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PERSONNEL EXPOSED TO REPEATED BLASTS

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ABSTRACT

Damage-risk criteria for man subjected to one or twenty short-duration blast waves were presented in terms of peak overpressure, duration, overpressure impulse, range, and yield. Threshold and severe injuries to the lungs, gastrointestinal tract, and larynx were considered. Predictions of a 1-percent probability of mortality and selected injury levels were also given for repeated blasts of long duration. The results suggested that repeated blasts of sub-threshold levels for a single exposure do not cause gross non-auditory injuries. For repeated blasts above threshold levels, the severity of blast injuries tended to increase with the number of blasts.

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This research was conducted according to the principles enunciated in the Guide for Laboratory Animal Facilities and Care prepared by the National Academy of Sciences-National Research Council.

INTRODUCTION

The Walter Reed Army Institute of Research (WRAIR) was formally tasked by the U. S. Army Medical Research and Development Command in February 1978 with establishing a research program to study the pathophysiological effects of blast overpressure. Among the questions to be answered were: (1) What physical characteristics of the blast wave are associated with injuries to vital organs? (2) What are the thresholds for injury to the various organ systems of man? (3) What approaches are available and most feasible for prophylaxis and treatment of blast overpressure injury?

The Army's interest in blast overpressure effects resulted from muzzle-blast measurements at the crew positions of Army weapons systems which exceeded the levels set forth in Military Standard 1474 (Reference 1). This document contains damage-risk criteria for auditory injury from impulse noise in terms of peak pressure, duration, number of exposures per day, and the hearing protection used. The Office of the Surgeon General has adopted the upper limit (Z-line) for impulse noise in this standard as the level that should not be exceeded because of the possibility of non-auditory blast injury.

Since 1978 our laboratory has been contracted by the Blast Overpressure Project, Department of Clinical Physiology, Division of Medicine, WRAIR, to study the consequences of repeated blast exposures in large animal models. For each of the experimental arrangements tested, lower overpressures were required for injury to the upper respiratory tract and intra-abdominal organs than those required for lung injury. Moreover, the results have shown that repeated blasts at threshold injury levels for single blasts will significantly

increase the severity of injuries. These data were reported in Reference 2 along with a summary of the literature on repeated blasts.

This presentation will first give damage-risk criteria for man subjected to one or twenty blasts of short duration. The criteria relate the peak overpressures required for threshold and severe injury to the lungs, larynx, and gastrointestinal tract (G.I. tract) as a function of duration and impulse. Secondly, damage-risk criteria for repeated blasts of long duration will be presented. These include selected injury levels produced by one or five blasts and curves relating a 1-percent probability of mortality to the incident blast overpressure and the number of blast exposures.

METHODS

EXPERIMENTAL DESIGN

The damage-risk criteria presented in this report were, for the most part, based on the results obtained from three studies.

The isopeak pressure study involved subjecting groups of six sheep to 20 consecutive blasts each having an incident peak pressure of 10 psi. The positive impulses ranged from 9.2 psi·msec from the 1-lb charges to 32.7 psi·msec for the 64-lb ones, Table 1.

The isoimpulse study consisted of exposing groups of six sheep to 20 blasts each with an impulse of 20 psi·msec from one of five charge weights. The peak pressures ranged from 38.5 psi in connection with the 3-lb charges to 3.8 psi from the 64-lb charges, Table 2.

TABLE 1
PRESSURE-TIME EVALUATED IN ISOPEAK PRESSURE STUDY

Charge Weight, lb	Range, ft (HOB, ft)	Peak Pressure, psi	Duration, msec	Impulse, psi·msec
1	11.1 (1.6)	10.0 ^a 0.4	2.3 0.1	9.2 0.4
8	21.3 (3.2)	9.4 0.6	4.3 0.2	16.1 1.2
16	27.0 (6.0)	10.1 0.9	5.8 0.8	21.3 1.2
32	34.5 (2.1)	10.1 0.5	6.8 0.8	27.3 2.6
64	44.2 (10.1)	10.1 1.1	8.6 0.9	32.7 3.4

^a Mean and standard deviation for 20 blasts.

Ambient pressure at test site: 12.0 psi.

TABLE 2
PRESSURE-TIME EVALUATED IN ISOIMPULSE STUDY

Charge Weight, lb	Range, ft (HOB, ft)	Peak Pressure, psi	Duration, msec	Impulse, psi·msec
3	7.8 (1.2)	38.5 ^a	1.8	18.7
		2.6	0.1	1.5
8	15.6 (3.2)	16.9	3.8	20.4
		0.9	0.3	1.5
16	27.0 (6.0)	10.1	5.8	21.3
		0.9	0.8	1.2
32	43.0 (6.0)	7.0	8.5	22.6
		0.8	1.3	2.2
64	76.3 (10.1)	3.8	11.7	19.4
		0.2	0.8	1.4

^a Mean and standard deviation for 20 blasts.

Ambient pressure at test site: 12.0 psi.

