INJURY TOLERANCE LEVELS IN BLUNT ABDOMINAL TRAUMA

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INTRODUCTION

Blunt abdominal trauma is a major cause of death in the United States. However, little experimental work has been done to clarify the mechanism of blunt abdominal injury,[2-9] and that which has been done was not always well controlled. In order to provide an engineering and medical approach to the subject of blunt abdominal trauma, a joint study was initiated by the Highway Safety Research Institute and the Section of General Surgery of the University of Michigan. An experiment was designed to study the forces involved in blunt abdominal trauma in general and to quantitate the forces involved in liver injuries in particular. While Winquist in 1953[11] produced injuries by impacting a moving animal against a stationary target, the injuries in this series were produced by impacting a stationary animal with a moving impactor.

METHODS AND MATERIALS

Ninety-six squirrel monkeys, Rhesus monkeys, and baboons were utiliated to study a range of primate masses and body proportions. In addition, fifteen pigs (Suis Scrofa) weighing approximately 100 pounds apiece were used because their abdominal visceral weights are known to approximate those of man. Each of these animals was exposed to a highly controlled and monitored abdominal impact. (Table 1). The animal to be tested was kept without food or water for twelve hours prior to the test and was anesthesized with intravenous Phenobarbital or Ketamine. An attempt was made to provide analgesia and yet keep muscle tone. The anesthesized animal was shaved and targeted for high speed photographic analysis. A complete set of anthropometric measurements was obtained.

In the first experiment, the animal was seated and held in an erect position with silk threads through the ears. The upper limbs were secured out of the field with masking tape. This method of support makes the animal essentially a free body, provides reproducible results, and eliminates the complicated boundary conditions of a seat or sling. Various sized inpactors were used to simulate common automotive injuries. In other tests, lap belts were used either to slap against the abdomen of the suspended animal or to contain the animal in a sled run. All impacts were carried out by a pneumatically-operated cannon specially constructed for impact studies. (Figure 1) The machine consists of a ground and honed cylinder, an air reservoir, and two carefully fitted pistons. The transfer piston (22 lbs.) is propelled by compressed air through the cylinder and transfers its momentum to the impact piston (22 lbs.). A striker plate, attached to the impact piston, travels a distance of about ten inches where an inversion tube absorbs the energy of the impact piston and halts its movement. The stroke of the impactor is controlled by its initial positioning, and its velocity is controlled by the reservoir pressure. The impactor is instrumented with an accelerometer and an inertia compensated force transducer. High-speed motion pictures at 3000 to 5000 frames per second were taken for photographic analysis. Contacting forces and pulse duration were photographically recorded from an oscilloscope. Impactor velocity was determined from the high-speed motion picture analysis.

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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 absorb the momentum of the animal after impact. Anterior impact areas were varied in location from the mid-epigastric to the supra-pubic region. These regions were defined as: Region I -- upper 1/3 of the abdomen, Region II -- mid 1/3 of the abdomen, and Region III -- the lower 1/3 of the abdomen. Some impacts were made in the right anterior oblique position one-half way between the xyphoid and the 12th rib.

The second experiment was designed to determine the precise energy needed to injure the liver itself. The liver was surgically mobilized in anesthesized Rhesus monkeys. A liver lobe was laid onto a small load cell while still being perfused in the living animal. Load deflection curves were established by varying the velocity of the impactor while keeping the percent penetration of the exposed lobe constant at 50%. A quartz load cell was attached to a hydraulically operated, servo-controlled testing machine capable of load compression at 30,000 in/min. Velocity was determined by using a Plastech optical tracking system with a frequency response of 30,000 Hz. Load deflection curves were recorded on film from a dual beam, storage unit oscilloscope.

All animals were autopsied following the impact. Injuries were then classified and rated on an Estimated Severity of Injury Scale (ESI) of 1-5 as defined in Table 2. The relative importance of various injuries was subjectively determined. When several organs were injured, the Estimated Severity of Injury Scale was made to reflect the severity of the total injury. Some injuries were judged to be at a level between two whole numbers and were given ratings accordingly. All injuries were photographed so that direct comparisons between animals could be made.

