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THE EFFECTS OF AMBIENT PRESSURE
ON TOLERANCE OF MAMMALS
TO AIR BLAST

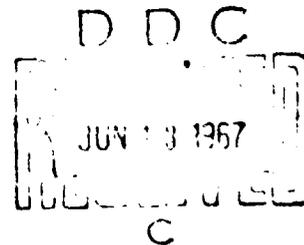
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Donald R. Richmond, and Clayton S. White

Technical Progress Report
on
Contract No. DA-49-146-XZ-372



This work, an aspect of investigations dealing with
the Biological Effects of Blast from Bombs, was
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Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

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FOREWORD

This report presents the results of experiments designed to investigate the relationship between animal tolerance to air blast and the ambient pressure existing at time of exposure. The tolerance of rats, guinea pigs, dogs, and goats exposed in shock tubes to reflected pressures with durations of 16 to 35 msec at experimental ambient pressures ranging from 5 to 42 psia was explored. The results indicated the effects of ambient pressure on mammalian response to "sharp"-rising overpressures of "long" duration were quite significant; viz., lethal overpressure varied by factors of 4 to 5.

The findings may be applied to problems involving the scaling of biological blast effects to differences in altitude - potential blast exposure in pressurized or evacuated locations. They are also of significance in the evacuation of blast-produced casualties by air or other methods involving ambient pressure changes.

This study is part of a broad program, the aims of which are the accurate prediction of human tolerance to air blast and the development of appropriate procedures for the diagnosis, prognosis, and treatment of blast injuries.

ABSTRACT

Seventy-six dogs, 43 goats, 211 rats, and 255 guinea pigs were exposed to reflected shock pressures at ambient pressures ranging from 5 to 42 psia in air-driven shock tubes. Animal tolerance, expressed as LD₅₀-one-hour overpressures rose progressively as the ambient pressure was increased.

By analysis of the results of this study, combined with those from previous shock-tube investigations, a general equation for the regression of LD₅₀ pressure on ambient pressure for mammals was derived. From this equation and previous estimates of the LD₅₀ pressure for man's tolerance to overpressures of 400-msec duration at an ambient pressure of 12 psia, an equation relating LD₅₀ pressure to ambient pressure was developed for the 70-kg mammal

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the personnel of the Department of Comparative Environmental Biology for their able technical assistance in conducting the study.

Appreciation is also expressed to Mr. Wilmer R. Kerzee, Dr. E. Royce Fletcher, Mr. Ray W. Albright, and Mr. Edward A. Spelich for conducting the probit and regression analyses.

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THE EFFECTS OF AMBIENT PRESSURE ON TOLERANCE OF MAMMALS TO AIR BLAST

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INTRODUCTION

Investigations have established that injuries from exposure to air blast occur more often in air-containing organs than in other regions of the body.¹⁻¹¹ As the lungs are very delicate air-containing structures and are more susceptible to blast injury than other vital organs, most of the causes of death from primary-blast effects, such as coronary and cerebral air embolism and pulmonary insufficiency may be traced directly or indirectly to pulmonary injuries.

A proposed biophysical mechanism of air-blast injury, which has gained increasing consideration in recent years, is that injury results from implosion of tissue and fluids into gas-containing organs as an effect of violent compression of the body by the positive phase of a blast wave.^{11, 12} This concept suggests a direct relationship between the extent of lung injury and the change in volume which lungs undergo when subjected to a blast load. Furthermore, the degree of change in lung volume, in relation to the magnitude of the blast overpressure, would be affected by the ambient pressure existing in the lungs at the time of blast exposure.¹³

Experiments involving exposure of mice to air blasts at different atmospheric pressures have verified that ambient pressure does affect animal tolerance to air blast.^{14, 15} Therefore, studies were extended to include other mammalian species in order to devise methods of defining the effects of ambient pressure on human tolerance to air blast.

This report presents the results of experiments in which rats, guinea pigs, goats, and dogs were exposed at different ambient pressures to long-duration reflected pressures in shock tubes.

MATERIALS AND METHODS

General

The effects of ambient pressure on animal tolerance to air blast were explored by exposing rats, guinea pigs, dogs, and goats to shock waves at altered ambient pressures in shock tubes. Previous studies have shown that compression or decompression of animals soon after blast exposure significantly affected the lethality.¹⁴ Therefore, in this study, all animals were held at the experimental ambient pressure (P_i) for one hour following blast exposure before returning them to the ambient pressure level (P_0) of the laboratory. Lethality was assessed during this one-hour-hold period.

Shock Tubes

12-Inch Diameter Shock Tube

The 12-inch diameter shock tube used for exposing rats and guinea pigs has been described in a previous report.¹⁶ For the present study, the endplate of the tube was fitted with a transparent window for observation of the animals during the post-shot, one-hour-hold period. Each animal was exposed to a reflected shock wave in a wire-mesh cage mounted inside the shock tube against the endplate. Procedural details for conducting these exposures have been reported.^{14,15}

24-40-Inch Diameter Shock Tube

The shock-tube arrangement in which dogs and goats were exposed is shown in Figure 1. The tube consisted of a compression chamber 24 in. in diameter and 3 ft long, and an expansion chamber 43 ft 10 in. in length constructed of three sections: (1) a 20-ft length of 24-in. diameter pipe connected to the compression chamber; (2) a transition section 46 in. in length which increased the diameter of the tube from 24 to 40.5 in.; and (3) a test section having a diameter of 40.5 in. and a length of 20 ft. A storage-tank reservoir, connected to the expansion chamber, was used to hold the desired pre-shot pressure level in the expansion chamber by adding to or reducing pressure as required.

A diaphragm, consisting of sheets of Du Pont Mylar[®] plastic, separated the compression and expansion chambers. Each sheet of Mylar (0.01 in. thick) had a bursting pressure of approximately 20 psi in this tube. The compression-chamber pressure, necessary to produce the desired reflected overpressure dose, was achieved by using an appropriate number of plastic sheets.

The dogs and goats were mounted against the endplate closing the test section, right-side-on to the incident shock with a restraining harness constructed of 1-in. nylon webbing. Electrocardiograph (ECG) leads were attached to the animals and passed through a hole in the endplate to a Sanborn Twin-Beam ECG. The ECG output was monitored visually on a cathode-ray oscilloscope to determine the time of death of each animal.