The peak pressure/impulse study was conducted to supplement the first two and evaluated 20 blasts each with one of the peak pressures and impulses listed in Table 3. There were five or six specimens per group.

TABLE 3
PRESSURE-TIME EVALUATED IN SELECTED
PEAK PRESSURE/IMPULSE STUDY

Charge Weight, lb	Range, ft (HOB, ft)	Peak Pressure, psi	Duration, msec	Impulse, psi·msec
64.0	52.0 (10.1)	7.5 ^a 0.27	9.7 0.94	28.6 0.38
0.5	7.5 (1.0)	13.6 0.74	1.7 0.10	8.2 0.23
8.0	14.5 (2.0)	18.5 1.35	3.6 0.08	21.0 1.38
0.5	5.9 (1.0)	22.2 0.84	1.4 0.13	9.0 0.25
8.0	13.5 (3.0)	22.7 0.84	3.6 0.15	24.0 0.97
0.5	5.2 (1.0)	29.6 0.86	1.1 0.04	10.8 0.23

^a Mean and standard deviation for 20 blasts.

Ambient pressure at the test site: 12.0 psi.

Within the three studies, groups of two or three subjects were exposed to a single blast at one of the pressure-time conditions evaluated.

EXPLOSIVE CHARGES

The 0.5-, 1.0-, 3.0-, and 8-lb charges were spheres of cast pentolite. The larger charges were made up of 8-lb blocks of cast TNT.

The charges were detonated by an FS-10 Portable Geophysics Exploding Bridgewire Firing Set using RP-83 EBW detonators (Reynolds Industries, Inc.). The detonators were placed in the center of the pentolite spheres and were taped to the TNT charges along with about 10⁻ of Composition C-3 as a booster.

There was about a 5-min interval between firings except for the 64-lb charges where the interval was near 10 min.

PRESSURE-TIME MEASUREMENTS

Pencil-shaped piezoelectric gages (Susquehanna Model ST-7) were used to make the free-field pressure-time measurements. The outputs from the gages were passed through a Textronix differential amplifier (Model AM502) and recorded on a magnetic-tape unit (Ampex Model PR2230). Paper strip chart records were obtained from the magnetic tape using a fiberoptic visicorder (Honeywell Model 1858). The peak overpressures, durations, and impulses were read from the hardcopy. The duration of the positive phase was measured from the initial pressure rise, zero time, until the trace first dropped below baseline. This is the A-duration and not the B-duration commonly used in the field of auditory effects of impulse noise.

TEST SPECIMENS

The test specimens were Columbia-Rambouillet cross open ewes of from 40- to 50-kg body weight. A fishnet harness was used to keep the sheep standing on all fours and oriented right-side-on to the blast. All were given sedative doses of Rompun® I.M. 15 min before testing.

INJURY ASSESSMENT

All animals were sacrificed 1 hr post blast by anesthetic doses of Nembutal® I.V. and exsanguination. Postmortem examinations were conducted. Gross pathological findings from the lungs, G.I. tract, and upper respiratory tract (larynx, pharynx, and trachea) were recorded. The minimal or threshold injuries consisted of small groups of petechiae on the lungs, light contusions in the wall of the G.I. tract, and petechiae lining the upper respiratory tract. In the opinion of the medical experts, such threshold injuries would not be expected to impair human performance. They would be benign, asymptomatic, and probably would not produce any discomfort to the individual. They would be self-healing without treatment.

Severe injury to the lung was characterized by large, confluent hemorrhages deep into the parenchyma and bloody froth in the bronchi and upper respiratory tract. Severe G.I. tract injuries consisted of large areas of subserosal and submucosal contusions scattered throughout the system with mucosal ulcerations hemorrhaging into the lumen of the organs. The severe upper-respiratory-tract injuries consisted of hematomas lining the larynx, pharynx, and trachea resulting in a reduction in the inside diameters of those organs. Severe injuries would present serious lesions that could be life threatening to the individual.

ANALYSIS

The measured overpressures, durations, and overpressure impulses were scaled to a 70-kg man at sea level using the procedures discussed in Reference 3. The scaled overpressures were plotted as a function of the scaled durations and curves were drawn to define the conditions for threshold and severe injury. In general, the threshold-injury curves were drawn through the highest overpressures where no or only very minimal injuries were detected, and the severe-injury curves were drawn through the lowest overpressures where severe injuries (as discussed in the previous paragraph) were detected. An analogous procedure was used to obtain injury curves for scaled overpressure vs scaled overpressure impulse.

Each point on the curves defined an overpressure and either a corresponding duration or a corresponding impulse which were then converted to a range and yield by assuming a TNT detonation at a scaled height-of-burst of approximately $2 \text{ ft/lb}^{1/3}$. In each case, the range-vs-yield points obtained from the overpressure-vs-impulse curve agreed closely with the corresponding points obtained from the overpressure-vs-duration curve. The final range-vs-yield curves were smoothed through all of the points obtained by both procedures.