RESULTS

Small changes in velocity produced large changes in the degree of injury. Less energy was required to produce an injury in the upper abdomen than in the lower abdomen. An Estimated Severity of Injury of 3 was found to be produced with an average of 87 psi using a rigid bar impactor and 22 psi with a large surface impactor. In the twenty animals impacted with a lap belt, the forces tested were high and comparable to those seen in the simulated crash impacts; however, the lap belt produced few injuries in these animals. This data was submitted to a computer-assisted statistical analysis for both positive and negative correlations between the various parameters and the Estimated Severity of Injury. It was found that the peak force and pulse duration had a high level of correlation with the Estimated Severity of Injury. (Table 3). The animals used in these experiments varied in size and weight. In order to integrate this data, dimensional analysis techniques were used with the aid of a computer. This resulted in a formula which conpensates for weight and contact area:

$$ESI \propto \text{Log}\ \frac{ft^2}{m\sqrt{a}}$$

Here, f=force of impact, t=duration of impact, m=Mass of the animal, and a=contact area. The data for all four species with anterior impacts was found to correlate with this formula as shown in Table 4.

The direct liver impact data was converted to energy density (inch-pounds of energy applied per cubic inch of tissue). Using a velocity of 12 ft/sec, a 5+ injury was produced by an average force of 16 to 18 in.lb./in.^{3}, a 4+ injury with 10 to 15 in.lb./in.^{3}, a 3+ injury with 7 to 9 in.lb./in.^{3}, a 2+ injury with 4 to 6 in.lb./in.^{3}, and 1+ injury with 1 to 3 in.lb./in.^{3}.

DISCUSSION

The injury produced by a given force was found to be a direct function of the surface area, duration of impact, and mass of the animal. Narrow impactors applied to the body surface overlying the liver resulted in tearing and transsection fractures of the liver, probably due to the localized and concentrated forces produced in the area. However, the liver tended to burst when the impact was made with a large diameter impactor. If the same force and velocity of impact were applied with a narrow bar impactor and a large surface impactor, the small bar tended to produce greater liver injury. When pressures of impact of the large diameter impactor and the bar impactor were the same, the greater injury was produced by the large impactor. Equal injuries (ESI-3) were produced when a pressure of 87 psi was applied with a bar impactor and 22 psi with a large diameter impactor.

These results can be explained by the fact that the liver is made of viscoelastic material. The viscoelastic properties of the liver cause high surface stresses resulting in structural failure over a large area. This property also accounts for the fact that the injury produced is dependent on the duration of impact. The injury produced by a given force if applied over a long period of time is much more severe than if that same force is applied briefly. The location of the impact greatly influences the injury produced. When the location of impact and mass of the subject are taken into account, the composite function, $ESI \propto \text{Log}\ ft^2/m\sqrt{a}$, relates well to the degree of injury produced in an anterior abdominal impact. Relatively small forces were required to produce severe injuries of the solid viscera when the impact was made in the upper abdomen (Region I, Table 4). However, much greater forces were required to produce comparatively severe injuries when force was applied to the lower abdomen (Region III).

The low incidence of injury of solid viscera associated with the use of lap belts confirms their value as a restraint system in the automobile. Few injuries other than hematomas of the mesentery and retroperitoneum were noted. Intestinal injuries were rarely produced and only occurred when an accidental maximal penetration was obtained. This agrees with Williams who postulated that lap belt injuries were associated with a crushing of the intestine between the abdominal wall and the spine.[1,10]

Only a small percent of the force applied to the experimental animals, and presumably to a human in an automobile accident, was actually transmitted directly to the liver. Whereas approximately 350 lbs. were needed to produce a 2+ injury in an intact animal, only about 150 lbs. were needed to produce a similar injury in the directly exposed liver. This can be explained by the protection provided by the abdominal wall, body movement, visceral resistance, and the dampening of an applied energy.

