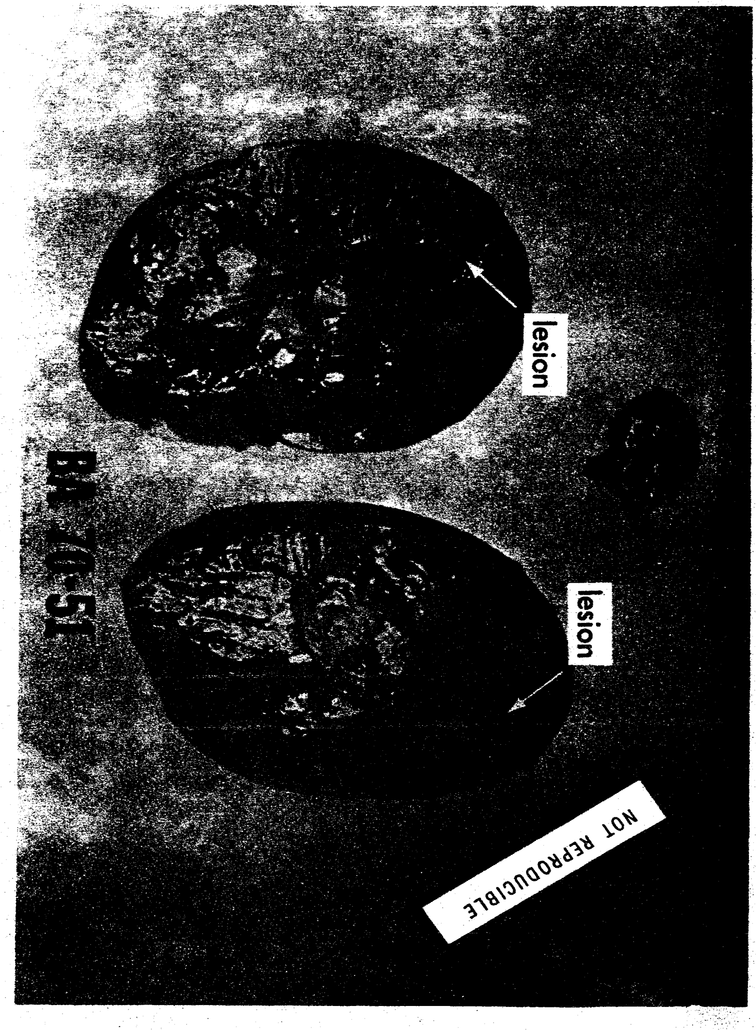


FIGURE 27. TYPICAL KIDNEY INJURY

Other types of injury seen were tears in the liver and mesentery. One injury observed for primarily whole body impact were pancreatic injuries. These injuries were to the body of the pancreas with a very small amount of hemorrhaging throughout the gland.

The results for all idealized impacts are given in Tables 8, 9 and 10.

3.3 PRIMATE SCALING

3.3.1 Head Injury Scaling

The head contact force, duration of impact, head angular acceleration, linear acceleration and velocity were obtained for each side impact. The values of these parameters used in the scaling relationships were taken from tests where the animal received an injury considered to be just below life-threatening. That is, approximately 3 on the injury scale.

The head mass, brain mass, average skull radius and average skull thickness for each test animal in a particular species group are reported as an average value for that species.

Previous work by McElhaney (1970) on the mechanical properties of bone, scalp and brain indicated that there was very little difference if any in the material properties of these tissues for primates. On the basis of this work, it was assumed that the material properties of scalp, brain, and bone was the same for all animals tested and that the results could be extrapolated to man.

Given the average values for the species physical properties along with the force time profile and the resulting mechanical responses needed to produce a desired injury level, the extrapolation to man was made by scaling relationships developed by dimensional analysis techniques.

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
70-15	sm	r. side head; no pad	1.41	0.181	.83	.039	2.1	290	1320	28.0	190,000	300	0.31	4	1	3	cracked
70-9	sm	r. side head; no pad	1.32	0.168	.77	.044	1.7	550	2620	59.0	415,000	423	0.59	5	1-2	3	cracked
70-11	sm	r. side head; no pad	1.32	0.168	.77	.042	1.2	500	2320	37.0	275,000	229	0.41	Same Day	20	3	cracked
70-12	sm	r. side head; no pad	1.76	0.224	.82	.041	1.3	375	2340	36.5	300,000	395	0.25	1	none	3	cracked
70-13*	sm	r. side head; no pad	1.32	0.168	.83	.041	1.6	400	1360	30.0	240,000	319	0.44	7	1-2	3	cracked
71-84	sm	l. side head; no pad	1.32	0.169	.87	.046	1.8	180	1300	34.0	150,000	150	0.21	3	2	3	cracked
70-8*	sm	r. side head; no pad	1.87	0.238	LOD	LOD	1.5	550	2380	44.3	185,000	230	0.63	5	2-3	4	cracked

*contrecoup LOD-Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
71-81	sm	l. side head; no pad	1.37	0.175	.82	.032	1.6	176	1706	37.0	150,000	200	0.18	2	none	2	none
71-83	sm	l. side head; no pad	1.10	0.141	.87	.050	2.1	180	630	24.0	120,000	220	0.19	3	0.5	1	none
70-3	sm	r. side head; no pad	1.71	0.217	LOD	LOD	1.5	320	1350	26.0	247,000	202	0.19	9	none	2	none
70-5	sm	r. side head; no pad	1.98	0.247	LOD	LOD	2.1	534	1530	45.0	124,000	135	0.78	Same Day	none	2	none
70-16	sm	r. side head; no pad	1.16	0.164	.87	.050	2.2	210	1130	25.6	345,000	285	0.21	5	1	2	cracked
70-14	sm	r. side head; no pad	1.76	0.175	.82	.041	1.6	375	2140	34.5	225,000	255	0.36	6	4-5	2	cracked
71-82	sm	l. side head; no pad	1.49	0.191	.88	.040	2.4	152	690	29.0	60,000	150	0.20	2	none	2	cracked

LOD=Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
70-57	cyn	l. side head; no pad	5.73	6.950	1.17	.070	3.6	650	843	33.0	100,000	205	0.83	3	60	3	none
71-78	cyn	l. side head; no pad	4.98	0.478	1.13	.081	2.0	725	1180	45.0	206,000	352	0.67	Same Day	None	3	none
71-76	cyn	l. side of head no pad	7.58	0.720	LOD	LOD	2.0	775	780	45.0	177,000	175	0.85	Same Day	8	3	none
70-17	rh	r. side head; no pad	9.24	0.993	LOD	LOD	2.4	1075	800	28.5	75,737	155	1.64	3	4-5	1	none
70-28	rh	l. side head; no pad	25.50	2.370	1.54	.085	3.0	2350	1000	36.3	145,000	160	3.35	7	0-1	2	none
71-88	rh	l. side head angled no pad	14.70	1.370	1.58	.125	2.2	1700	1200	44.0	125,000	155	1.80	Same Day	None	2	none

LOD=Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA
(Continued)

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
70-7	sm	r. side head; no pad	1.76	0.224	LOD	LOD	LOD	LOD	1460	42.5	153,588	278	LOD	Same Day	Never Regained	5	depressed
70-10	sm	r. side head; no pad	1.32	0.168	LOD	LOD	1.5	320	1220	37.8	254,000	288	0.48	1	5	5	depressed
70-55	cyn juvenile	l. side head; no pad	5.40	0.657	1.21	.053	2.0	950	760	35.5	130,000	268	0.99	3	2	1	none
70-56	cyn	l. side head; no pad	5.30	0.641	1.15	.064	2.3	500	960	27.8	99,000	250	0.67	3	1	1	none
71-85	cyn	l. side head; no pad	7.05	0.846	1.60	.075	2.8	800	1450	45.0	80,000	295	1.16	Same Day	None	3	cracked
70-58*	cyn	l. side head no pad	6.05	0.731	1.18	.065	1.7	800	1220	35.0	95,000	184	0.99	3	None	3	none
71-86	cyn	l. side head angled no pad	7.15	0.860	1.34	.074	3.6	625	900	45.0	110,000	160	0.78	Same Day	5	3	depressed

*contrecoup
LOD=Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA
(Continued)

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
71-89*	rh	l. side head angled; no pad	9.50	0.880	1.39	.110	3.5	LOD	730	43.5	1,598,000	240	Not Determined	3	None	3	depressed (eggshell inside)
70-23	rh	l. side head; no pad	20.20	1.960	1.48	.127	3.2	2800	1190	50.0	160,000	209	3.05	3	5	4	none
70-24	rh	l. side head; no pad	20.60	1.820	1.50	.124	3.0	2500	1150	42.0	80,000	201	3.26	Same Day	Never Regained	5	depressed
70-27	rh	l. side head; no pad	23.50	2.180	1.52	.122	3.6	2200	890	26.5	145,000	171	3.83	Same Day	Never Regained	5	cracked
71-75	ch	l. side head angled; no pad	62.00	5.930	2.11	.175	4.6	4400	406	46.0	65,700	138	13.20	2	None	2	none
71-80	ch	l. side head; no pad	65.00	6.210	2.08	.185	4.9	4600	550	40.0	1,310,000	185	11.10	2	1	3	none

*contrecoup
LOD = Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA
(Continued)

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
70-25	rh	l. side head; no pad	23.30	2.190	1.53	.083	2.8	1800	580	30.0	60,000	195	2.70	6	None	2	none
70-29	rh	l. side head; no pad	11.90	1.060	1.39	.076	2.0	1600	940	36.4	110,000	218	1.46	7	None	2	none
70-26	rh	l. side head; no pad	23.80	2.200	1.54	.128	3.0	2000	641	31.0	95,000	220	3.00	4	2	2	cracked
71-90	rh	l. side head; no pad	15.30	1.420	1.56	.112	2.1	1450	1290	42.5	480,000	130	1.71	3	None	3	none
70-22	rh	l. side head; no pad	21.60	2.100	1.50	.135	3.5	2050	940	38.0	75,000	179	3.25	6	4-5	3	none
71-87 *	rh	l. side head; no pad	12.80	1.180	1.38	.170	2.8	1470	1600	54.0	80,000	140	1.60	Same Day	None	3	cracked

*contrecoup

TABLE 8. SIDE HEAD IMPACT DATA
(Continued)

Run No.	Animal Species	Area & Type of Impact	τ Impact Duration (ms)	Peak Contact Force (lbs.)	Max. Head Accel. (Vector Sum, g's)	Termination (Days After Impact)	Loss of Consciousness (min)	Scaling Index No.
71-109	rh	l. side head 1.5" padding	6.2	1250	770	3	10	2
71-114	cyn	l. side head 1.5" padding	5.0	750	1135	3	None	1
71-116	cyn	l. side head 1.5" padding	4.0	500	756	2	2	2
70-19	sm	r. side head 2" padding	5.3	150	743	1	None	1
70-20	sm	r. side head 2" padding	6.4	160	890	1	None	1

TABLE 9. PADDED IMPACTOR HEAD DATA

Run No.	Animal Species	Area & Type of Impact	Total Body Weight (lbs.)	Head Weight (lbs.)	a (Average Skull Radius, in.)	h (Average Skull Thickness, in.)	τ Impact Duration (ms)	Peak Contact Force (lbs)	Max. Head Accel. (Vector Sum, g's)	Max. Head Vel. (Vector Sum, mph)	Max. Head Angular Accel. (rad/sec^2)	Max. Head Angular Vel. (rad/sec)	Impulse (lb-sec)	Termination (Days After Impact)	Loss of Consciousness (min)	Injury Index	Skull Fractures
70-74	ch	l. side head angled; no pad	47.10	4.500	2.05	.190	3.0	4800	675	38.0	24,700	174	6.86	Same Day	2	5	depressed
70-30	cadaver human	l. side head; no pad	~250.00	~10.000	LOD	LOD	LOD	LOD	390	10.0	40,000	35	LOD	-	-	2	depressed

LOD = Loss of Data

TABLE 8. SIDE HEAD IMPACT DATA (Continued)

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-36	rh	Left Region II	8.40	55.0	180	20.0	9.8	1.08	Same Day	Subpleural hemorrhage in left lung; marked dilatation of right side of heart; single laceration of liver anterior to coronary ligament.	3
70-37	rh	Left Region I	9.00	45.0	280	31.2	8.0	1.30	Same Day	Minor hemorrhage on left lung.	1
70-38	sm	Right Region I	1.32	32.0	80	8.9	8.0	0.55	Same Day	Moderate hematoma right kidney and right adrenal.	1
70-39	sm	Left Region I	1.30	32.6	60	6.7	5.2	0.32	Same Day	Several petechiae on lungs.	1
70-40	sm	Right Region I	1.16	35.6	140	15.5	5.8	0.40	Same Day	Several small petechiae on lungs; focal epicardial hemorrhage.	2
70-41	sm	Left Region III	1.14	32.8	LOD	LOD	LOD	LOD	3	Focal subcapsular hemorrhages of liver; focal atelectosis of lungs.	2
70-42	sm	Right Region III	1.28	33.5	LOD	LOD	LOD	LOD	3	Small hemorrhage right lower lobe of lung. Pancreas: Focal hemorrhage.	1
70-43	sm	Left Region III	1.26	32.0	397	9.9	6.6	1.32	5	Multiple petechiae on both lungs; retroperitoneal hematoma; small omental hematoma.	2

LOD = Loss of Data

TABLE 10. SIDE BODY IMPACT DATA
(Continued)

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-31	rh	Right Region II	13.40	36.5	280	31.0	7.8	1.40	Same Day	Cause of death: exsanguination of 150 cc's blood into peritoneal cavity,also noted multiple liver lacerations.	5
70-32	rh	Left Region II	8.90	43.9	260	28.9	9.2	1.60	Same Day	Lacerations and fractures of left lateral lobe of liver, small lacerations and fractures of right lateral lobe of liver; 20 cc hemoperitoneum. Cause of death (possible) - blood loss associated with liver damage.	5
70-33	rh	Right Region II	11.30	34.8	260	28.9	10.6	1.60	Same Day	Ruptured left lower lobe of liver. hemorrhage in right lung; right adrenal hemorrhage.	4
70-34	rh	Right Region II	9.30	27.8	7	8.4	2.6	1.50	Same Day	Hemorrhage on diaphragmatic surface of both lungs: left lower lung lobe atelectatic; petechiae on lesser curvature of stomach.	1
70-35	rh	Left Region I	8.80	41.7	360	40.0	9.8	2.10	Same Day	Focal hemorrhages on lower lobes of both lungs (non-prominent on left side).	2

TABLE 10. SIDE BODY IMPACT DATA

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-50	rh	Left Region III	11.30	46.0	2350	26.1	8.8	LOD	Same Day	Marked congestion of left lung; scattered petechiae in right lung; severe autolysis noted in pancreas.	4
70-51	ba	Left Region II	32.60	56.0	1220	30.4	3.1	1.62	Same Day	Multiple petechiae in all lobe of lung. 50 cc hemoperitoneum; large laceration of liver; hemorrhage in right kidney, right adrenal, and pancreas.	5
70-59	ba	Right Region II	31.00	38.2	505	12.6	10.0	4.25	Same Day	Contusion of left lower lobe, petechiae in right lung; small subcapsular hemorrhage.	2
70-60	ba	Left Region II	25.70	45.5	755	18.8	12.0	15.90	Same Day	Small hemorrhage in right and left lower lobes; contusion of left lung at 8th rib; extensive hemorrhage in several areas. Adrenals, spleen: evidence of hemorrhage.	3
70-61	cyn	Left Region III	6.06	48.6	1450	363.0	12.0	8.60	Same Day	Fracture left clavicle; multiple small hemorrhages in all lobes of lungs; two subcapsular hemorrhages in right lobe liver; brain congested.	3
70-62	cyn	Left Region III	7.49	42.0	915	23.0	5.8	3.25	1	Several small petechial hemorrhages in both lungs.	1
70-63	cyn	Right Region III	4.96	47.8	1240	31.0	7.0	4.44	1	Few small petechiae in right lung.	2

LOD = Loss of Data

TABLE 10. SIDE BODY IMPACT DATA
(Continued)

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-44	sm	Right Region III	1.28	39.0	LOD	LOD	LOD	LOD	Same Day	Petechial hemorrhage in right lung.	2
70-45	sm	Left Region III	1.84	42.6	456	5.7	9.0	3.12	Same Day	Petechial hemorrhage in left lung.	1
70-46	rh	Right Region III	12.90	39.5	1820	20.6	13.8	LOD	Same Day	Focal hemorrhage in right lower lobe of lung.	2
70-47	rh	Left Region III	7.46	36.1	1700	18.9	8.4	6.60	Same Day	Acute passive congestion of left lung; pancreas: hemorrhage into interstitium.	1
70-48	rh	Left Region III	10.90	38.7	2360	25.8	11.2	7.90	Same Day	Liver: laceration of capsula and parenchyma, hematoma noted in liver substance; Pancreas: focal hemorrhage; Lungs, kidney, spleen: Acute passive congestion.	2
70-49	rh	Right Region III	9.25	44.9	2680	28.6	10.0	12.20	Same Day	Focal hemorrhage in both lungs, liver, and pancreas; severe autolysis noted in pancreas; acute passive congestion of adrenals.	4