RESULTS

DAMAGE-RISK CRITERIA FOR REPEATED BLASTS OF SHORT DURATION

The incident overpressures necessary for threshold and severe injuries from 1 or 20 blasts appear as a function of duration in Figure 1. In general, the curves bend upwards at the shorter durations. The threshold

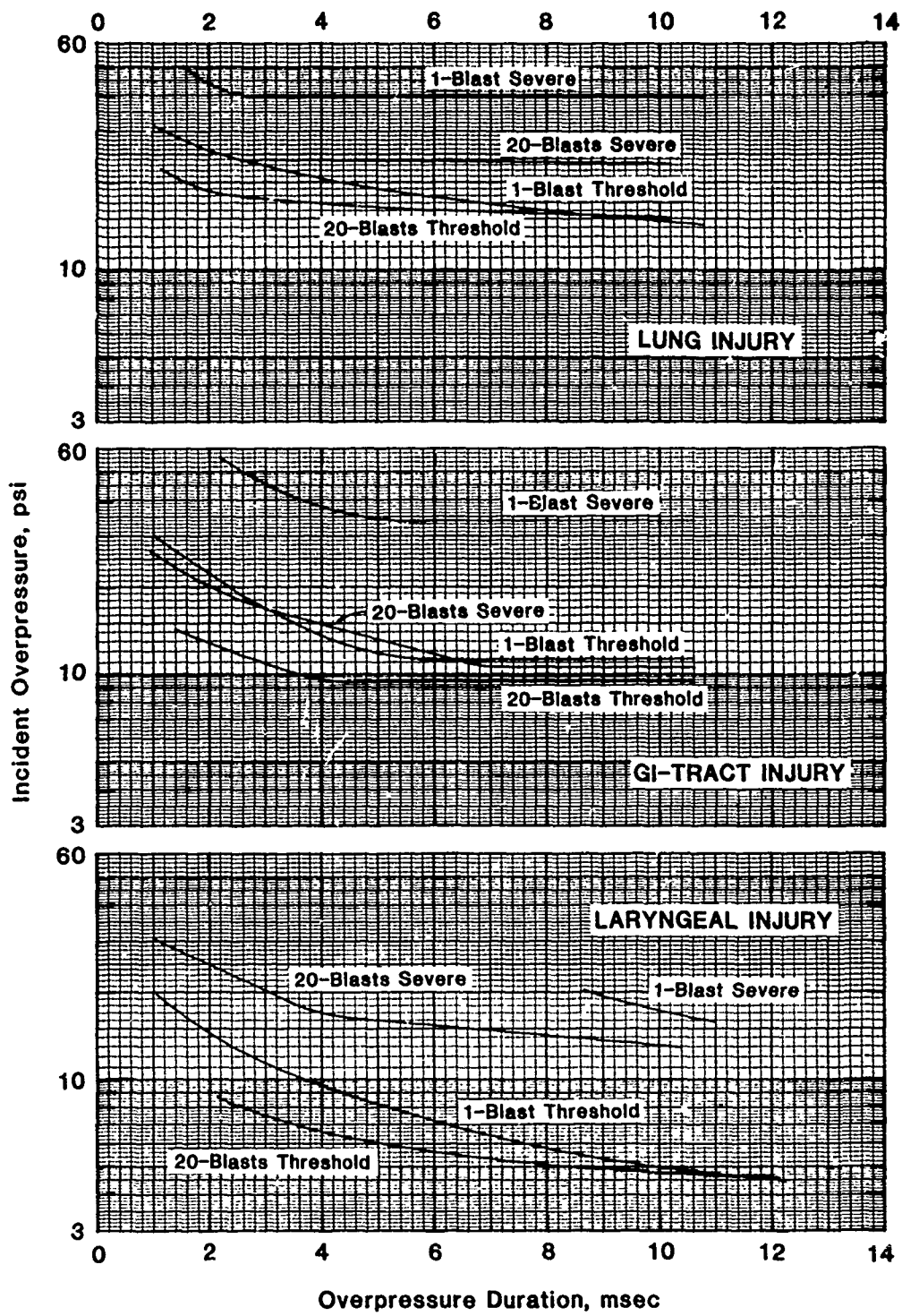


Figure 1. Damage Criteria Curves for Personnel Standing in the Open in Relation to the Incident Overpressure and Duration.

overpressures associated with 20 blast exposures are highest for the lung and lowest for the larynx. For example, with blast waves of 8-msec duration these threshold overpressures are near 15.5 psi for the lung, 9.5 psi for the G.I. tract, and 5.0 psi for the larynx. Except for very short durations, there are no important differences between the incident overpressures required for threshold injuries from 1 blast and those required from 20 blasts. This would suggest that the number of blast exposures is unimportant provided the overpressures are at subthreshold levels for 1 blast. As seen in Figure 1, for the G.I. tract, the curve for 1-blast threshold injury is about the same as the curve for 20-blasts severe injury.