Pressure-Time Measurements

Three piezoelectric pressure transducers were used on each test — two to measure the peak reflected pressures and one to record the pre-shot and post-shot, pressure-time events. Details of pressure-gauge recording and calibrating systems have been previously reported.¹⁶⁻¹⁸

For measuring peak reflected pressures, two pressure gauges containing sensors of lead metaniobate (Model ST-2, Susquehanna Instruments, Bel Air, Md.) were mounted flush with the inside wall of the tube 3 in. upstream from the endplate. This arrangement placed the gauges directly above the back of the animal. The mean of the peak reflected pressures recorded by the two gauges was taken as the overpressure dose for a given test. A typical pressure-time waveform recorded by one of these gauges is shown in Figure 2.

Pre-shot and post-shot, pressure-time events were recorded with a quartz piezoelectric pressure transducer (Model PZ-14, Kistler Instrument Corp., N. Tonawanda, N. Y.) mounted in the wall of the tube 9 in.

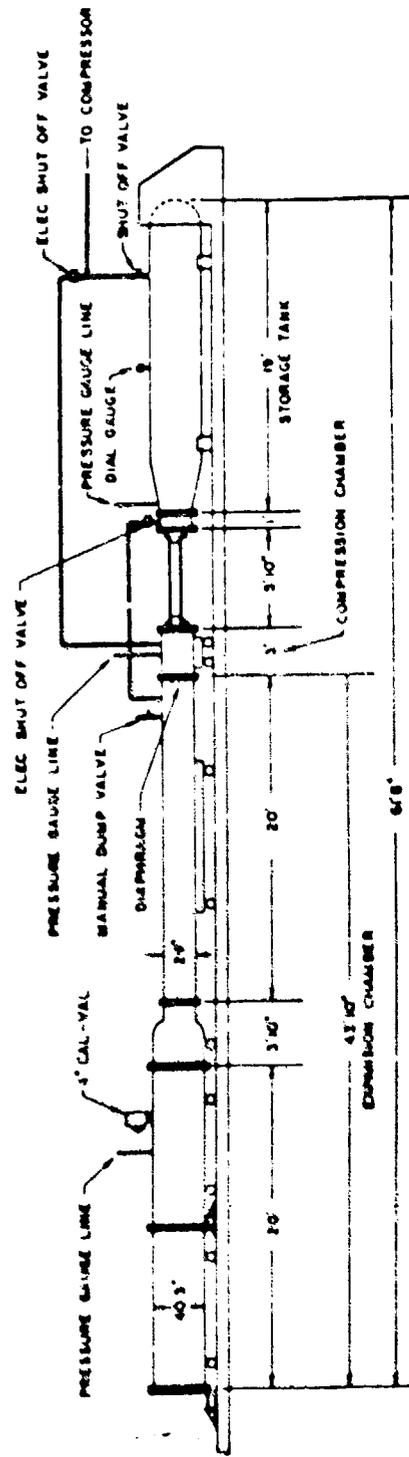


Figure 1. Diagram of 24-40-inch Diameter Shock Tube.

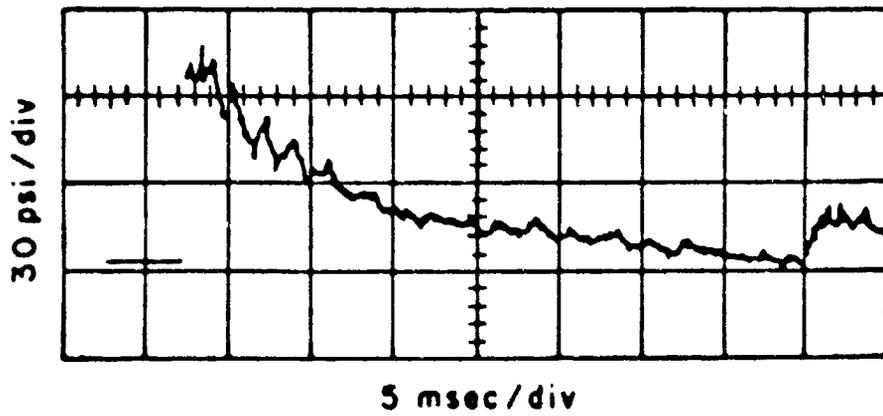


Figure 2. Typical Pressure-Time Waveform Recorded by Gauge 3 Inches from Endplate.

upstream from the endplate. The signal from this gauge was passed via a Kistler Amplifier - Calibrator into a cathode - ray oscilloscope. The sweep on the oscilloscope was set at 5 sec/cm and manually triggered to record the following:

- (1) pressure change from P_0 to P_i ,
- (2) decompression from the immediate post-shot, static pressure level (P_b) to P_i , and
- (3) decompression from P_i to P_0 . This step was performed after the animal was dead (as determined by the ECG) or, in the case of survivors, one hour following the shot.

Pre-shot and post-shot pressurization and decompression times were also measured with a stopwatch.

Pressure-Time Sequences

The sequences of pressure-time events to which the animals were exposed in each experiment are illustrated in Figures 3 a-d. Presented in these figures are the mean times and pressures for the tests conducted at experimental ambient pressures of 7, 12, 15, and 18 psia.

Referring to Figure 3d, the mean rise-time (the change in pressure from P_0 to P_i ; i. e., t_1) was 7 seconds. The time at P_i pre-shot (t_2) was 443 seconds. With the arrival of the shock wave, the pressure rose near-instantaneously to the reflected shock level (ΔP). The positive-phase duration of the initial reflected wave was 36 msec (t_3). Following the shot, the pressure became stabilized in the tube at 30 psia, P_b . It was retained at this level for 17 seconds (t_4) before it could be returned to P_i in 6 seconds (t_5). The animals were then retained at this pressure level for one hour (t_6), after which they were decompressed to P_0 in 7 seconds (t_7).

Experimental Animals

The number, type, and body-weight data for animals exposed in this study are given in Table 1. Both sexes were used in all groups.

In order to check for possible effects of the pre-shot and post-shot pressure changes to which the animals were subjected, controls were exposed to the most rigorous combinations of increase, hold, and release of pressure (minus the blast) experienced by the test animals. No effects from these pressure changes were detected in the control animals.

Fatalities were autopsied soon after death; survivors were sacrificed on the day following exposure.