LOD = Loss of Data

TABLE 10. SIDE BODY IMPACT DATA
(Continued)

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-71	ba	Right Region I	31.00	53.0	1020	25.5	3.6	2.60	Same Day	Edema in right and left lungs; diffuse hemorrhage at base of both lungs; 5 cc blood in right side of abdomen; small subcapsular hemorrhage in liver.	2
70-72	ba	Left Region II	42.70	51.8	890	22.0	8.0	2.30	Same Day	Hemorrhage in 7th - 11th intercostal spaces; large contusion left lung; massive hemoperitoneum; contusions and hemorrhages in both kidneys, pancreas, and liver; several lacerations in liver.	4
70-73	ba	Right Region II	47.50	47.0	1140	28.5	8.0	4.10	Same Day	Hemorrhage in left lung; massive hemoperitoneum; fracture inferior right lobe of liver; hemorrhage noted in liver, pancreas, left adrenal, and both kidneys.	5

TABLE 10. SIDE BODY IMPACT DATA
(Continued)

Run No.	Animal: Species	Area and Type of Impact	Total Body Weight lb	Velocity (ft/sec)	Peak Contact Force, lb	Average Contact Pressure psi	Impact Duration msec	Impulse lb-sec	Termination (Days After Impact)	Injury	Injury Index
70-64	cyn	Left Region III	6.06	45.8	1464	36.6	9.4	6.34	1	Patchy atelectasis of right and left lungs; right lobe liver shows acute subcapsular hematoma.	2
70-65	cyn	Left Region III	5.82	52.3	1520	38.0	6.4	4.87	Same Day	Massive hemorrhage into peritoneum; multiple liver lacerations.	4
70-66	cyn	Right Region III	5.30	53.0	1380	34.5	11.0	6.75	Same Day	Multiple liver lacerations; hemoperitoneum (life-threatening),	4
70-67	ba	Right Region II	32.00	44.5	816	20.4	7.8	4.47	Same Day	Hemorrhage in left lung; hemoperitoneum; rupture and contusions of right side of liver, right adrenal.	4
70-68	ba	Right Region II	34.80	41.2	756	18.9	12.6	4.05	Same Day	Several petechiae in right lung; severe contusion of right kidney and adrenal.	3
70-69	ba	Left Region II	33.50	47.5	750	18.7	11.6	7.10	Same Day	Several petechiae in left lung; contusions of left adrenal, spleen and descending colon; rupture of splenic artery; contusion left lobe liver.	3
70-70	ba	Left Region I	30.80	56.0	1020	25.5	8.4	7.30	Same Day	10 cc blood in left thorax; focal hemorrhage of left lung; heart hemorrhage; liver lacerated.	3

TABLE 10. SIDE BODY IMPACT DATA
(Continued)

The extrapolated tolerable acceleration and pulse duration for man were then used as input parameters to the Maximum Strain Criteria (MSC) curve (Stalnaker and McElhaney, 1970). The resulting MSC curve is the human side impact tolerance for closed head injuries over a pulse duration ranging from 0.6 milliseconds to 100 milliseconds.

3.3.1.1 Dimensional Analysis

Let us consider the variables A, τ, F, V, a, h, m where:

A = linear head acceleration (ft/sec^2)
τ = acceleration pulse duration (msec)
F = head contacted force (lb)
V = change in head linear velocity (ft/sec)
a = average skull radius (in.)
h = average skull thickness (in.)
m = head mass (slugs)

Let us assume that π, a dimensionless quantity, is a function of these variables.

$$\pi = f(V, A, \tau, F, V, a, h, m) \qquad (1)$$

Then, from Buckingham's Theorem of Dimensional Analysis, Eq. (1) (Langhear, 1951) can be written as follows:

$$\pi = f(\pi_1, \pi_2, \pi_3, \pi_4) \qquad (2)$$

where π_1, π_2, π_3, π_4 are dimensionless quantities of the form

$$\pi_1 = \frac{h}{a} \qquad (3)$$

$$\pi_2 = \frac{V\tau}{h} \qquad (4)$$

$$\pi_3 = \frac{A}{V^2/h} \qquad (5)$$

$$\pi_4 = \frac{VM}{F\tau} \qquad (6)$$

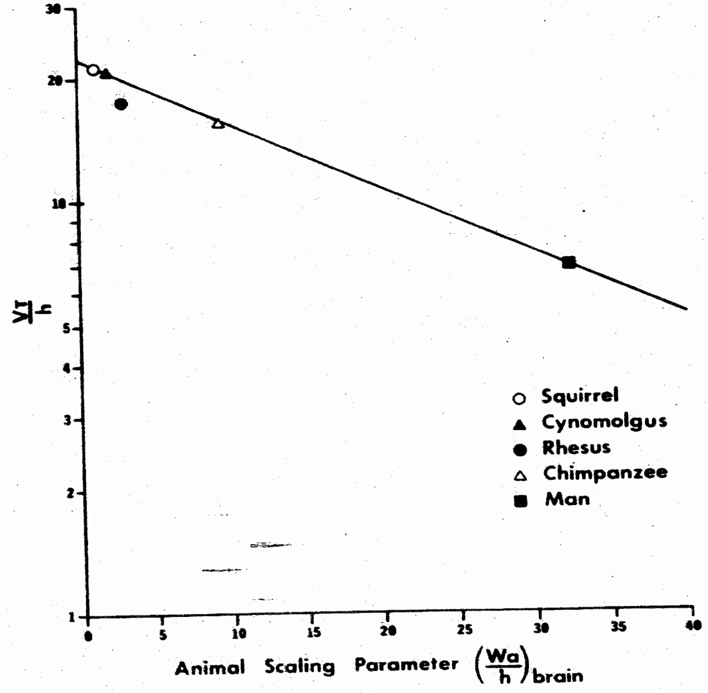
The dimensionless variable $\frac{a}{h}$ was weighted by multiplying it by the brain mass of each species tested. This species dependent term π_1^* was then plotted against each of the remaining dimensionless variables.

The scaling parameter π_1^* was plotted against the dimensionless variable π_2 for each species represented. (Figure 28) From this plot the value of π_2 was found for man by extrapolation. This yields a tolerable impact velocity of 15 mph for the human head when impacted at the side by a large flat rigid striker.

The scaling parameter π_1^* was then plotted against the dimensionless variable π_3 for each species. (Figure 29) From this plot the value of π_3 was found for man. Knowing h and V from Figure 28, the tolerable peak acceleration for the side of the head under these impact conditions was found to be 56 G's. The final plot of π_1^* against π_4 gives a peak contact force of 800 pounds for an impact force resulting in a survivable closed brain injury. (Figure 30)

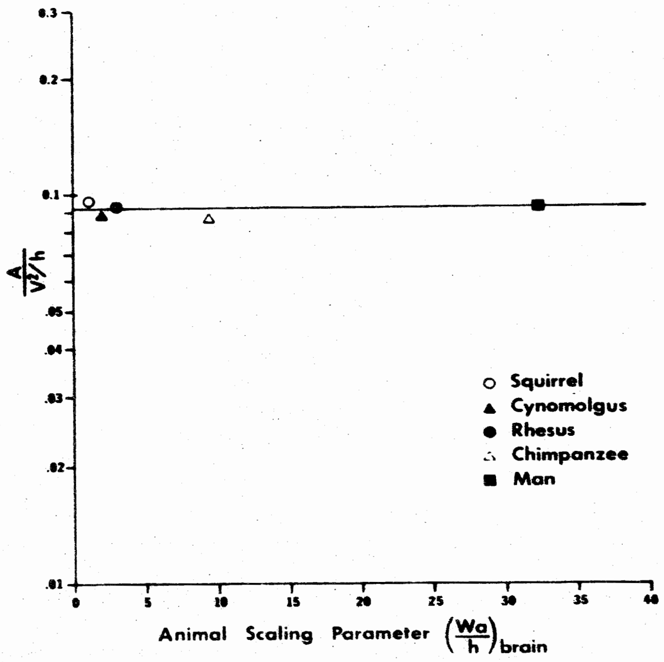
The scaling parameters used in the extrapolation to man and the resulting human parameters derived from the scaling are given in Table 11.

If the dynamic response of the head is known for a wide range of frequencies and if injury can be related to this response, then a tolerance curve can be generated for variable pulse durations and shape, given only one point on the tolerance curve, provided the injury mechanism does not change over that range.



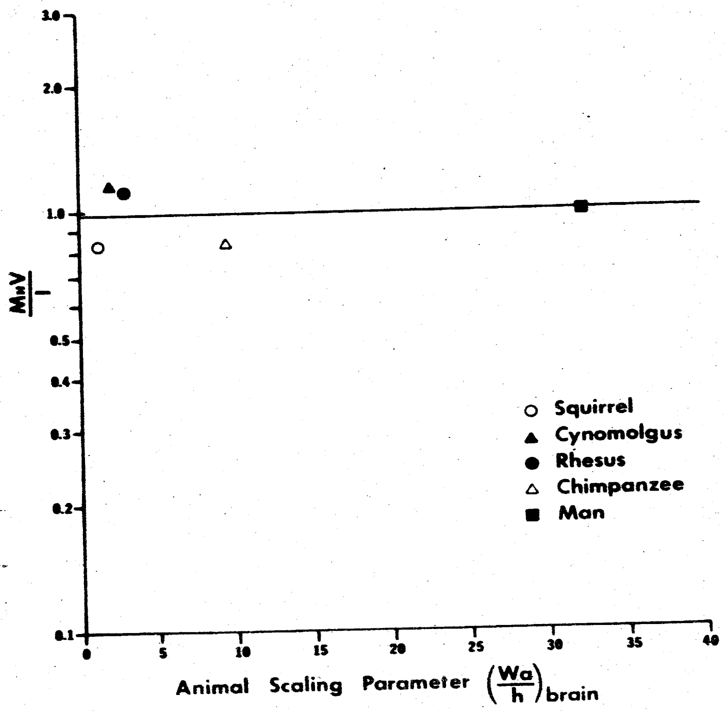
Note: All data points are for an injury scaling number of three.

FIGURE 28. VELOCITY SCALING PARAMETER FOR HUMAN SIDE HEAD IMPACT



Note: All data points are for an injury scaling number of three.

FIGURE 29 ACCELERATION SCALING PARAMETER FOR HUMAN SIDE HEAD IMPACT



Note: All data points are for an injury scaling number of three.

FIGURE 30 IMPULSE SCALING PARAMETER FOR HUMAN SIDE HEAD IMPACT

Species	Average $\frac{a}{h}$	Average Brain Weight W_B lb.	Average Head Weight W_H lb.	Average Skull Thickness h in.	Impulse I lb-sec	Acceleration Pulse Duration τ msec.	Peak Vector Sum Head Accel. A G's	Peak Vector Sum Head Velocity V in/sec	π_1* $W_B \frac{a}{h}$	π_2 $\frac{V\tau}{h}$	π_3 $\frac{A}{V^2/h}$	π_4 $\frac{M_H V}{I}$
Squirrel	18.8	.0644	.189	.043	.36	1.5	1260	608	1.21	21.2	.096	0.83
Cynomolgus	15.4	.132	.716	.071	.98	2.4	1220	616	2.03	20.8	.088	1.15
Rhesus (20 lb)	13.2	.232	2.120	.115	3.25	3.0	940	670	3.06	17.5	.093	1.10
Chimpanzee	11.4	.835	5.260	.184	11.10	4.2	550	680	9.54	15.5	.086	0.83
Human (Extrapolated)	10.8	3.00	10.0	.283	6.00	7.5†	56	256	32.5	6.8	.092	0.98

TABLE 11. SCALING PARAMETERS

3.3.1.2 Maximum Strain Criterion for Primates

The mechanical driving point impedance of a human cadaver and all test species heads was determined over a frequency range of 30-5000 hertz utilizing the following experimental design.

The monkey was anesthetized and a 10 millimeter (mm) circular hole was cored 0.25 inch above the ear canal on the side which was attached to an electromagnetic shaker. The loading fixture was then fastened to the skull at this site. On the opposite side of the skull a similar hole was made and a miniature accelerometer attached.

†Discussed in the next section.

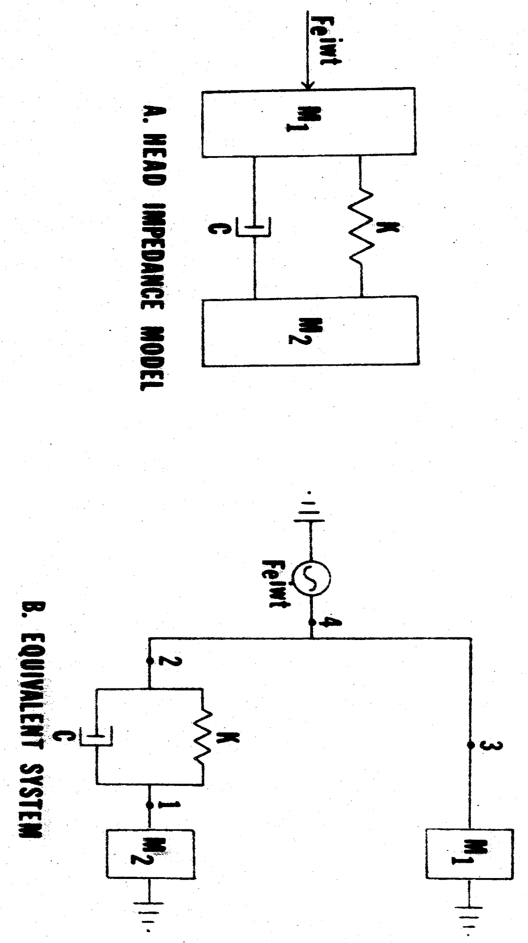
The monkey's skull via the load cell was rigidly attached to the platen of a 200-pound electromagnetic shaker. The body was supported in a sling hammock, and a respirator was connected to the trachea to provide respiration when needed. A servc controller was then set to apply a sinusoidal constant amplitude acceleration of either 10 or 20 G's to the head. In addition, an accelerometer was placed on the free side of the head and the transmitted acceleration recorded. A sweep oscillator drove the shaker system over a 30 to 5000 Hz cycle range, while an automatic on-line analogue impedance computer was used to convert the force-time and acceleration-time information into a phase and impedance versus frequency plot. With this system, the test could be performed in less than one minute (depending on sweep rate) and a continuous plot of impedance produced. Mechanical impedance versus frequency on an x, y_1, y_2 recorder was recorded for the various living anesthetized primates used in this study.

The same experiment was performed on an unembalmed 71-year old human male cadaver, who had been dead approximately 30 hours prior to the experiment. Constant accelerations of 1, 5, and 10 G's were applied over the frequency range 30-5000 Hz.

The two-degree-of-freedom system shown in Figure 31A had been previously developed by Stalnaker, McElhaney and Fogle (1971) to closely approximate the impedance characteristics of the head of various primates as measured in these experiments.

If the system is represented schematically as in Figure 31B, the system elements are combined in parallel and series. Using the rule of parallel systems the impedance at point 4 is

$$z_4 = z_3 + z_2 \qquad (8)$$



A. HEAD IMPEDANCE MODEL

B. EQUIVALENT SYSTEM

FIGURE 31. 2-DEGREE-OF-FREEDOM SYSTEM

Using the rule of series system the impedance z_2 at point 2 is

$$\frac{1}{z_2} = \frac{1}{z_1} + \frac{1}{z_k + z_c} \qquad (9)$$

so now

$$z_4 = z_3 + \frac{1}{\frac{1}{z_1} + \frac{1}{z_k + z_c}} \qquad (10)$$

Substituting

$$z_4 = i\omega m_1 + \frac{1}{\frac{1}{i\omega m_2} + \frac{1}{\frac{k}{\omega i} + c}} \qquad (11)$$

or

$$z_4 = i\omega(m_1 + m_2) \left[\frac{1 - \frac{\omega^2 m_1 m_2}{k(m_1 + m_2)} + \frac{i\omega c}{k}}{1 - \frac{\omega^2 m_2}{k} + \frac{i\omega c}{k}} \right] \qquad (12)$$

This model has one antiresonance and one resonance. At low frequencies, the system impedance approximates the total mass of the system; a high frequencies it approximates the impedance of the drive mass element m_1. The phase angle shifts from +90° through 0° at the antiresonance frequency to -90°, and from -90° through 0° at resonance frequency back to +90°. The height of the peak and the depth of the valley are controlled by the amount of damping. The spring can be approximated for this model by stiffness line going through the inflexion point of the portion of the mechanical impedance curve between the antiresonance and resonance.

