EXPERIMENTAL IMPACT PROTECTION WITH ADVANCED RESTRAINT SYSTEMS:

Preliminary Primate Tests with Air Bag and Inertia Reel/Inverted-Y Yoke Torso Harness

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I. Introduction

Protection and survival of motor vehicle occupants, as well as those of aircraft, spacecraft, and other types of vehicles exposed to crash impact forces, are dependent upon a number of environmental factors. In any vehicle environment, however, the occupant restraint system is of primary importance. Research to prevent or reduce injury during impact, and to prevent ejection in ground vehicle accidents is related to similar problems first met in the air. Possibly the first use made of a restraint was by Pilâtre de Rozier — in the form of hanging rather apprehensively onto a guy rope — in his first tethered balloon flight in France in 1783.[2]

It is naive, however, to consider that aircraft restraint developments can be simply transferred into automobiles with the same degree of success. While it is true that the major research efforts and system advances were by the aircraft industry during the past 25 years, (probably dating back to the first ejection seat experiments in Germany in 1939)[35] it should be noted that there are significant differences, often overlooked, in application, requirements, and environments as well as in respective populations for which they are designed. An Astronaut couch, for example, is specifically designed for a narrow range of healthy young males, representing only the 25th–80th percentile American male stature,[45,50] while the automobile occupant population covers a wide range from infants to the very elderly and those with disabling infirmities.

The hypothesis behind most restraint studies is that the majority of deaths and injuries in accidents could be prevented or considerably decreased by safely restraining the occupant if the accident could not be prevented.[38, and others]

Some of the major differences between aircraft and automotive restraint systems are as follows. In aircraft, the direction of applied force (body orientation) is rarely in direction(s) other than forward ($-G_X$) application, while in automobiles protection against rear and side impacts also must be considered. The forces of impact are often greater in an automobile[24] than in many survivable aircraft crashes[20,28] with a much shorter vehicle deceleration distance, time duration, and resultant higher loads and onset rates on the occupant. Seat-belt webbing in civil aircraft tensile strength requirements are 2,250 pounds for single occupancy but only 1,500 pounds single occupancy strength for whole belt assembly.[21] Military (Air Force and Navy) webbing requirements are now 5,500 pounds minimum tensile strength,[46,47] although in practice most aircraft in the field still have the 2,000 pounds webbing previously required.[47] In contrast, automobile seat belt tensile strength, required by regulation to meet 6,000 pounds tension loads,[22] usually exceeds this by a significant margin, and sometimes 8,000 pounds is observed in actual crash tests.[24] In aircraft, military and civil, few would think of not fastening the safety belt, yet in automobiles in which seat belts are available, numerous studies have shown that fewer than 30%[4,26,34] and probably closer to 15–20%[36] bother to use the restraint provided.

The most effective aircraft restraint systems are found in military aircraft having cockpits designed to withstand 40g. impact. Another critical difference between the aircraft and automotive restraint system is mass-production quality control: for 1968 automobiles alone, 352 million feet of webbing were required for 16 million torso belts and 48 million lap belts, and

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if inertia reels were used, some 35 million would have been required[9] — compared to the few thousand produced currently for the aviation industry.

A related series of experiments on restraint protection and impact injuries, using baboon subjects on the Holloman AFB Daisy Decelerator was conducted. The first of these, on the effect of lap-belt restraint on the pregnant maternal and fetal organism, was reported at the last Stapp Conference,[41] and the final results in subsequent medical meetings.[16,42] Another study, which compared the effectiveness of four basic restraint systems used in automotive vehicles and brought together related past studies, was reported in April, 1967.[42] The present investigation was designed to provide a preliminary evaluation of two advanced restraint concepts which are being developed for possible future automotive use, but which lacked biomechanical evaluation.

Among new types of restraint systems being considered for automotive vehicle occupant protection are the yoke harness with inertia-locking reel and the air-bag restraint system. Independently, each has had extensive development by several engineering and research organizations. Originally, both systems were intended for aircraft use, but neither has been utilized in other than experimental tests.

The yoke harness with inertia reel (Fig. 1) is a distinct variation of an aircraft torso harness and reel system in that the torso harness is independent of the seat back. In the new system reported here, the reel is attached overhead, rather than to the seat, thereby avoiding any downward force on the shoulders (which may contribute to the submarining action) and direct loading to the top of the seat back (high cg.). This system also differs in that the left and right shoulder belts come together as a yoke ("inverted–Y") behind the head, continuing upwards to the reel as a single belt. In 1957, work by Barecki of American Seating Company was an early design of this type of system.[5] In 1958, several tests of this device were conducted by Col. Stapp at Holloman AFB, using cars which were towed and snubbed to a stop.[6] In three tests, human volunteers with heads positioned forward (pre-flexion) were exposed to 18 (average) g. on the chest (26 peak g.).

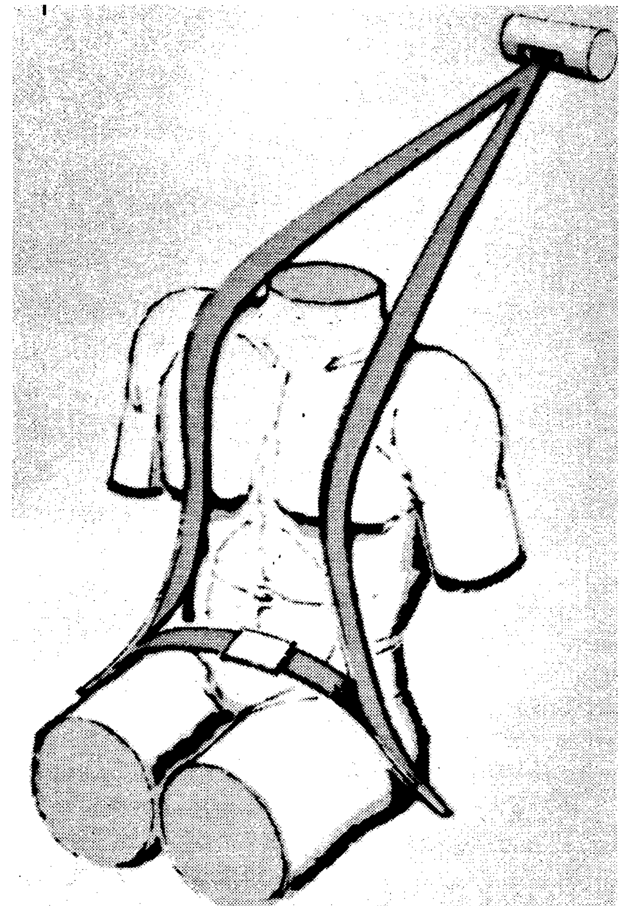


FIGURE 1. Inverted-Y yoke harness with inertia-locking reel. The shoulder belts are attached to the floor at the lower end, and the upper torso is free to move until reel automatically locks at pre-set value during braking or impact.

Air-bag restraint systems have been proposed since at least 1935 when Manson filed a patent for a pneumatic airplane seat.[37] However, it was not until 1952 that interest was again regained and sporadic proposing, developing, and testing was subsequently initiated by various investigators.[30,31] Despite this development work, including tests with both anthropomorphic dummies and human volunteers previously conducted by various investigators for both systems, neither air bags nor yoke restraints have had adequate experimental biomedical evaluation under carefully controlled test conditions.

Although its actual origins may have been a decade earlier in the occasional instance of some aircrew member prematurely inflating his Mae-West or life raft prior to a crash landing, several members of the author's (RGS) 7-man crew did just this during the crash landing of a B–25 in April, 1951. This experience contributed to the proposed design of a personnel restraint system[43] to the Air Force in 1957 by one of the authors (RGS), while at the Applied Research Laboratory of the College of Engineering, University of Arizona, but which was rejected in favor of the Chance-Vought system.[25]

The most vigorous proponent of this type of restraint, Clark, who discovered advantages of employing air-stop restraint in 1960, has contributed substantially to the potentialities of this system.[12,15] As in much other research, however, a considerable amount of study and development by independent investigators and organizations has been involved, particularly in the past few years, but which has not been published. The current test series is a continuation of a long-range investigation of the relative impact injury protection and effectiveness of major restraint systems utilized in general aviation aircraft and in limited automotive use. The objective of these tests was to determine how much protection these advanced restraint concepts provided and to obtain preliminary biomechanical and physiological data under controlled impact conditions. In addition, it was hoped in this preliminary series of experiments to provide an initial basis for direction of future test requirements.

