J. Biomechanics, Vol. 3, pp. 223–227. Pergamon Press. 1970. Printed in Great Britain

THORACIC FORCE-DEFLECTION STUDIES IN PRIMATES*†‡

DAVID L. BECKMAN and MARVIN F. PALMER

Highway Safety Research Institute, The University of Michigan, Ann Arbor, Mich. 48105, U.S.A.

Abstract—Thoracic force-deflection characteristics have been measured in the living sub-human primate as a step towards the analysis of cardio-thoracic injuries. Mechanisms of injury were investigated by subjecting Rhesus monkeys seated on a sled to static and dynamic chest displacements (24 tests) by means of a charge fired projectile equipped with a 3 in. dia. impact plate and compensated strain gauges. Forces up to 30 lb were developed in the static press tests for 2 in. deflections. Dynamic tests were run with similar deflections at 3 different initial impact velocities: 36–45 ft/sec, 43–57 ft/sec and 65–85 ft/sec with corresponding peak forces at 80–245 lb, 150–370 lb and 410–700 lb.

The thorax of the Rhesus monkey thus shows a very low linear stiffness under static loading but then exhibits a progressive change with increasing velocity, showing more of a spring-mass-like response with an initial linear region of stiffness followed by a pronounced drop off. These data may thus help explain the wide disparity noted between human thoracic behavior during closed chest heart massage and that noted in full scale cadaver tests.

INTRODUCTION

In order to investigate more thoroughly the mechanisms of cardio-thoracic injury, a series of 24 experiments were performed to determine the thoracic force-deflection characteristics of the sub-human primate. Static force-deflection data is compared to changes induced by dynamic inputs in 168 measurements at several velocities.

Previous investigators (Patrick, Kroell and Mertz, 1966; Kroell and Patrick, 1966) reported on static and dynamic chest force-deflection testing of cadaver material. In these studies, curves from static tests were relatively linear for loads up to 180 lb with a 1-in. chest deflection. Dynamic loading at speeds between 16½ and 22½ m.p.h. resulted in forces over 2500 lb for a 3-in. chest deflection. The dynamic curves were fairly linear for deflections up to 1½ in. Gadd and Patrick (1968) reported on the value of system tests vs. laboratory impact procedures when studies of force-deflection characteristics of cadavers are to be applied directly to the design of steering systems. The 'wrap-around' of the shoulders and upper limbs greatly reduced the loading which otherwise would be taken by the chest alone.

Studies of correlations between cadaver and *in vivo* results have indicated that the relationship between the 2 types of experimental subjects must be carefully evaluated if cadaver test results are to be used for evaluating the *in vivo* situation (Roberts and Lissner, 1966; Life and Pince 1967). Although cadavers provide the appropriate size and shape for impact studies, the tissue response to static and dynamic loading has been shown to vary somewhat and make direct projections from cadaver to living man difficult. The use of the living primate may help to bridge the gap when scaling techniques are put to their best use. In this preliminary work only Rhesus monkeys have been studied but the results should serve as a step towards validating calculations for the living human response.

METHODS

Thoracic force-deflection data was recorded from Rhesus monkeys (*Macaca mulatta*, male, weight 3·1–4·7 kg) impacted in the thoracic area (24 tests, 168 measurements)

**Received* 22 *January* 1969.

†Presented at the ASME Third Biomechanical and Human Factors Division Conference at the University of Michigan, Ann Arbor, June 12–13, 1969.

‡Supported by USPHS Grant SM-16912-01.

by means of a modified cartridge firing Remington Humane Stunner, Model 412-A (Fig. 1). The stunner was modified so that a tubular sleeve which served as the impactor fitted over the normal stunner rod and was fired as a free missile. To the end of the sleeve was attached a force transducer and a 3 in. dia. flat impact plate. The output of a built-in accelerometer was adjusted and subtracted electrically from the force transducer output to compensate for the force necessary to accelerate the mass in front of the transducer.