A plot of the mechanical impedance of living subhuman primates and an embalmed cadaver head impedance are shown in Figure 17. The values of the model constants are given in Table 12.

Species	W_1 lb	W_2 lb	C $\frac{\text{lb-sec}}{\text{in}}$	K $\frac{\text{lb}}{\text{in}}$	Antiresonance Hz	Resonance Hz
Squirrel	0.05	0.20	0.25	4,000	443	987
Cynomolgous	0.04	0.681	0.94	11,000	430	1500
Rhesus (20 lb)	0.07	1.96	1.70	40,000	530	1700
Chimpanzee	0.08	4.75	2.40	35,000	265	2070
Man	0.40	9.00	2.40	26,000	167	812

TABLE 12. MSC MODEL PARAMETER FOR PRIMATES

In interpreting the model constants, the following considerations apply. The calvarius is divided into approximately four major sections: the frontal bone, left and right parietal bone, and the occipital bone, which in the case of a monkey is almost entirely under the brain. The attachment to the shaker was made through one of the parietal sections. These sections of the skull are connected by sutures which provide isolation from one section to another. This implies that m_1 in the model is approximately the parietal section of the skull. The spring element in the model corresponds for the most part to the skull stiffness. The damping is due mostly to the skin, muscle and brain. (Figure 32)

3.3.1.3 Results of Head Injury Scaling

With this linear two-degree-of-freedom model as a mathematical analogy of the head, many dynamic inputs to the head can be studied. The model

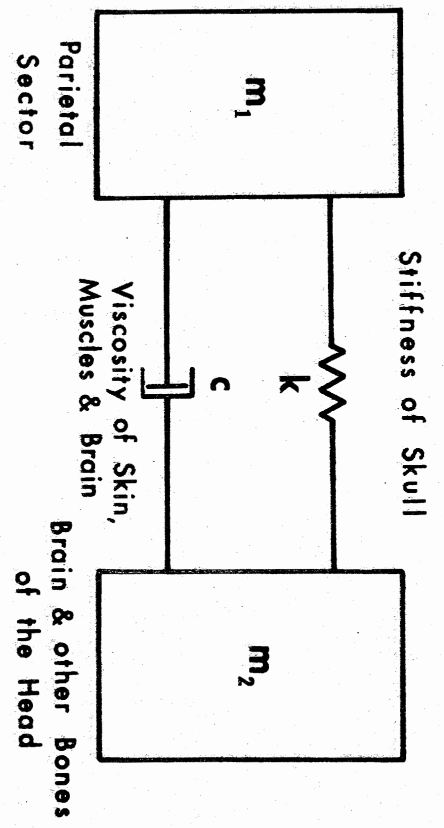


FIGURE 32. MAXIMUM STRAIN CRITERION HEAD MODEL

response can be expressed in terms of the following linear differential equations. (Figure 33)

$$m_1\ddot{x}_1 = c(\dot{x}_2 - \dot{x}_1) + k(x_2 - x_1) \qquad (13)$$

$$m_2\ddot{x}_2 = -c(\dot{x}_2 - \dot{x}_1) - k(x_2 - x_1) \qquad (14)$$

where

$$X = x_2 - x_1 \qquad (15)$$

and

$$x_2 = X + x_1 \qquad (16)$$

thus

$$m_2\ddot{X} + c\dot{X} + kX = -m_2\ddot{x}_1 \qquad (17)$$

Letting

$\ddot{x}_1 = a(t)$ any input acceleration

then

$$\ddot{X} + \frac{c}{m_2}\dot{X} + \frac{k}{m_2}X = -a(t) \qquad (18)$$

Substituting equation (15) into equations (13) and (14) and then substituting equation (14) from equation (13) we finally arrive at

$$\ddot{X} + \left(1 + \frac{m_2}{m_1}\right)\frac{c}{m_2}\dot{X} + \left(1 + \frac{m_2}{m_1}\right)\frac{k}{m_2}X = 0 \qquad (19)$$

The required equations of motion of the model are therefore equation (18) for a forced vibration input and equation (19) for a free vibration. With these two equations and the model constants developed above, the dynamic response of the head model can be studied for a variety of input impulses. The resulting curve is the Maximum Strain Criterion (MSC) for head tolerances in respect to side impacts.

The tolerable acceleration and pulse duration for each species studied were used as the input parameters to the MSC. The extrapolated tolerable acceleration and pulse duration for man were also used as an input parameter to the MSC. The resulting MSC curves (Figure 34) based on this extrapolated point are given for an average acceleration based on a triangular pulse shape with a 1/3 τ rise time. This was the most representative pulse shape for head impact with a flat rigid striker. (See Appendix A)

All the head injury data for each species is plotted on the MSC curve for that species. The ordinate is the average accelerations based on the triangular pulse shape discussed above. (Figures 35 through 38)

It should be noted that the contact time for a head impacted by a large flat rigid striker is given by the minimum point of the MSC curve. For the human this contact time was 7.5 msec.

3.3.2 Body Injury Studies

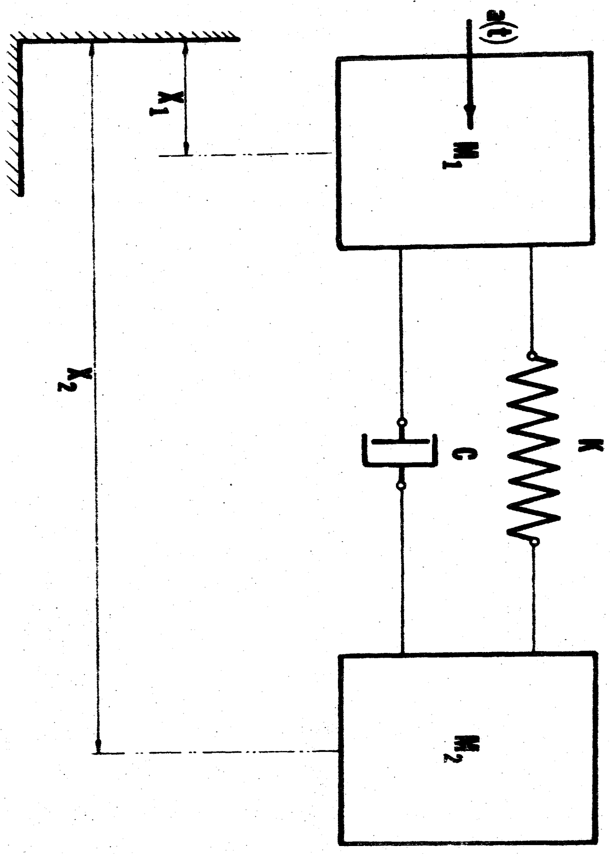
In this series, the injuries were produced in the upper torso area by a blunt wedge shaped impactor resembling an arm rest. [Regions I and II of Figures 22 and 23] The previously discussed computer studies and accident investigations indicated that Region II was the part of the upper torso most likely to be injured in a side impact. The thorax was less frequently involved and the lower abdomen almost never. Additional experiments were performed with a large flat impactor that contacted the animal over the complete torso.

3.3.2.1 Results of Body Injury Studies

The results of the blunt wedge impacts to Region II are summarized in Figure 39 which shows the average peak contact pressure (computed by dividing

FIGURE 33.

REFERENCE SYSTEM for HEAD MODEL



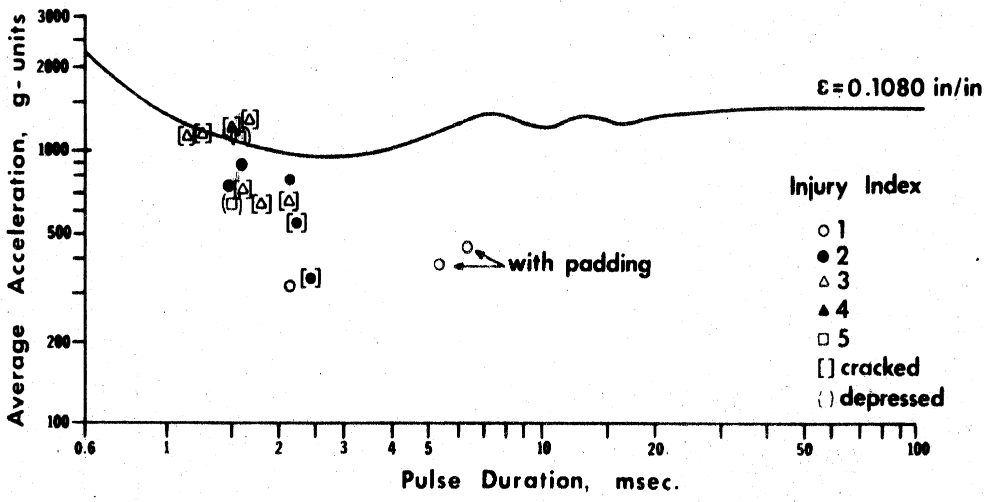


FIGURE 35. MAXIMUM STRAIN CRITERION FOR SQUIRREL MONKEY, SIDE HEAD IMPACTS (TRIANGULAR PULSE)

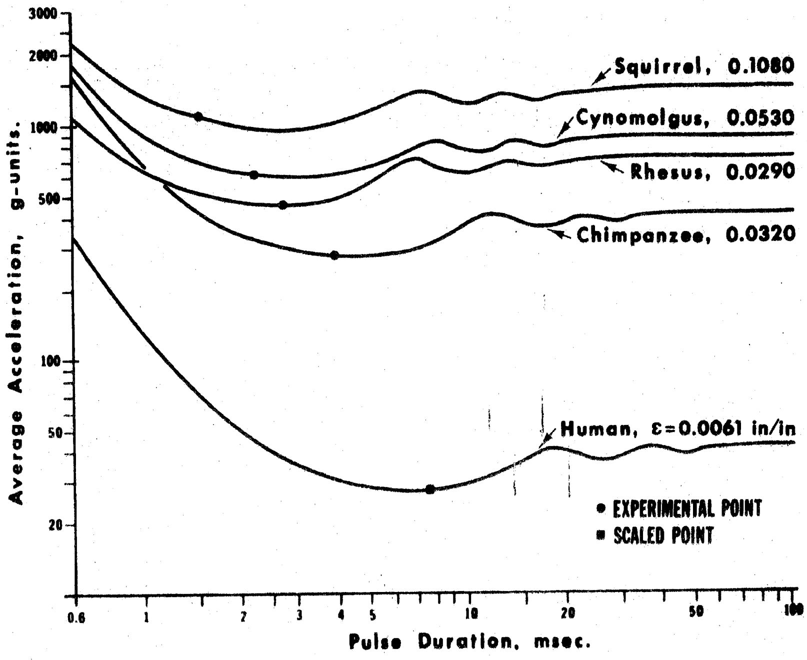


FIGURE 34. MAXIMUM STRAIN CRITERION FOR PRIMATES, SIDE HEAD IMPACTS (TRIANGULAR PULSE)

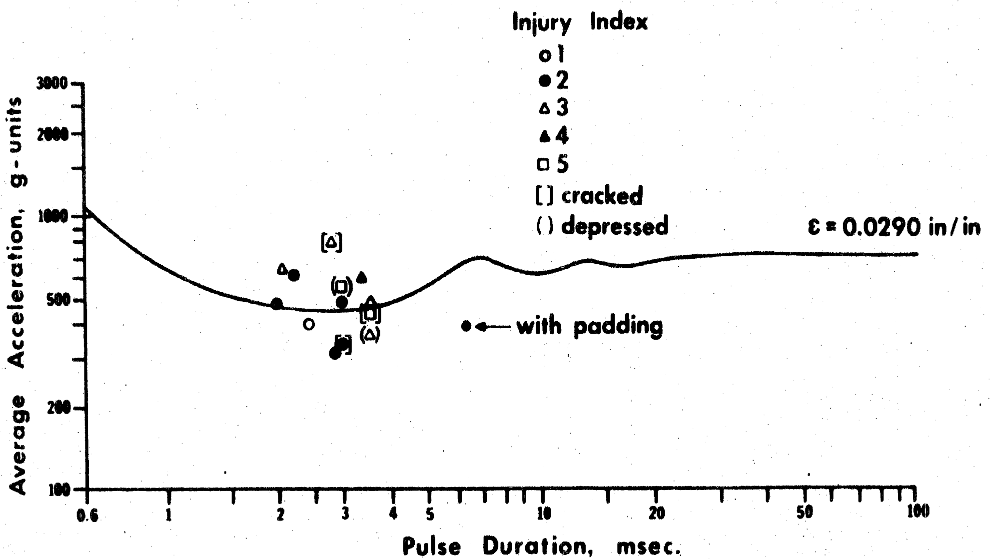


FIGURE 37. MAXIMUM STRAIN CRITERION FOR RHESUS MONKEY, SIDE HEAD IMPACTS (TRIANGULAR PULSE)

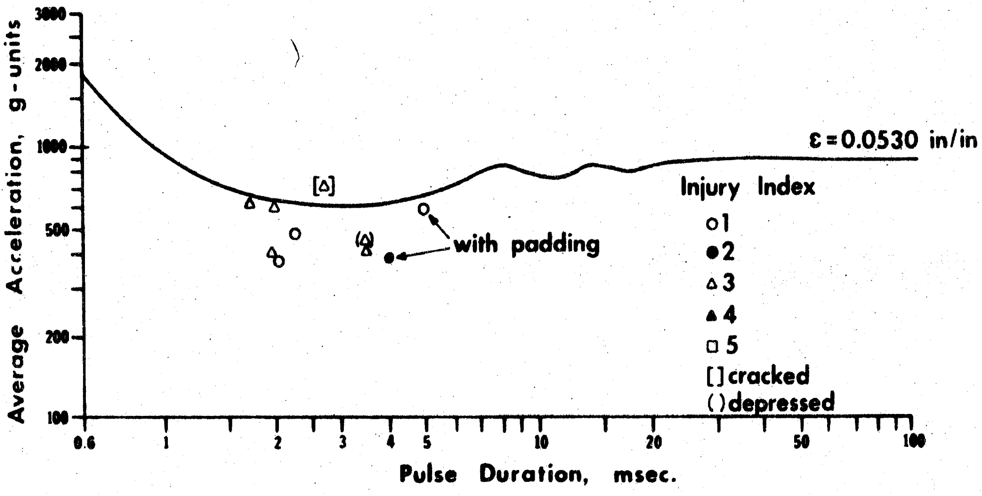


FIGURE 36 MAXIMUM STRAIN CRITERION FOR CYNOMOLGUS MONKEY, SIDE HEAD IMPACTS (TRIANGULAR PULSE)

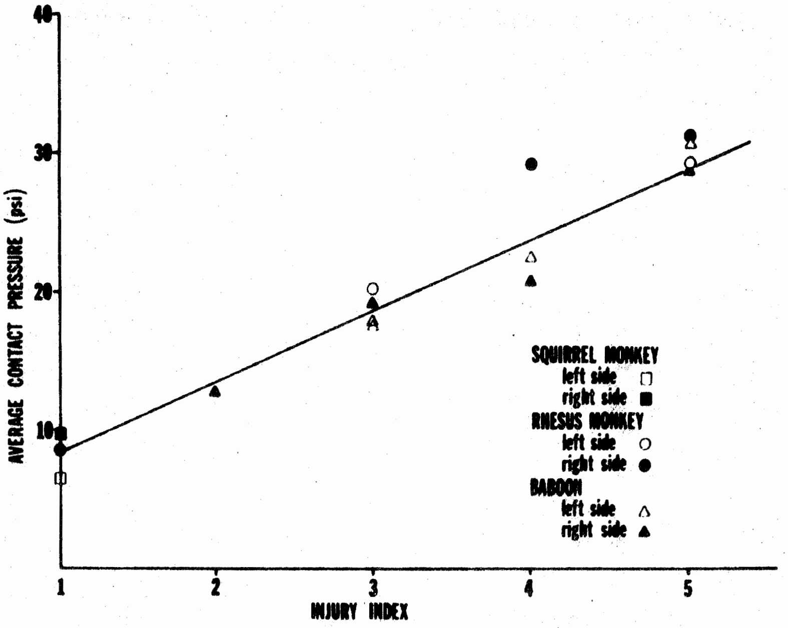


FIGURE 39 PRESSURE vs INJURY INDEX FOR SIDE IMPACTS WITH A SCALED ARMREST TO REGION II

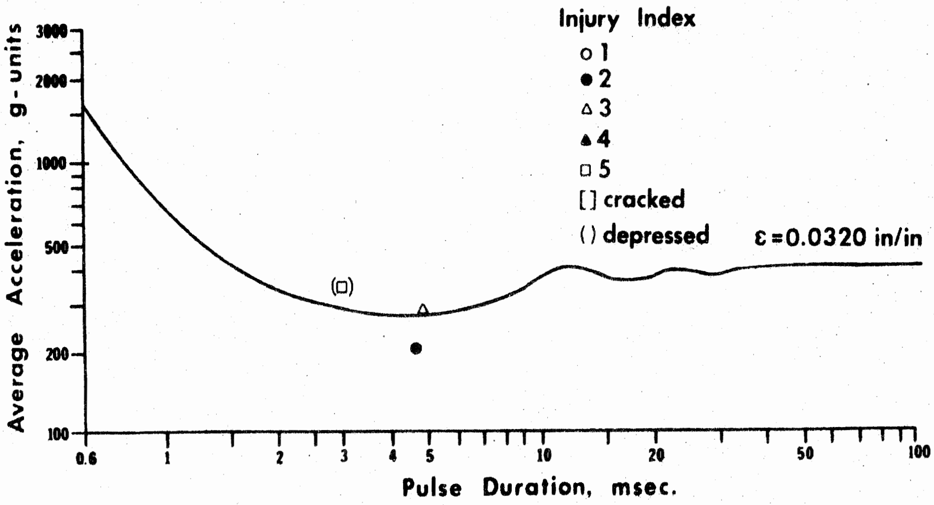


FIGURE 38. MAXIMUM STRAIN CRITERION FOR CHIMPANZEE, SIDE HEAD IMPACTS (TRIANGULAR PULSE)

the peak impactor force by the estimated contact area) versus the injury index. For an injury index of 3 this contact pressure was approximately 19 psi for the rhesus monkey and the baboon. It was the same for both the right and the left side. Figure 40 shows the impact velocity versus injury index for impacts with a scaled arm rest to Region II. A significant difference (approximately 20%) in the tolerable impact velocity were observed for the right and left side of the baboon and rhesus monkey.