II. Method and Materials

Thirteen impact tests were performed using eleven adult female Savannah baboons* *(Papio cynocephalus)*,** ranging in body weight from 15½ to 34½ pounds. Four of these tests were conducted using the yoke harness and inertia-locking reel (three forward, one 90° side-facing), with four different test subjects, and nine air-bag restraint tests utilizing seven different subjects (all forward facing). Animals were obtained from the breeding colony of the Southwest Foundation for Research and Education at San Antonio, Texas, and from International Animal Imports, Ferndale, Michigan. All were shipped by air from 2 to 6 days prior to tests at Holloman AFB.

Tests were run between May 29 and June 3, 1967, utilizing the Daisy Decelerator[11] of the 6571st Aeromedical Research Laboratory at Holloman AFB, New Mexico (Fig. 2). The seat was an F–111 test frame, modified for baboons, and mounted on the ARL Omni-directional Sled. The 4,500 pounds tensile strength nylon lap belt used in each test and the upper torso yoke webbing used in the Y-yoke tests were replaced after each test. The lap belt was installed at a 55° angle to the seat pan. Prior to each run, static belt tension for each side of the lap belt was stabilized at 1.5 kg. (3.3 lb.). Each subject was thus provided with the same degree of initial belt tightness (tension).

Test conditions involved 0°–0°–0° forward-facing ($-G_X$) seat orientation in all air-bag tests and in three of the four Y-yoke tests. In one Y-yoke test, 0°–90°–0° body orientation ($-G_y$) was utilized for a 90° side impact. (Additional side impacts at 90°– and 50°–body orientation were run concurrently with subjects restrained by 3-point harnesses for comparison, but these are not included in the above totals.) The seat back was 13° from the vertical plane in all tests, and shoulder harness angle for the yoke harness tests was measured at 45° (relative to the horizontal) over the shoulder in each case.

For the double-torso inverted-Y yoke system, protocol was established for one run at 30g. (sled avg. g.) in both forward-facing and side-facing positions, one run at 43g., and one run at 49g. An initial value of 30g. was selected as this was the level at which impact injury was evident in other types of restraint systems using baboon subjects in similar deceleration patterns. Sled g. was measured since this could be accurately determined and compared to previous tests. Subject decelerations, as measured by chest or head accelerometers, had proven to be extremely unreliable in previous tests due to orientation and, in particular, mounting problems.

Air-bag tests were designed as duplicate tests, from 30g. to 50g. (sled avg. g.), with one animal terminated immediately post-impact (3–6 minutes), and the second animal for each series allowed to survive for chronic post-impact monitoring. Two of the latter were monitored for 4 weeks post-impact before being terminated to allow for any possible trauma as a result of impact to become evident. One subject impacted

*The animals used for these experiments were lawfully acquired and treated in accordance with the Principles of Laboratory Animal Care issued by the Animal Facilities Standards Committee of the Animal Care Panel, U.S. Department of Health, Education, and Welfare, Public Health Service, March 1963.

**Previously designated by primatologists as Kenya baboons *(Papio doguera)*, and so identified in previous papers.

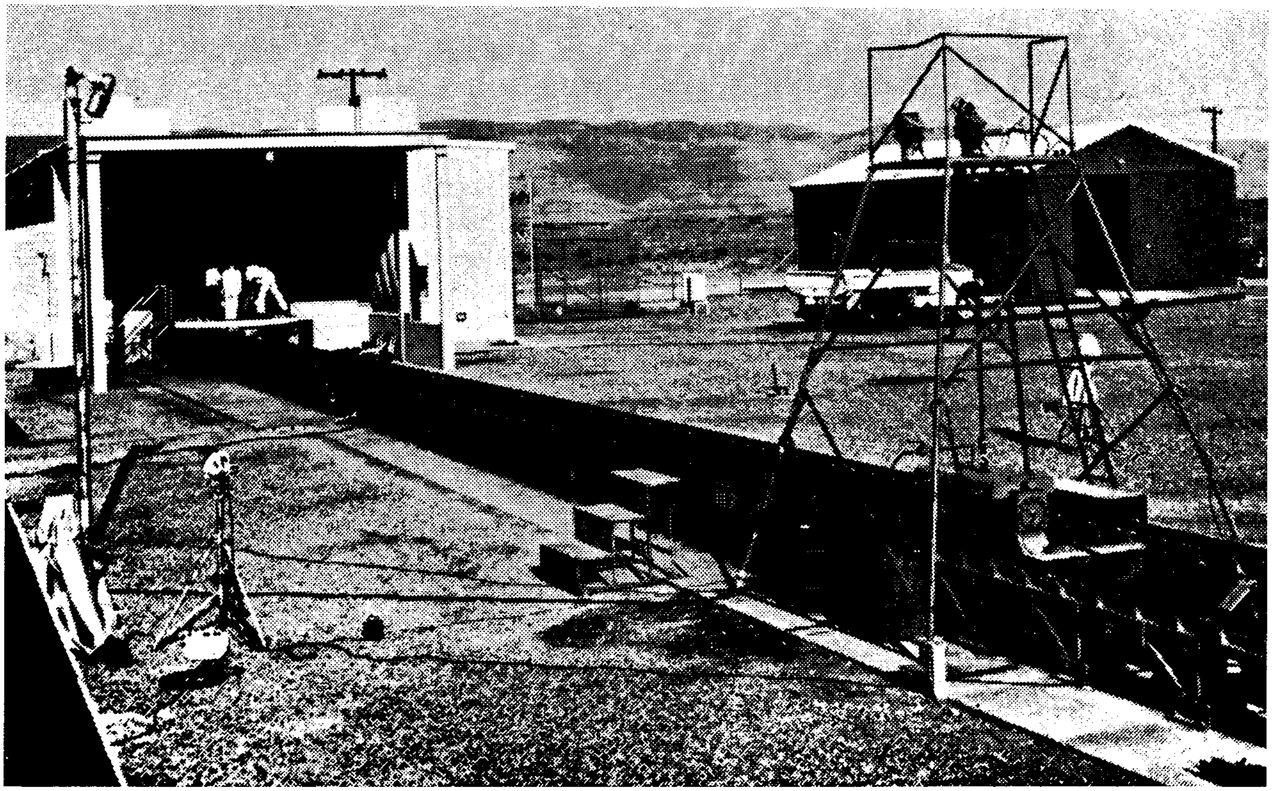


FIGURE 2. View of the Daisy Decelerator from the midpoint of the 120′ track. The omnidirectional sled used in these tests is shown at the far end of the building housing an air gun accelerator. High-speed overhead cameras are positioned on the tower located over the water brake. Instrumentation and fire control buildings and animal quarters are to the left of this view.

at 33g. (avg. g.) was monitored for 12 weeks post-impact. Time duration was to remain a constant, but actually varied slightly from 0.045 to 0.060 sec. (plateau duration) and 0.073 to 0.094 sec. total duration for the yoke harness, and from 0.040 to 0.060 sec. (plateau duration) and 0.059 to 0.091 sec. total duration for the air-bag tests. Entrance velocities varied from 73.6 ft./sec. (50 mph) to 94.4 ft./sec. (64 mph) for the yoke tests, and from 71 ft./sec. (48 mph) to 94.2 ft./sec. (64 mph) for the air-bag tests. Rates of onset ranged from 2,700 g./sec. to 6,100 g./sec. for the yoke restraint, and from 3,300 g./sec. to 5,900 g./sec. for the air-bag tests. Table I provides a summary of these yoke data together with belt loadings measured. (See Table 1 on page 7.)

The air-bag restraint system was scaled down to be the same relative (1/3) size for the baboon subject as the full-size version for humans, previously tested in automobiles with anthropomorphic dummies. Each bag was folded into a test instrument panel placed 10½ inches from the subject's chest: The top of the panel was level with the subject's nipple height (which is proportionately lower in the human), and was moved 2 inches lower in all subsequent tests. A standard 1-inch lap belt was positioned on each animal. Actuation of the system was initiated by an electronic impulse as the sled probe penetrated the brake system and the bag was fully deployed in 0.020 second. Energy dissipation was accomplished by deflating the bag as the occupant moved into it.