Analysis of the Data

The reflected pressures required to produce 50-per cent lethality (LD_{50}) for each experiment were determined by probit analysis of the one-hour-lethality data.¹⁹ Statistical analyses indicated no significant differences in the slopes of the probit regressions for the various tests at the 95-per cent confidence level. As a result of these analyses, a set of parallel probit regressions for each species was fitted to the data for all of the experiments. LD_{50} pressures and their 95-per cent fiducials were obtained from these parallel regressions.

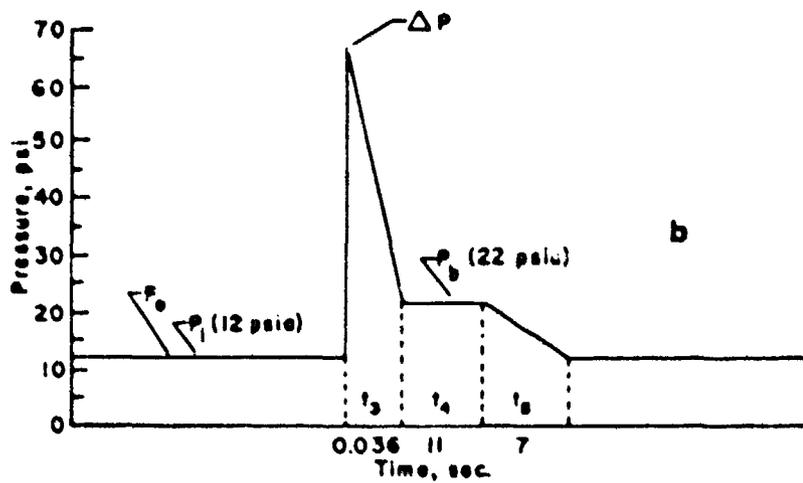
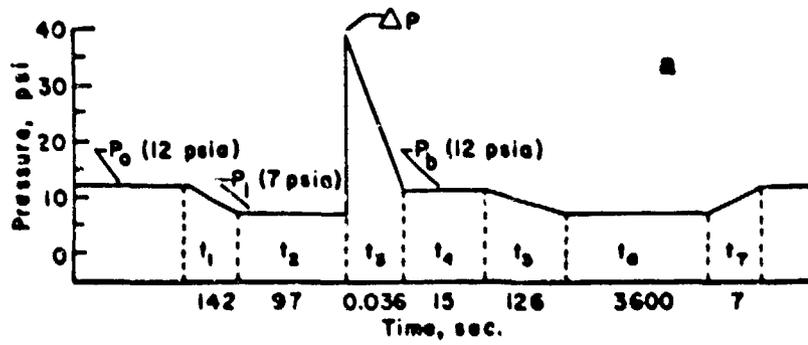


Figure 3 (a-b). Overall Pressure-Time Profiles at Ambient Pressures of 7 and 12 Psia.

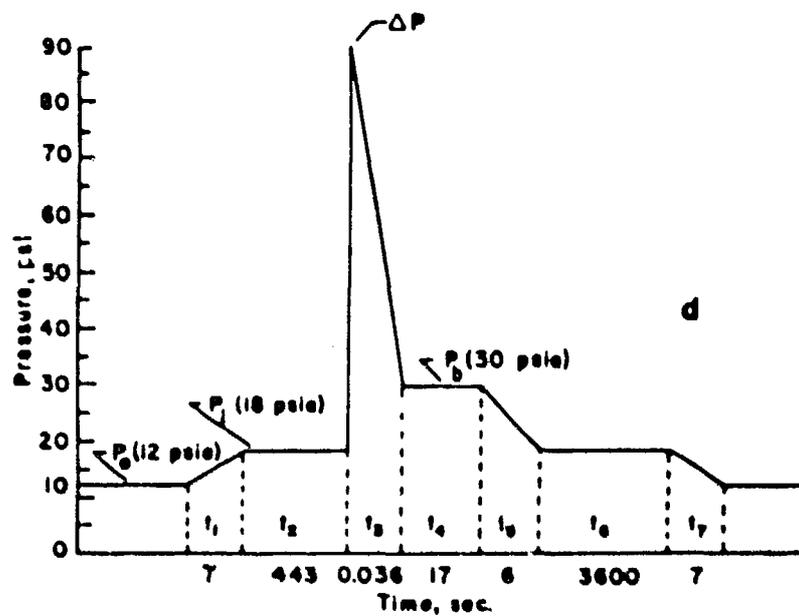
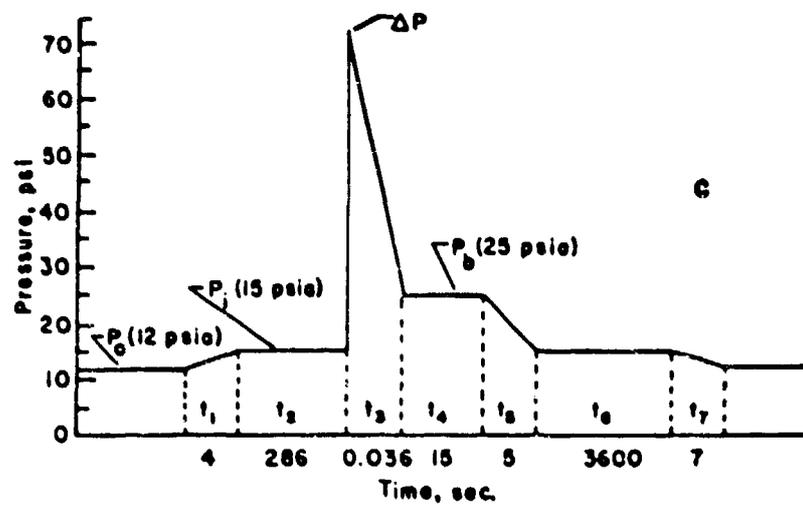


Figure 3 (c-d). Overall Pressure-Time Profiles at Ambient Pressures of 15 and 18 Psia.

