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The findings of this report are not be be construed as an official Department of the Army position unless so designated by other authorized documents.

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ABSTRACT

Small, bare charges were detonated inside an M59 armored personnel carrier (APC) in an attempt to simulate the complex blast waves generated by the jets from shaped-charge warheads penetrating into armored vehicles. Anesthetized sheep were placed inside the APC at 91- and 122-cm ranges from 57- or 113-g pentolite charges. Pressure-time was measured by pressure transducers either mounted on the animals or free standing at comparable ranges on the opposite side of the vehicle. In general, the waveforms were characterized by an initial shock wave of less than 1-msec duration followed by repeated reflections of decreasing magnitude. No deaths nor lung hemorrhages were observed, but all the animals sustained severe ear injury. Animals subjected to peak overpressures of 1.2 to 2.3 bar from the 113-g explosions also received slight non-auditory blast injuries to the upper respiratory and gastrointestinal tracts; those exposed to peak overpressures of just under 1 bar from the 57-g charges did not. The non-auditory blast injuries inside the APC were more severe than those sustained by sheep at comparable distances from 113-g charges in the open. The results suggested that the biological consequences of a complex wave of the type encountered in this study may be equated approximately to a Friedlander wave with a peak overpressure equal to that of the complex wave and with a total impulse equal to the impulse over the first 2 to 3 msec of the complex wave.

INTRODUCTION

A complex blast wave may be defined as any blast wave that does not have the classical or Friedlander waveform that is typical of those measured freestream in the open. Complex waves may result from the interaction of Friedlander waves with obstacles in the open or from the entrance of such waves into field fortifications, structures, vehicles, or naval craft. Complex waves are also generated by weapons fired from inside enclosures or by the jets from shaped-charge warheads penetrating into armored vehicles or naval vessels.

Information has been reported on the biological effects produced by complex blast waves occurring inside a variety of structures and field fortifications.[1,2] Except for foxholes, the waveforms were characterized by a series of shock reflections (diffraction phase) superimposed on a relatively slow-rising overpressure (fill phase). Inside foxholes the diffraction phase predominated and the fill phase was insignificant.

Except for eardrum rupture, which was apparently related to the peak overpressure, the animals showed more resistance to those complex blast waves than they did to Friedlander waves having the same peak overpressures. The results of laboratory experiments showed that, for blast waves that rose in two or more steps, as in the diffraction phase, the peak overpressure tolerated by animals was about 1.8 times the value for Friedlander waves. For smooth-rising overpressures, as in the fill phase, the peak overpressure tolerated by animals was more than five times the value for Friedlander waves.[3] The results from the laboratory experiments agreed with those obtained inside full-scale structures on field tests.

It has been reported that complex blast waves resulting from firing a recoilless weapon from inside an enclosure produced lung injury in rabbits at one-fifth the peak overpressure required for a Friedlander-type wave.[4] It was suggested that the series of shockwave reverberations in the enclosure matched the natural frequency of the rabbit's thorax resulting in injury at peak overpressures as low as 0.4 bar.

This presentation gives the results of an exploratory study wherein small, bare charges were detonated inside an armored personnel carrier to simulate the complex wave forms that are generated by the jets from shaped-charge warheads penetrating into an enclosure. The ultimate objective of these investigations is to obtain pressure-time patterns inside the thorax of sheep exposed to complex blast waves to provide input for an existing mathematical model currently used to calculate the intrathoracic pressures resulting from exposure to Friedlander waves.

PROCEDURES

Vehicle

The personnel carrier used in these studies was the M59 vehicle, armored, infantry, full-tracked and is shown in Figure 1 along with its inside dimensions. The aft 338-cm portion (8.7 m^3) was designated as the passenger compartment and the forward 174-cm section (4.5 m^3) as the crew compartment. The first three tests were conducted with animals and explosives in the passenger compartment. The driver's hatch remained open but the back door was closed. Next, a partition was installed between the passenger and crew compartments to change the volume of the enclosure. The partition contained an opening, equal to the area of the driver's hatch (0.20 m^2). Two tests were run with subjects and charges in the passenger compartment and only the driver's hatch open as before. Next, two tests were conducted with charges and subjects inside the crew compartment with only the back door being open. Finally, two tests were conducted with animals in the open for comparison.