Two previous studies were designed to evaluate the forces required to injure the liver. Glenn dropped resected cadaver livers from various heights and dropped weights onto the abdomen of living dogs.[3] He was able to produce typical bursting injuries by applying energies of 250 ft.lb. to the dogs and by dropping livers from 7 to 25 feet. Mays injected cadaver livers with barium to reproduce their perfused turgor and then dropped them from various heights to produce injuries.[7] He found that 30 ft.lb. produce capsular tears and 300 to 360 ft.lb. produced massive bursting injuries. However, to our knowledge, no one has done direct impact studies on a normally perfused primate liver in the living animal. When Mays' data is converted to strain energy density, i.e., the total energy available divided by the volume of the liver, it can be compared with the results of our direct liver impacts. Mays' results convert to 4 in.lb./in^3 for capsular tears and 40-48 in.lb./in.^{3} for massive bursting injuries. Because of the viscoelastic properties of soft tissues, that is, its velocity dependency, only the lowest injury level of 2+ of Mays' study is comparable to this set of tests. Mays' massive bursting injuries were obtained with velocities in excess of 60 ft./sec. This was necessary in his experimental design to obtain the higher forces needed to produce this type of injury. Because our energy was not velocity dependent, we found that at 12 ft./sec. an energy density level of only about 17 in.lb./in.^{3} was needed to obtain massive bursting injuries. This is only about one-third that of Mays' values. Because of the rate sensitivity of soft tissue, we would expect the energy density to increase for a given injury level with an increase in velocity, thus making Mays' human cadaver tests quite comparable to our monkey liver tests.

SUMMARY

There is a positive correlation between the degree of abdominal injury produced in blunt abdominal trauma and the force, surface area, animal mass, and duration of impact in pigs and three species of primates. Only a small percent of the force applied to the abdomen of an experimental animal in these experiments, and presumably to a human in an auto accident, is actually transmitted directly to the liver. When the location of impact and the mass of the subject are taken into account, a composite function, $ESI \propto \mathrm{Log}\ ft^2/m\sqrt{a}$, relates well to the degree of injury produced in an impact. This formula might be expected to apply to man for the following reasons: 1) the visceral weights of the pigs approximate those of man, 2) the other species studied were primates, and 3) the mass of the subject was taken into account in the formula.

(The research upon which this paper is based was performed pursuant to Contract Nos. FH-11-7288, FH-11-7608, and H5-031-2-382 with the Department of Transportation, National Highway Safety Bureau, and Gift Funds from the Motor Vehicle Manufactures Association, U.S.A.)

REFERENCES

1. Baxter, C.F. and Williams, R.D.: Blunt abdominal trauma. J. Trauma 1:241-247, 1961.

2. Beckman, D.L., McElhaney, J.H., Roberts, V.L. and Stalnaker, R.L.: Impact Tolerance - Abdominal Injury. NTIS #PB204171.

3. Glenn, F., Mujahed, Z. and Grafe, W.R.: Graded trauma in liver injury. J. Trauma 3:133-141, 1963.

4. Grimelius, L. and Hellstrom, G.: Patho-anatomical changes after closed liver injury: an experimental study in dogs. Acta. Chir. Scand., 131: 485-494, 1966.

5. Hellstrom, G.: Intra-vascular pressure response to closed liver injury: an experimental study in dogs. Acta. Soc. Med. Upsal. 70:167-190, 1965.

6. Hellstrom, G.: Electrocardiographic, Blood pressure, respiratory and electroencephalographic responses to closed liver injury, an experimental study in dogs. Acta. Soc. Med. Upsal., 70:152-166, 1965.

7. Mays, E.T.: Bursting injuries of the liver. Arch. Surg. 93:92-103, 1966.

8. Mertz, H. and Kroell, C.: Tolerance of thorax and abdomen. In Gurdjian, E.S. Impact injury and crash protection, C. Thomas, Springfield, Ill., 1970, pp. 372-401.

9. Stalnaker, R.L., McElhaney, J.H., Snyder, R.G. and Roberts, V.L.: Door Crashworthiness Criteria. NTIS #PB203721.

10. Williams, R.C. and Sargent, F.T.: The mechanism of intestinal injury in trauma. J. Trauma 3:288-294, 1963.

11. Windquist, P.G., Stumm, P.W. and Hansen, R.: Crash injury experiments with the monorail decelerator. AF Technical Report No. AFFTC 53-7, April 27, 1953.