TABLE 1
ANIMALS EXPOSED TO AIR BLAST AT DIFFERENT AMBIENT PRESSURES

Species	Experimental Ambient Pressure, psic	Number of Animals	Body Weight, grams	
			Mean & Range	Standard Deviation
Rats (Sprague Dawley)	7.0	28	201.1 (170-227)	± 12.6
	12.0	40	188.5 (162-235)	± 15.6
	14.7	27	174.9 (157-230)	± 16.8
	18.0	76	192.1 (170-219)	± 13.5
	42.0	40	195.2 (160-271)	± 22.4
Total		211	191.0 (157-271)	± 17.6
Guinea Pigs (English Breed)	5.0	43	515.5 (400-895)	± 144.4
	7.0	76	589.1 (403-892)	± 158.6
	12.0	38	421.6 (400-471)	± 20.1
	18.5	53	431.5 (397-499)	± 25.6
	40.0	45	433.4 (400-500)	± 29.4
Total		255	491.5 (397-892)	± 127.5
Dogs (Mongrel)	7.0	31	16.7 kg (15-24.7)	± 2.7
	12.0	15	17.5 (10.2-25)	± 4.8
	18.0	30	17.1 (11.4-27.3)	± 3.5
Total		76	17.8 (10.2-27.3)	± 3.5
Goats (Mixed Breed)	7.0	29	21.7 kg (15-32.3)	± 5.8
	15.0	14	31.2 (14.5-41.8)	± 11.1
Total		43	24.8 (14.5-41.8)	± 9.1
Total		585		

RESULTS

Pathological Findings

The types of lesions sustained by the animals exposed to air blast at different ambient pressures were not different from those generally reported in the literature on Blast Biology. The major types of injuries exhibited were lung hemorrhage, arterial air embolism, hemothorax, pneumothorax, hemorrhage of the spleen, kidneys, liver, walls of the gastrointestinal tract, intercostal regions, and sinuses, and rupture of the eardrums, sometimes with disruption of the auditory ossicles.

Results of the Probit and Regression Analyses

Results of the probit analysis are summarized in Table 2. Presented are the probit equation constants, LD₅₀ pressures, and ambient pressures for each experiment. The results indicate that for each species the LD₅₀ pressures rose with increasing ambient pressure. Parallel dose-response curves fitted to the data are presented in Figures 4-7.

All tolerance values obtained to date for the five species of animals used in ambient-pressure studies are presented in Table 3. Regressions of the form, $\log y = a + b \log x$ (where y = the LD₅₀ pressure in psig, a = the intercept constant, b = the regression coefficient, and x = the experimental ambient pressure in psia), were obtained for each species from these data. Because the slopes of these regressions were not significantly different at the 95-per cent confidence level, a set of regressions having common slopes was fitted to the data. These curves and their equations are shown in Figure 8.

DISCUSSION

Effects of Ambient-Pressure Changes on Animal Tolerance to Air Blast

The results of this study, which indicate that five species of mammals exhibit uniformly increasing tolerance to air blast with increasing ambient pressure, are directly applicable to animal response to "sharp"-rising reflected pressures of "long" duration. The data apply only indirectly to situations involving animal exposure to non-ideal waveforms or blast waveforms having positive-phase durations shorter than 1-2 msec for mice, 2-3 msec for guinea pigs and rats, and about 15 msec for dogs and goats. 20, 21

Results obtained here were comparable to those reported by Kolder and Wohlzogen involving explosive compression of rats from initial pressures of 1-3 atmospheres to final pressures of 2-12 atmospheres, with rise time to final pressure near 1 msec, and animals returned to normal atmospheric pressure in approximately 3 seconds after the test (1 atmosphere = 14.7 psia).²² LD₅₀ values for initial pressures of 1, 2, and 3 atmospheres computed from probit regression equations were 34.5, 69.0, and 100.4 psig, respectively. These values compare favorably with rat LD₅₀ pressures of 38.8, 68.8, and 96.3 psig for initial pressures of 1, 2, and 3 atmospheres, respectively, in the present study.

TABLE 2
RESULTS OF PROBIT ANALYSIS

Species	Experimental Ambient Pressure, P ₁ (psia)	Number of Animals	LD ₅₀ One-Hour Reflected Pressure, ΔP (psig)	Probit Equation Constants	
				Intercept, a	Slope, b
Rate	7.0	28	22.0 (20.3-23.8)	-14.880	14.810
Rate	12.0	40	30.8 (28.8-32.9)	-17.037	14.810
Rate	14.7	27	41.5 (38.2-45.0)	-18.953	14.810
Rate	19.0	26	46.1 (43.5-48.5)	-19.641	14.810
Rate	42.0	40	95.4 (89.5-101.6)	-24.313	14.810
Guinea Pig	3.0	43	13.6 (12.6-14.6)	-11.774	14.810
Guinea Pig	7.0	26	20.4 (19.4-21.4)	-14.397	14.810
Guinea Pig	12.0	30	34.6 (32.3-37.1)	-17.796	14.810
Guinea Pig	18.5	33	54.1 (50.7-57.8)	-20.663	14.810
Guinea Pig	40.0	45	104.2 (97.9-110.8)	-24.806	14.810
Dogs	7.0	31	31.3 (29.1-33.9)	-17.154	14.810
Dogs	12.0	15	53.7 (48.5-59.4)	-20.616	14.810
Dogs	18.0	30	70.4 (65.3-76.2)	-22.361	14.810
Cats	7.0	29	25.2 (23.4-27.2)	-15.761	14.810
Cats	15.0	14	54.9 (51.1-63.3)	-20.908	14.810