Charges

Two weights of charges were used: 57 g and 113 g. They were bare, pentolite spheres detonated at their centers with exploding bridgewire detonators (Reynold's Model RP-83). In connection with the tests conducted in the passenger compartment, the charges were detonated in the exact center of the compartment midway between the floor and ceiling. In the crew compartment, the sheep was seated in the driver's seat, and the charge was forward and to the right of the subject at a range of 91 cm.

Pressure-Time Instrumentation

There were four channels of pressure time. Piezo-electric gauges (Susquehanna Model ST-2) of cylindrical shape were mounted with the sensing surface being horizontal and side-on to the charge which was approximately at the same height above the floor. The outputs from the gauges were passed through a Textronix differential amplifier (Model AM502) and recorded on a magnetic tape unit (Ampex Model 2200). Analog records were obtained from the magnetic tape using a fiberoptic strip chart recorder (Honeywell Visicorder Model 1858). The magnitude of the overpressures and times were read from the hardcopy. The impulse versus time was computed on a MINC 11/23 computer (DEC Model MNC11-HA).

Inside the passenger compartment, gauges were placed on the ventral surfaces of the two animals seated on a bench along the right side of the compartment at 91 and 122 cm from the charge, and two additional gauges were placed at comparable locations over the unoccupied bench along the opposite wall. In the crew compartment, one gauge was on the animal and one was at the same range and adjacent to the subject.

During the tests in the open, gauges were placed on the animals and side-on in the freestream at comparable distances from the charges.

Animals

Sixteen female sheep weighing between 34 and 54 kg were used. Each animal was anesthetized to a surgical level with Sodium Pentobarbital at 15 minutes before testing. There were two per test inside the passenger compartment. They were seated upright on the bench on the right side of the vehicle at 91 and 122 cm from the charge. Inside the crew compartment there was one animal per test located in the driver's seat and 91 cm from the charge. There were two on each of the two tests in the open, both at the 91-cm range. One was in the freestream seated on a box and the other was seated against a 1.22 x 1.22-m steel plate. Within 30 minutes post shot, all the subjects were sacrificed with Sodium Pentobarbital (30 mg/kg) given intravenously prior to postmortem examination and exsanguinated via bilateral carotid transection.

RESULTS

Pressure-Time Measurements

The pressure-time patterns recorded by gauges inside the vehicle when the 113-g charges were detonated are illustrated in Figure 2.

In general, the waveforms were characterized by an initial shock wave of less than 1-msec duration followed by repeated reflections of decresing magnitude. Peak overpressures were on the order of 2 bar at 91 cm and 1 bar at 122 cm from the 113-g charge. Inside the passenger compartment the second pressure rise represents the reflections of the initial shock from the left wall, the floor, and the ceiling of the vehicle. The third pressure rise recorded by Gauge 4, 122 cm from the charge, resulted from reflections from the rear of the vehicle. The third pulse was hardly discernible in the record from Gauge 1 which suggests that these shocks decayed rapidly over relatively short distances of travel. Consequently, the waveforms would have been different at various locations in the compartment.

The waveforms recorded from the 57-g charge firings were similar to those illustrated in Figure 2 for the 113-g ones except that the pressures were lower. Those recorded in the open corresponded to just the initial shock wave portion (i.e., less than 1 msec) of those recorded inside the vehicle.

The durations of the overpressures measured in the passenger compartment, with or without the partition in place, ranged from 36 to 39 msec. Inside the crew compartment, with the partition in place, the durations were greater than 40 msec. Thermal effects on the gauges caused a baseline shift making it difficult to determine the exact durations.

Pathological Findings

General

All 16 subjects survived the blast. They were first examined 20 seconds after the detonations. With two exceptions, they all appeared normal. Two looked dazed but returned to normal within a few minutes. At autopsy, some of the animals had small amounts of carbon deposited in the mucosal secretions lining their nasal cavity and trachea. The only thermal effect detected was a trace amount of singeing on some of the animals at the 91-cm range.

Ear Injury

The most severe blast injuries were found in the middle ears. Examples of this form of ear injury appear in Figure 3. All the eardrums that were assessable were ruptured. Some of the ears were not assessable (N/A) because ticks and/or wax blocked the external ear canals. Most of the eardrums were over 50-percent destroyed with significant hemorrhages. There were 14 cases involving fracture or dislodgement of the malleus bone--an ossicle in the middle ear. Because the sample size was small and all of the ear injury was of a severe form, it was not possible to judge whether or not the incidence and/or severity of this lesion varied between groups.

