THE TOLERANCE OF CATTLE TO "LONG"-DURATION REFLECTED PRESSURES IN A SHOCK TUBE

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FOREWORD

This report, in the field of Blast and Shock Biology, is part of an interspecies approach to the problem of accurate prediction of human tolerance to air blast.

It presents the results of an experiment in which 27 cattle were exposed to "sharp"-rising reflected pressures of 184-msec duration in an air-driven shock tube. The results apply directly to animals with 180-kg body weight exposed side-on against a surface to reflected pressures of "long" duration and are only indirectly applicable to data from other pressure-time waveforms or other animal species.

This information may be useful in military, industrial, and agricultural situations involving potential exposure of men and domestic animals to air blast.

ABSTRACT

Twenty-seven steers, mounted side-on against the endplate of an air-driven shock tube, were exposed to "sharp"-rising reflected pressures of 184-msec duration. Pressure-time measurements were made with piezoelectric pressure transducers. Autopsies were performed on all animals and the nature of their blast injuries determined.

The LD50 reflected pressure, obtained by probit analysis, was 43.1 psi for steers having a mean body weight of 180 kg. The results are compared with tolerance values obtained in previous investigations involving exposure of eight species of smaller animals to overpressures of 400-msec duration. Twenty-four hour, time-lethality data for steers are compared with those of five species of smaller animals.

The potential use of blast-injured domestic animals, as a source of food, is briefly discussed.

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INTRODUCTION

Estimates of blast pressures likely to cause injury or lethality in man have been derived from investigations involving the exposure of various species of animals to air blast.^{1, 2} Studies of this kind conducted in the past decade have been mainly of two types: (1) those aimed at determining the relative effects of various physical parameters involved in the exposure of the test organism (viz., the effects of the duration of the positive phase of the blast wave, the shape of the leading edge of the pressure-time waveform and the ambient air pressure existing at the time of exposure);³⁻⁷ and (2) those aimed at elucidating the biological variables which affect animal response to air blast, such as body size and species effects.^{1, 2}

In the latter category, correlation of data from high-explosive blast waves of "short" duration suggests that animals with large bodies are more resistant to "sharp"-rising overpressures than those of small body size. However, as data of additional animal species exposed to overpressures of "long" duration become available, it appears evident that body weight has less effect on animal tolerance to such blast waves than previously supposed.⁸ Nevertheless, in the absence of better criteria, present estimates of blast pressures likely to produce 50-per cent lethality in man have been derived by extrapolation of regressions relating LD₅₀ pressures to body weight based on data obtained from animal species smaller than man.⁹

In previous studies of the tolerance of cattle to air blast, 5 heifers were exposed to the detonation of a 2000-kg charge and 24 steers to 500 tons of TNT.^{10, 11} In the former case, the duration of the blast wave was relatively short (11.8 msec), and in the latter the results were obscured by crater debris and other extraneous effects. No other data are known on the air-blast response of animals larger than man. Accordingly, a need exists for data on the primary-blast response of large animals exposed to overpressures of "long" duration to provide additional information on the effects of body weight and other biological parameters on animal tolerance.

The objectives of this investigation were to obtain a dose-response curve for 180-kg steers exposed against the endplate of a shock tube to reflected shock pressures of near 180-msec duration and to determine the nature and extent of the blast injuries sustained by the animals.

METHODS

Shock Tube

Details of the air-driven shock tube (Figures 1 and 2) used in this study have been previously reported.¹² Briefly, the tube consisted of a compression chamber 15 ft long and 42 in. in diameter and an expansion

Figure 1. Diagram of 42-72-Inch Diameter Shock Tube.

Figure 2. 42-72-Inch Diameter Shock Tube.

chamber comprised of a tube 125 ft long with a diameter of 42 in., a cone-shaped transition section 9 ft in length, and a test section 6 ft in diameter and 30 ft long. The compression and expansion chambers were separated by a diaphragm of multiple layers of Du Pont Mylar® plastic. In these tests, the diaphragms were allowed to rupture spontaneously as the compression chamber was pressurized. Desired compression chamber pressures, obtained by selecting diaphragms with appropriate thicknesses, were sufficiently uniform for the purpose of the test series.

The effect of ambient pressure on animal tolerance to air blast has been discussed.^{6,7} Since the shock tube was operated with five of its eight vents open, the air inside the expansion chamber was initially at the local ambient pressure of 12 psia.