The incident overpressures associated with these injury criteria are plotted as a function of overpressure impulse in Figure 2. These curves are similar to the critical-load curves used to predict structural damage. That is, there is a critical peak pressure and impulse both of which have to be exceeded in order to inflict damage to a particular structure. The critical overpressures can be estimated from many of the curves in Figure 2, but additional data would have to be obtained at close ranges from very small charges in order to accurately estimate the critical impulses. For underwater blasts, the critical impulses could be estimated at greater ranges from larger charges because the surface cut-off wave truncates and thereby shortens the duration of the incident wave.

Criteria in Relation to Range and Charge Weight

Figures 3 through 6 present curves for charge weight vs range where threshold injury or severe injury can be expected to occur from 1 or

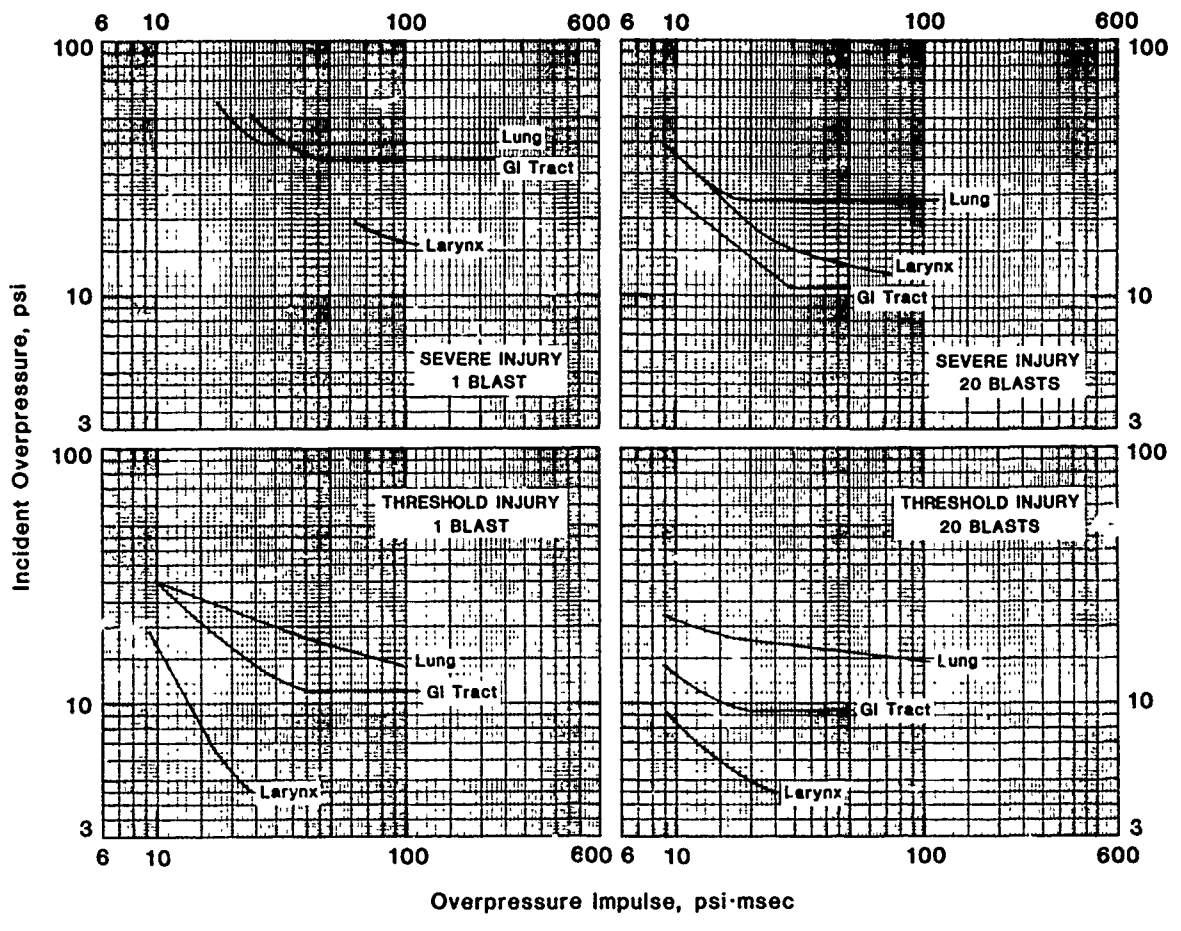


Figure 2. Damage Criteria Curves for Personnel Standing in the Open in Relation to the Incident Overpressure and Impulse.