Non-Auditory Injuries

Non-auditory blast injuries were of minimal severity. They consisted of petechial hemorrhages and small contusions in the mucosal lining of the upper respiratory (UR) tract. The former has been found in 4 percent of control animals and could have been due to transport and handling. There were also small contused areas in the submucosal tissues lining the gastrointestinal (GI) tract. No lung hemorrhages were observed in any of the specimens.

Figure 4 shows the distribution of blast lesions among the subjects exposed to blast from the 113-g charge inside the vehicle. All seven of them sustained non-auditory blast injuries. Six received slight injuries to both the UR and GI tracts. None of the five animals tested inside the vehicle in connection with the 57-g charges sustained any non-auditory blast lesions. One of the four subjects tested in the open at 91 cm from a 113-g charge received a UR tract lesion.

DISCUSSION

Summated Impulse

Although the data from the present study were limited, the results were compared with previous information on sheep response to ideal waves in an attempt to define the parameters of complex blast waves associated with non-auditory blast injuries. This was done by computing, for each recorded wave, both the maximum overpressure, which in all cases was either the peak (P_0) in the initial pulse or the peak (P_2) in the second pulse, and the cumulative impulses from the beginning of the wave to the end of either the first (I_1), second (I_3), or third (I_5) pulse. These values were then averaged according to charge weight and subject distance from the charge, Table 1. These data points are plotted in Figure 5 along with threshold injury curves for exposure to a single Friedlander blast wave.[5] The curves were compiled from results obtained by exposing sheep to blasts from 0.23-kg to 29-kg charges in the open. The curves show the peak pressures and the impulses that have to be exceeded in order to injure the particular organ systems.

In general, the data points associated with impulses out to 1 msec (I_1) fall far to the left of the iso-damage curves. This suggests that the initial (first) pulse alone could not account for the observed injury. The data points associated with impulses out to 2-3 msec (I_3) were in better agreement with the curves, and the data points associated with impulses out to 5-6 msec (I_5) were too far to the right of the curves judging from the fact that no extensive blast lesions were observed. If the total impulses (I_6) were plotted in the figure, the data points would fall even farther to the right of the curves. The results suggest that the biological consequences of a complex wave may be equated to that of a Friedlander wave with a peak overpressure equal to that of the complex wave and with a total impulse equal to the impulse over some initial portion of the complex wave.

The summated impulse criteria would not be expected to apply to complex blast waves that have the peak overpressure to strong shocks occurring later in the wave, i.e., beyond 5 msec.

Partial Impulse

The above approach of summating the impulse over the early portion of the wave is similar to the partial-impulse criteria used previously to predict mortality and lung injury for complex blast waves recorded inside field fortifications.[6] These criteria take into account the impulse delivered over the initial portion of the blast wave up to a specified time. This critical time is related to the body weight of the animal species. The partial impulse (I) corresponding to an LD_{50} and the critical time (T) were estimated to be:

$$I\ (\mathrm{Pa \cdot sec}) = 896(m/70)^{1/3}\ (P/101)^{1/2}\ P_{sw}/414$$

$$T\ (\mathrm{msec}) = 2.1(m/70)^{1/3}\ (101/P)^{1/2}$$

where P is the ambient pressure (kPa), m is the body weight (kg), and P_{sw} is the overpressure (kPa) resulting in 50-percent mortality for a square wave with an ambient pressure of 101 kPa (14.7 psi).

According to the partial-impulse criteria, an impulse of 159 Pa·sec (one fifth of the LD_{50} value) delivered within 1.98 msec would be required to produce threshold lung injury in 44-kg sheep at an ambient pressure of 83 kPa. The impulses encountered in the present study, I_3 listed in Table 1, that were delivered over the first 2-3 msec portion of the blast wave were all well below the 159 Pa·sec required for lung injury. No lung hemorrhages were observed which is in agreement with the partial-impulse criteria.

Quasi-Static Overpressure

Another attempt to establish the airblast loading from complex blast waves has been to average the oscillations in the pressure-time record.[7] That is, the complex wave is approximated by a smooth Friedlander-like wave by drawing a curve midway between the peaks and troughs from the baseline at the end of the positive phase back to zero time. This procedure gives a total wave duration T_0 to T_6 (T_0-T_6) and impulse (I_6) approximately equal to the values as read in the present study and an initial peak overpressure equal to approximately half the value as read in the present study.