Pressure-Time Measurements

Piezoelectric gauges were used throughout these tests for pressure-time measurements. Details of the gauges, gauge mountings, electronic components, and calibration procedures have already been reported.¹²

Peak reflected pressures were measured by gauges containing lead metaniobate sensing elements (Model ST-2, Susquehanna Instruments, Bel Air, Md.) mounted side-on in the walls of the tube at locations 3 and 6 in. upstream from the endplate. A quartz piezoelectric transducer (Model 613, Kistler Instrument Corp., N. Tonawanda, N. Y.) similarly mounted 12 in. upstream from the endplate was used to measure the duration of the positive phase of the reflected shock. The mean of the reflected pressures recorded by the gauges was taken as the peak overpressure to which the animal was exposed on each test. The average difference between the highest and lowest pressures recorded by the gauges was 4.0 psi or about 9 per cent of the mean.

Animals

A total of 27 Hereford steers, approximately one year old, were used in these tests. The mean, standard deviation, and range of their body weights were 180 ± 20.3 and 140-217 kg, respectively. Loading was accomplished by opening the shock tube at the transition section, and leading the animal down the tube. The animal was secured left-side-on to the endplate with a restraining harness constructed of nylon webbing.

Blood samples for hematological studies were obtained from each animal before and after blast exposure. The results of these studies will be presented in a separate report.

Animals killed by the blast were autopsied immediately after death; survivors were sacrificed and autopsied on the day following exposure. The nature and extent of the blast lesions observed were recorded—lungs and major blast lesions were photographed.

Analysis of the Data

All animals not dying within one hour after blast exposure survived for 24 hours; therefore, the LD₅₀ pressure was derived by probit analysis of the one-hour-lethality data.¹³

RESULTS

Pressure-Time Records

3 A typical pressure-time record obtained from a gauge mounted in the tube wall, 6 in. upstream from the endplate, is shown in Figure 3. The reflected shock waves were generally flat-topped for about 10 msec. The duration of the positive phase of the shock wave ranged from 145 to 215 msec with a mean and standard deviation of 184 ± 20.3 msec.

Lethality

The 27 steers were exposed to reflected pressures ranging from 34.5 to 49.8 psi. For probit analysis, the animals were grouped as shown in Table 1. The probit regression and its 95-per cent fiducials are presented in Figure 4. The LD₅₀ pressure and the 95-per cent confidence limits were 43.2 and 39.6-45.4 psi, respectively.

Gross Pathological Findings

The gross pathological findings are summarized in Tables 2-4. In general, the types of injuries observed were similar to those previously reported in the literature on blast biology; namely, lung hemorrhage (Figure 5), arterial air embolism (Figure 6), contusions and rupture of the spleen (Figure 7), rupture of the kidneys (Figure 8), and hemorrhages in the walls of the gastrointestinal tract. 14-19

Arterial air embolism (either cerebral, coronary or both) was observed in 14 (93.3 per cent) of the 15 fatalities. The fatally injured animal in which air embolism was not detected was one which had a post-shot survival time of 35 minutes (Table 5).

Coronary air embolism was observed in 12 (80 per cent) of the fatalities (Figure 6) and cerebral air embolism was found in all 13 of those assessed.

The observation of infarcts on the kidneys of animals sacrificed 24 hours after blast exposure (Figure 9) is of particular interest in that it probably indicates occurrence of air emboli in survivors.

Time of Death

The time of death for each fatality is given in Table 5. The longest survival time for fatalities occurring within a 24-hour period was 35 minutes. No correlation between overpressure and survival time was detected. A plot of the time-lethality data is presented in Figure 10.

DISCUSSION

LD₅₀ Tolerance Comparison

The main objective of this study was to determine the LD₅₀ pressure for a species larger than man exposed to "fast"-rising overpressures of "long" duration.

A comparison of the LD₅₀ pressures previously reported for eight species of animals exposed to "sharp"-rising reflected pressures of 400-

Figure 3. Typical Pressure-Time Record for Long-Duration Reflected Shock Wave.