The yoke-restraint system (Fig. 3) consisted of a single lap belt (scaled for baboon) of 1-inch, 4,500 pounds tensile strength nylon webbing, adjusted statically pre-run to 1.5 kg. (3.3 lbs.) tension. Strain gauges were mounted on both sides to record belt forces. The torso portion of the harness was attached separately at each side adjacent to the lap belt tie-downs and was equipped with strain gauges. The yoke of the harness came together behind the head at the occipital protuberance, but did not touch the head or neck.

FIGURE 3. Yoke-type restraint with subject in place prior to run. Shoulder belt angle is 45° to inertia reel. Note position of right shoulder belt strain gauge.

It may thus provide some rearward motion protection (we did not test to what degree it could offer hyper-extension protection in rear impact). The yoke was attached overhead at a 45° shoulder angle (relative to the vertical plane) to the inertia reel, which was set at 0.3g. activation. A new reel was used in the first three tests, one reel being used twice.

Each subject was anesthetized with 1 mg./kg. body weight of Sernylan (R) prior to each run. The subject was removed from the cage after the drug had taken effect and prepared for the tests in an adjacent surgical room. Hands and feet were covered with tape to provide improved photometric kinematic targets. The animals were muzzled to prevent injury to the tongue during impact and for photometric usage. The animal was next taken to the test sled, positioned, and the seat-belt tension adjusted. Low-strength masking tape was used to keep the legs and thorax in proper position for the run; however, this easily tore at impact and did not provide additional restraint protection. In the air-bag tests a loop of rope under the arms and attached over the seat back supported the animal in an upright position until mechanically released by cable 0.6 sec. prior to impact. Muscle tonus was carefully monitored to assure that all runs were made at the same clinical level.

The strain gauges were fabricated for the 6571st Aeromedical Research Laboratory by Land-Air Division of Dynalectron at Holloman AFB. They were originally designed for the standard 2-inch wide belt, but were modified to the 1-inch webbing used in these tests. Gauges were placed at each end of the belt, two for lap belts and two additional gauges for the lower ends of the torso yoke. Each strain gauge buckle was instrumented with four strain gauges in order to measure the bending moment due to the force imposed upon the belt. When the belt was stretched, the metal of the buckle was stressed and deflected. Although each buckle contained eight elements, it electrically appeared as a four-active-arm bridge. Resistance of the electrical elements changed as a result of changes of strain on the metal. Calibrations were made by placing a known force on the belt and measuring the electrical output of the bridge.

Photographic coverage included use of a Waddel 16–1A 2,000 fps camera for frontal view, and two Ippolito Fastex 2,000 fps cameras for lateral views, film from one of the laterals being processed immediately and wet-viewed to examine results of each test quickly prior to the succeeding test. One each 16 mm. documentary color film, 35 mm. still color film, and 4x5 still photography were also obtained. In addition, three black and white Polaroid photos were obtained for each run; pre-impact, during impact, and post-impact. These served as useful working references to note specific position, cross-check run numbers and animals, and other details of note.

Gross autopsy was conducted at the 6571st Aeromedical Research Laboratories immediately post-impact for the terminated subjects, and at the facilities of Space/Defense Corporation, Birmingham, Michigan, for the three terminated 4- and 12-weeks post-impact. Whole body post-impact X-rays were taken prior to autopsy and radiography was conducted at the FAA Civil Aeromedical Institute, Oklahoma City, as was pathological histology. Gross and microscopic tissue study of the brain was complemented by electron-microscopic examination for fibrinolytic activity.

All animals were examined for external evidence of trauma post-impact, and one of each pair at each impact level was sacrificed post-run with 650 mg. Nembutal.(R) The surviving animals were held for observation for 1 week and then shipped to Gasow Veterinary Hospital, Birmingham, Michigan, where they were further observed for post-impact effects and for weekly blood analysis by Space/Defense Corporation.

III. Discussion

Although these tests have been conducted concurrently the data have been treated individually and will be discussed as separate systems in this section.

A. ***Inertia-Locking Reel with Inverted-Y Yoke Torso Harness:*** The lap belt combined with a yoke harness has been demonstrated to be the most effective belt restraint system devised of those evaluated. It has been compared to the lap belt alone (which offers no torso protection against jack-knifing), to the single diagonal belt (as used in many European vehicles and which provides absolutely no pelvic restraint, allowing the lower portion of the body to swing free and rotate about the belt), and the 3-point harness (which offers limited protection). However when the torso harness is tightened, an operator may not be able to reach controls on the instrument panel, is not free to move the upper portion of his body, or may be uncomfortable or become fatigued, any of which might contribute to accident causation. Thus to assure a practical and effective system, provision must be made for relatively unrestricted upper torso motion during normal driving activities; however, instant and automatic "locking" of the torso restraint is desired during emergency braking ("panic stops") and required at impact. An inertia-reel mechanism can fulfill this requirement. Reels have been used successfully in aircraft for many years, but there are two major and significant differences between aircraft and automotive use which are not generally recognized: (1.) Since the aircraft is not normally subjected to the rapid braking decelerations like the automobile, the loadings at which activation occurs is greater. Usually this is at about 2g. in the aircraft reel, while in the automobile, reel activation must occur at much more sensitive settings, varying from 0.3 to 0.5g. (DOT Standard for inertia-reel activation states that this must not be over 0.5g., thus most reel manufacturers design for 0.3g. quality control to insure compliance); (2.) The state-of-the-art in achieving quality control for mass production of such devices has apparently not reached an accepted level of reliability. The 8.5 million cars (current annual production) for example, would require 30 to 40 million reels (including replacement stocks), compared to present aircraft needs of a few thousand, almost all of which are for military type aircraft. To date, no manufacturer has had experience in quality control for such mass production. The upper restraint inertia-reel for general aviation aircraft is still being evaluated by the Federal Aviation Administration Flight Standards Service. The aircraft type installation with the shoulder straps extending over the top and down behind the seat imposes loads at the top of the seat back, and would restrict adjustment and require major structural changes in present automobile seats, tie-down, and environmental structure. This can be avoided in automobiles by utilizing a roof attachment, but also requires adequate roof support to take the additional loadings.

To our knowledge, the only automobiles currently utilizing a yoke-type double-shoulder torso restraint with inertia reel are the specially modified Shelby Mustang GT 350 and GT 500 cars. These restraints, which were originally developed by Ford, have not had previous biomechanical evaluation. To date there have been no reports of accidents involving this type of harness system in automobiles, thus our knowledge is restricted to the anthropomorphic dummy tests previously conducted, and the current animal study.

The tests conducted with the yoke restraint consisted of three tests in the forward-facing ($-G_x$) 0°-0°-0° body orientation at 30, 43, and 49 peak g., and one side-facing (lateral 90°) test ($-G_y$) 0°-90°-0° at 32 peak g. (Table I). Respective entrance velocities ranged from 73.6 ft./sec. (50 mph) to 94.4 ft./sec. (64.5 mph), onset rates from 2,700 to 6,100 g./sec., and time plateaus from 0.045 to 0.060 second.