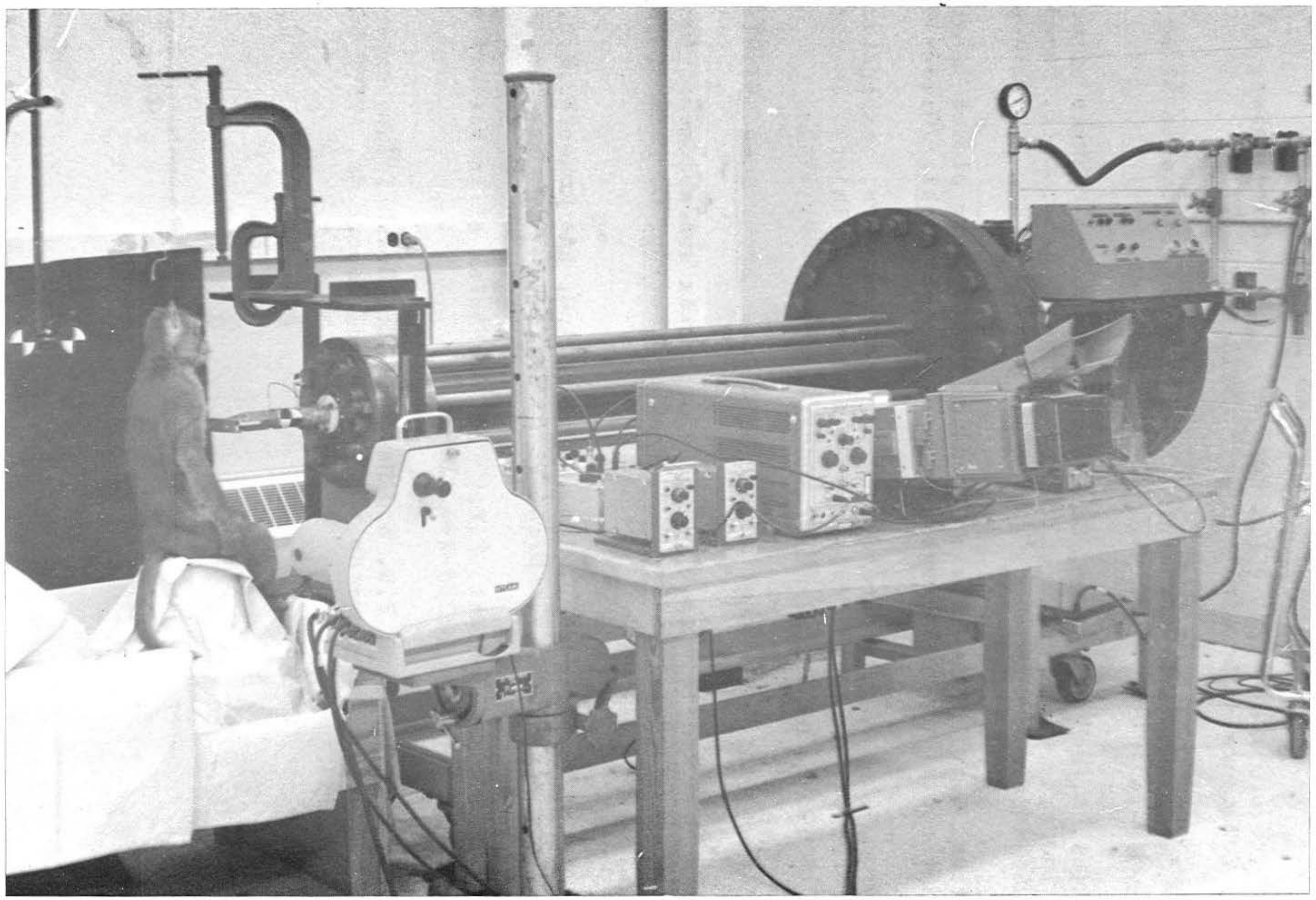


FIGURE 1. THE PNEUMATIC CANNON IS USED TO PROPEL THE IMPACTOR AGAINST THE TEST SUBJECT

TABLE I. SUMMARY OF ABDOMINAL IMPACTS ON 111 ANIMALS

Species	Flexible Belt			Rigid Bar					Circular - Rigid				Padded Scaled Wedge		Seat Belt Sled	Liver Exposed	Total
	6"x½"	6"x1"	6"x2"	8" x½"		8"x1"		8"x2"	3" dia		3"dia w/ 1½" foam	6" dia				2½" dia	
	AP	AP	AP	AP	RS	AP	RS	AP	RAO	LAO	AP	RAO	RS	LS	LB		
Squirrel													2	1			3
Rhesus	7	4	5	9	4	8	4	7			2	7	3	4	4	15	83
Baboon													5	5			10
Pig									8	7							15
Total	7	4	5	9	4	8	4	7	8	7	2	7	10	10	4	15	111