The impacts to the other regions of the torso are limited in number and the results cannot be generalized. However, it is clear that pressure tolerance in Region I is higher than in Region II, approximately 27 psi. Whole side body pressure tolerance is, however, much higher than Region II or that of Region III.

3.4 ANIMAL SLED TEST

3.4.1 Introduction

The impacts in section 3.2 were carried out under very idealized laboratory conditions. The location, impacting surface, and velocity of impact were very precisely controlled. Crash simulations on the HSRI Impact Sled were conducted to verify that the injury patterns seen in the controlled impacts were representative of the injuries seen in a less controlled impact environment simulating more closely an actual automobile side collision.

3.4.2 Experimental Setup for HSRI Large Sled

Ten test animals were used for the crash simulations: four baboons; one chimpanzee; three cynomolgus; and, two rhesus. Scaled doors were made for each size animal. These doors were made with a steel rim and a plywood

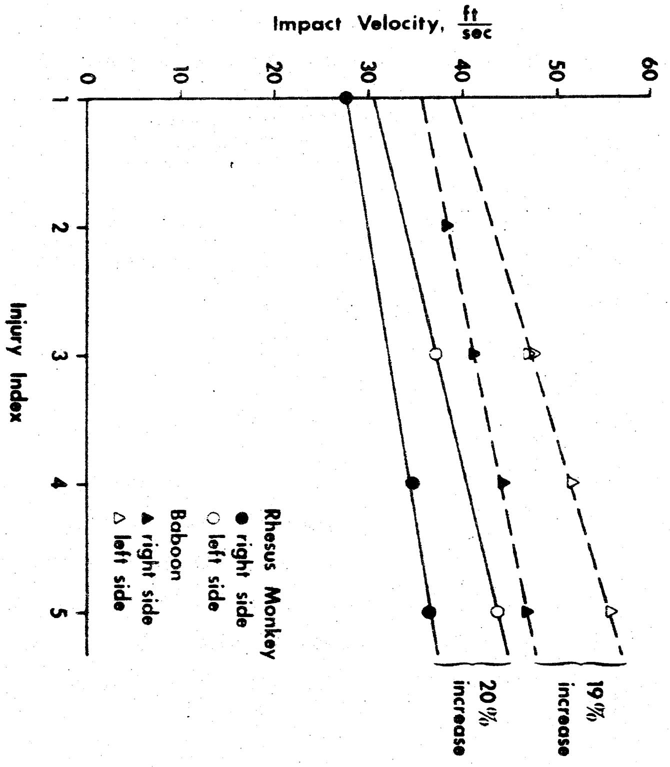


FIGURE 40 VELOCITY vs INJURY INDEX FOR IMPACTS WITH A SCALED ARMREST TO REGION NO. II

center. A scaled tempered glass window was supplied by Pittsburgh Plate & Glass Industries for each door.

The four baboons and one chimpanzee were tested on the HSRI Impact Sled. This sled, driven by a compressed gas operational ram, accelerates slowly. Collision is simulated by an abrupt stop caused by impacting an adjustable hydraulic shock absorber. The pulse shape may be varied from approximately square (rise time less than 10 ms) to a quite long pulse duration depending on speed, contacting surface and shock absorber setting.

The deceleration stroke is up to three feet, the top speed, 40 mph and up to 88 G's deceleration, may be obtained. The sled payload is 1600 pounds.

A complete data acquisition and recording system has been incorporated in the sled design including high speed cameras and a 50,000 watt lighting system. Forces and accelerations are transduced and recorded simultaneously on magnetic tape and a light beam oscillograph. All controls are remotely operated using a safety-interlocked electronic sequencer.

The head accelerations were obtained by the use of a microminiature Columbia Model 612 TX Tri-axial Accelerometer, and three onboard charge amplifiers. The tri-axial accelerometer was placed on the right side of the test animal's head with tape. Great care was taken to obtain good alignment with the x, y, z direction of the accelerometer and the anterior-posterior (A-P) left-right (L-R) and superior-inferior (S-I) directions of the test animals head. (Figure 41)

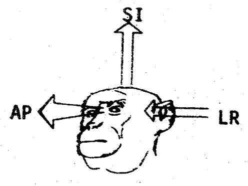


FIGURE 41. HEAD DIRECTION CONVENTIONS
Arrows indicate positive acceleration.

3.4.2.1 Test Results, HSRI Large Sled

Test No. 71-91: Baboon 43 ft/sec sled run with a 15 G's acceleration pulse. In this run the 1/2" thick door and window was not damaged and the baboon suffered only moderate injuries to the liver and pancreas.

Test No. 71-92: Baboon 65 ft/sec sled run with a 53 G's acceleration pulse. In this run the 1/4" thick door was damaged extensively and the window was broken by the baboon's head. The injury was again moderate to the liver and pancreas, this time because the door failed, thus increasing the stopping distance.

Test No. 71-93: Baboon 60 ft/sec sled run with a 32 G's acceleration pulse. In this run a 1/2" thick door with 1/2" of vinyl foam (60 psi at 50% strain) and an arm rest made from a polyethylene foam (132 psi at 50% strain) was used. The door was not damaged and the window broke. Injury was severe to the liver and spleen. This injury was a result of the arm rest. There were no head injuries.

Test No. 71-94: Baboon 59 ft/sec sled run with a 31 G's acceleration pulse. The same door was used with one change, the padding was changed to 3 inches thick and a stiffness of 500 lb/in. The door was not damaged, and the window did not break. The injuries were a bit lower than 71-93, but still severe injury to the liver and lungs. No head injuries were seen.

Test No. 71-95: Baboon 59 ft/sec sled run with a 34 G's acceleration pulse. The same set up as 71-94 but the arm rest was removed. The door was not damaged and the window did not break. The body injuries were moderate to spleen and kidney and pancreas. There was a severe contrecoup head injury. The accelerations to the head were the highest of all the tests.

Test No. 71-96: Chimpanzee 59 ft/sec sled run with a 31 G's acceleration pulse. The same set up as 71-93. The door and window were damaged. The injury was moderate to the spleen and pancreas. No head injury. A typical sled and head acceleration trace is shown in Figure 42, filtered at 250 Hz.

3.4.3 Experimental Set-Up for Small Sled

The smaller monkeys were run on the HSRI small high velocity sled. The transfer piston and impact piston were removed from the air cannon. A single piston with a 5-foot connecting rod was installed. A 25-foot track and a pneumatically operated braking system was used to decelerate the sled. The instrumentation was the same as previously described. This sled is of the reverse acting type, that is, the sled is rapidly accelerated (test phase) and then decelerated slowly. (Figure 43) Three vervet and two rhesus monkeys were used in these tests.

3.4.3.1 Test Results for Small Sled

Test No. 71-103: Vervet 66 ft/sec sled run with a 28 G's acceleration pulse. In the run the door was 1/4" thick with no padding and an arm rest. The animal was not injured. The door broke, not the window.

Test No. 71-104: Vervet 72 ft/sec sled run with a 26 G's acceleration pulse. Same set up as 71-103. Moderate head injury. The door broke, but not the window.

Test No. 71-105: Vervet 70 ft/sec sled run with a 19 G's acceleration pulse. Same set up as 71-104, but modified door mounts to the sled. The injuries were moderate to the lungs, liver and pancreas. No breakage to the door or window.

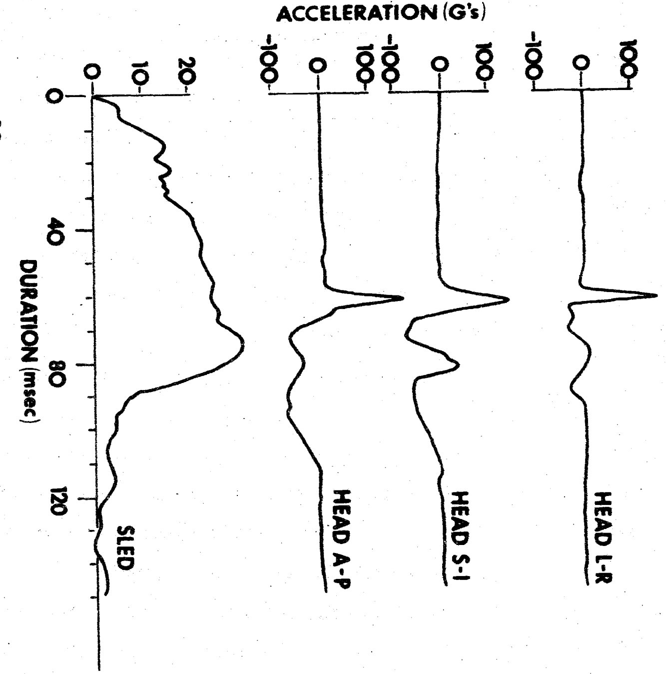
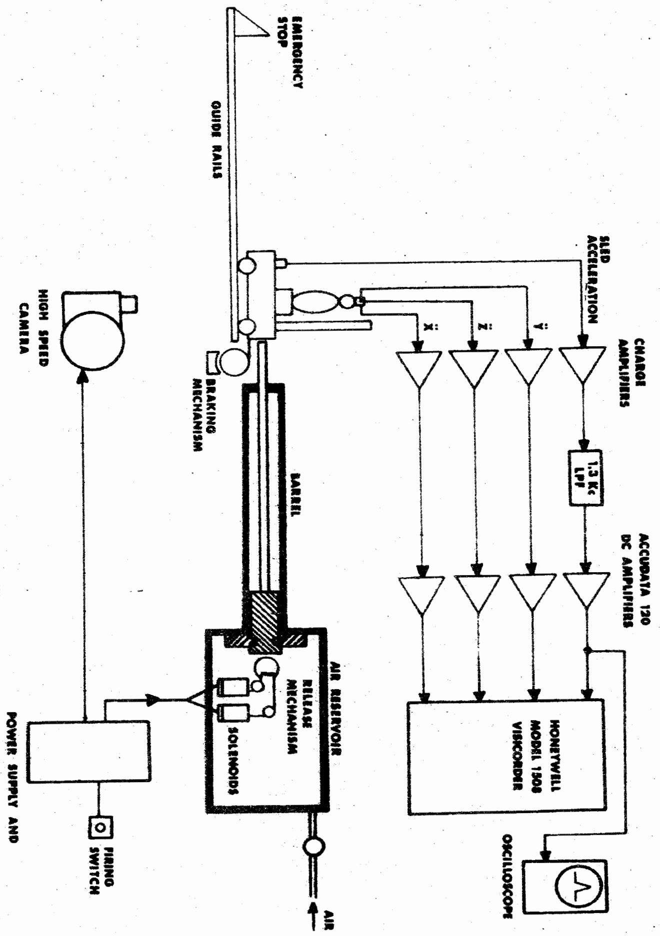


FIGURE 42. SLED TEST: 71-96 CHIMPANZEE



BLOCK DIAGRAM of HIGH ACCELERATION TEST FACILITY

FIGURE 43

Test No. 71-106: Rhesus 67 ft/sec sled run with a 18 G's acceleration pulse. Same set up as 71-104, but bigger door. The door failed, but the window did not break. Moderate injury to the liver and kidney.

Test No. 71-107: Rhesus 65 ft/sec sled run with a 16 G's acceleration pulse. Same set up as 71-105 but door better fastened to the sled. No breakage to door or window. Moderate injury to the liver and pancreas.

The injuries seen on the sled runs were very similar to those seen in the idealized impacts. Liver injuries caused by direct blows from the scaled arm rest impactor were found to be identical to those caused by the test animal impacting the scaled door in the sled test. While pancreatic injuries were seen in most of the sled tests, very few were found in any of the idealized tests, other than the whole body impacts.

Head injuries were found to be minimized by side window glass fracture. If the window did not break, these injuries were found to be more severe. In either case, the injuries were similar to the idealized impacts. The contrecoup injury was observed in the sled test as well as the idealized test.

A summary of all the test results are given in Table 13.

3.5 50TH PERCENTILE MALE DUMMY SIDE DOOR CRASH SIMULATIONS

3.5.1 Introduction

A series of six side impacts were simulated on the HSRI Impact Sled, with six doors representing four makes of automobiles. Two of the runs were with lap belts, while the rest were unbelted.

These tests were conducted to determine the differences, if any, between car doors with guard beams and car doors without guard beams when impacted from the inside by an occupant.

TABLE 13. ANIMAL SIDE DOOR CRASH SIMULATIONS (Cont'd.)

Species & Test Numbers	Door, Padding and Arm Rest	Sled Acceleration G's	Sled Velocity ft/sec	Sled Acceleration Pulse Duration msec	Animal Impact Velocity ft/sec	Head L-R		Head S-I		Head A-P		Door and Window Damage	Injury Index
						Acceleration G's	Duration msec	Acceleration G's	Duration msec	Acceleration G's	Duration msec		
Vervet 71-103	1/4" Door No Padding Arm Rest	*36.7/28	66.6	30/56	15	LOD		LOD		LOD		Window (No) Door (No)	Head 1 Thorax 1 Abdomen 1
Vervet 71-104	1/4" Door No Padding Arm Rest	43/25.9	72.0	28/63	17.9	1260	1.5	174	1.0	-320	2.0	Window (No) Door (No)	Head 2 Thorax 1 Abdomen 1
Vervet 71-105	1/4" Door No Padding Arm Rest	37.7/19.4	70.0	26/60	32.0	560	1.7	625	2.0	-1160	3.0	Window (No) Door (No)	Head 1 Thorax 2 Abdomen 2
Rhesus 71-106	1/4" Door No Padding Arm Rest	32.4/18.4	67.4	32/68	26.6	610	1.7	450	1.0	-600	2.4	Window (No) Door (No)	Head 1 Thorax 1 Abdomen 2
Rhesus 71-107	1/4" Door No Padding Arm Rest	28.5/16.0	65.6	38/68	25.0	610	2.0	-520	4.6	450	2.3	Window (No) Door (No)	Head 1 Thorax 1 Abdomen 2

*Peak/Average

LOD = Loss of Data

TABLE 13. ANIMAL SIDE DOOR CRASH SIMULATIONS

Species & Test Numbers	Door, Padding and Arm Rest	Sled Acceleration G's	Sled Velocity ft/sec	Sled Acceleration Pulse Duration msec	Animal Impact Velocity ft/sec	Head L-R		Head S-I		Head A-P		Door and Window Damage	Injury Index
						Acceleration G's	Duration msec	Acceleration G's	Duration msec	Acceleration G's	Duration msec		
Baboon 71-91	1/2" Door 1/2" Padding Arm Rest	*17.0/15.0	43.4	130	34.8	223	8.0	-86	11	-120	10	Window (No) Door (No)	Head 1 Thorax 1 Abdomen 2
Baboon 71-92	1/4" Door 1/2" Padding Arm Rest	52.6	65.2	77	52.0	150	8.0	110	20	-255	10	Window (Yes) Door (Yes)	Head 1 Thorax 2 Abdomen 2
Baboon 71-93	1/2" Door 1/2" Padding Arm Rest	31.6	59.7	123	48.0	300	7.0	-110	10	-130	6	Window (Yes) Door (No)	Head 1 Thorax 2 Abdomen 4
Baboon 71-94	1/2" Door 3" Padding Arm Rest	30.8	58.8	122	47.4	390	8.0	-230	10	235	10	Window (No) Door (No)	Head 1 Thorax 1 Abdomen 3
Baboon 71-95	1/2" Door 3" Padding Arm Rest	33.5	58.5	122	47.8	128	4.0	-340	6	340	20	Window (No) Door (No)	Head 3 Thorax 1 Abdomen 2
Chimpanzee 71-96	1/2" Door 1/2" Padding Arm Rest	31.4	58.5	122	47.3	153	7.0	135	10	176	10	Window (Yes) Door (Yes)	Head 1 Thorax 1 Abdomen 2

*Peak/Average

The difference between a belted occupant and a non-belted occupant was also explored.