The quasi-static overpressure data points, which correspond to one half of the values given in Table 1, are plotted in Figure 6 long with iso-damage curves derived for Friedlander waves. It can be seen that the quasi-static overpressure data points would predict injury to the larynx (UR tract) in all four groups and lung hemorrhage in the group exposed at 91 cm from the 113-g charges; in reality, no lung hemorrhages occurred in the latter group, and there were no UR tract lesions among the animals in the two groups that were subjected to blasts from 57-g charges.

Behavioral Consequences of Ear Injury

At the present time, eardrum rupture, regardless of severity, is not usually considered to be incapacitating to personnel. However, evidence from two sources suggests that ear injury can modify behavior and, in some cases, may result in incapacitation:

First, in our laboratory, a study was conducted on 88 ear sections taken from sheep that were located at several ranges from fuel-air explosions. Physicians (otologists) were asked (1) to record the extent of tympanic membrane damage and the condition of the ossicles in the middle ears, (2) to estimate the conductive hearing loss that could be expected in man having a corresponding degree of ear injury, and (3) to comment on the behavioral effects to be expected from each ear injury with reference to incapacitation. The results are summarized in Figure 7 wherein the information is grouped according to the percent area of the eardrum destroyed. The observed incidence of the fracture of an ossicle (usually the malleus) was 45 percent for cases of less than 25 percent destruction of an eardrum, and 56 percent for 50 to 75 percent destruction of the eardrum. When the eardrums were completely destroyed, the ossicles were always fractured and/or dislodged.

In general, for a given amount of eardrum destruction, the hearing loss and behavioral effects would be greater when there was an associated fracture of an ossicle. For instances of less than 25 percent of the eardrum destroyed, the expected hearing loss would be from 0 to 15 dB without a fracture and from 10 to 15 dB with a fracture. In either case, there would only be minimal to slight transitory disorientation. For instances of more than 50 percent of the eardrum destroyed, a greater loss of hearing could be expected. An immediate transitory disorientation and immediate incapacitation would be predicted where there was total destruction of the eardrum.

The second source of information dealing with the consequences of ear injury from blast is in reports by Kerr and Bryne,[8,9] who treated a number of victims of a Belfast terrorist bombing. The reports describe a very high incidence of immediate deafness and tinnitus (ringing in the ears) as a consequence of relatively minor ear injury. A 2.3-kg bomb was exploded in a crowded resturant where the exact locations of 80 people were documented. Many of the victims described pain in their ears but not all of them had perforations. Some with perforations did not experience any pain. Almost everyone experienced temporary severe deafness. Some said that they could not hear the ambulance attendants speaking even though they could see their lips moving. In general, they recovered from the severe deafness within a matter of hours. Almost all complained of severe tinnitus immediately after the blast. There were 60 eardrums perforated without any ossicular damage in these patients. Subsequently, 49 to the 60 eardrums healed spontaneously. Of the remaining 11 cases, seven were operated on for repair.

The lack of ossicular damage and the fact that 49 to 60 were self healing, suggests that the severity of the ear injury was not more than that described in the first two groups of Figure 7. An important point illustrated here is the severe tinnitus immediately after the blast along with the pain and temporary severe deafness. Tinnitus is a neurosensory phenomenon linked to effects in the inner ear. As already mentioned, Figure 7 takes into account only conductive hearing loss associated with lesions in the middle ear.

The technique of detonating small explosive charges inside an armored vehicle in order to simulate the complex blast wave produced by High Explosive Antitank (HEAT) charges was used to study their biological effects. The results indicate that ear injury would be the primary blast overpressure hazard to personnel under the conditions of this experiment.

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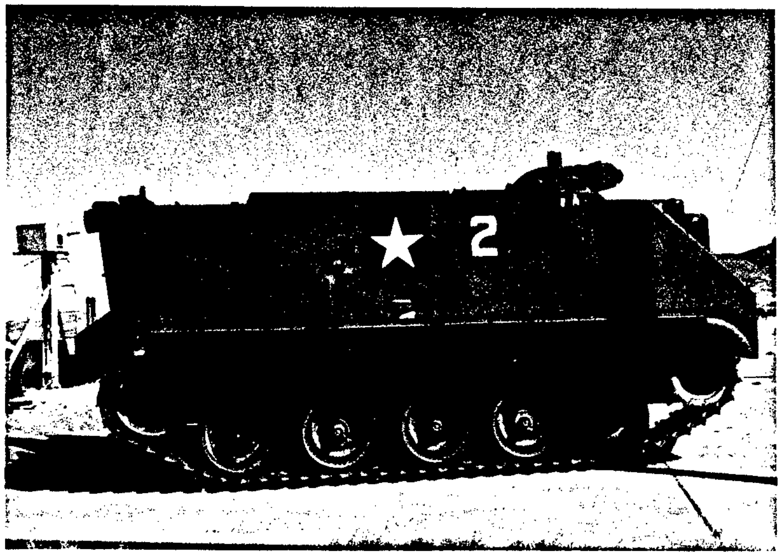