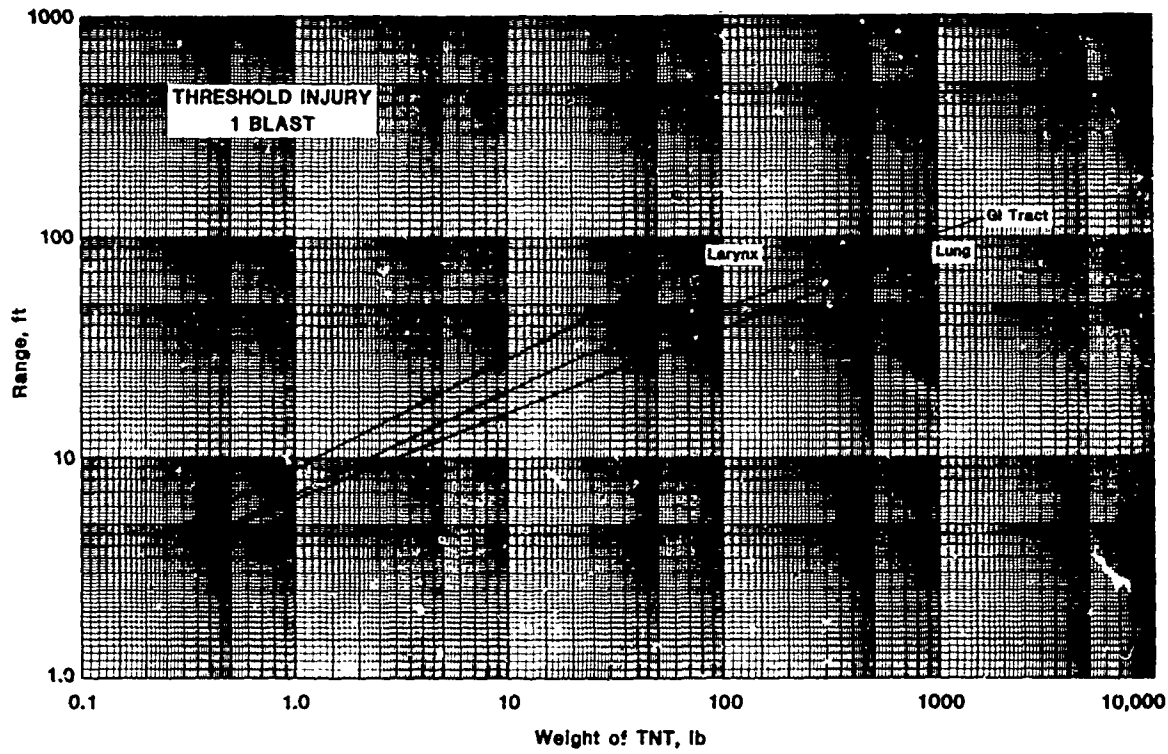


Figure 3. Ranges for Threshold Injuries in Personnel Exposed to 0- Blast as a Function of Charge Weight.

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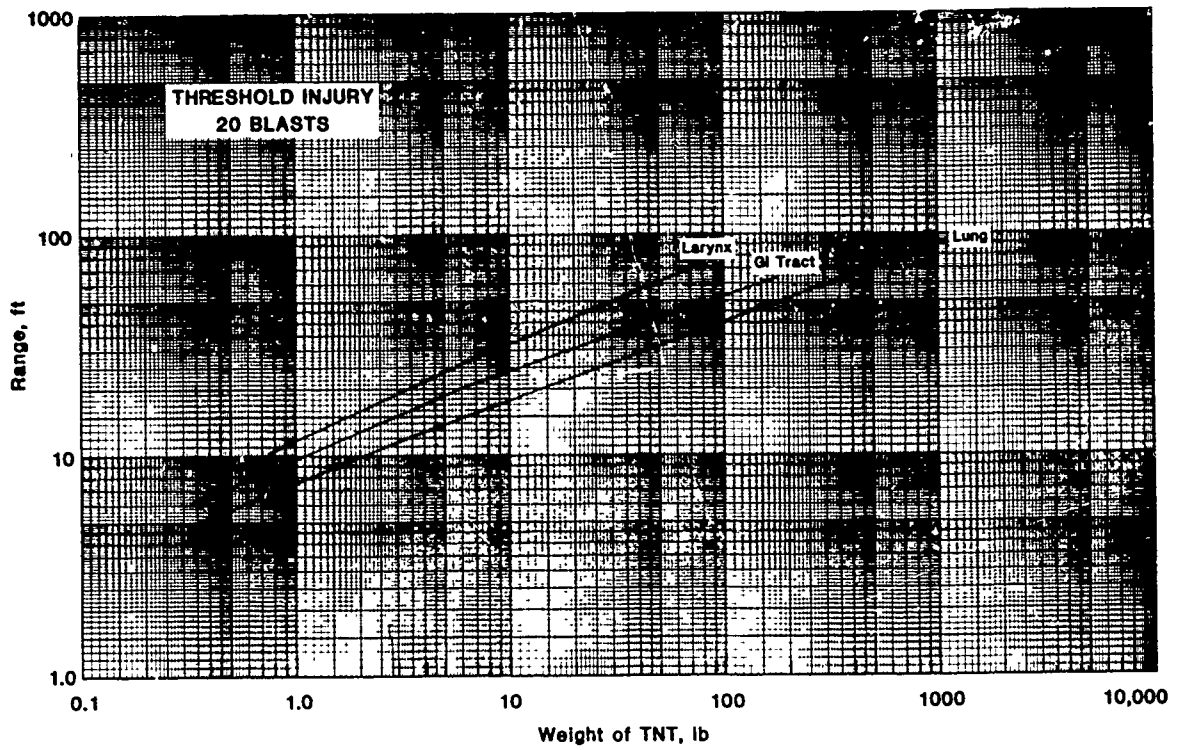


Figure 4. Ranges for Threshold Injuries in Personnel Exposed to 20 Blasts as a Function of Charge Weight.