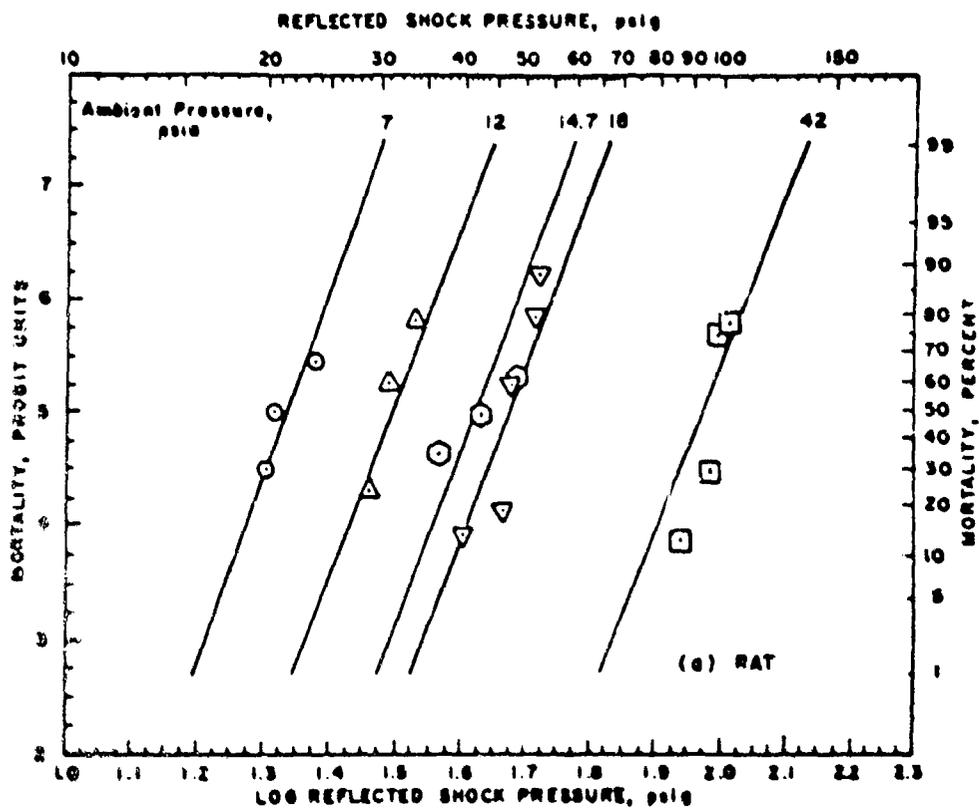


Figure 4. Probit Mortality Lines for Rats Exposed to Reflected Pressures of 16-Msec Duration at Various Ambient Pressures.

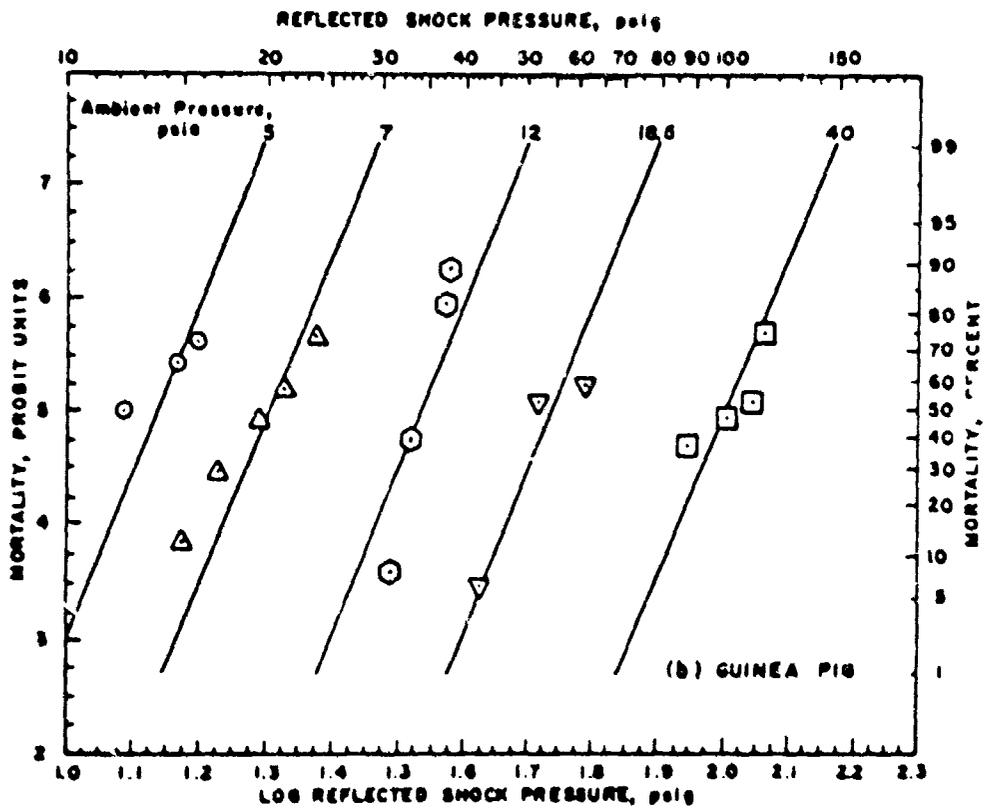


Figure 5. Probit Mortality Lines for Guinea Pigs Exposed to Reflected Pressures of 16-Msec Duration at Various Ambient Pressures.

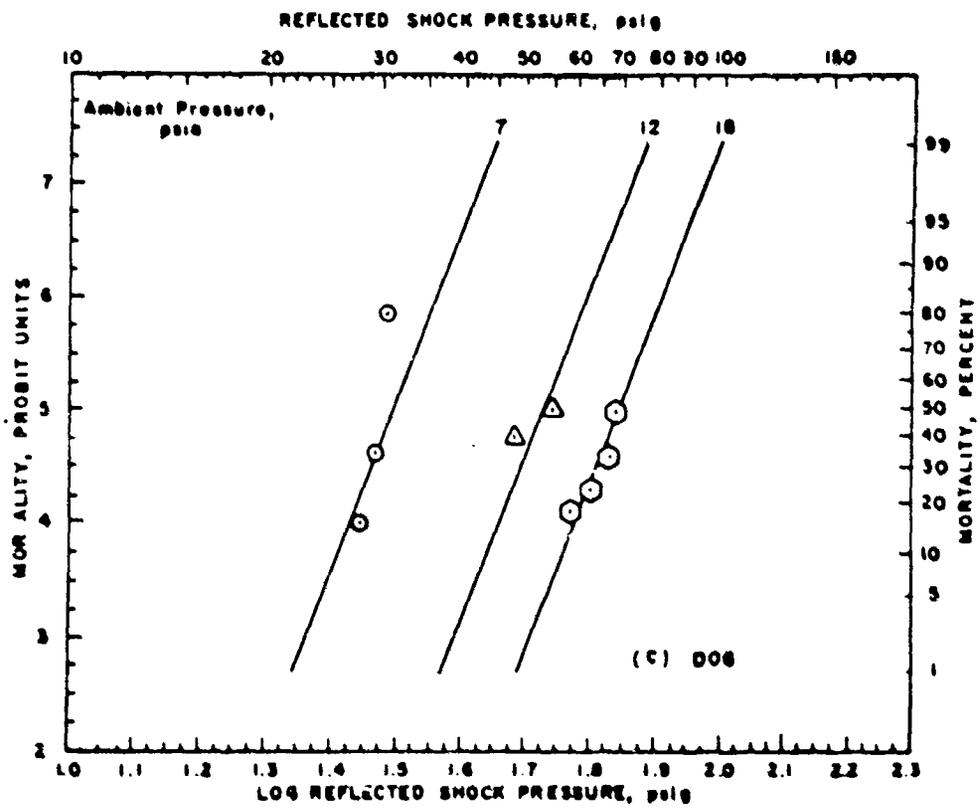


Figure 6. Probit Mortality Lines for Dogs Exposed to Reflected Pressures of 35-Msec Duration at Various Ambient Pressures.