The dynamic output of this arrangement, then, was a measure of only the force on the impact head. Photodiode, light, and film strip combinations were used to monitor the movement of the impactor, sled and monkey. High speed photography was used as a check on this system, and movement of the monkey was allowed for in the final force-displacement calculations. A strain gauge tension transducer monitored respiration. The various signals were recorded with a Honeywell electronic medical system. In addition, the force and deflection measurements were recorded with a Tektronix oscilloscope in order to expand the time base.

The primates, deeply anesthetized with Sernylan* (phencyclidine hydrochloride) and Sodium pentobarbital, were seated against a solid backrest on a freely moveable sled†.

A static force-deflection test was performed by forcing the stunner plate step-wise into the monkey's chest while held in place. Each primate was then hit three times progressing from a low to a high velocity impact. For the dynamic impacts, the gun was placed 1–3 in. away from the chest to insure that the impactor acted as a free missile with no additional force supplied by the gun. The impactor or sleeve mass of 0·84 lb was not varied throughout these experiments; the impact plate was centered in front of the thorax. The interval between impacts was determined by the length of time required for respiration and the electrocardiogram to return to an approximately normal state; this usually varied between 5 and 30 min.

RESULTS

Force-deflection curves have been determined for Rhesus monkeys at 3 different velocities of impact and under static conditions. One set of force time curves are given as a typical example (Fig. 2). A peak force of 130 lb was developed at the low velocity impact, 300 lb at the intermediate velocity and 570 lb at the highest velocity. The maximum force developed in the static deflection test was 30 lb (Fig. 3). Similar values were

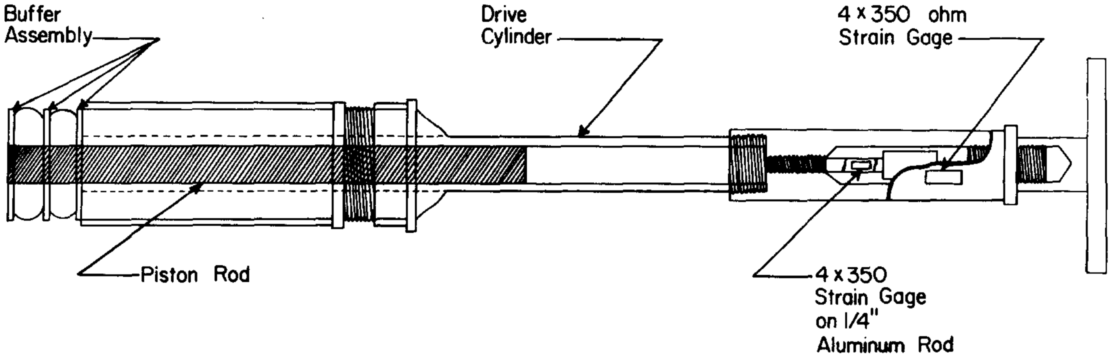

Fig. 1. Modified humane stunner (Model 412-A).

---

*Mfg. by Parke–Davis.

†These experiments were conducted in accordance with the 'Principles of Animal Care' established by the National Society for Medical Research.

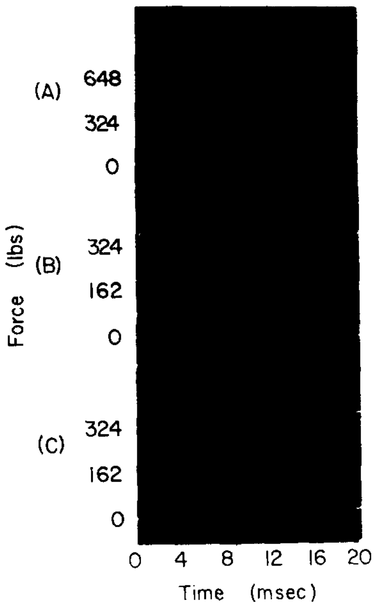

Fig. 2. Force-time curves for monkey #6. (A) Initial velocity 90 ft/sec. (B) Initial velocity 57 ft/sec. (C) Initial velocity 43 ft/sec.

obtained for the other primates used in this study (Table 1). The data for all Rhesus monkeys are presented by the force-deflection curves (Fig. 3). Appropriate allowance was made when necessary for movement of the monkey during dynamic force-displacement measurements.