3.5.2 Side Door Crash Simulation Set Up

The HSRI Impact Sled with the supporting data acquisition system was used for these tests. The 50th percentile anthropometric dummy was used in all runs. The following doors were fastened to the sled through the hinges and locking mechanisms:

1. 1962 Oldsmobile
2. 1966 Ford
3. 1970 Chevrolet (with guard beam)
4. 1971 Ford (with guard beam)

a 1966 Ford bucket seat was used for all tests. The sled velocity was 55 ft/sec and an average deceleration of 23 G's was used. Head and chest acceleration in the A-P, S-I and L-R directions were recorded and analyzed for each test.

3.5.3 Results of Side Door Crash Simulation Studies

Table 14 summarizes the results of this series of tests. In all cases the head struck the door window and shattered it. In the unbelted tests the dummy was partially ejected through the door. All doors tested were from hardtop convertible models with the window glass relatively unsupported. Significantly higher head and chest accelerations were observed for the doors with the reinforcing guard rail.

The doors were badly deformed by the dummy impacts with maximum extrusion distances of up to 10 inches. Table 15 summarizes the extrusion of these doors compared with the door length.

TABLE 14. 50th PERCENTILE MALE DUMMY SIDE DOOR CRASH SIMULATIONS

Test No.	Type of Restraint	Type of Door	Sled Acceleration G's	Sled Velocity ft/sec	Sled Acceleration Pulse Duration msec	Dummy Impact Velocity ft/sec	Head L-R		Head S-I		Head A-P		Chest L-R		Chest S-I		Chest A-P	
							Accel-eration G's	Dura-tion msec	Accel-eration G's	Dura-tion msec	Accel-eration G's	Dura-tion msec	Accel-eration G's	Dura-tion msec	Accel-eration G's	Dura-tion msec	Accel-eration G's	Dura-tion msec
71-97	No Belt	1966 Ford	22.3	55.7	90	47.1	35	23	0	0	-14	40	28	20	6	10	0	0
71-100	Belt	1966 Ford	23.0	54.3	93	47.7	48	29	-18	10	-24	60	23	20	-11	7	-5	10
71-98	No Belt	1962 Olds	22.4	55.6	90	47.7	32	23	-37	10	-20	45	67	20	-15	20	-7	8
71-101	Belt	1962 Olds	22.6	55.1	90	48.0	32	24	-12	11	-24	35	82	10	+19	10	-16	12
71-99	No Belt	1971 Ford	22.5	55.0	86	47.5	38	20	-12	6	-15	50	33	20	-10	4	11	8
			Dummy Impact With Door Guard Rail				65	30	-46	60	0	0	105	20	0	0	-16	8
71-102	No Belt	1970 Chevy	23.0	54.5	100	47.6	12	20	-18	11	-18	14	39	40	-12	20	-7	6
			Dummy Impact With Door Guard Rail				40	20	-63	7	30	10	81	20	-34	25	-26	10

All accelerations given are peak values

Type	Extrusion Inches	Door Length Inches
Rignt 1962 Oldsmobile	7.75	38.25
Left 1962 Oldsmobile	6.75	38.25
Right 1966 Ford	10.00	49.5
Left 1966 Ford	9.50	49.5
Right 1970 Chevrolet	8.25	50.25
Left 1971 Ford	8.75	55.5

TABLE 15. DOOR TYPES AND EXTRUSION DISTANCES

Figure 44 shows a typical sled test setup with the dummy and door geometry. Figure 45 shows the typical deformation that occurred when the dummy impacted the door. Figure 46 is a photograph of a side impact accident with the following details.

At 8:30 a.m. on Monday, August 19, 1968, a 1968 Pontiac Catalina two-door hardtop, driven by a 52-year-old male (5 feet 8 inches, 170 pounds), was traveling east on a two-lane paved roadway at a police-estimated speed of 45 mph. The vehicle went off the south side of the road; the right side of the Pontiac scraped against a tree. The vehicle then spun around and struck a second tree 80 feet down the road at the left front wheel well. At this time, the driver was ejected through the left front door window. The car, without the driver, went on down the roadway coming to rest 26 feet beyond the second tree. The left door of the Pontiac was severely deformed outward from driver impact.

The driver had back pain, mild concussion, chest pain, slight abrasions on his left side, abrasions of the left foot, open fracture left shin.

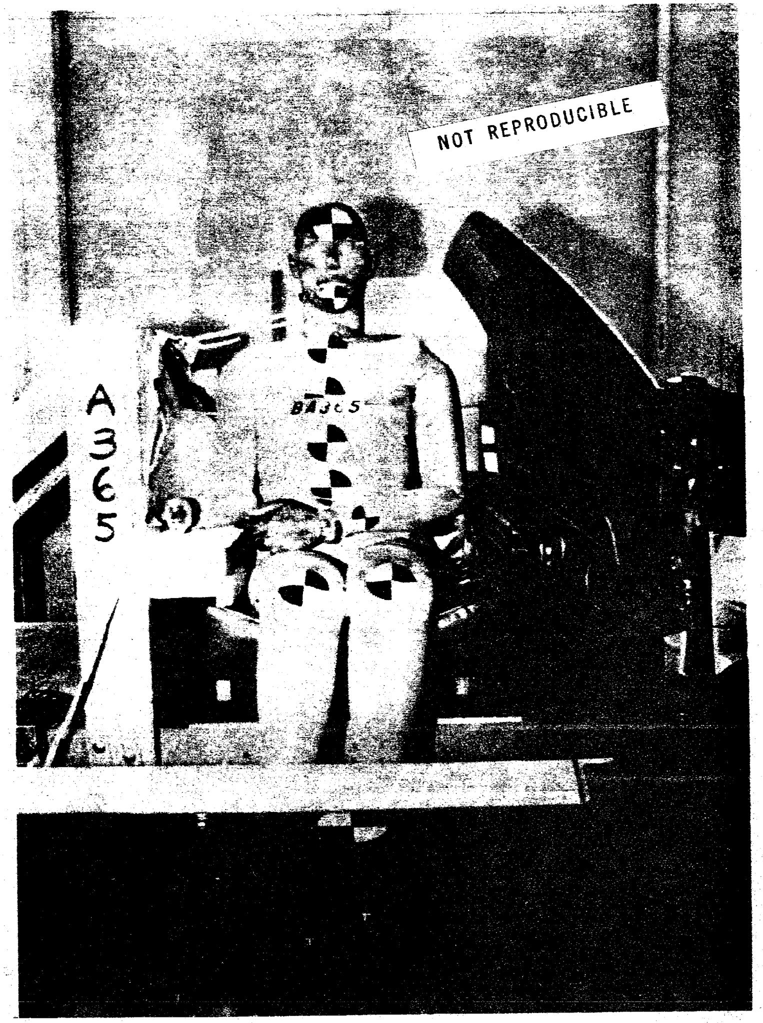


FIGURE 44. TYPICAL TEST SET-UP FOR SIDE CRASH SIMULATION

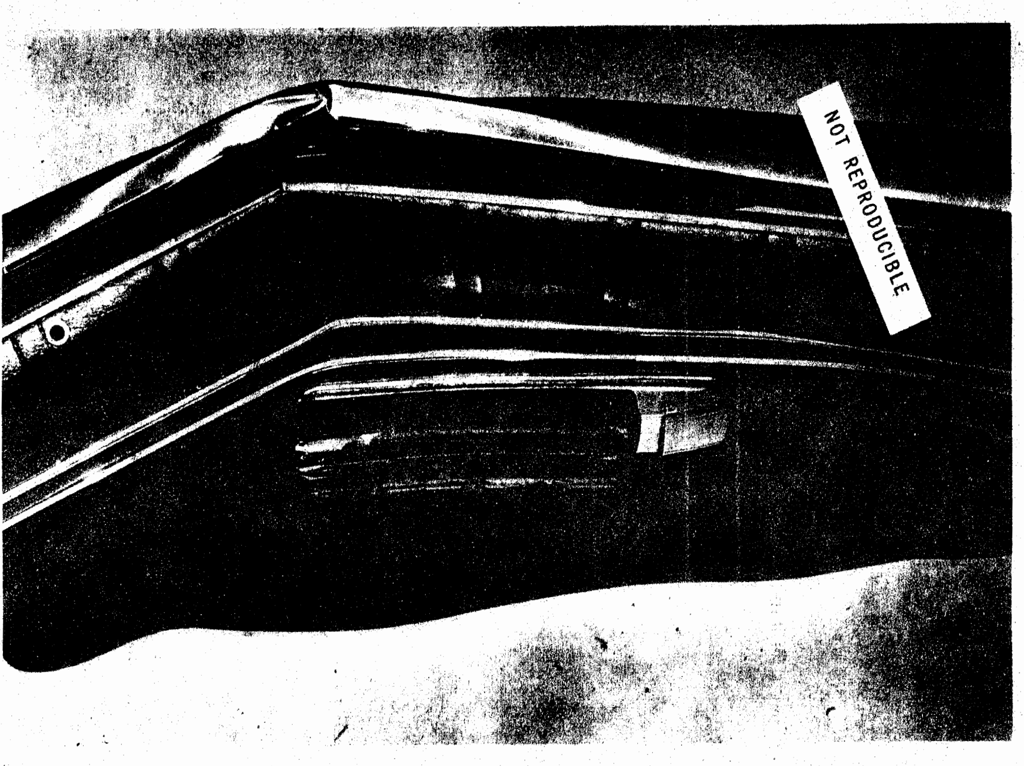


FIGURE 45 1971 FORD DOOR AFTER TEST #71-105

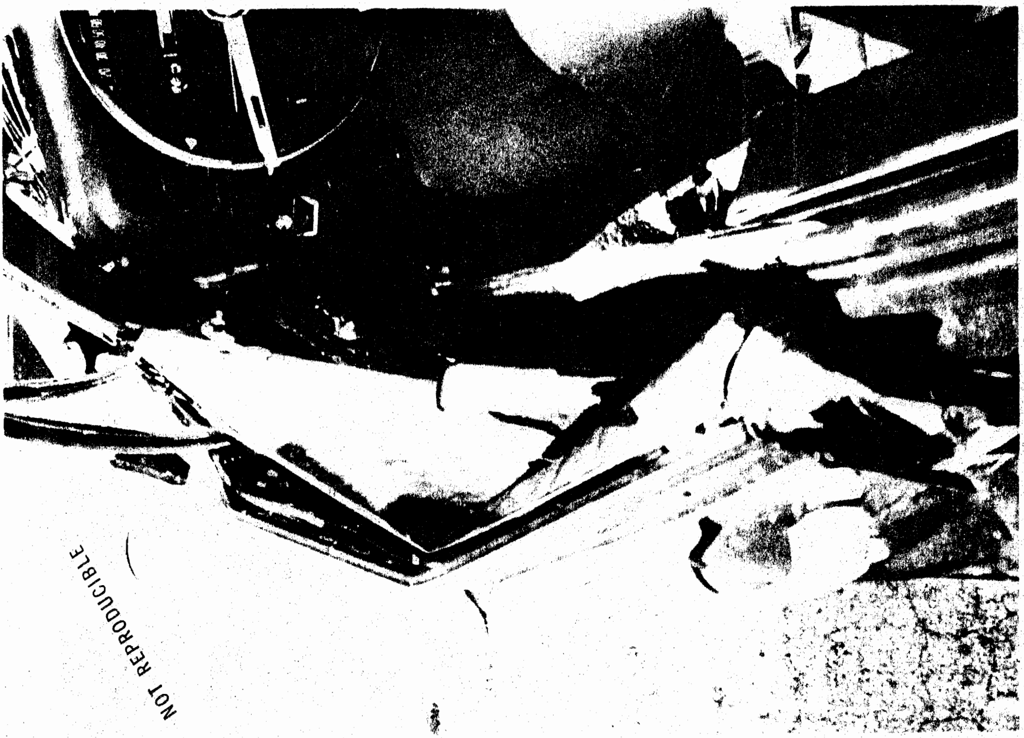


FIGURE 46. 1968 PONTIAC ACCIDENT,
Case UM-113-68

4. DISCUSSION AND CONCLUSIONS

A study of door crashworthiness criteria has been made utilizing elements of computer modeling, controlled animal experiments and sled simulations with animals and dummies. A selected group of real accidents were investigated for comparison with the results of these studies.

The results of the computer modeling indicate the most probable causes of injury are head impacts with the header, window and door posts. Additionally, injuries in the mid-abdominal region occur upon impact with the arm rest. The limited number of accidents investigated in this study support these conclusions. Unbelted occupants run a high risk of being ejected through the window during a side impact.

A head injury tolerance model (MSC) has been developed that allows the computation of injury for variable acceleration and force pulses to the side of the head. Utilizing the 3-D kinematic model of the vehicle occupant to predict the velocity and altitude of the head at impact and the characteristics of that portion of the car that the head impacts, the MSC model can be used to estimate injury. Optimization studies can now be performed to establish the best padding arrangement to provide head protection in side impact.

A tolerable pressure of 19 psi has been estimated for the mid-abdominal region when impacted in the side by an arm rest-like striker. Abdominal injury patterns were similar when the autopsy results of the accident investigators, controlled animal impacts and animal sled tests are compared.

It must be recognized that autopsy findings related to an injury scale require careful and skillful interpretation. In this study a major emphasis was placed on the autopsy and injury evaluation.

5. RECOMMENDATIONS

1. Additional stiffening of the side structure to reduce intrusion.
2. Significantly heavier padding on the door, header and posts.
3. Removal or recessing of the arm rest and door and window levers.
4. Use of the 3-D kinematic model and the MSC head injury model to evaluate the injury reduction potential of new designs.

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APPENDIX A

SUMMARY DATA SHEETS

DOOR CRASHWORTHINESS CRITERIA
Contract FH-11-7288

SUMMARY SHEET

1.	Run Number		70-14	
2.	Animal, Species and Sex		Squirrel Monkey, Male	
3.	Area and Type of Impact		Right side head, no pad	
4.	Impact Velocity		24.4	mph
5.	Animal Total Body Weight		1.76	lbs.
6.	Animal Head Weight		.175	lbs.
7.	Animal Brain Weight		.0762	lbs.
8.	Animal Skull Dimension*	w	1.26	inches
		l	2.02	inches
		h	.041	inches
		a	.82	inches
		h/a	.0500	
9.	Impact Duration		1.6	msec.
10.	Peak Contact Force		375.	lbs.
11.	Head Acceleration (F=MA)		2140.	g's
12.	Maximum Head Acceleration (Vector sum $\ddot{x}$ and $\ddot{y}$ from Vanguard)		1260.	g's
13.	Maximum Head Velocity (Vector sum $\dot{x}$ and $\dot{y}$ from Vanguard)		34.5	mph
14.	Maximum Angular Head Acceleration		225,000.	$\frac{rad}{sec^2}$
15.	Maximum Angular Head Velocity		255.	$\frac{rad}{sec}$
16.	Impulse		.360	lb-sec.
17.	Camera Framing Speed		10,600.	Frames/sec.
18.	Blow-up Factor		1.45	in/Van.in.
19.	Quality of Movie		Good	

20. Animal Arrival: July 30, 1970 Impact: July 30, 1970
Termination: August 5, 1970 Dates

21. Evidence of Injury Post-Impact: Possible skull fracture near right parietal area. Whole body tremor noted.

SUMMARY SHEET (Cont'd.)
Page 2

22. Loss of Consciousness unconscious <5 min.

23. Heart-Beat Rate Pre-Impact 130 beats/min.

Post-Impact 140 beats/min.