TABLE 1

MORTALITY IN STEERS EXPOSED TO
REFLECTED SHOCK PRESSURES

Reflected Pressure, psi		Duration, msec		One-Hour Mortality*	
Mean	Range	Mean	Range	No. Dead Total	Per Cent
37.6	(34.5-39.0)	161	(145-169)	0/4	0.0
42.6	(41.2-43.6)	184	(165-209)	5/10	50.0
44.9	(44.1-45.4)	176	(170-182)	3/5	60.0
46.8	(46.0-48.2)	195	(184-204)	5/6	83.3
49.6	(49.5-49.8)	215		2/2	100

* There was no change in the mortality within 24 hours. The LD₅₀ pressure and its 95-per cent confidence limits, as obtained by probit analysis, were 43.2 and 39.6-45.4 psi, respectively.

Figure 4. Probit Regression Relating Per-Cent Mortality in Probit Units to Log Reflected Shock Pressure for Steers.

TABLE 2

OCCURRENCE OF HEAD INJURIES IN STEERS EXPOSED TO AIR BLAST

Reflected Shock Pressure, psi		Number of Cases	Orbital "Blow-Out" Fractures		Eardrum Rupture		Blood or Bloody Froth at Mouth and/or Nose
Mean	Range		Unilateral	Bilateral	Unilateral	Bilateral	
<u>Survivors:</u>							
37.6	(34.5-39.0)	4	0	1 (25%)	0	4 (100%)	3 (75%)
42.6	(41.2-43.6)	5	1 (20%)	1 (20%)	0	4 (80%)	3 (60%)
44.9	(44.1-45.4)	2	0	1 (50%)	0	2 (100%)	2 (100%)
46.8	(46.0-48.2)	<u>1</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>1 (100%)</u>	<u>1 (100%)</u>
Totals		12	1 (8.3%)	3 (25%)	0	11 (91.7%)	9 (75%)
Grand Totals		12	4 (33.3%)		11 (91.7%)		9 (75%)
<u>Fatalities:</u>							
42.6	(41.2-43.6)	5	0	3 (60%)	1 (20%)	4 (80%)	3 (60%)
44.9	(44.1-45.4)	3	0	3 (100%)	1 (33%)	1 (33%)	2 (67%)
46.8	(46.0-48.2)	5	1 (20%)	3 (60%)	1 (20%)	3 (60%)	5 (100%)
49.6	(49.5-49.8)	<u>2</u>	<u>1 (50%)</u>	<u>0</u>	<u>2 (100%)</u>	<u>0</u>	<u>2 (100%)</u>
Totals		15	2 (13.3%)	9 (60%)	5 (33.3%)	8 (53.3%)	12 (80%)
Grand Totals		15	11 (73.3%)		13 (86.7%)		12 (80%)

TABLE 3

INTRATHORACIC INJURIES IN STEERS EXPOSED TO AIR BLAST

Reflected Shock Pressure, psi		Number of Cases	Cardiac Hemorrhage		Hemothorax	Lung Weight Percent of Body Weight
Mean	Range		Epicardial	Endocardial		
<u>Survivors:</u>						
37.6	(34.5-39.0)	4	1 (25%)	2 (50%)	0	1.42±0.30*
42.6	(41.2-43.6)	5	1 (20%)	0	0	1.63±0.53
44.9	(44.1-45.4)	2	2 (100%)	2 (100%)	0	2.54±0.09
46.8	(46.0-48.2)	<u>1</u>	<u>1 (100%)</u>	<u>1 (100%)</u>	<u>0</u>	<u>2.28</u>
Totals		12	<u>5 (41.7%)</u>	<u>5 (41.7%)</u>	<u>0</u>	<u>1.76±0.56</u>
Grand Totals		12	6 (50%)**		0	1.76±0.56
<u>Fatalities:</u>						
42.6	(41.2-43.6)	5	5 (100%)	5 (100%)	1 (20%)	2.21±0.39*
44.9	(44.1-45.4)	3	2 (67%)	1 (33%)	0	2.01±0.63
46.8	(46.0-48.2)	5	3 (60%)	5 (100%)	1 (20%)	2.39±0.41
49.6	(49.5-49.8)	<u>2</u>	<u>2 (100%)</u>	<u>0</u>	<u>1 (50%)</u>	<u>2.42±0.11</u>
Totals		15	<u>12 (80.0%)</u>	<u>11 (73.3%)</u>	<u>3 (20%)</u>	<u>2.26±0.42</u>
Grand Totals		15	14 (93.3%)**		3 (20%)	2.26±0.42

* The mean and standard deviation.