The graphs of static curves consistently revealed low peak forces for relatively large deflections. Peak forces remained below 25 lb for chest deflections up to 1½ in. and began to rise somewhat sharply after 2 in. to reach a final peak at less than 100 lb force. Under dynamic conditions at the minimum velocities ranging from 36 to 45 ft/sec at impact (Table 1) there was considerable variation in the shape of the curves. Most curves reached a peak force after 0·3–0·9 in. deflection and then gradually decreased. All the curves but one, #6, reached a force peak below 200 lb.

At the medium velocities which ranged from 45 to 57 ft/sec the curves were quite similar in appearance to those at the lower velocity and reached a peak between 150 and 400 lb

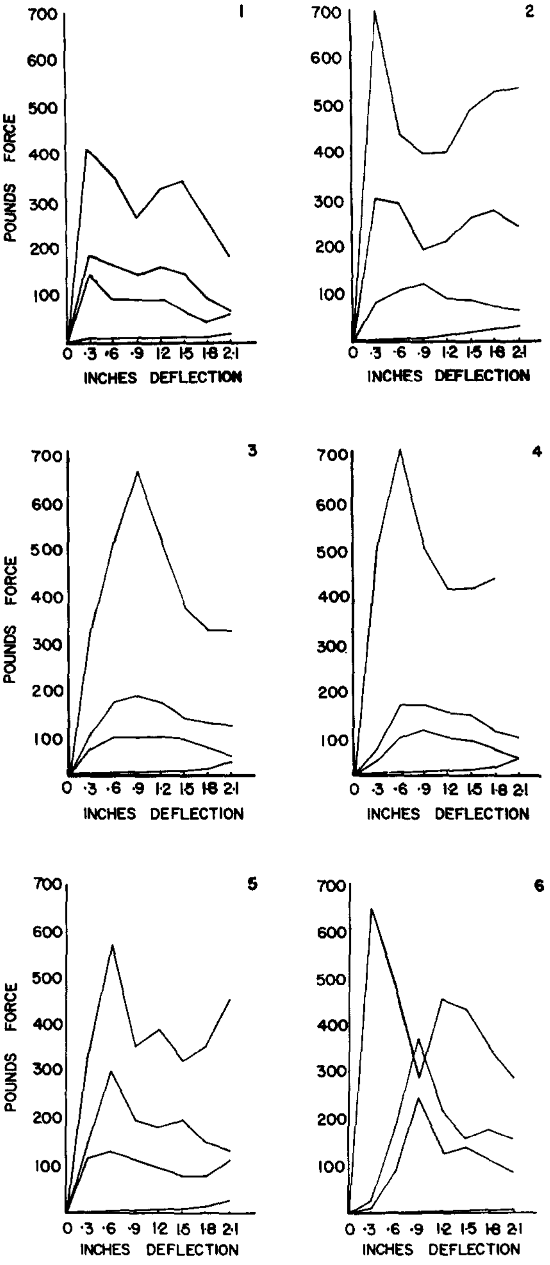

Fig. 3. Force-Deflection curves for six Rhesus monkeys. Curves on each graph are in ascending order of velocity increases:

Lowest curve corresponds to static tests. Next curve up corresponds to the lowest velocity dynamic measurement. Third curve from bottom corresponds to the medium velocity measurement. Highest curve corresponds to the greatest velocity.