The 90° lateral impact was at a severe level, but due to the rebound of the subject's head

Table I - Yoke Restraint Tests, Physical Data Summary

Test	Daisy Test No.	Baboon No.	Wgt. (LBS)	Body Orientation Relative to Force Direction (1)	Seat Back Orientation (Angle) (2)	SLED						PEAK BELT FORCE (LBS)				
						Peak G	Ave G	Entrance Vel. (ft/sec)	Onset Rate (g/sec)	Time Duration (secs) Plateau	Time Duration (secs) Total	RT Lap Belt	Left Lap Belt	RT Diagonal	Left Diagonal	Yoke
1	3589	3346	30	90 Left 0-90-0	13^{o}	32	31	75.2	4300	0.060	0.093	960	360	450	---	950
2	3591	636	33.5	Forward 0-0-0	13^{o}	30	29	73.6	2700	0.054	0.094	440	440	420	360	---
3	3593	2605		Forward 0-0-0	13^{o}	43	43	88.0	5400	0.049	0.083	---	---	---	---	---
4	3605	2706	28	0-0-0	13^{o}	49	47	94.4	6100	0.045	0.073	780	650	490	420	---

(1) Forward Facing ($-G_x$)

(2) Relative to vertical

during impact into the plywood side panel, a fatal artifact was introduced. Radiographic studies revealed a comminuted fracture involving the cranial vault, with multiple fracture lines throughout the frontal-parietal area probably extending to both sides of the midline. Some of the fragments were separated by some 3 mm. No gross trauma to the neck was observed, although sub-clinical complaints could not be evaluated. In previous similar side impact tests at this level with both the European diagonal belt and the 3-point belt, fractured necks resulted from the impact. One might speculate that the less rigid yoke system may decrease the possibility of this type injury in side impact, assuming package space is available to minimize artifact.

The forward-facing yoke impacts were initiated at the 30g. level (where previous tests with other systems had shown injury becoming evident) and progressed to 49 peak g., far higher than was survivable for the unrestrained torso systems. In one forward impact at 43 peak g. (88 ft./sec.) a transverse fracture of the neck of the scapula, proximal to the glenoid process, occurred, with slight displacement. As shown in Table II, injuries were severe at 49g.

As expected, there was a general trend of increasing number and severity of trauma with increasing g. levels in this particular series. The type and degree of trauma experienced by the 49g. subject is rather severe, both in systemic function and integrity of supporting structures. In this particular case, it appears that the extensive structural trauma of the pectoralis muscles, superficial contusions over the shoulder, and abdominal areas and the partial dislocation of the humerus, were the direct result of restraint belt pressures produced at this relatively high g. level. As evidenced by this series of tests, the yoke-type restraint may cause distinctive injury patterns.

The occurrence of cardiac hemorrhage is of interest since it occurs in all test subjects, increasing in severity, like other injuries, with increasing g. levels.

Lung edema and hemorrhage were observed in all but one subject. Single cases of uterine congestion and adrenal hemorrhage occurred.

Belt forces were measured according to the technique previously described. These are listed in Table I. In Daisy runs Number 3589 (32g. side impact) and Number 3591 (30g. forward impact) strain gauges were attached to the lower portion of both lap belts and both torso belts. In addition, for these tests, a strain gauge was attached to the Y-yoke above the torso belt junction; however, due to the sensitivity of the inertia reel, the slight additional weight created belt slack and allowed the animal to slump forward. In the subsequent tests a yoke tension measurement was not attempted for this reason. Note that in the left-side impact the force on the right lap belt was nearly three times (960 lbs.) that on the left lap belt (360 lbs.). This corresponds with the ratios of the left-to-right belt forces previously found in side-impact tests. Note that in run Number 3591 (30g.) the lap-belt and torso-belt forces were fairly close, although in run Number 3065 (49g.) there was a wider discrepancy. Subsequent dummy tests by investigators at various laboratories, including Ford, General Motors, and the National Bureau of Standards, have also indicated that belt loads are often close for both lap and torso harnesses.

Table II - Yoke Restraint Tests, Medical Data Summary: Pathology

G	NUMBER	GROSS	MICROSCOPIC
30	3591	Dural Congestion	Cardiac Hemorrhage Lung Congestion and Edema
32	3589	Cranial Fracture Dural Hemorrhage Abdominal Contusions	Cardiac Hemorrhage Cerebrum Hemorrhage Lung Edema and Hemorrhage
43	3593	Dural Congestion Bilateral Contusions of Anterior Axillary Folds and Adjacent Deltoid Areas Abdominal Contusions Scapular Fracture	Lung Edema Cardiac Hemorrhages Uterine Congestion
49	3605	Dural Congestion Pericardial Hemorrhage Broad Ligament Hemorrhage Mesentery Hemorrhage Abdominal Wall Hemorrhage Bilateral Avulsion of the Pectoralis Major Muscles Incomplete Bilateral Avulsion of the Pectoralis Minor Muscles Bilateral Contusions of Shoulder-Neck Area Incomplete Displacement of Humerus	Adrenal Congestion and Hemorrhage Myocardial Fragmentation Pyknosis and Karyolysis of Nuclei of Myocardial Fibers

Note body kinematics in a 30g. impact as shown in Figure 4. Insufficient tests were made with this restraint system to provide statistically significant data. Yet, based upon relative comparisons with over 60 tests previously made with the baboon subject, in identical deceleration patterns, with various restraint systems, some valid general inferences may be made (Fig. 5). The yoke-restraint system tested has been demonstrated to offer relatively better protection for the subject than the lap belt alone, the European single diagonal belt, or the current 3-point system. This confirms previous studies conducted with anthropomorphic dummies. It also appears to be a more feasible restraint system than the seat-attached double-torso harness either with or without inertia reel retraction: in the first case because of the structural seat changes necessary due to the higher center of gravity loading, and in the latter case because of the loss of unrestricted motion for the fixed restraint occupant. In addition, the ease of placing and adjusting the overhead restraint system on the occupant, as well as comfort considerations (the torso belts go over the shoulders but slope to the sides by the lap belt, thus avoiding pressures or impingement over the breast area) and minimal distortion of clothing, have been demonstrated by previous human subjective tests, but were items not within the scope of these tests.

B. *Air Bag Tests:* The physical data for the nine air-bag tests conducted with seven baboon subjects are presented in Table III. All tests were in the forward-facing body orientation, with seat pan 13° relative to the horizontal. Entrance velocities varied from 71 to 94.2 ft./sec. (or 48 to 64 mph), and onset rates from 3,300 g./sec. to 6,000 g./sec. Total deceleration time durations of 0.059 second to 0.091 second were recorded. These patterns were as close to the actual automotive crash profiles as was possible to achieve with this particular weight (4,500 lbs.) sled used on the Daisy Decelerator.

As with the yoke series, initial tests were at 30g. (average). Each level of force magnitude above this pattern was probed for subjective non-reversible tolerance effects prior to proceeding to a higher level. In this regard, one Ippolito

Table III - Airbag Restraint Tests, Physical Data Summary

Test	Daisy Test No.	Baboon No.	Wgt. (LBS)	Body Orientation Relative to Force Direction (1)	Seat Back Orientation (Angle) (2)	SLED Peak G	Ave G	Entrance Vel. (ft/sec)	Onset Rate (g/sec)	Time Duration (secs) Plateau	Total	PEAK BELT LOADS (LBS) RT Lap Belt	LEFT Lap Belt
1	3595	2675	33.5	Forward 0-0-0	13^{o}	33	30	71.0	3300	0.060	0.091	450	450
2	3597	2075	34.0	0-0-0	13^{o}	36	33	74.0	3700	0.056	0.086	410	$360^{(4)}$
3	3598	-(3)	15.5	0-0-0	13^{o}	46	37	85.6	4900	0.047	0.076	410	375
4	3599	-(3)	15.5	0-0-0	13^{o}	46	37	85.1	4600	0.052	0.081	300	240
5	3600	-(3)	15.5	0-0-0	13^{o}	50	39	86.0	5600	0.048	0.074	330	300
6	3601	---	20.5	0-0-0	13^{o}	47	37	85.4	5300	0.047	0.075	360	420
7	3602	---	25.0	0-0-0	13^{o}	47	42	85.7	4900	0.046	0.075	600	$600^{(5)}$
8	3603	---	22.0	0-0-0	13^{o}	55	50	94.0	6000	0.040	0.059	640	600
9	3604	---	26.5	0-0-0	13^{o}	57	50	94.2	5900	0.051	0.079	540	$510^{(5)}$

(1) Forward Facing ($-G_x$)
(2) Relative to vertical
(3) Same animal
(4) Allowed to survive 12 weeks post-impact prior to autopsy
(5) Allowed to survive four weeks post impact prior to autopsy

Table IV - Airbag Restraint Tests, Medical Data Summary: Pathology

G	NUMBER	GROSS	MICROSCOPIC
33	3595	DURAL CONGESTION	
46	3598*	DURAL CONGESTION BLADDER RUPTURE	BLADDER HEMORRHAGE
47	3601	DURAL CONGESTION	LUNG HEMORRHAGE AND EDEMA PANCREAS HEMORRHAGE ADRENAL HEMORRHAGE
47	3602		LUNG ATELECTASIS WITH EMPHYSEMA FRAGMENTATION OF VENTRICLE GLOMERULITIS PIGMENT LADEN MACROPHAGES IN SPLEEN
55	3603	DURAL CONGESTION BROAD LIGAMENT HEMORRHAGE	
57	3604	LUNG CONGESTION LIVER CONGESTION	PULMONARY EDEMA LUNG ATELECTASIS WITH EMPHYSEMA PIGMENT LADEN MACROPHAGES IN LUNG & SPLEEN

* SUBJECT WAS IMPACTED THREE CONSECUTIVE TIMES AT THIS G LEVEL. PATHOLOGY IS ACCUMULATIVE.