AP - Direct anterior

RS - Right side

LS - Left side

RAO - Right anterior oblique

LAO - Left anterior oblique

LB - Lap belt

TABLE II. DEFINITION OF ESTIMATED SEVERITY OF INJURY (ESI)

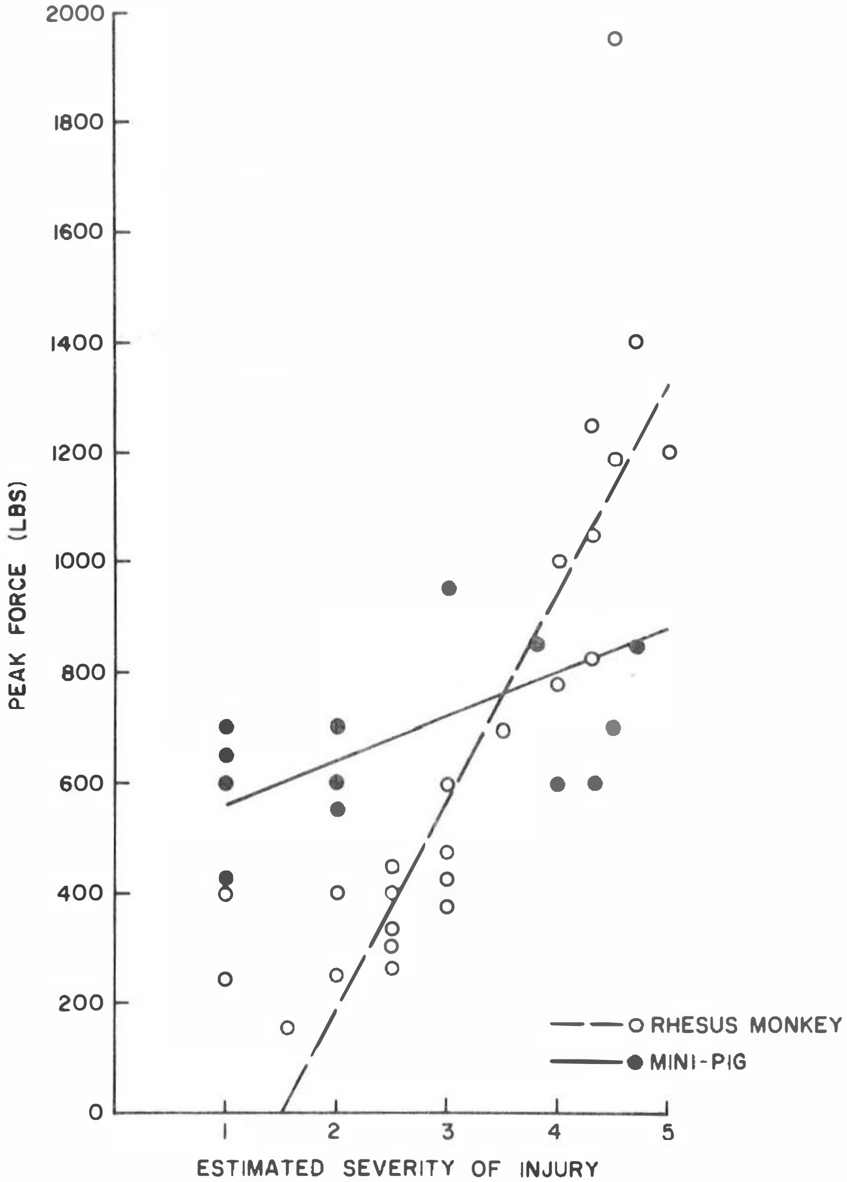
1+ - Minor Trauma - Retroperitoneal hematoma, mesenteric abrasion, subcapsular hematoma of liver.

2+ - Mild Trauma - Splenic hematoma, intestinal hematoma, small non-bleeding liver laceration or capsular hematoma.