24. Respiratory Rate Pre-Impact (slightly erratic) 44 breaths/min.

Post-Impact (very erratic) 32 breaths/min.

25. Reflex State (pupillary, eyelid, ear pinch, etc.)

Pre-Impact present and normal

Post-Impact returned after 5 min. - normal

26. Behavior Pre-Impact appears normal and healty

Post-Impact cannot be determined immed.
appears normal & healthy next day

27. Anesthetic Used Ketamine (I.P.) & Na Pento Amount 52.7 and 12.5 mg/kg

Approx. Time Last Injection Given 2:45

Approx. Time Impact 3:15

Condition of Animal Prior-Pento active/hallucinatory
Post-Limp

28. X-Rays Pre-Impact None

Post-Impact yes; taken (1 day after impact)

29. Blood Samples: Does not apply

	Pre					
SGOT						Int. Units
SGPT						Int. Units
LDH						Int. Units
AlKP'tase						Int. Units
CPK						Int. Units

30. Skull Cleaned and Stored yes - saved and cleaned

31. EKG Pre-Impact yes - saved and marked

Post-Impact yes - saved and marked

SUMMARY SHEET (Cont'd.)
Page 3

32. Autopsy Comments: Fracture right parietal bone (2 places). Some hemorrhages in muscle and slight congestion in brain. Occipitals fractured.

Autopsied 6 days post impact.

Histopathology: Brain: acute passive congestion. Focal small subarachnoid hemorrhage over cerebellum at 4th ventricle level. Perivascular small hemorrhages in cerebrum. No other tissues analyzed.

33. Scaling Index Number 2

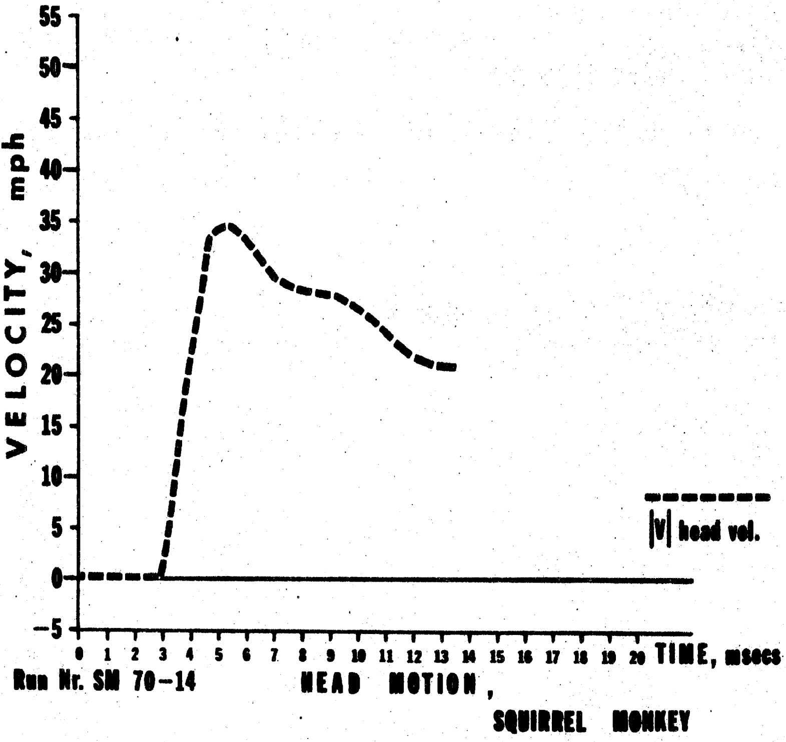


FIGURE A-2. RESULTANT OF LINEAR VELOCITIES

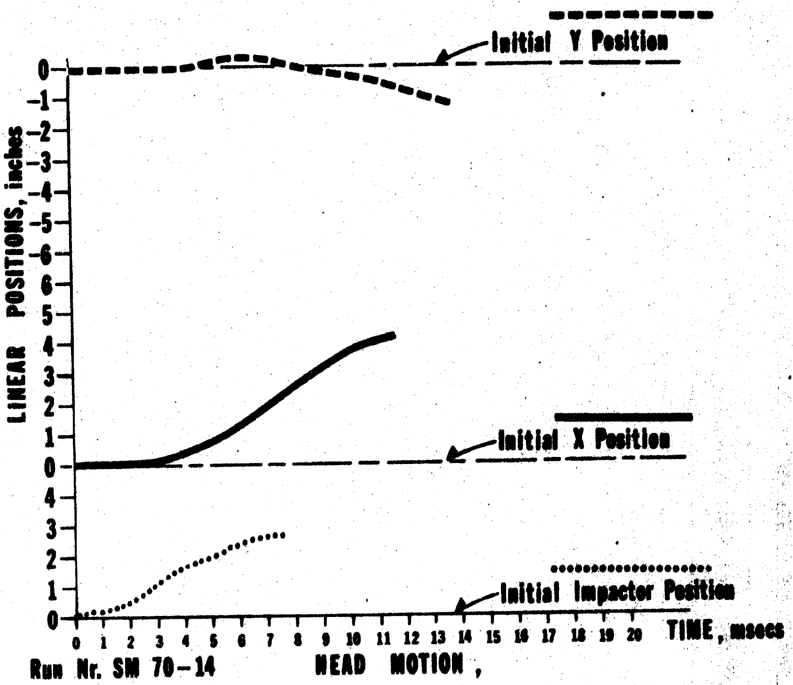


FIGURE A-1

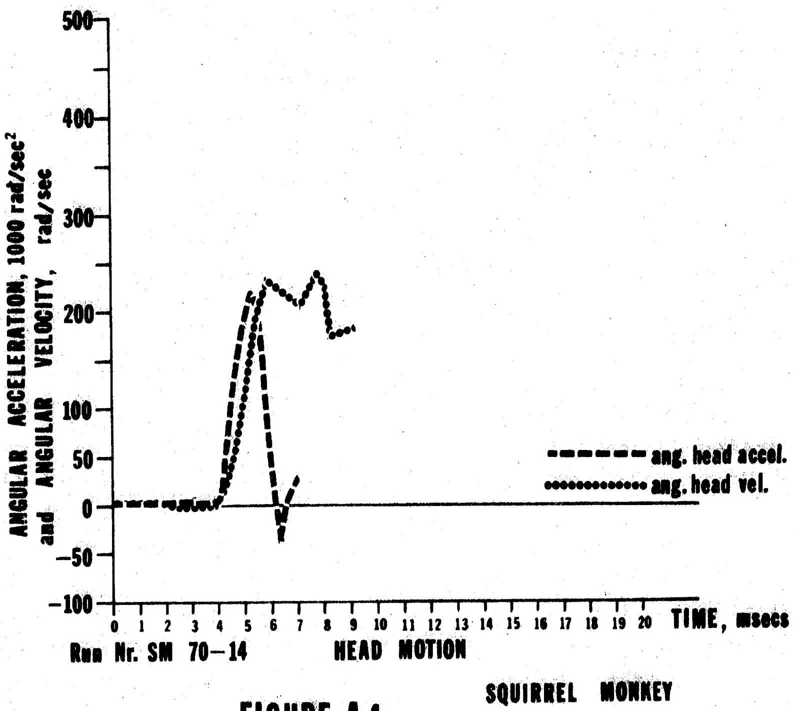


FIGURE A-4

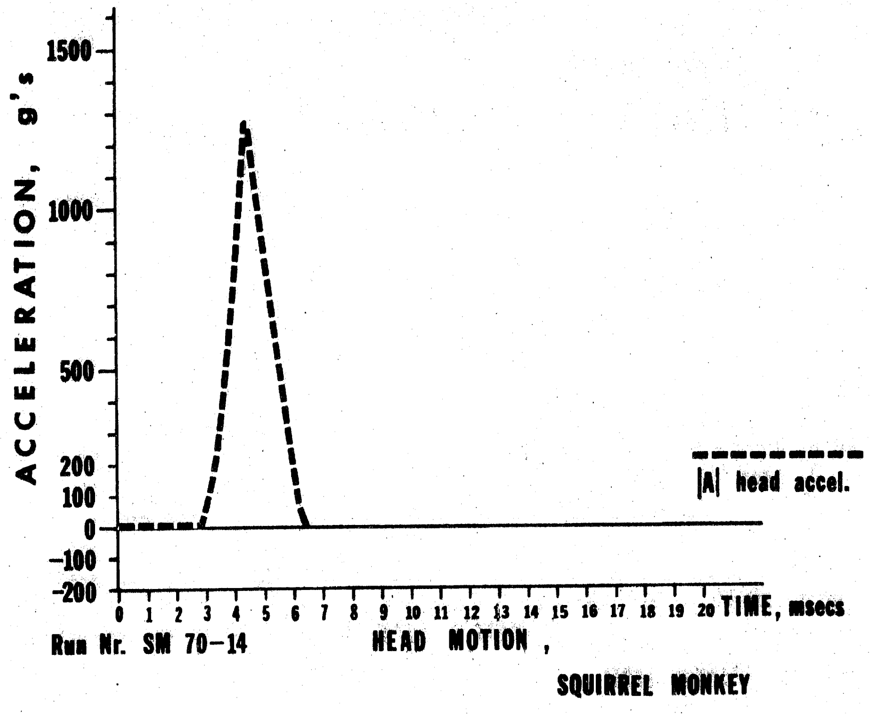


FIGURE A-3. RESULTANT LINEAR ACCELERATION

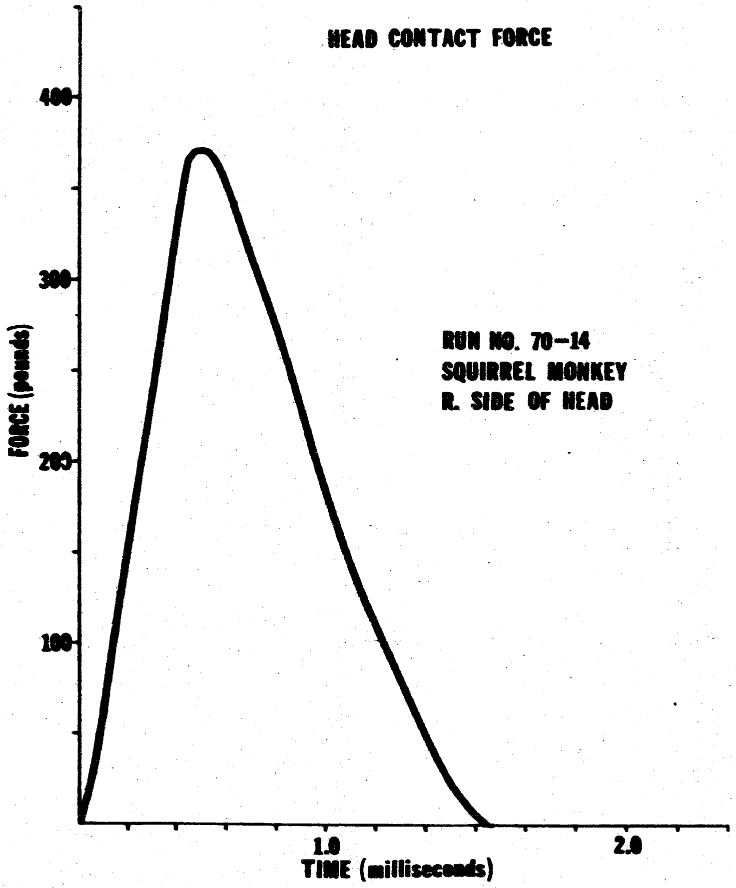


FIGURE A-5

DOOR CRASHWORTHINESS CRITERIA
Contract FH-11-7288

SUMMARY SHEET

1. Run Number 70-58
2. Animal, Species and Sex Cynamolgus Monkey, Male
3. Area and Type of Impact Left side head, no pad
4. Impact Velocity 23.0 mph
5. Animal Total Body Weight 6.05 lbs.
6. Animal Head Weight .731 lbs.
7. Animal Brain Weight .122 lbs.
8. Animal Skull Dimension* w 1.95 inches
l 2.78 inches
h .065 inches
a 1.18 inches
h/a .055
9. Impact Duration 1.7 msec.
10. Peak Contact Force 800. lbs.
11. Head Acceleration (F=MA) 1090. g's
12. Maximum Head Acceleration (Vector sum $\ddot{x}$ and $\ddot{y}$ from Vanguard) 1220. g's
13. Maximum Head Velocity (Vector sum $\dot{x}$ and $\dot{y}$ from Vanguard) 35.0 mph
14. Maximum Angular Head Acceleration 95,000. $\frac{rad}{sec^2}$
15. Maximum Angular Head Velocity 184. $\frac{rad}{sec}$
16. Impulse .985 lb-sec.
17. Camera Framing Speed 5550. Frames/sec.
18. Blow-up Factor 2.2 in/Van. in.
19. Quality of Movie Good
20. Animal Arrival: October 16, 1970 Impact: October 16, 1970
Termination: October 19, 1970 Dates
21. Evidence of Injury Post-Impact: Zygomatic arch fractured left side head. No other obvious injury.

SUMMARY SHEET (Cont'd.)
Page 2

22. Loss of Consciousness stunned ~ 3 min.
23. Heart-Beat Rate Pre-Impact 137 beats/min.
Post-Impact 167 beats/min.
24. Respiratory Rate Pre-Impact 32 breaths/min.
Post-Impact 44 breaths/min.
25. Reflex State (pupillary, eyelid, ear pinch, etc.)
Pre-Impact all normal
Post-Impact not recorded
26. Behavior Pre-Impact appeared normal and healthy
Post-Impact never fully regained from drug
27. Anesthetic Used Ketamine (I.M.) Amount not record. mg/kg
Approx. Time Last Injection Given 9:00
Approx. Time Impact 11:00
Condition of Animal deep-moderate
28. X-Rays Pre-Impact none
Post-Impact none
29. Blood Samples: Does not apply.

	Pre	Post	1 day	2 days	Other	
SGOT						Int. Units
SGPT						Int. Units
LDH						Int. Units
AIKP'tase						Int. Units
CPK						Int. Units

30. Skull Cleaned and Stored yes
31. EKG Pre-Impact yes
Post-Impact yes

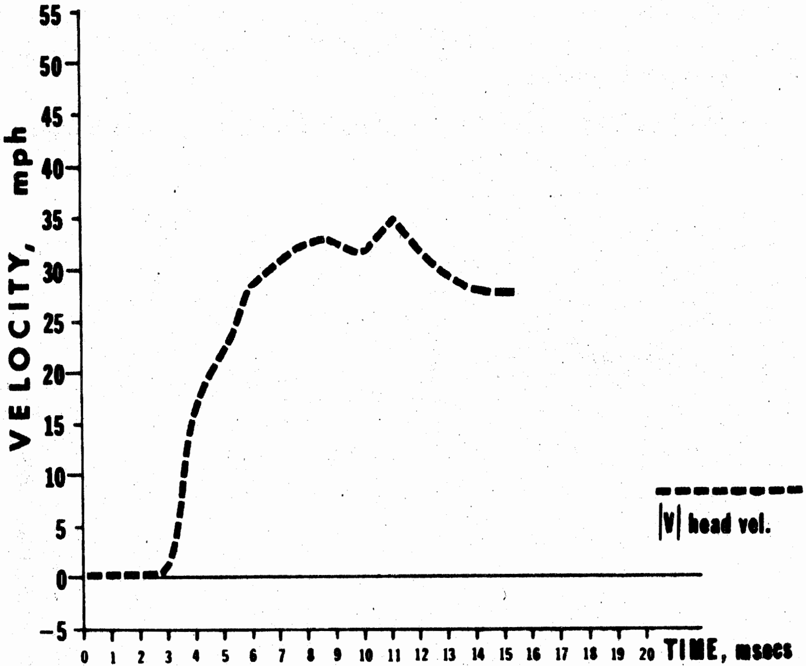
SUMMARY SHEET (Cont'd.)
Page 3

32. Autopsy Comments: Multiple fractures left zygoma. Hematoma left temporalis muscle. Moderate congestion epidural and on brain. Contrecoup - hematoma right side brain.

Autopsied same day as impact.