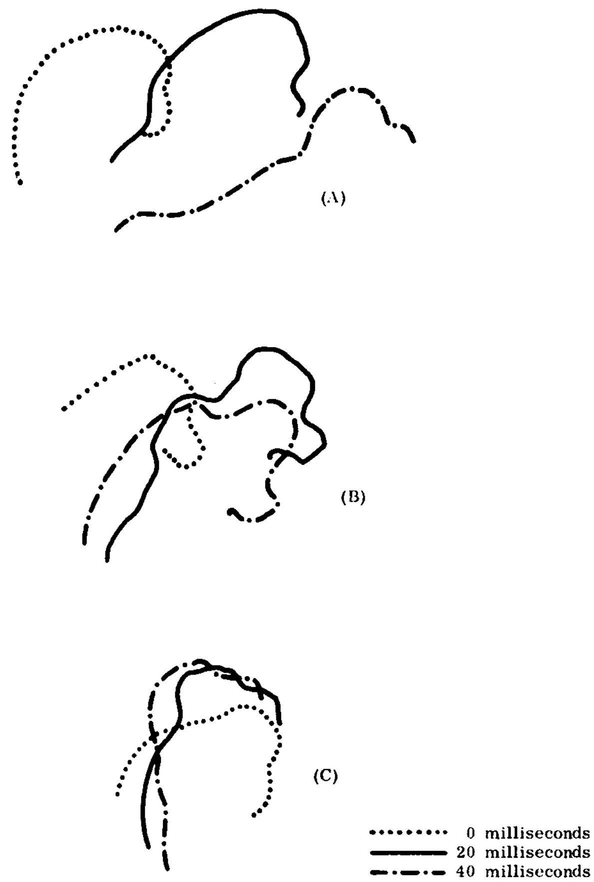


FIGURE 4. A comparison of the body kinematics with (A) lap belt only, (B) yoke harness, and (C) air-bag restraint system at 30g. impact; at 0, 20, and 40 milliseconds of body deceleration time.

high-speed motion picture film was wet-read immediately post-impact, and a physical examination was made of the subject. Paired tests were made at 30g., 42g., and 50g. average sled loads, with one subject immediately terminated post-impact, and the other allowed to survive. In the latter case two were observed for 4 weeks prior to autopsy, and the third for 12 weeks.

Necropsy protocols were completed in each case utilizing techniques of both gross anatomical examinations by dissections and microscopic analyses of histological samples. Table IV summarizes the medical findings.

In general, it is extremely difficult to assess the significance of observed pathology to evaluate restraint functions. In previous studies a number of specific traumas have been observed to occur and have no correlation with basic environmental factors or changing environmental conditions. There appears, however, to be a generalized trend of characteristic pathology that corresponds to certain experimental conditions of impact. This phenomenon has been demonstrated, in part, during the course of this and related studies using the baboon subject.

Dural congestion and/or hemorrhage was observed in all yoke tests from 30 to 49 peak g. exposures (Table II). Similarly, this condition was observed in all air-bag restraint test subjects that were terminated immediately post-impact for autopsy procedures. Exposure levels for these particular tests were 33 to 55 peak g. loads and extended to 57g.'s for the entire air-bag series. Two subjects from the air-bag series, having no apparent clinical difficulties, were placed under observation for a 4 week post-impact period then terminated to complete necropsy protocols. It is interesting to note that one subject demonstrated only questionable evidence of dural trauma, while no evidence of congestion or hemorrhage appeared in the other even though these subjects had been exposed to the higher 47 and 57g. loadings, respectively. A third subject, impacted at 33g., and not observed to have any injury, was monitored for 3 months prior to termination. Upon autopsy no trauma (or dural congestion) was found. Since we have observed a high frequency of dural congestion and hemorrhage in previous baboon impacts of 16g. to 55g. peak levels, we may tentatively suggest that this condition is typical but transient in nature. If our conclusion is valid, this condition would not be a useful criterion in restraint system evaluation.

The summary of medical data for the air-bag restraint subjects (Table IV) relates the degree of increasing trauma severity to increasing g. levels. Dural congestion, as expected, was present in all subjects terminated immediately post-impact and the regional congestion of the lungs and liver in one subject, which may or may not be typical, was still apparent 4 weeks post-impact. Identical lung and spleen pathology was demonstrated in both subjects terminated 4 weeks post-impact: atelectasis with emphysema and edema in the lungs and occurrence of pigment-laden macrophages in the spleen. In addition, glomerulitis was apparent in the 47g. subject. The bladder of a 46g. exposure subject was ruptured and another exposed to 47g. experienced hemorrhage in certain lung areas, pancreatic, and adrenal tissues.

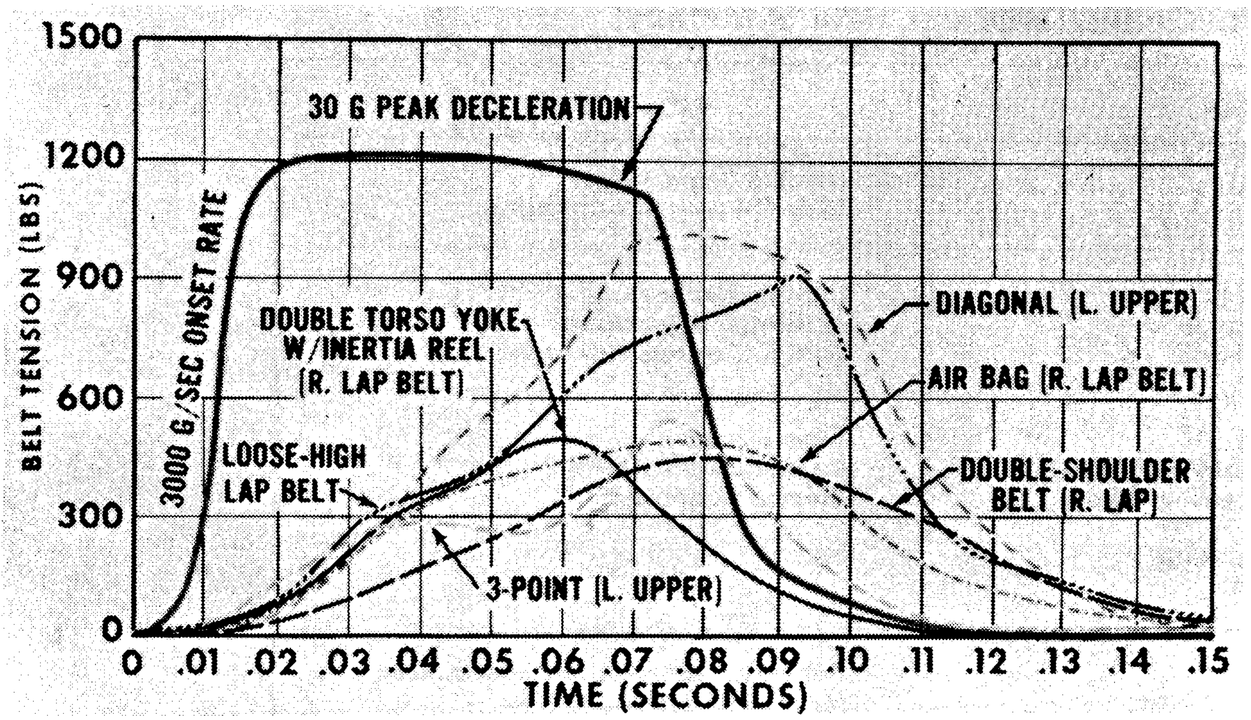


FIGURE 5. Comparison of belt loads in baboon subjects; 30g. impact with six restraint systems.