** Total number and per cent of animals exhibiting either epicardial or endocardial hemorrhage or both.

TABLE 4

OCCURRENCE OF INTRA-ABDOMINAL INJURIES IN STEERS EXPOSED TO AIR BLAST

Reflected Shock Pressure, psi		Number of Cases	Kidney Injuries				Spleen		Caecum
Mean	Range		Hemorrhage		Rupture		Contused	Ruptured	Hemorrhaged
			Unilateral	Bilateral	Unilateral	Bilateral			
Survivors:									
37.6	(34.5-39.0)	4	0	3 (75%)	1 (25%)	0	3 (75%)	3 (75%)	3 (75%)
42.6	(41.2-43.6)	5	1 (20%)	4 (80%)	1 (20%)	0	5 (100%)	4 (80%)	3 (60%)
44.9	(44.1-45.4)	2	2 (100%)	0	0	0	2 (100%)	0	2 (100%)
46.8	(46.0-48.2)	1	1 (100%)	0	0	0	1 (100%)	1 (100%)	1 (100%)
Totals		12	4 (33.3%)	7 (58.3%)	2 (16.7%)	0	11 (91.7%)	8 (66.7%)	9 (75%)
Grand Totals		12	11 (91.7%)				11 (91.7%)		9 (75%)
Fatalities:									
42.6	(41.2-43.6)	5	1 (20%)	3 (60%)	1 (20%)	1 (20%)	4 (80%)	2 (40%)	3 (60%)
44.9	(44.1-45.4)	3	1 (33%)	1 (33%)	1 (33%)	0	2 (67%)	1 (33%)	1 (33%)
46.8	(46.0-48.2)	5	0	2 (40%)	2 (40%)	0	2 (40%)	2 (40%)	3 (60%)
49.6	(49.5-49.8)	2	0	2 (100%)	0	0	1 (50%)	0	0
Totals		15	2 (13.3%)	8 (53.3%)	4 (26.7%)	1 (67%)	9 (60.0%)	5 (33.3%)	7 (46.7%)
Grand Totals		15	10 (66.7%)				9 (60.0%)		7 (46.7%)

Figure 5. Dorsal Surface (Upper) and Incised Views (Lower) of Lungs from a Steer Survivor (Left) and Fatality (Right) Exposed to Reflected Pressures of 41.2 and 45.0 Psi, Respectively.

Figure 6. Heart of Steer Exposed to Reflected Pressure of 184-Msec Duration Showing Coronary Air Emboli and Epicardial Petechia.

Figure 7. Ruptured Spleen of Steer Exposed to Reflected Pressure of 184 Msec.

Figure 8. Kidney of Steer Exposed to Reflected Pressure of 184-Msec Duration Showing Interlobular Rupture.

TABLE 5
TIME OF DEATH OF STEERS EXPOSED TO
REFLECTED SHOCK PRESSURES

Reflected Pressure, psig	Duration, msec	Time After Exposure	
		Death, minutes	Sacrifice, hours
49.8	215	22	
49.5	215	35	
48.2	192	5	
47.8	200	4	
46.5	190		24
46.4	204	6	
46.0	184	18	
46.0	197	30	
45.4	182	19	
45.1	NR*		24
45.0	170	15	
44.8	175		24
44.1	NR*	24	
43.6	167		24
43.4	165	14	
43.3	196	30	
43.3	185		24
43.3	NR*		24
42.8	180		24
42.8	NR*	9	
41.5	209	30	
41.2	180	6	
41.2	192		24
39.0	167		24
38.9	169		24
38.1	145		24
34.5	162		24

* No record.

Figure 9. Kidney of Steer Exposed to Reflected Pressure of 184-Msec Duration Showing Hemorrhagic Infarct.