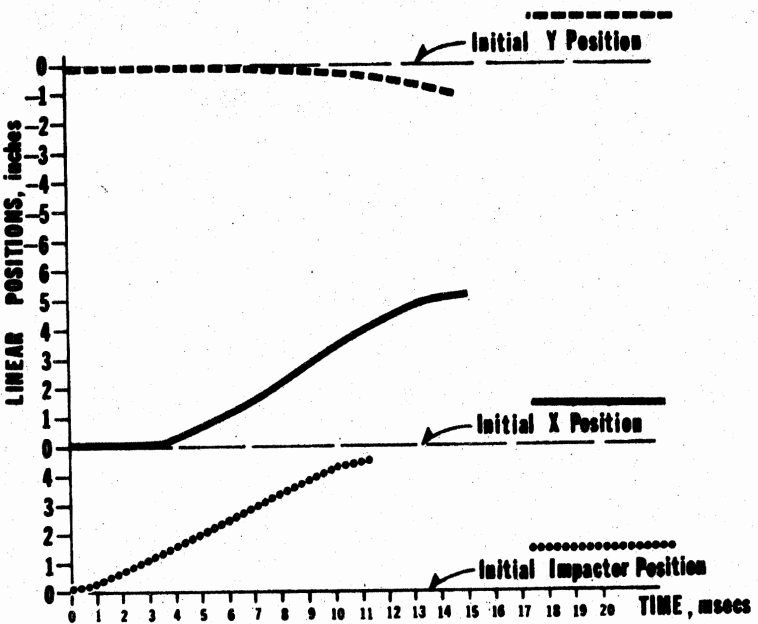
Histopathology: Brain: focus of destruction of cortex with hemorrhage in one section. Retro-peritoneal L. N. - sinus histocytosis. Lung: mild acute passive congestion. All else appears normal.

33. Scaling Index Number 3



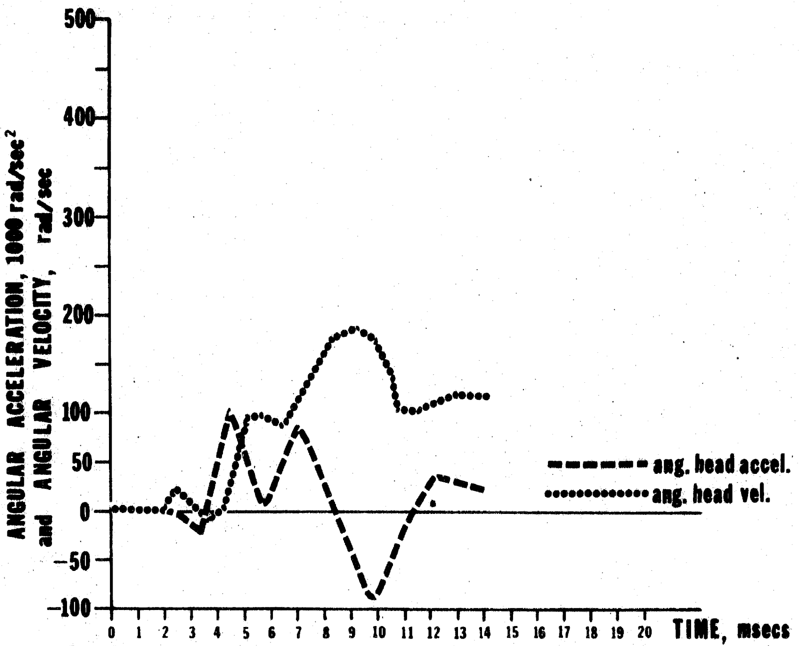
Run Nr. CY 70−58 HEAD MOTION, CYNAMOLGUS MONKEY

FIGURE A-7. RESULTANT OF LINEAR VELOCITIES



Run Nr. CY 70−58 HEAD MOTION, CYNAMOLGUS MONKEY

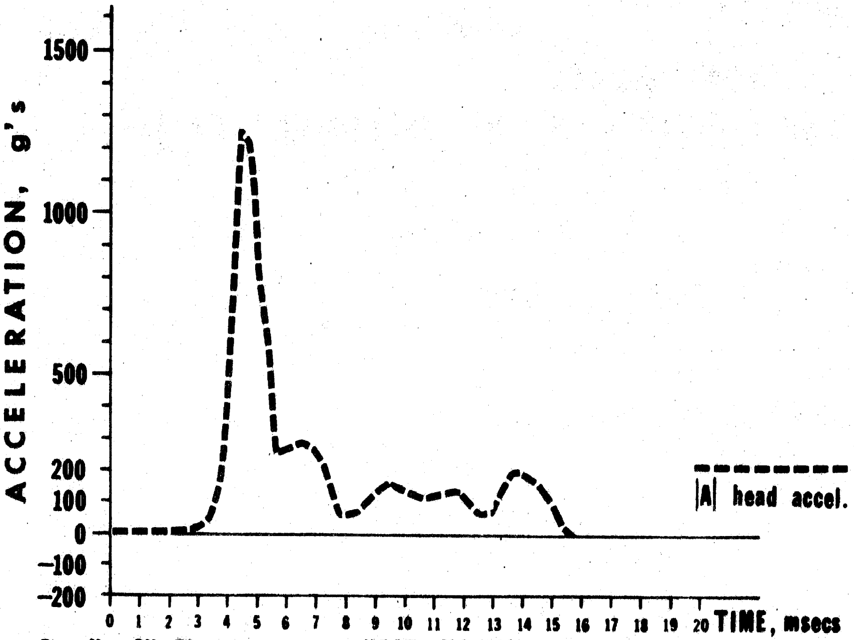
FIGURE A-6



Run Nr. CY 70–58 HEAD MOTION,

CYNAMOLGUS MONKEY

FIGURE A-9



Run Nr. CY 70–58 HEAD MOTION,

CYNAMOLGUS MONKEY

FIGURE A-8. RESULTANT LINEAR ACCELERAIION

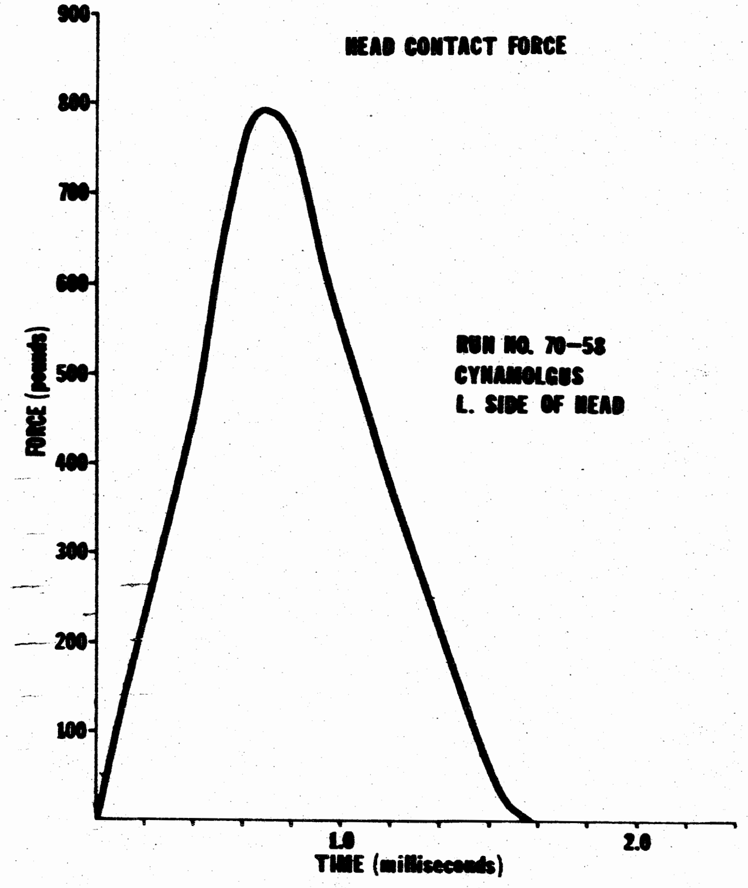


FIGURE A-10

DOOR CRASHWORTHINESS CRITERIA
Contract FH-11-7288

SUMMARY SHEET

1. Run Number 70-22
2. Animal, Species and Sex Rhesus Monkey, Male
3. Area and Type of Impact Left side head, no pad
4. Impact Velocity 33.4 mph
5. Animal Total Body Weight 21.6 lbs.
6. Animal Head Weight 2.10 lbs.
7. Animal Brain Weight .243 lbs.
8. Animal Skull Dimension*
   w 2.30 inches
   l 3.72 inches
   h .135 inches
   a 1.50 inches
   h/a .090
9. Impact Duration 3.5 msec.
10. Peak Contact Force 2,050. lbs.
11. Head Acceleration (F=MA) 975. g's
12. Maximum Head Acceleration (Vector sum $\ddot{x}$ and $\ddot{y}$ from Vanguard) 940. g's
13. Maximum Head Velocity (Vector sum $\dot{x}$ and $\dot{y}$ from Vanguard) 38. mph
14. Maximum Angular Head Acceleration 75,000. $\frac{rad}{sec^2}$
15. Maximum Angular Head Velocity 179. $\frac{rad}{sec}$
16. Impulse 3.25 lb-sec.
17. Camera Framing Speed 10,400. Frames/sec.
18. Blow-up Factor 2.13 in/Van.in.
19. Quality of Movie Good
20. Animal Arrival: August 13, 1970 Impact: August 13, 1970
    Termination: August 19, 1970 Dates
21. Evidence of Injury Post-Impact: Compound fracture in cheek area, deep laceration in left cheek and large amounts of blood spouting. Abrasions left side of face.

SUMMARY SHEET (Cont'd.)
Page 2

22. Loss of Consciousness mildly unconscious <5 min.

23. Heart-Beat Rate Pre-Impact 125 beats/min.
Post-Impact 115 beats/min.

24. Respiratory Rate Pre-Impact (fairly regular) 23 breaths/min.
Post-Impact (fairly regular) 24 breaths/min.

25. Reflex State (pupillary, eyelid, ear pinch, etc.)
Pre-Impact normal eye reflexes
Post-Impact return ~ few min. normal

26. Behavior Pre-Impact appears normal and healthy

Post-Impact approx. 2 hrs. post-impact awake and responsive wound still part open

27. Anesthetic Used Ketamine (IM) Amount 25.5 mg/kg
Approx. Time Last Injective Given 2:30 note:lac. sutured and Vicillin shot given post-impact
Approx. Time Impact 2:45
Condition of Animal Quite active and mobile

28. X-Rays Pre-Impact none
Post-Impact yes; 4 days post-impact

29. Blood Samples: Not taken.

	Pre	Post	1 day	2 days	Other	
SGOT						Int. Units
SGPT						Int. Units
LDH						Int. Units
AIKP'tase						Int. Units
CPK						Int. Units

30. Skull Cleaned and Stored yes - saved and cleaned

31. EKG Pre-Impact yes
Post-Impact yes

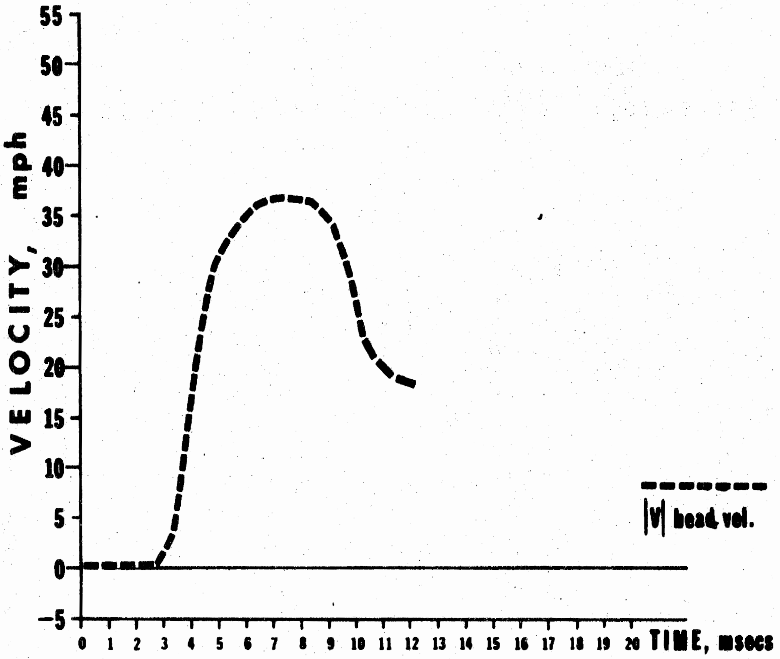
SUMMARY SHEET (Cont'd.)
Page 3

32. Autopsy Comments: Fracture both zygomatic arches. Fracture clavicle. Massive hematoma all over left side head, temporalis muscle, etc. Brain appears normal.

Autopsied 6 days post impact.

Histopathology: Lungs: right side congested and edema due to lung mite, also lung left side. Spleen: congested. Liver: congested. Brain: cerebral cortex satellitosis of glial cells around neurons and white matter. Prominent vacuolar change in brain parenchyma. Also in spinal cord. Cerebellum: vacuolar change restricted to white matter.

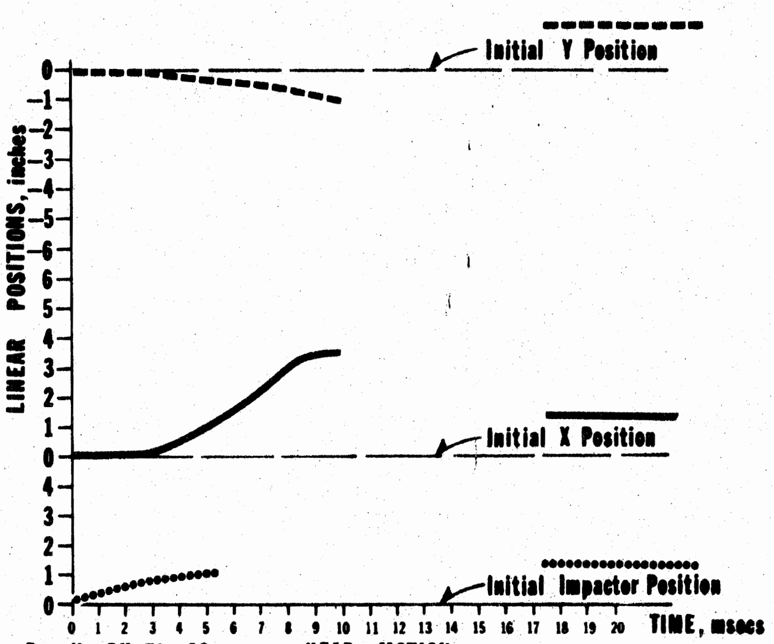
33. Scaling Index Number 3



Run Nr. RH 70-22 HEAD MOTION,

RHESUS MONKEY

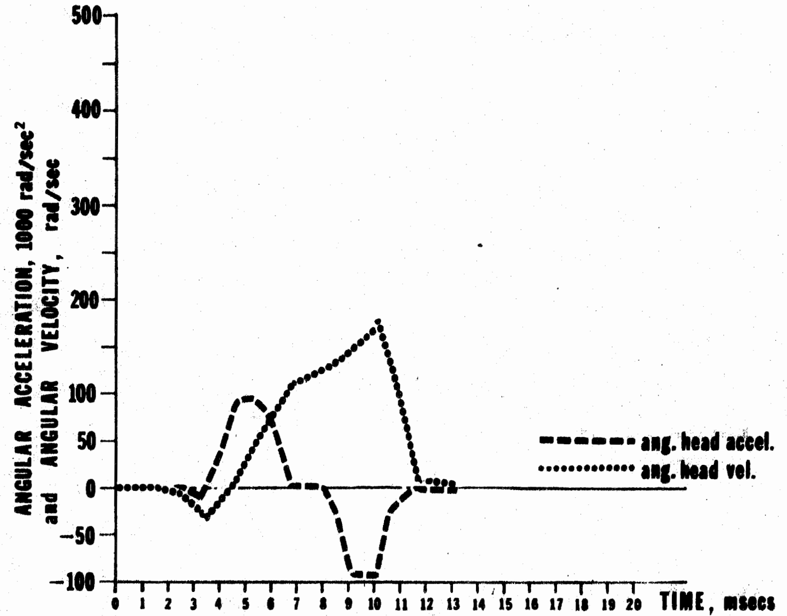
FIGURE A-12. RESULTANT OF LINEAR VELOCITIES