The significance of these injuries is probably related to the g. exposure levels since gross structural damage, internally and superficially, was not evident. It is interesting to note that subject Number 3598, exposed to 46g. was exposed to this g. level in three consecutive impacts at 60- and 45-minute intervals. Although this subject sustained a ruptured bladder, which is considered serious, the only other pathology was the typical dural congestion. Anterior-posterior and lateral view radiographic studies of the thorax, abdomen, pelvis, neck, skull, and extremities revealed no evidence of skeletal injury.

To reinforce the macroscopic and microscopic autopsy data, brain tissue was further studied at the cellular level through electron-microscopy, which confirmed the trauma indicated in Table IV.

To search for further biochemical indicators of impact stress or damage to body tissues as a result of these tests, blood samples were taken from 5–10 minutes prior to impact, 5–15 minutes post-impact, and in the case of the three animals observed 4 and 12 weeks post-impact, at 7-day intervals for 1 month. The hematology is summarized in Table V. Specific techniques employed are those provided in detail in the study of Life,[33] and general methods are as previously noted in the materials and methods discussion. Although the sample was too small to be statistically significant, some trends should be pointed out.

Glucose is grossly elevated in stress as a result of sympathetic mechanisms. The three animals observed for 1 to 3 months post-impact clearly reacted to the pre-impact handling as a stressful event; gluclose was greatly elevated over its normal level of about 100 mg. percent. After impact it went even higher, to fall again sharply post-impact. The abnormally high CHO figures for the other blood determinations are probably an artifact of the time involved in shipment of these particular blood samples, since a dilution error was not probable.

In the three animals observed long term, hemoglobin (mg. %) values were observed to rise post-impact, and it is hypothesized that this is a compensatory event secondary to traumatic injury. Red blood cells in this series were reduced post-impact, except for a rise observed in one animal (Number 3597), which might be attributed to a compensatory release of RBC's from reserves. Changes in circulatory ionic calcium (as a result of trauma) may be produced either by blood loss or trauma to hard tissue. Since the elevation in blood calcium seems highest

Table V - Hematology Summary

Sample Identification		Total Protein gm %	Calcium mg %	Lee-White Time (Min.)	Hemoglobin hg mg %	Bilirubin mg %	Acid Phosphatase ul %	Alkaline Phosphatase ul %	RBC $10^3/mm^3$	White Blood Cells $10^3/mm^3$	Glucose (CHo) mg %
A. TERMINAL AIR BAG TESTS (Animal terminated immediately post-impact)											
3595	Pre-Impact	7.15	4.63			0.56	0.82	1.54			319.7
3595	Post-Impact	5.23	2.94			0.55	0.64	2.71			268.3
3603	Pre-Impact	5.67	3.86			3.70	0.51	4.71			240.5
3603	Post-Impact	7.15	3.86			0.56	0.51	5.06			251.6
3598	Pre-Impact	5.18	3.86			10.0	0.74	5.49			240.2
B. CHRONIC AIR BAG TEST (Animal allowed to survive post-impact)											
3602	Pre-Impact	6.16	3.86			11.1	0.42	2.67			277.5
3602	Post-Impact	6.16	4.29			11.1	0.41	2.72			284.9
3602	Post-One Week (6/16/67)	5.38	4.68	18.0	9.3	0.32	0.53	3.74	7.9	9.5	64.5
3602	Post-Two Weeks (6/23/67)	4.73	5.40	6.5	8.7	0.41	0.57	3.13	4.5	6.7	53.3
3602	Post-Three Weeks (6/30/67)	4.58	4.53	-	10.5	0.68	0.93	3.03	5.1	6.3	80.5
3604	Pre-Impact	4.68	3.68			2.50	0.61	3.26			206.5
3604	Post-Impact	4.68	3.31			1.98	0.74	3.33			304.1
3604	Post-One Week (6/16/67	4.33	2.26	6.0	7.8	0.11	0.49	3.80	5.0	8.3	90.7
3604	Post-Two Weeks (6/23/67)	6.48	5.20	8.5	8.2	3.22	0.80	5.11	3.5	10.9	74.2
3604	Post-Three Weeks (6/30/67)	4.23	3.35	3.5	9.4	0.28	0.79	5.06	3.7	12.0	83.1
3597	Pre-Impact	4.68	3.12			0.93	0.71	2.53			240.2
3597	Post-Impact	6.16	2.94			3.47	0.43	2.80			271.8
3597	Post-One Week (6/16/67)	5.36	6.36	10.0	9.5	0.38	0.44	2.85	3.8	5.9	53.4
3597	Post-Two Weeks (6/23/67)	7.02	8.36	3.5	10.9	0.44	0.76	3.41	7.0	7.8	61.5
3597	Post-Three Weeks (6/30/67)	3.96	3.99	1.0	13.4	7.76	0.40	2.62	3.0	5.5	70.4
C. TERMINAL YOKE RESTRAINT TESTS											
3605	Pre-Impact	5.03	5.15			3.85	0.38	1.66			251.7
3605	Post-Impact	5.67	2.83			0.00	0.38	1.07			275.9

at the second week post-impact it would appear that in this case the rise was due to bone tissue damage and repair rather than to extensive blood loss and consequent ionic shift. No consistent pattern in acid photophatase is evident, though a general elevation can be discerned. This elevation might be the effect of the release of this substance from RBC's (where it is known to be in high concentration) as a result of hemolytic trauma. Alkaline phosphatase, an indication of hard tissue change, is usually elevated in bone diseases and injury. One possible reason for the elevation noted is the extrusion of the enzyme from the injured bone tissue. Another possibility is the over-production of the alkaline phosphatase enzyme in compensatory repair. Elevated levels are seen in all animals in this series, perhaps indicating that injury and repair to bony tissue occurred. Bilirubin elevated levels in trauma are evidence of either (or all) of the following: RBC breakdown usually as a function of hemorrhage; hepatic injury; destruction of muscle tissue. The pattern observed in these cases is not clear, since usually bilirubin is normally low pre-impact, and elevated post-impact. This was observed only in animal Number 3597.

Lee-White coagulation times for the chronic tests were high in each animal post-impact. By 3 weeks, post-impact coagulation times had decreased to normal range. Apparently the coagulation mechanisms were altered by the impact stress, but what the modification was is not now known. As an indication of the inflammatory stress reaction, one would expect white blood cells to rise sharply post-impact. However, no trend was discernible in the WBC data obtained here. Changes in total plasma protein as a consequence of trauma is due to release of fibrinogen, RBC destruction, and soft tissue disruption. Elevation of these values was observed in Number 3597 and Number 3604, suggesting such traumatic sequelae in these subjects. An unexplainable decrease was found in animal Number 3602.

These values have been compared to mean hematology and blood chemistry values for 201 baboons studied by de la Peña and Goldzieher,[18] but due to a number of differences in obtaining blood samples between our series and theirs, no conclusions may be drawn at this time.

Body kinematics during impact are of special interest in restraint system evaluation. As shown in Figure 4, in contrast to other restraint systems tested, the upper thorax and head are pushed back by the opening air bag while the lower torso moves slightly forward. Figure 6 shows one animal in position prior to the run. Note that the restraint over the back of the seat was released 0.6 second prior to impact by mechanical means, and the masking tape used to hold the animal in position also breaks at impact. Figure 7 shows inflation of the air bag at the moment of impact. Figures 8 and 9 show the subject position immediately post-impact and regaining an upright position by 20 seconds post-impact. One important feature observed in the use of this system in contrast to all other restraint systems previously tested, was that subjects appeared to make almost immediate recovery from impacts even up to 57g. Motion of the arms was observed within 10 seconds, and within 20 seconds body response occurred, with the animal rapidly appearing alert. In contrast, subjects appeared "stunned" by the impact at half this force in other systems. In aircraft particularly, this feature might have critical evacuation implications. Analysis of individual sequential frames of the high-speed 16 mm. motion picture films indicates clearly that the subject is well restrained in an upright position during the impact, although the air bag obscures portions of the subject during the deceleration. Rebound effect did occur in these tests, and in several instances the animal's head hyperextended to the side of the seat as it rebounded back against the seat, missing it partially to the right. In an actual automobile seat this might be inconsequential, and was not observed to produce direct injury. It should be noted, in all fairness, that although considerable research has gone into volumetric requirements, gaseous compositions, exhaust port sizing, and materials to produce the most optimum air bag for human use, the scaled-down versions used in these tests were constructed in 48 hours prior to delivery and the ports exhaust requirements were estimated. All air bags in these tests performed as designed.