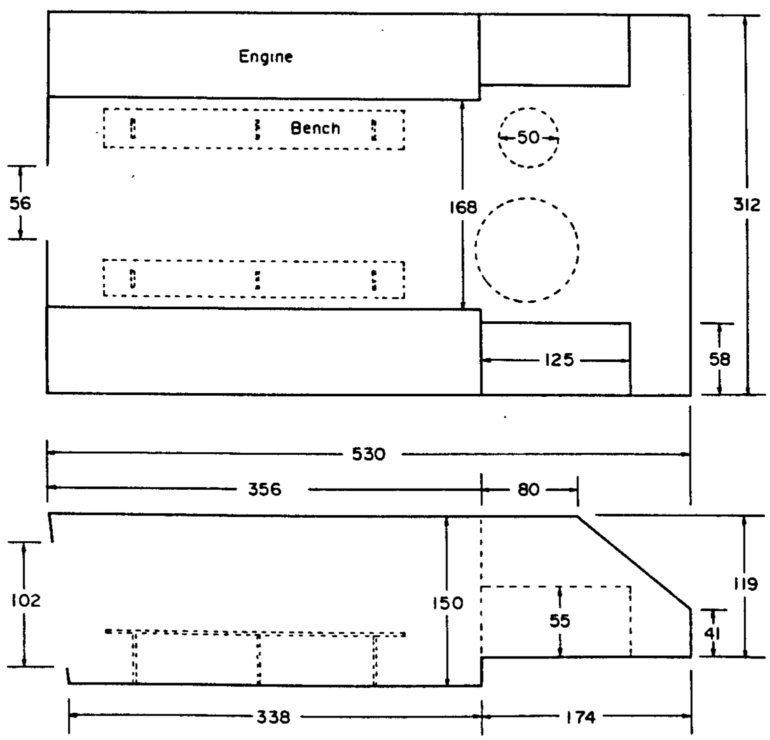


Figure 1. Dimensions (in centimeters) of the M59.