3+ - Moderate Trauma - Splenectomy or liver injury requiring suture repair.

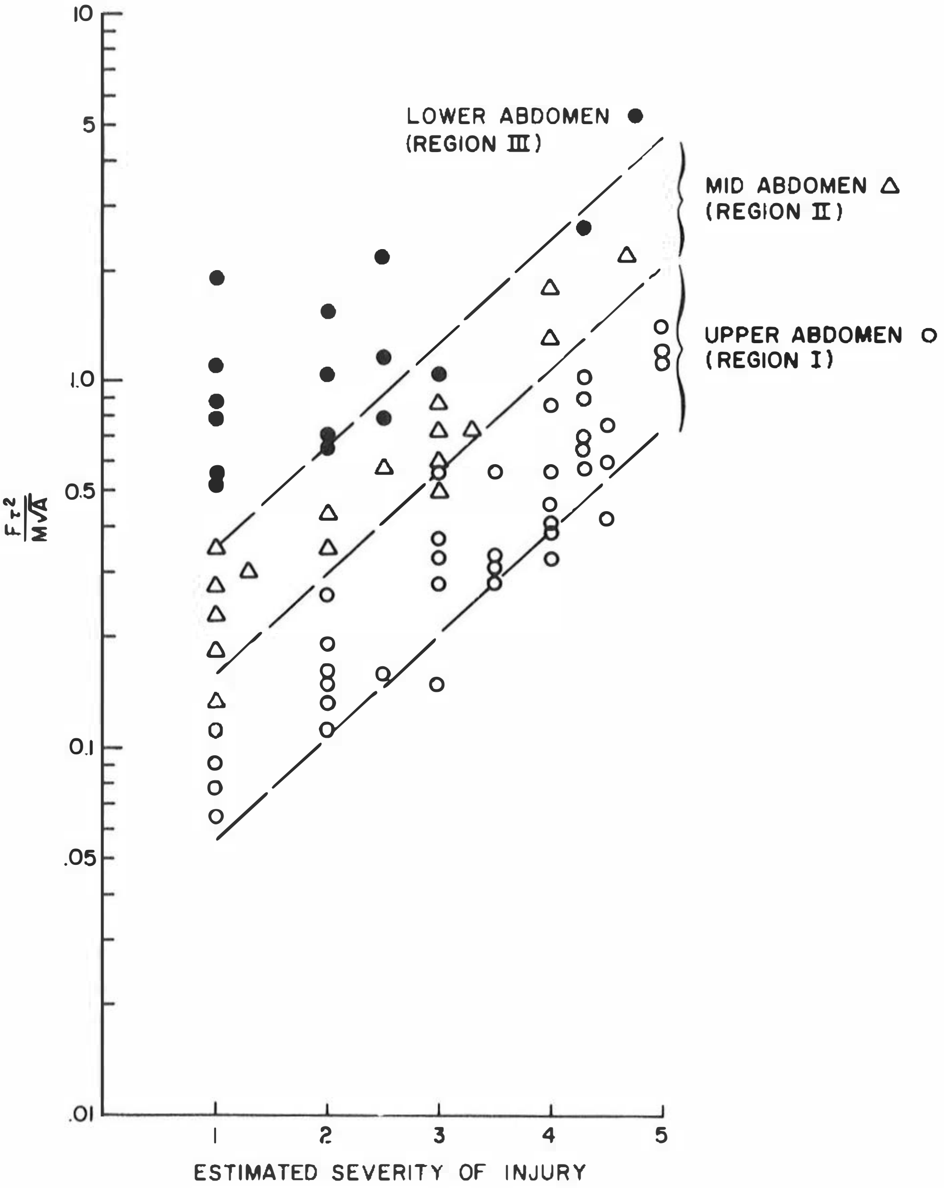
4+ - Major Trauma - Hepatic resection, pancreatic fracture - survival only with maximum surgical care.

5+ - Massive Trauma - Complete maceration of liver, spleen, or pancreas. Presumably lethal at accident scene.



PEAK CONTACT FORCE vs ESTIMATED SEVERITY OF INJURY.

TABLE III



EXPERIMENTAL SCALING FACTOR FOR ABDOMINAL INJURY SENSITIVITY.

TABLE IV