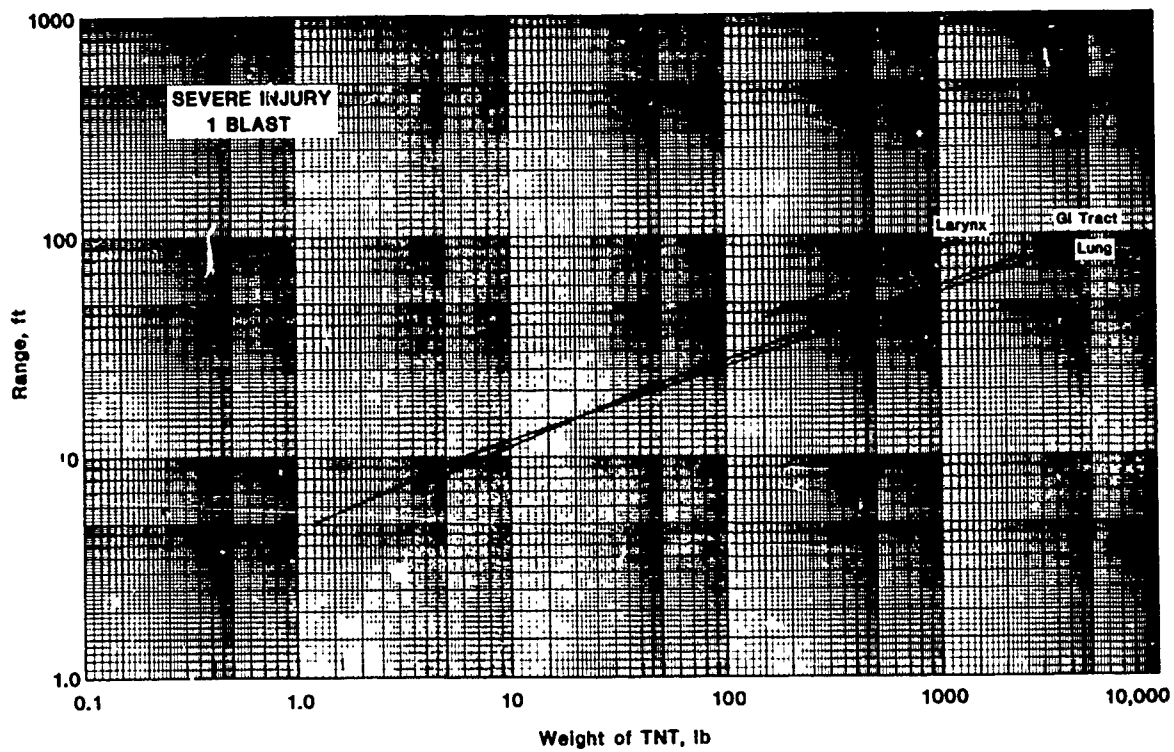


Figure 5. Ranges for Severe Injuries in Personnel Exposed to One Blast as a Function of Charge Weight.