Run Nr. RH 70-22 HEAD MOTION,

RHESUS MONKEY

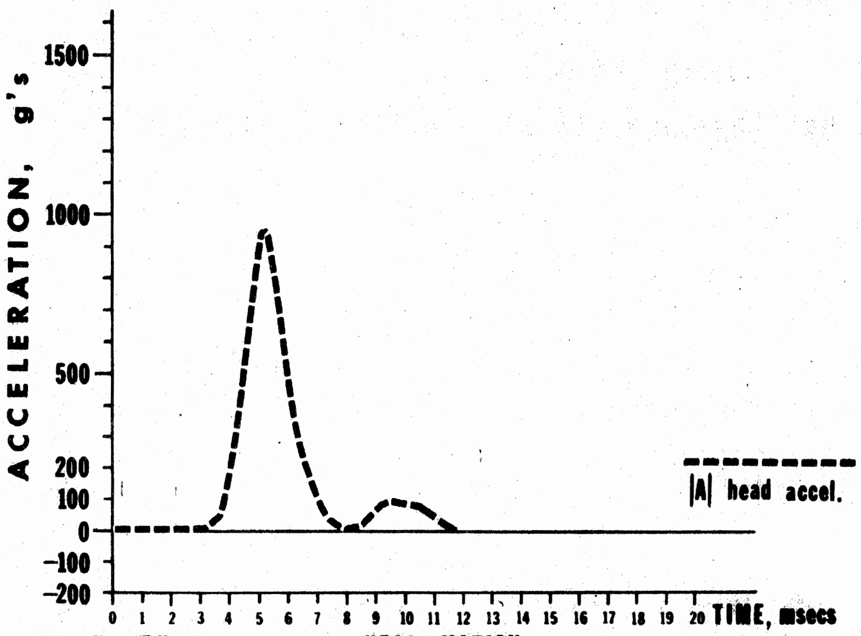
FIGURE A-11



Run Nr. RH 70-22 HEAD MOTION

RHESUS MONKEY

FIGURE A-14



Run Nr. RH 70-22 HEAD MOTION ,

RHESUS MONKEY

FIGURE A-13. RESULTANT LINEAR ACCELERAIION

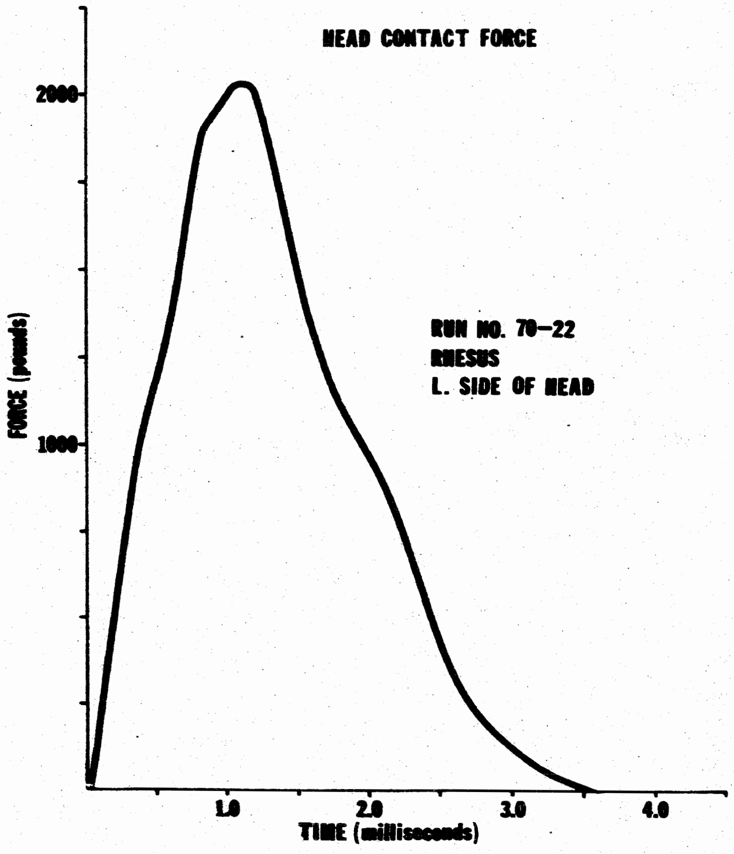


FIGURE A-15

DOOR CRASHWORTHINESS CRITERIA
Contract FH-11-7288
SUMMARY SHEET

1.	Run Number		71-80	
2.	Animal, Species and Sex		Chimpanzee, Female	
3.	Area and Type of Impact		Left side head, no pad	
4.	Impact Velocity		30.4	mph
5.	Animal Total Body Weight		65.0	lbs.
6.	Animal Head Weight		6.21	lbs.
7.	Animal Brain Weight		.782	lbs.
8.	Animal Skull Dimension*	w	3.43	inches
		l	4.91	inches
		h	.185	inches
		a	2.08	inches
		h/a	.089	
9.	Impact Duration		4.9	msec.
10.	Peak Contact Force		4600.	lbs.
11.	Head Acceleration (F=MA)		740.	g's
12.	Maximum Head Acceleration (Vector sum $\ddot{x}$ and $\ddot{y}$ from Vanguard)		550.	g's
13.	Maximum Head Velocity (Vector sum $\dot{x}$ and $\dot{y}$ from Vanguard)		38.5	mph
14.	Maximum Angular Head Acceleration		525,000.	$\frac{rad}{sec^2}$
15.	Maximum Angular Head Velocity		55.	$\frac{rad}{sec}$
16.	Impulse		11.1	lb-sec.
17.	Camera Framing Speed		5050.	Frames/sec.
18.	Blow-up Factor		3.13	in/Van. in.
19.	Quality of Movie		Poor - not enough light	

20. Animal Arrival: January 19, 1971 Impact: January 20, 1971
Termination: January 22, 1971 Dates

21. Evidence of Injury Post-Impact: Imprint of impactor on left side head. No other obvious injury.

SUMMARY SHEET (Cont'd.)
Page 2

22. Loss of Consciousness: Cannot determine min.

23. Heart-Beat Rate Pre-Impact: 130 beats/min.

Post-Impact: 145 beats/min.

24. Respiratory Rate Pre-Impact: 40 breaths/min.

Post-Impact: 32 breaths/min.

25. Reflex State (pupillary, eyelid, ear pinch, etc.)

Pre-Impact: All normal

Post-Impact: None (due to drugs)

26. Behavior Pre-Impact: Appears normal

Post-Impact: No apparent change

27. Anesthetic Used Ketamine (I.M.) Na Pento Amount not recorded mg/kg

Approx. Time Last Injection Given: Not recorded

Approx. Time Impact: Not recorded

Condition of Animal: Moderate

28. X-Rays Pre-Impact: None

Post-Impact: None

29. Blood Samples:

	Pre	Post	1 day	2 days	Other	
SGOT	44	55	107	103		Int. Units
SGPT	53	19	48	28	—	Int. Units
LDH	148	183	178	179		Int. Units
AIKP'tase	11	13	14	16		Int. Units
CPK	160	450	915	598		Int. Units

30. Skull Cleaned and Stored: Yes

31. EKG Pre-Impact: Yes

Post-Impact: Yes

SUMMARY SHEET (Cont'd.)
Page 3

32. Autopsy Comments: Hemorrhage in temporalis muscle. Cerebral-spinal fluid cloudy-pink colored. Brain parenchyma hemorrhage in right lateral cerebral cortex. 2 areas 1 cm diameter affected (Contrecoup) brain.

Autopsied 2 days post impact.

Histopathology: Right lung: foreign body granulamar. Left lung: acute passive congestion. Kidneys: congested.

Brain: congestion and focal red blood cells in arachnoid. Petechae Cerebrum: focal destruction cortex & hemorrhage (outer margin) also lymphatic infiltrate in meninges-meningitis & cerebenitis from trauma. All else appears normal.

33. Scaling Index Number: 3

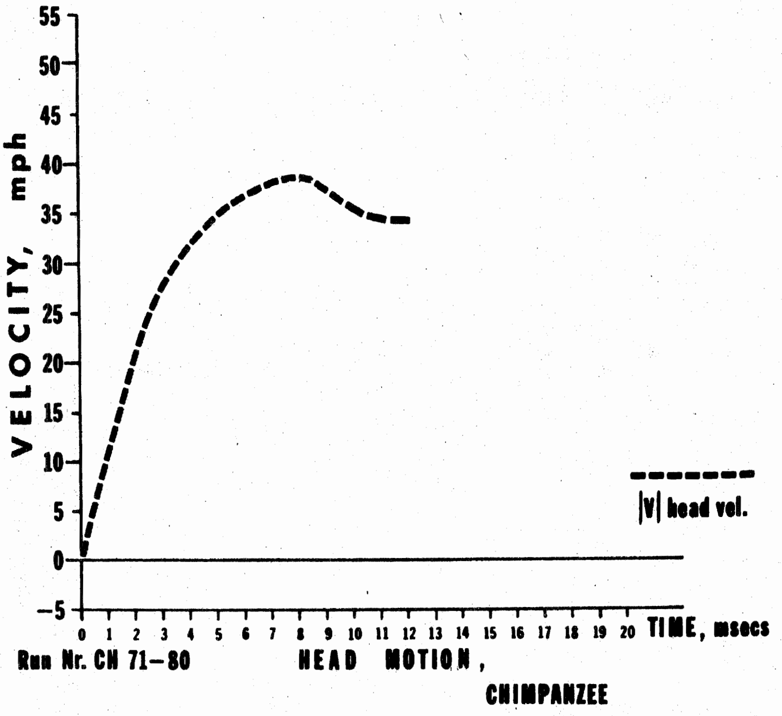


FIGURE A-17. RESULTANT OF LINEAR VELOCITIES

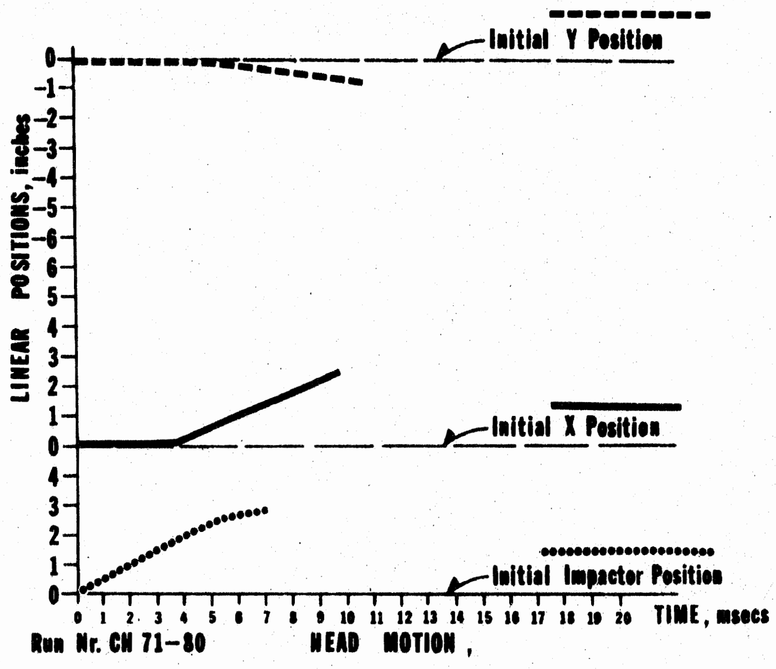


FIGURE A-16

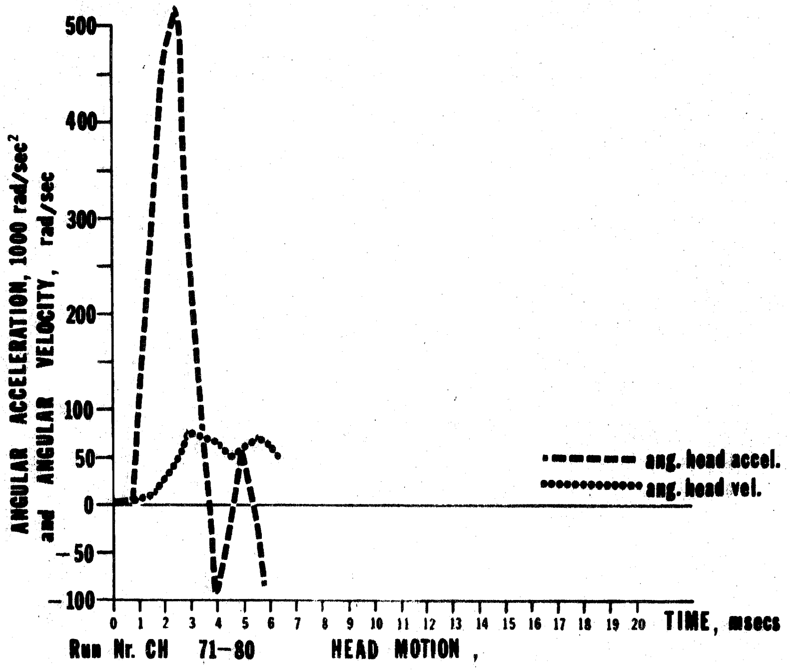
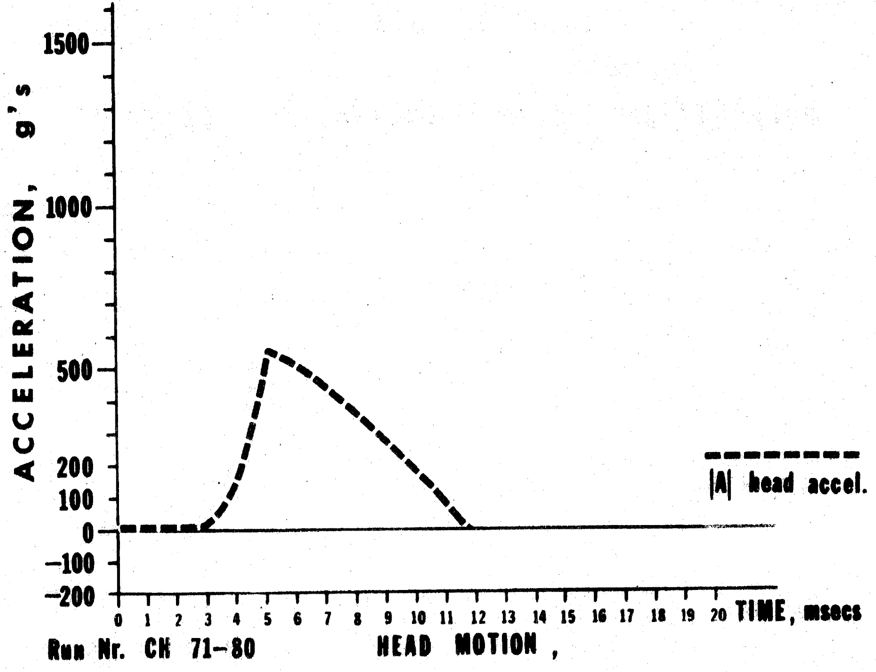


FIGURE A-19 CHIMPANZEE



CHIMPANZEE

FIGURE A-18. RESULTANT LINEAR ACCELERATION

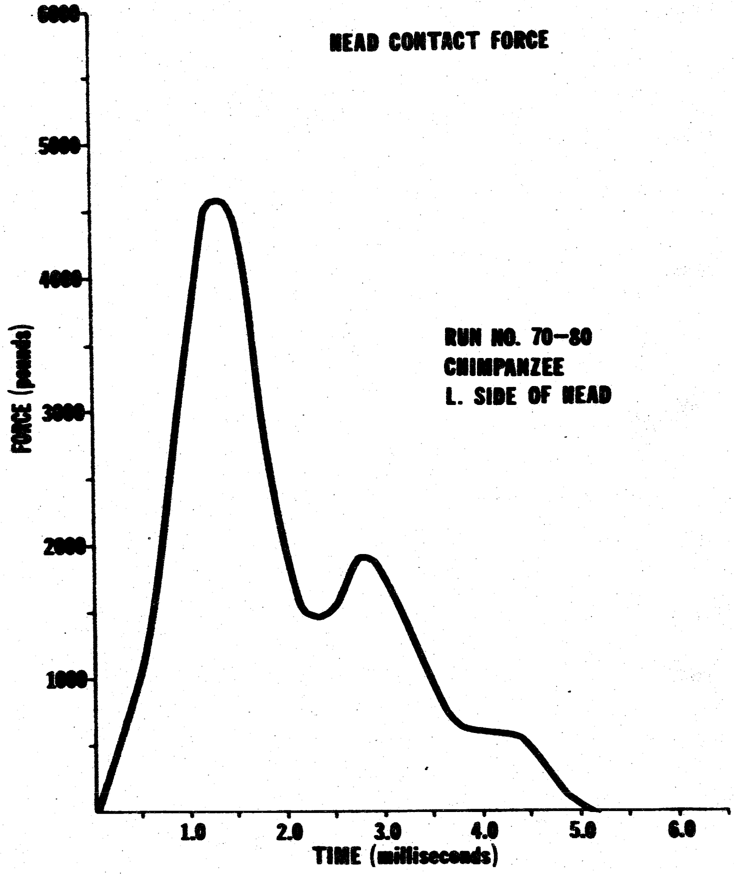


FIGURE A-20

Appendix B

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