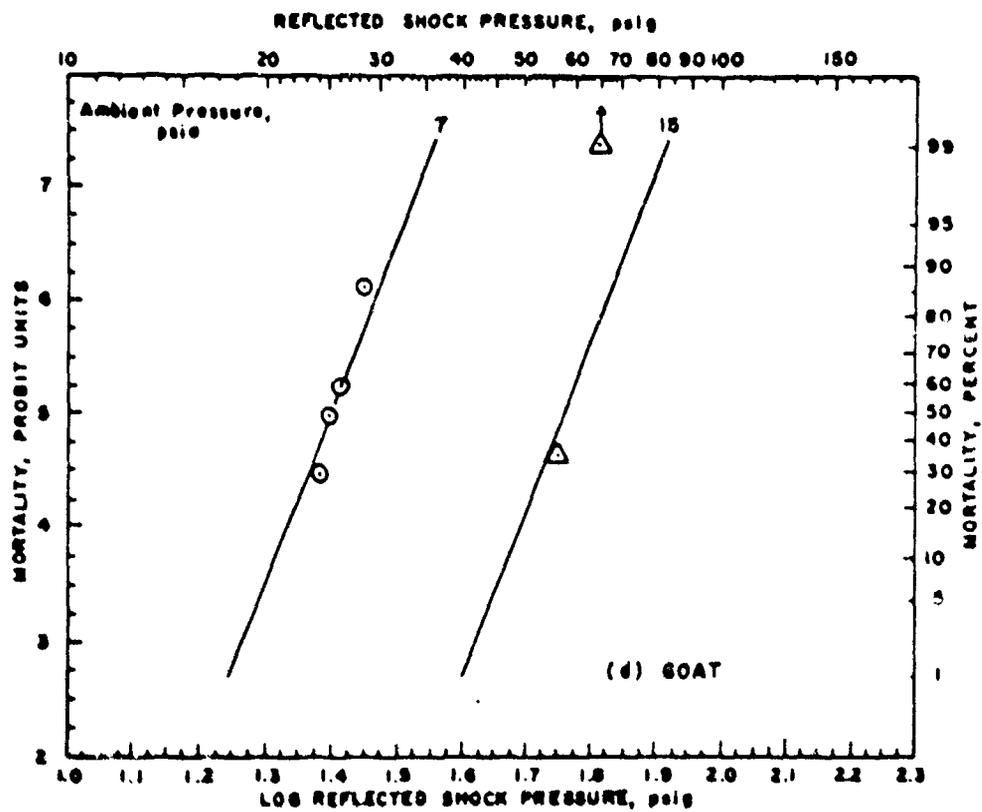


Figure 7. Probit Mortality Lines for Goats Exposed to Reflected Pressures of 35-Msec Duration at Various Ambient Pressures.