IV. Results

With regard to the air-bag study described above, it must be emphasized that our tests have only attempted to probe one aspect of this restraint's effectiveness. There are a number of unknowns for which data must be obtained before a realistic evaluation can be made. Some

FIGURE 6. Air-bag restraint system in position prior to run. Note that restraint over back of seat is released 6 secs. prior to impact, and masking tape about chest breaks. Both hold animal in normal seated position during run, but are released at impact.

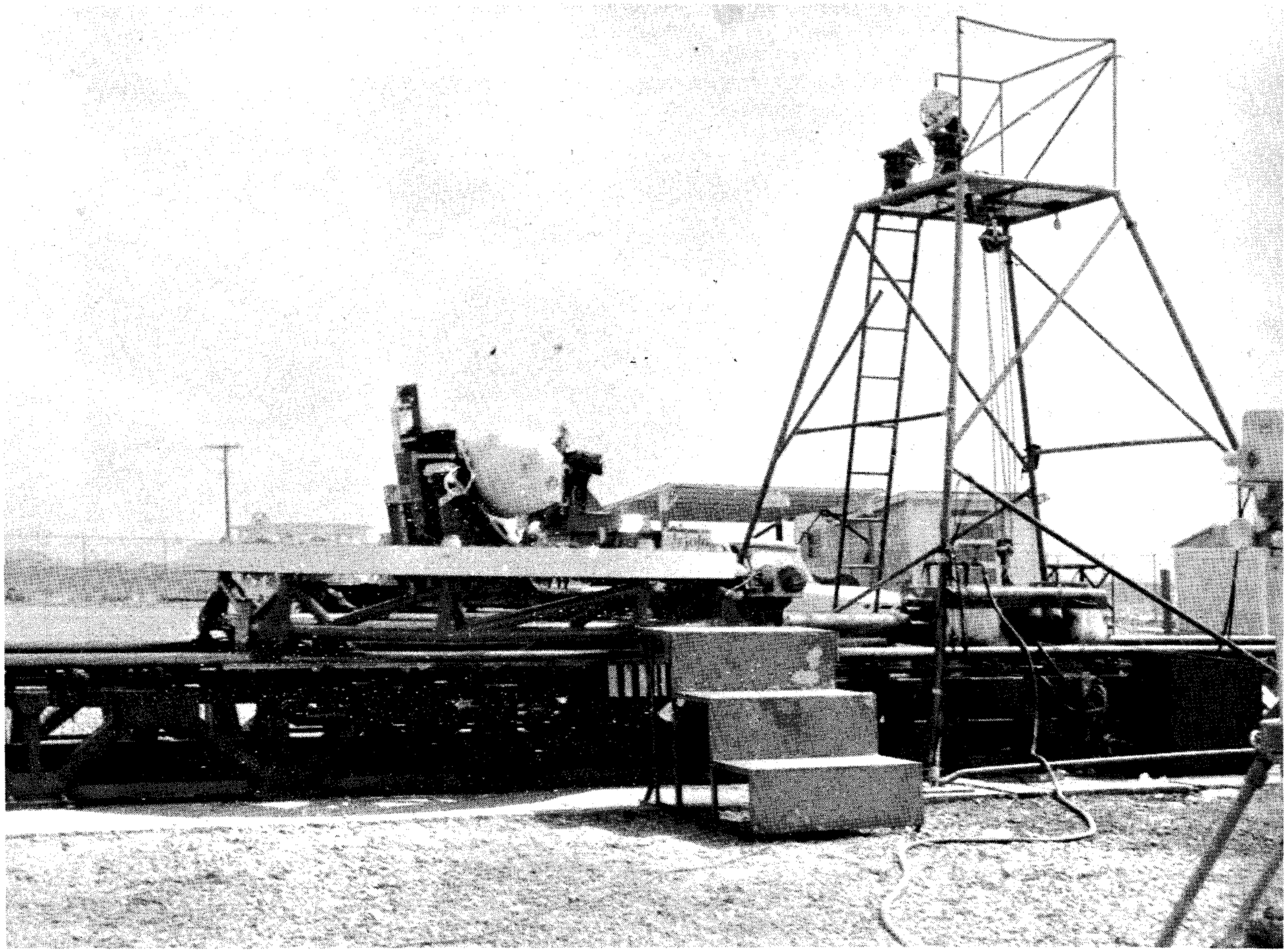
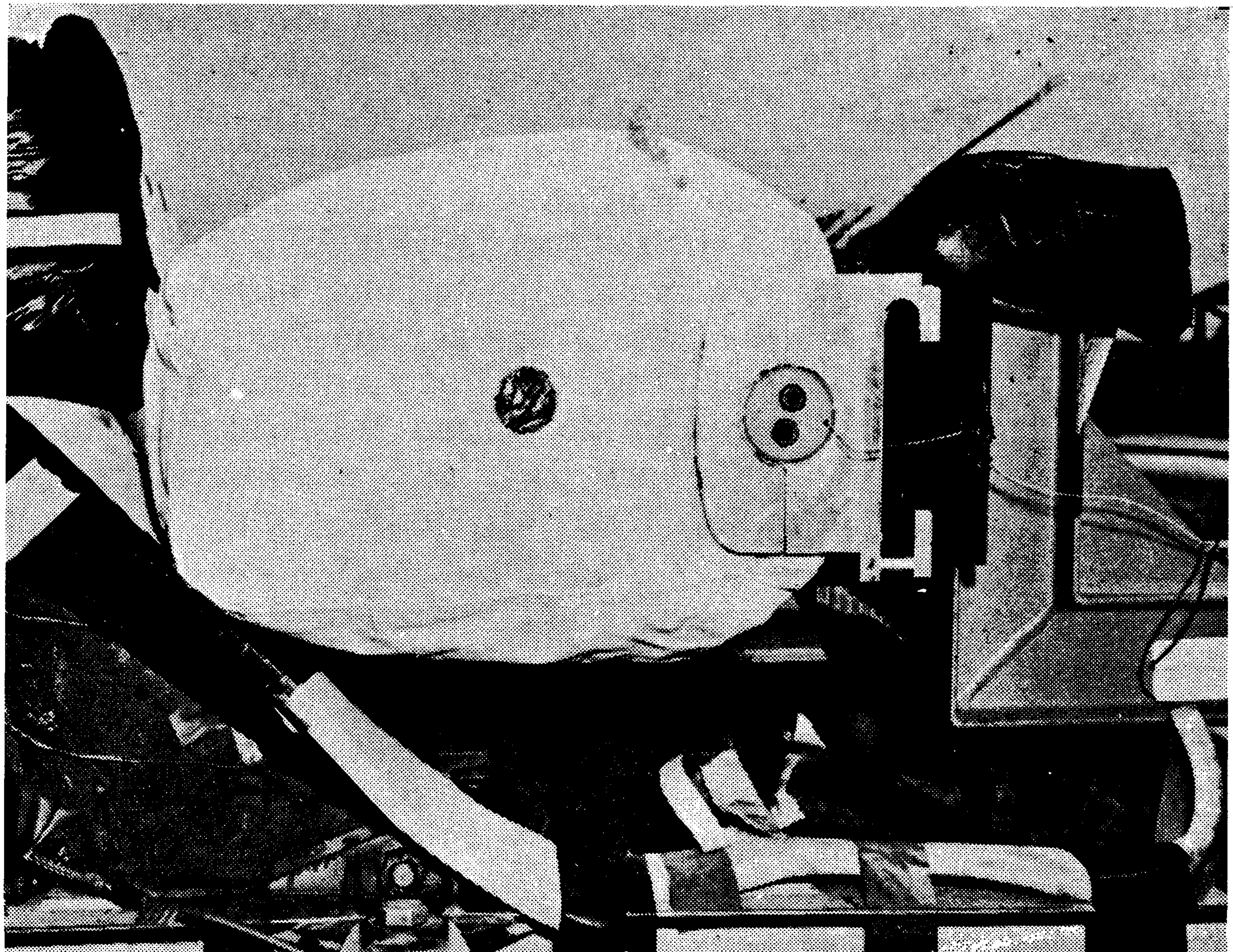


FIGURE 7. Air-bag restraint test at moment of impact and inflation



FIGUGE 8. Air-bag immediately post-impact in fully inflated contour. Subject has been restrained by bag during 50g. deceleration and released as gas escaped from ports. Within 20 secs. subject will be upright and alert, and within 10 secs. will show motion.