Figure 10. Cumulative Per Cent of Mortally Wounded Steers Dying Over a 24-Hour Period from Exposure to "Sharp"-Rising Reflected Shock Pressures of "Long" Duration.

msec duration with that of the steer is shown in Figure 11.8,9 The data for the last four species indicate that the tolerance of steers weighing 180 kg (43.2 psi) is as low as that of cats weighing 2.5 kg (43.6 psi) and significantly lower at the 95-per cent confidence level than that of either dogs (47.8 psi) or goats (53.0 psi). Thus, considering their size, steers have a relatively low tolerance to overpressures of "long" duration. For blast waves of "short" duration, however, the tolerance of large animals is generally much greater than that of small animals.¹⁻³ For example, cattle have been reported as slightly more resistant than dogs to overpressures of 11.8-msec duration. The pressure associated with "lethal limits" (maximal distance at which 100-per cent lethality occurred) for dogs and heifers exposed to a 2000-kg charge were 74 and 85 psi, respectively.¹⁰ It appears that for overpressure durations shorter than about 20 msec, cattle tolerance to air blast would increase faster with decreases in the duration than would that of small species.

Gross Pathological Findings

The gross pathological findings were of the same general nature as those observed and reported for other species. Many of the blast lesions observed in these animals (orbital blow-out fractures, hemorrhages on the dorso-lateral wall of the rumen, interlobular ruptures of the kidneys, and contusions and rupture of the spleen) were typical of those found in steers exposed in the open to the detonation of 500 tons of TNT.¹¹ As the steers in the present study were not struck by missiles or subjected to translational effects, all lesions reported here may be considered primary-blast injuries.

The occurrence of renal infarcts observed not only in these animals but also recently seen in sheep exposed to "long" duration reflected pressures²⁰ is of interest as a potential cause of hypertension in survivors from blast exposure. Therefore, studies of the effects of blast on the blood pressure of surviving animals are currently being planned.

Food Potential of Blast-Injured Animals

In the event of a nuclear attack, food reserves for survivors are apt to be in short supply. Thus, proper disposition of domestic animals exposed to a detonation may be of great importance in subsequently providing an adequate food supply.

From the standpoint of blast effects, animals exposed to a detonation could be divided into three general classes for disposition:

- (1) those killed outright by the blast,
- (2) those surviving with skeletal fractures or other serious injuries, and
- (3) those exhibiting no or only slight external signs of injury, such as the presence of blood or bloody froth at either the mouth, nostrils, or both.

Meat could be salvaged from those killed by the blast and by timely slaughter of the seriously injured animals provided that it is not contaminated with radioactive material or by bacteria from sites of injury in the gastrointestinal tract. The clinical syndrome in cattle exposed to lethal and sublethal doses of ionizing radiation and the problem of salvaging such animals for food have been described and discussed.²¹

REGRESSION EQUATION:

$$\log LD_{50} = 1.5275 + 0.0812 \log m$$

Where LD_{50} = Pressure required for
50 per cent mortality, psi

m = Body mass, kg

	Mouse	Hamster	Rat	Guinea Pig	Cat	Rabbit	Dog	Goat	Steer
No. Animals	200 ^b	110 ^b	150 ^b	120 ^b	48 ^b	40 ^b	35 ^b	30 ^b	27
Body Weight ^a	20.7g (13-28)	89g (71-114)	200g (134-267)	424g (352-544)	2.48kg (1.3-4.1)	3.70kg (3.1-4.7)	15.1kg (9.5-24.5)	20.5kg (13.6-25.9)	180kg (140.2-216.8)
LD ₅₀ (psi)	26.4	28.6	30.6	25.6	43.6	24.9	47.9	52.6	43.2

a. Mean and range.

b. Reference 8.

Figure 11. Regression Relating LD₅₀ Pressure to Body Weight for Mammals Exposed to "Sharp"-Rising Overpressures of "Long" Duration.

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According to data from a 60-day survival study of sheep subjected to blast exposures similar to those of the cattle in this study, it may be concluded that, from the standpoint of primary-blast injuries, most animals surviving for 24 hours after exposure may be expected to recover without any special treatment.²⁰ This is so, even though animals surviving with no or only slight external signs of injury may have sustained such internal injuries as lung hemorrhage, myocardial hemorrhage, and infarcts on the kidneys. Some delayed lethality might be expected as a result of rupture of the spleen, liver, kidneys or portions of the gastrointestinal tract. During the recovery period, injured animals may be slaughtered or used for food provided they do not exhibit generalized peritonitis as a result of rupture of the gastrointestinal tract, and provided the body temperature is within the normal range.

In addition to injuries resulting from blast and radiation, animals exposed in the open may also exhibit injuries caused by the thermal effects of a nuclear detonation. Unfortunately, little is known of the combined effects of these three stresses, and further discussion of this subject must await the results of investigative efforts in these areas.

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