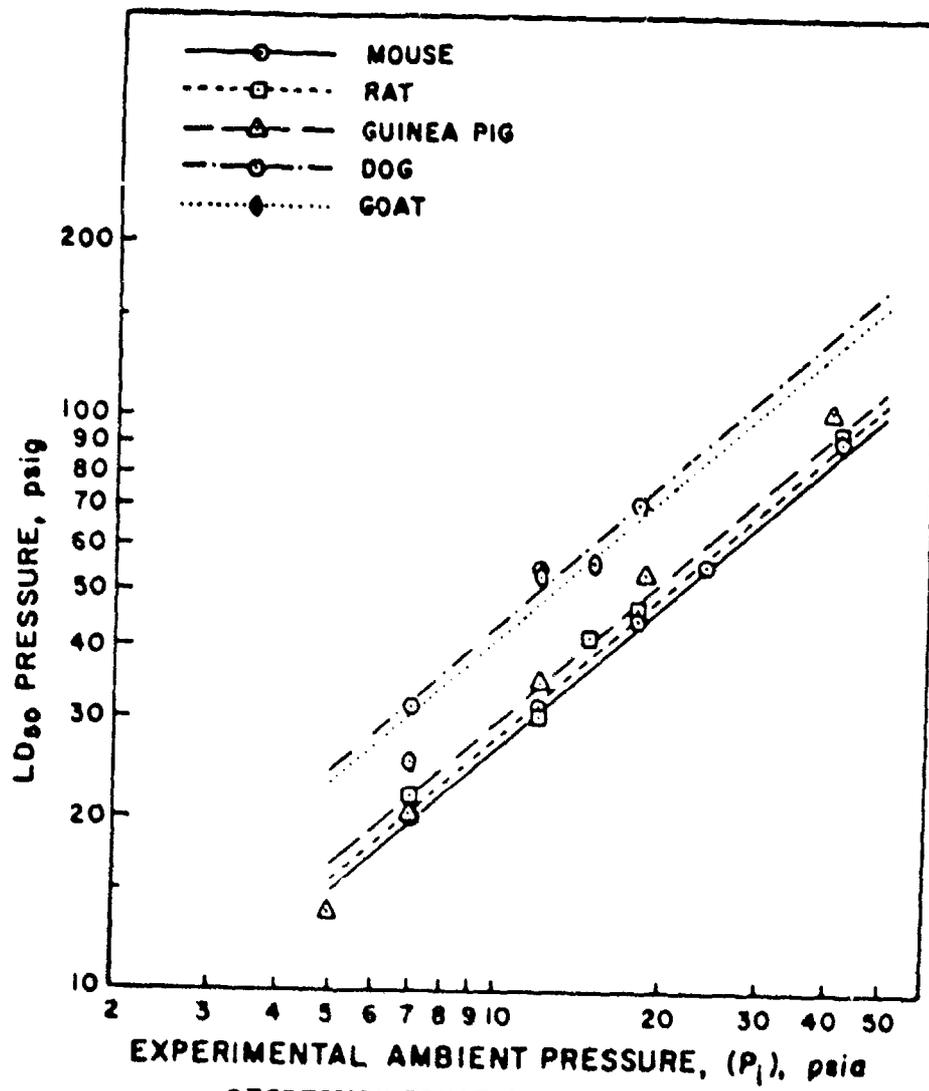
TABLE 3
EFFECTS OF AMBIENT PRESSURE ON TOLERANCE OF MAMMALS TO AIR BLAST

Experimental Ambient Pressure, P ₁ (psia)	Moose ^b			Rat			Guinea Pig			Goat		
	Reflected Shock AP (psig)	Pressure Ratio AP/P ₁	LD ₅₀ Pressure	Reflected Shock AP (psig)	Pressure Ratio AP/P ₁	LD ₅₀ Pressure	Reflected Shock AP (psig)	Pressure Ratio AP/P ₁	LD ₅₀ Pressure	Reflected Shock AP (psig)	Pressure Ratio AP/P ₁	LD ₅₀ Pressure
5				13.6	2.72 (2.52-2.92)							
7	30.3	2.90 (2.73-3.07) ^c		20.4	3.14 (2.90-3.40)		31.3	4.47 (4.16-4.84)		25.2	3.60 (3.34-3.89)	
12	31.2	2.66 (2.45-2.77)		34.6	2.57 (2.40-2.74)		53.7	4.48 (4.04-4.93)		52.9 ^c	4.41 ^c (4.03-4.82)	
14.7				41.5	2.82 (2.60-3.04)							
15												
18	64.3	2.47 (2.33-2.63)		66.1	2.56 (2.43-2.69)		70.4	3.91 (3.63-4.21)				
18.5				94.1	2.92 (2.76-3.12)							
24	55.3	2.90 (2.79-3.42)										
60				104.2	2.60 (2.45-2.77)							
42	91.7	2.18 (2.07-2.33)		95.4	2.27 (2.13-2.43)							

^a 95 per cent confidence limits.

^b Data from Reference 14.

^c Data from Reference 17.



REGRESSION EQUATIONS:

MOUSE	$\text{Log } y = 0.599 + 0.828 \log x$
RAT	$\text{Log } y = 0.622 + 0.828 \log x$
GUINEA PIG	$\text{Log } y = 0.650 + 0.828 \log x$
DOG	$\text{Log } y = 0.812 + 0.828 \log x$
GOAT	$\text{Log } y = 0.789 + 0.828 \log x$

Where $y = \text{LD}_{50}$ PRESSURE, psig

$x = \text{EXPERIMENTAL AMBIENT PRESSURE, (P}_1\text{), psia}$

Figure 8. Effects of Ambient Pressure on Mammalian Tolerance to "Long"-Duration Overpressures.

The animal exposures in these experiments differed from the true blast situation in the open in that the pressure in the shock tube, after each shot, momentarily stabilized (11-17 seconds) at a static level above that of the pre-shot ambient pressure before it could be reduced to the experimental ambient-pressure level. This difference, however, was probably of little biological significance because the LD50 values obtained in the studies for guinea pigs and dogs at the normal ambient pressure (12 psia) were in good agreement with those previously obtained from animal-blast exposures free of such aberrations; for example, the 34.6- and 53.7-psig values for guinea pigs and dogs, respectively, in the present study, as compared with 34.5 and 52.9 psig for these species exposed in a shock tube with open vents at 12 psia to overpressures of near 400-msec duration.^{17, 23} Additional similar comparisons suggest that it was the initial "sharp" rise in pressure and the duration of the positive phase of the blast wave that were significant in causing lethal blast injuries, and not the immediate post-shot pressure events to which these animals were subjected. Because lethality was assessed during the one-hour, post-shot period in which survivors were held at the experimental ambient-pressure level before returning them to the normal atmospheric pressure level, the mortality data can be considered free of any bias due to this last pressure change.

The partial pressure of oxygen (P_{O₂}) in the ambient air during the post-shot, one-hour-hold period was dependent upon the experimental ambient pressure (P_i). Control experiments indicated that animals not subjected to blast injury tolerated the lowest and highest pressures (with their attendant P_{O₂} values) for the times involved in the experiments without detectable effects. Possible effects of differences in the P_{O₂} on one-hour survival of blast-injured animals in experiments of this type have not yet been investigated.