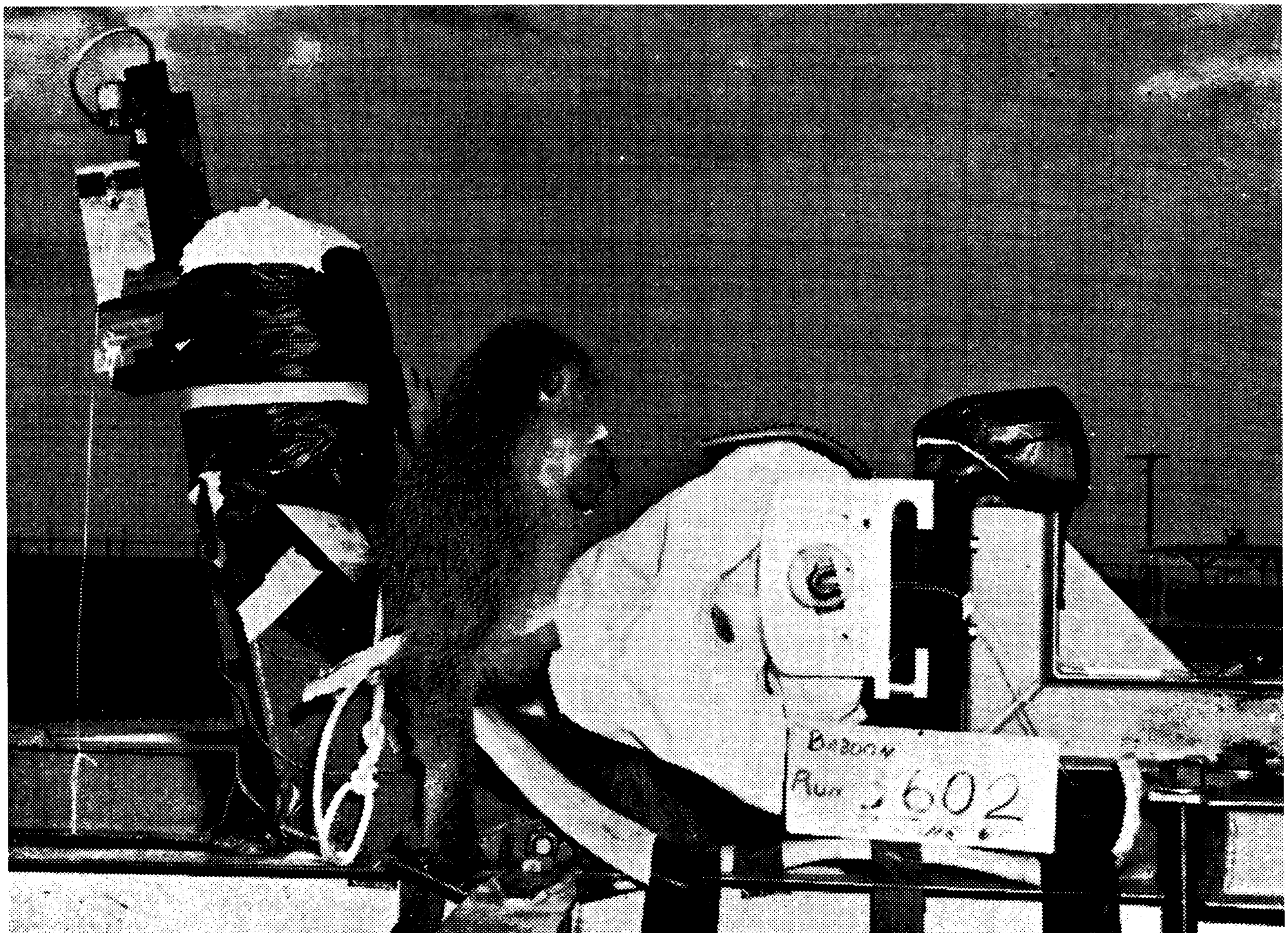


FIGURE 9. Air-bag test 20 secs. post-impact, showing typical recovery of subject after 47g. impact.

of these factors would include system reliability, blast effects (over-pressures on the eardrum), and other injury potentials, as well as engineering factors still to be resolved.

V. Summary

The limited nature of this study suggests only tentative conclusions which must be confirmed by more extensive biomedical investigation. Nevertheless, these tests have demonstrated:

A. *Air Bag Restraint System:*

1. Paired baboon subjects survived impacts from 33 to 57 peak g. (64 mph impact velocity) at an onset rate of 5,900 g./sec. for 0.079 second total duration. Although evidence of lung, pancreatic, and adrenal hemorrhage was produced in one animal impacted at 47g., and a significant bladder hemorrhage and rupture in a second animal impacted three times at 46, 46, and 50 peak g. (accumulative), a third 47g. impact resulted in no evidence of clinical trauma whatever. Gross injury at 55 and 57g. was not felt to be significant.

2. While injury was thus demonstrated to occur with this type of restraint, it must be pointed out that the magnitude of force tested was in excess of that which produced fatal injury (about 40g.) in other systems tested, and the maximum protective tolerance level was not reached for either nonreversible injury or survival.

3. Post-impact observation of three animals for 4 to 12 weeks (of the paired tests, with one at each level being terminated immediately post-impact) suggested that biochemical changes consistent with stress and tissue trauma occurred but were not conclusive nor of a statistically significant nature due to insufficient sample.

4. Dural congestion, evident in four of six animals autopsied immediately post-impact in air-bag tests and in all four yoke restraint tests, was not observed in the two animals autopsied 4 weeks nor one animal autopsied 3 months post-impact. This suggests that this brain injury typically observed immediately post-impact is reversible.

5. Belt loadings (of lap restraint) were half normal loads occurring with lap belt and in no cases were belt contusions evident.

6. Rebound effect may occur and the air bag system exhaust deflation capability should be considered.

7. All subjects moved within 10 seconds of impact and were alert and active within 20 seconds of impact. In comparison, no other system tested to date resulted in such immediate subject recovery post-impact. This may have important implications where immediate evacuation is important, provided that the deflated bag does not become an obstacle.

8. Kinematic review of the high-speed movies suggests that a concave shape to the expanded air bag might provide additional directional stability as the subject is decelerated.

9. Future tests should be conducted in a closed environment and directed toward investigation of physiological effects of acoustics and blast upon the organism.

B. *Inertia-Locking Reel Inverted-Y Yoke Torso:*

1. The yoke restraint system with inertia reel offered relatively better restraint than the lap belt alone, the single diagonal belt, or the 3-point system.

2. In the forward-facing position tests were survivable (with reversible injury) at 43g., but appeared marginal for survival at 49g. Marked contusions from the webbing were observed.

3. The documentation of myocardial fragmentation (transverse rupture of muscle fibers) observed in the 49g. level exposure, suggests a rather significant departure from other types of cardiac damage (microhemorrhage) in terms of severity.

4. In all four tests conducted with this system, the inertia reel locked satisfactorily at impact. However, in two of the four tests the reel base was deformed by the force of the impact and made the reel inoperable until repaired.

5. Distribution of impact loads were nearly equal between the lap and shoulder belts, thus suggesting that upper torso webbing strength should be as strong as lap belt webbing.

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