Table 1. Impact and force-deflection data

Monkey	Body wt. (kg)	Max. initial velocity of impactor (ft/sec)	Max. force (lb)	Energy $\frac{1}{2}mV^2$ (ft-lb)	Phase of respiratory cycle at impact	Sled velocity (ft/sec)
1	3·8	Static	28	—		0
		36	137	17	Mid. exp.	1·6
		45	186	27	Begin insp.	2·0
		65	410	55	Begin insp.	3·0
2	4·7	Static	36	—		0
		36	114	17	End. exp.	1·5
		57	300	43	Mid. insp.	2·4
		83	700	91	Mid. insp.	3·8
3	4·4	Static	25	—		0
		34	80	15	End insp.	1·5
		47	165	29	Mid. exp.	1·9
		86	650	97	Mid. insp.	4·2
4	4·2	Static	36	—		0
		34	95	15	Mid. insp.	1·4
		43	150	24	Mid. insp.	1·7
		86	700	97	Mid. insp.	3·8
5	3·1	Static	30	—		0
		43	130	24	End insp.	2·1
		57	300	43	Begin exp.	3·0
		90	570	103	End insp.	4·7
6	3·1	Static	18			0
		45	245	27	Mid. exp.	2·2
		57	370	43	Begin exp.	3·3
		83	650	91	End exp.	4·4

force. Five out of 6 of the curves reflected two peaks, with the first somewhat higher than the second. The highest velocity impact curves, which ranged from 65 to 90 ft/sec, differed considerably in shape with 4 out of 6 showing a double peak. Peak force values were between 400 and 700 lb.

The phase of respiration was at random during the dynamic deflections but was recorded (Table 1). During the static deflection test, the monkey continued to breathe until the range of maximum deflection was reached, at which point respiration was usually not possible.

DISCUSSION

In order to investigate the mechanisms of cardio-thoracic injury, a series of 24 preliminary experiments were performed on anesthetized Rhesus monkeys to determine the thoracic force-deflection characteristics. These preliminary findings do not readily lend themselves to statistical treatment; however, it is felt that certain trends expressed in the results have developed and are pertinent in view of the paucity of available information in this area.

Experiments were performed with the primates seated in a moveable sled to permit the recoil of the sled and monkey, thus minimizing excessive cardiac injury. It is clear that allowance would have to be made for any movement of the monkey during impact in order to determine the actual chest wall deflection. The high speed photography consistently indicated that there was less than 0·1 in. movement of the back of the monkey during the first 2 in. of chest deflection as plotted in Fig. 3. In addition, most of this displacement occurred near the end of the curves, thus being a relatively insignificant factor in the data.

The phase of the respiratory cycle did not appear to affect the force-deflection data. Taking, for example, the low velocity impact data from monkeys 1 to 4 where initial velocity is relatively consistent (range 34–36 ft/sec), maximum force developed related to the phase of respiration in ascending order of force is as follows: 80 lb – end insp. (inspiration); 95 lb – middle insp.; 114 lb – end exp. (expiration); 137 lb – middle exp. Other values also appeared to be scattered, generally negating the influence of respiration in these studies. It is possible that the unusual anatomy of the Rhesus monkey, which reportedly does not have an operational glottis, may help to serve as a partial explanation for the apparent lack of respiratory effects.

A wide disparity has been noted between human thoracic behavior during closed heart massage and full scale cadaver tests. This difference is apparently due in part to the differences in tissue response in the living and embalmed state and perhaps, as these data suggest, (Fig. 3) due even more so to the change in stiffness exhibited under conditions of low and high velocity loading.

REFERENCES

Gadd, C. W. and Patrick, L. M. (1968) System vs. laboratory impact tests for estimating injury hazard. *SAE Paper* No. 680053.

Kroell, C. K. and Patrick, L. M. (1966) A new crash simulator and biomechanics research program. *Proc. 8th Stapp Car Crash Conf.*, pp. 185–228.

Life, Jeffry S. and Pince, Bruce W. (1967) Comparative response of small and medium sized primates, both live and embalmed, to impact stress. *Proc. 11th Stapp Car Crash Conf.*, pp. 136–152.

Patrick, L. M., Kroell, C. K. and Mertz, H. J., Jr. (1966) Forces on the human body in simulated crashes. *Proc. 9th Stapp Car Crash Conf.*, pp. 237–259.

Roberts, V. L. and Lissner, H. R. (1966) A correlation between cadaver and *in vivo* results. *Proc. 8th Stapp Car Crash Conf.*, pp. 134–146.