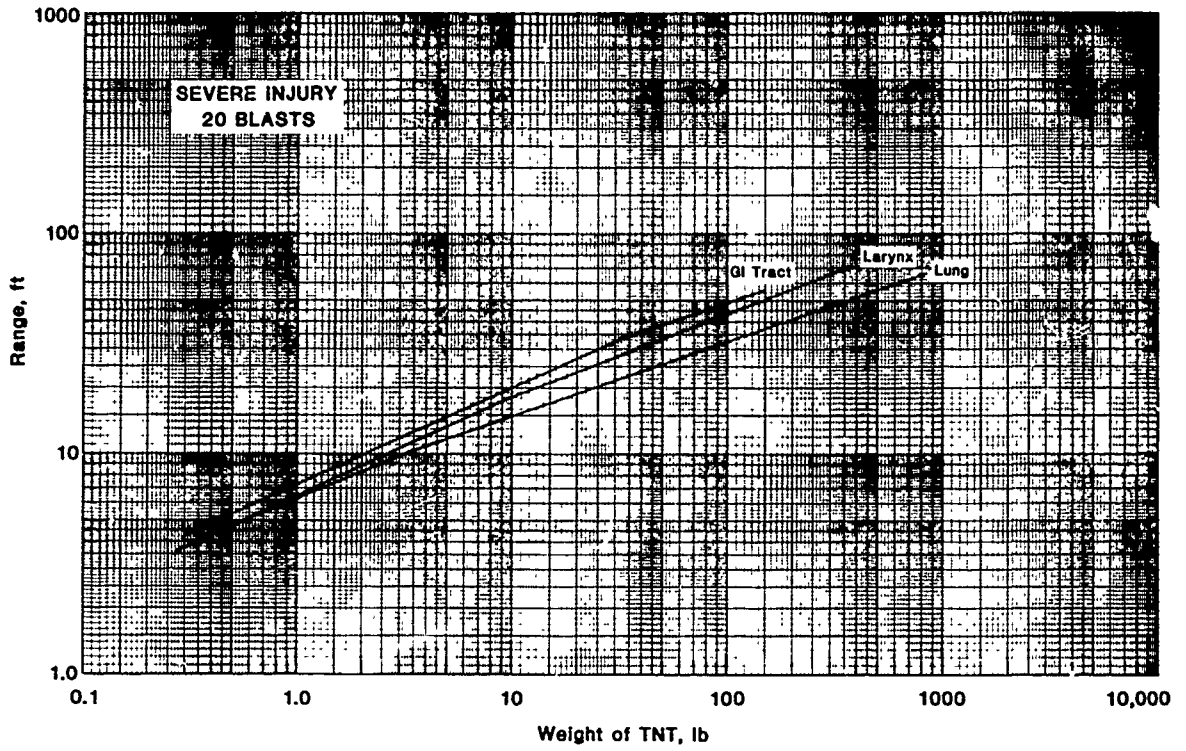


Figure 6. Ranges for Severe Injuries in Personnel Exposed to 20 Blasts as a Function of Charge Weight.

20 blasts. These curves apply to a man standing near detonations at low heights of burst for sea-level conditions.

In regard to threshold injury from 1 or 20 blasts (Figs. 3 and 4) lesions to the larynx were the most far-reaching effect, followed by the G.I. tract and the lung. This sequence changes with respect to severe injury from 20 blasts (Fig. 6) where G.I. tract injury is the most far-reaching effect. This is probably due to the fact that repeated blasts can cause a threshold contusion in the G.I. tract to grow in size leading to disruption of the mucosal lining with concomitant hemorrhaging into the lumen of the organ which warrants a severe rating.

The ranges for threshold injury from 1 and 20 blasts were about the same except for charges of less than 10 lb (Figs. 3 and 4).

It can be seen in Figures 5 and 6 that the ranges at which severe injury to the G.I. tract can occur from 20 blasts are nearly twice those for a single blast. The difference in these ranges for severe lung injury was far less than that for the G.I. tract.

DAMAGE-RISK CRITERIA FOR REPEATED BLASTS OF LONG DURATION

Injuries

Table 4 gives estimates of the peak overpressures for 1 and 5 blasts required to produce selected injuries in man, Reference 2. The estimates were based on the results of tests wherein sheep and swine were exposed to high-explosive-generated blasts while against a reflector plate in a shock-tube. The durations of the blast waves were on the order of 10 msec. They were delivered at a rate of 1 per min. The overpressures required to produce selected injury levels in animals were scaled to long-duration ones at sea level and to the body weight of man.

TABLE 4

INJURY VS OVERPRESSURE FROM ONE OR FIVE LONG-DURATION BLASTS

Injury Level	Effective Overpressure, psi	
	One Blast	Five Blasts
<u>LARYNX</u>		
<u>Slight</u>		
Threshold	6	3
50% Incidence	10	5
<u>Moderate-Severe</u>		
Threshold	10	5
50% Incidence	12	8
<u>GASTROINTESTINAL TRACT</u>		
<u>Slight</u>		
Threshold	8	7
50% Incidence	12	8
<u>Moderate-Severe</u>		
Threshold	12	8
50% Incidence	18	14
<u>LUNGS</u>		
<u>Slight</u>		
Threshold	11	11
50% Incidence	16	16
<u>Moderate-Severe</u>		
50% Incidence	27	21

Effective overpressure may be:

- a. incident overpressure if personnel are end-on to the blast,
- b. incident plus dynamic pressure if side-on to the blast, or
- c. reflected overpressure if against a reflecting surface.

The predicted threshold for lung hemorrhage in man from a single blast obtained by this method was 11 psi which was in agreement with previous estimates of 10-12 psi, Reference 3. As seen in Table 4, the threshold values from single blasts for laryngeal lesions (6 psi) and G.I. tract injury (8 psi) were below that for lung hemorrhage. The overpressures required for given levels of laryngeal lesions from five blasts were on the order of half those from a single blast. A 50-percent incidence of moderate-severe injuries from five blasts could be expected to occur at overpressures of 8 psi for the larynx, 14 psi for the G.I. tract, and 21 psi for the lungs.

Mortality

Previously reported estimates for a 1-percent probability of mortality for man in various initial orientations are shown as a function of the peak incident overpressure and number of blasts in Figure 7, Reference 2. The curves were derived by taking the overpressures associated with 1-hour mortality in large animals tested in the shocktube and scaling them to a 70-kg man and long-duration blast waves at sea level. The figure gives the incident overpressures necessary to generate the same effective airblast dose for three conditions of exposure. For personnel prone end-on to the blast, the side-on incident overpressure constitutes the airblast dose. A single blast of 40 psi could be expected to produce 1-percent mortality. Three blasts of 25 psi could produce the same mortality rate.