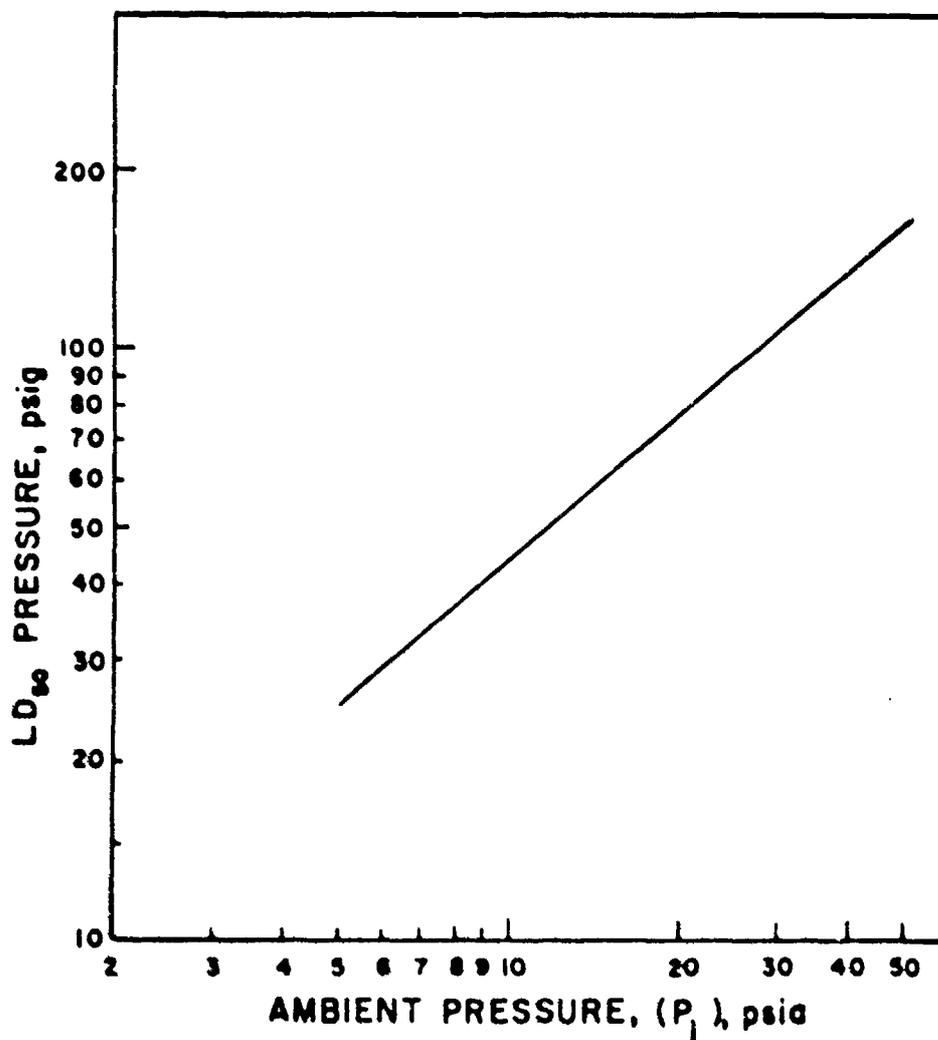
Estimates for the 70-Kg Mammal

As the curves presented in Figure 8 have common slopes, their regression coefficient was used in deriving the following general equation for mammals:

$$\log y = a + 0.828 \log x$$

where: y = the LD₅₀ pressure in psig
a = the intercept constant for a particular species
x = the ambient pressure at exposure in psia

An equation for the 70-kg mammal was then derived from this general equation. The estimated LD₅₀ pressure of 52 psi at an ambient pressure of 12 psia, as previously reported,²⁰ for the 70-kg mammal was used in order to obtain the intercept constant for the regression. The resultant curve and its equation, presented in Figure 9, may tentatively be used for estimating human tolerance to "sharp"-rising overpressures of "long" duration at different ambient pressures. It should be noted that all data on which the regression is based were obtained from blast exposure of animals against reflecting surfaces.



REGRESSION EQUATION:

$$\text{Log } y = 0.823 + .828 \log x$$

where $y = \text{LD}_{50} \text{ PRESSURE, psig}$

$x = \text{AMBIENT PRESSURE, (P}_i\text{), psia}$

Figure 9. Predicted Effects of Ambient Pressure on Tolerance of the 70-Kg Mammal to "Long"-Duration Overpressure.

Pressure Ratio

The data in Table 3 indicate that the ratio of the LD₅₀ reflected pressure (ΔP) to the experimental ambient pressure (P_i) generally decreased with increasing ambient pressure. This trend was clearly indicated by the mouse and rat data, but was less evident from the data for the other three species.

The fact that the LD₅₀- $\Delta P/P_i$ pressure ratio did not tend to remain constant with changes in P_i was indicated in 10 of 16 experiments at altered ambient pressures where the LD₅₀- $\Delta P/P_i$ ratio was outside the 95-per cent confidence limits of this ratio for the given species at normal ambient pressure (12 psia). As the majority of these data do not indicate that the LD₅₀ pressure ratio is a constant for each species, the curves and regression equations presented in Figures 8 and 9 should be used for scaling LD₅₀ pressures to differences in ambient pressure instead of using the normal LD₅₀-pressure ratio as a factor for biological blast scaling as tentatively suggested in an earlier work. 14

Practical Implications

The results of these studies have significant implications in assessing hazards from blast exposures in pressurized or evacuated spaces, such as caisson tunneling and mining operations, cabins of aircraft aloft, space capsules, and perhaps underwater for certain conditions of exposure. For example, if a given biological response, such as 50-per cent lethality, results from exposures to "long"-duration blast waves with peak pressures near 60 psi at a sea-level surface, then where an ambient air pressure of 3 atmospheres exists, peak pressures of slightly more than 150 psi would be required to produce the same effect; e. g., underwater tunneling has been carried out above and below the ambient pressures noted here and explosions in such locations, all other factors being comparable, would be less hazardous than at sea level.

The meaning of the present study as far as underwater blast is concerned is more difficult to assess for a number of reasons. Among them are complicating events such as the depth of the water and explosive charge; the location of the target with respect to the water surface and the bottom; positive reflections from the latter, the magnitude of which — among other things — is a function of the nature of the bottom; and negative reflections from the surface, which critically influence the duration of the overpressure, the pulse being very short for near-surface locations and progressively longer with increasing depth. Also, there is the fact that the durations of blast overpressures in water are generally much shorter than in air. Too, there are no doubt differences in the efficiency with which energy is imparted to a biological target by blast waves in air on the one hand and in water on the other. Such factors make it clear that a straightforward increase in blast tolerance may or may not occur for exposures at increasing depths underwater. Without question, the matter is complex and is hardly within the scope of the experiments reported and discussed here.

Implicit in the present study, but documented elsewhere^{6, 10, 14, 15} is the fact that post-exposure pressure changes have important effects on

chances of survival of those injured by blast. As movement and evacuation of blast casualties may entail subjecting them to changing ambient pressures, those who treat blast casualties should know and remember that decompression is very hazardous to blast patients, particularly if it occurs soon after injury such as during early air evacuation. In contrast, immediate or early compression has reduced mortality significantly in experimental animals and no doubt would be effective in man; viz., blast injury occurring in flight in aircraft would subsequently be benefitted by flying at the lowest practical altitude.

Finally, though the results of the present study clearly indicate ambient pressure is a physical parameter of major importance in specifying blast effects, investigations to date have been limited to assessing animal response to "sharp"-rising overpressures of "long" duration. Further work will be required to demonstrate that ambient pressure variation is of significance either for non-ideal waveforms or for blast overpressures enduring for quite short periods of time.

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1. ORIGINATING ACTIVITY (Corporate author) Lovelace Foundation for Medical Education & Research Albuquerque, New Mexico 87107		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
3. REPORT TITLE The Effects of Ambient Pressure on Tolerance of Mammals to Air Blast		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Progress		
5. AUTHOR(S) (Last name, first name, initial) Damon, Edward G., Gaylord, Charles S., Hicks, William, Yelverton, John T., Richmond, Donald R., and White, Clayton S.		
6. REPORT DATE August 1966	7a. TOTAL NO. OF PAGES 37	7b. NO. OF REFS 23
8a. CONTRACT OR GRANT NO. DA-49-146-XZ-372	8b. ORIGINATOR'S REPORT NUMBER(S) DASA 1652	
9. PROJECT NO. 03.012	9b. OTHER REPORT NUM(S) (Any other numbers that may be assigned this report)	
10. AVAILABILITY LIMITATION NOTICES Distribution of this report is Unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY	
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DD FORM 1473

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