For personnel prone side-on to the blast or standing, the incident side-on overpressure plus the dynamic overpressure represents the airblast dose. An effective dose of 40 psi and a 1-percent mortality would be

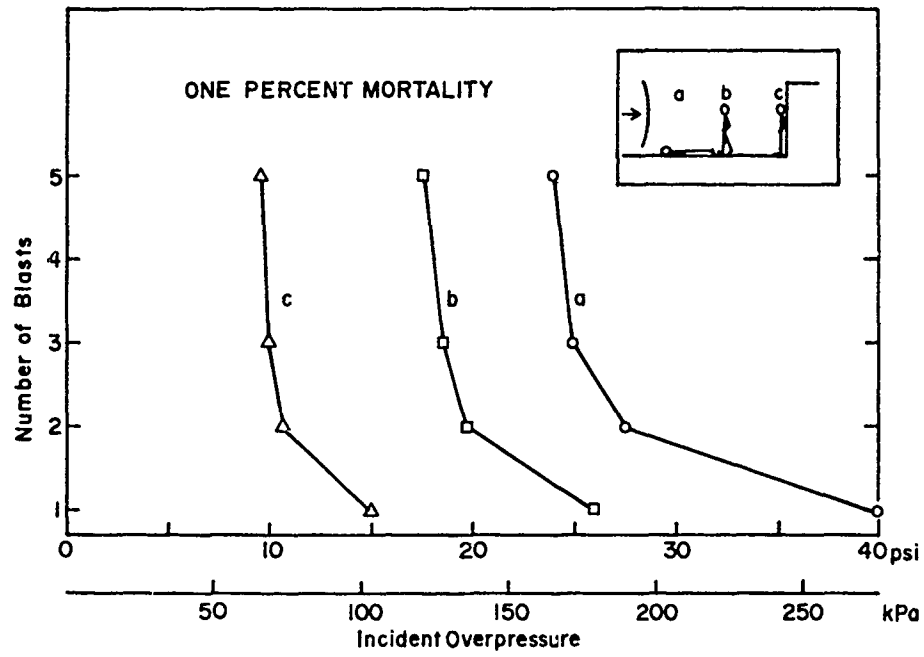


Figure 7. Estimated 1-Percent Mortality Curves for Man Exposed to Repeated Blasts of Long Duration.

generated by an incident shock wave of 26.5 psi plus the associated dynamic pressure of 13.5 psi, Figure 7. Three blasts of about 18.5 psi would cause a 1-percent incidence of death.

For individuals against or close to a large reflecting surface, the reflected pressure would be the damaging airblast parameter and, in this case, an incident shockwave of 14.6 would reflect to 40 psi and result in a 1-percent probability of death (Fig. 7). Three blasts having incident overpressures of 10 psi could inflict 1-percent mortality among persons exposed under this condition.

DISCUSSION

It appears from the results of the present and previously-reported studies that repeated blasts of subthreshold levels for single exposures are of no consequence as far as non-auditory injuries are concerned. During one experimental series, sheep were given 50 blasts at a rate of 1 per min daily for 4 consecutive days without gross injury detectable in their lungs or G.I. tracts. The blast overpressure was 7.5 psi (duration about 10 msec), which was below the single-exposure thresholds for injury to the lungs (13 psi) or G.I. tract (10 psi).

Nearly all the investigations on repeated blast effects previously reported were obtained by keeping the peak overpressure and time between blasts constant within a given experimental series. The effects of varying the magnitudes of the blasts and the time intervals between blasts deserve further study.

Another area deserving attention is the effect of repeated blasts on the unprotected ear. In particular, information is needed on the extent of damage to the eardrum and ossicular chain as a function of the number and the intensity of the blasts.

The injuries reported in the present study were determined by gross observations. More sensitive methods of detecting injury to the lung from repeated blasts are underway which include pulmonary function tests and techniques to detect and measure pulmonary edema. Various biochemical markers are also being evaluated in the blood serum of blast-injured animals as an early indicator of disruption of tissue in the lung and G.I. tract. Detailed histological studies of tissues from specimens subjected to a wide range of blast overpressures are also being conducted.

In regard to the mechanism of lung injury, intrathoracic pressures (ITP's) have been measured in volunteers exposed in various orientations to shockwaves of 1, 2, and 3 psi, all of which are below the Z-line. On some of the tests, the volunteers wore clothing and protective garments. The data are currently being correlated with the ITP's computed by a mathematical lung model for man and with ITP's measured inside sheep as well as in the foam-plastic lung of a fluid-filled dummy exposed over a wider range of blast overpressures. Preliminary results indicate that the trends in the ITP's measured in the volunteers receiving incident overpressures of less than 3 psi continued in the experimental animals and dummy at higher levels.

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