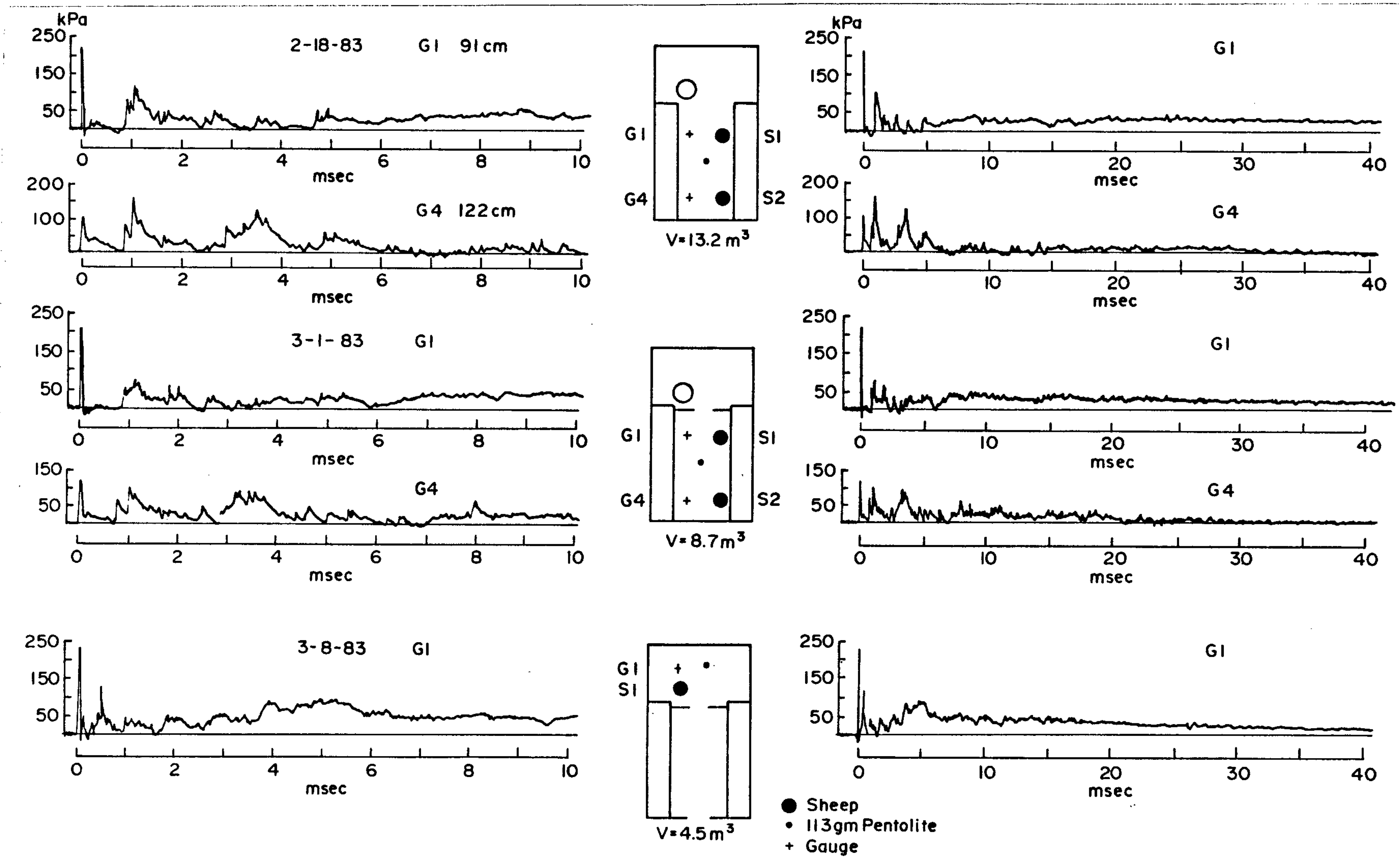
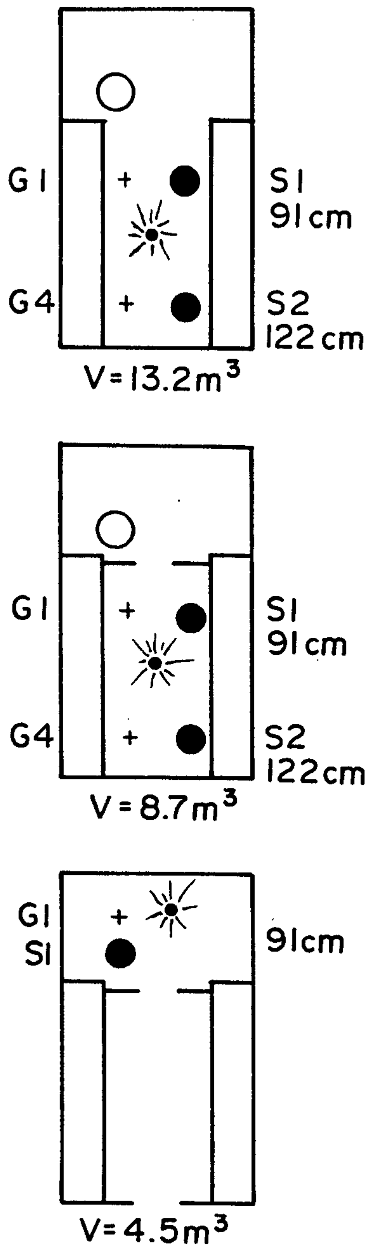


Figure 2. Pressure-Time Recordings from 113-g Charges.

(A)

(B)

Figure 3. Ear Injury Viewed from Middle Ear Side of Eardrum. (A) Right ear of subject in crew compartment, 91 cm from 113-g charge. (B) Left ear of subject in passenger compartment (with partition) 122 cm from 57-g charge.



Blast Injuries		
GI Tract	UR Tract	Ears
2 Traces	2 Slights	2/2 *
Trace Moderate	2 Slights	2/2 *
Trace	–	2/2
Moderate	Petechia	2/2
Slight	Moderate	2/2

● Sheep
• 113 g Pentolite
+ Gauge
* 2 Ears Not Assessable

Figure 4. Blast-Injuries Associated with the Detonation of a 113-g Charge Inside the Vehicle.

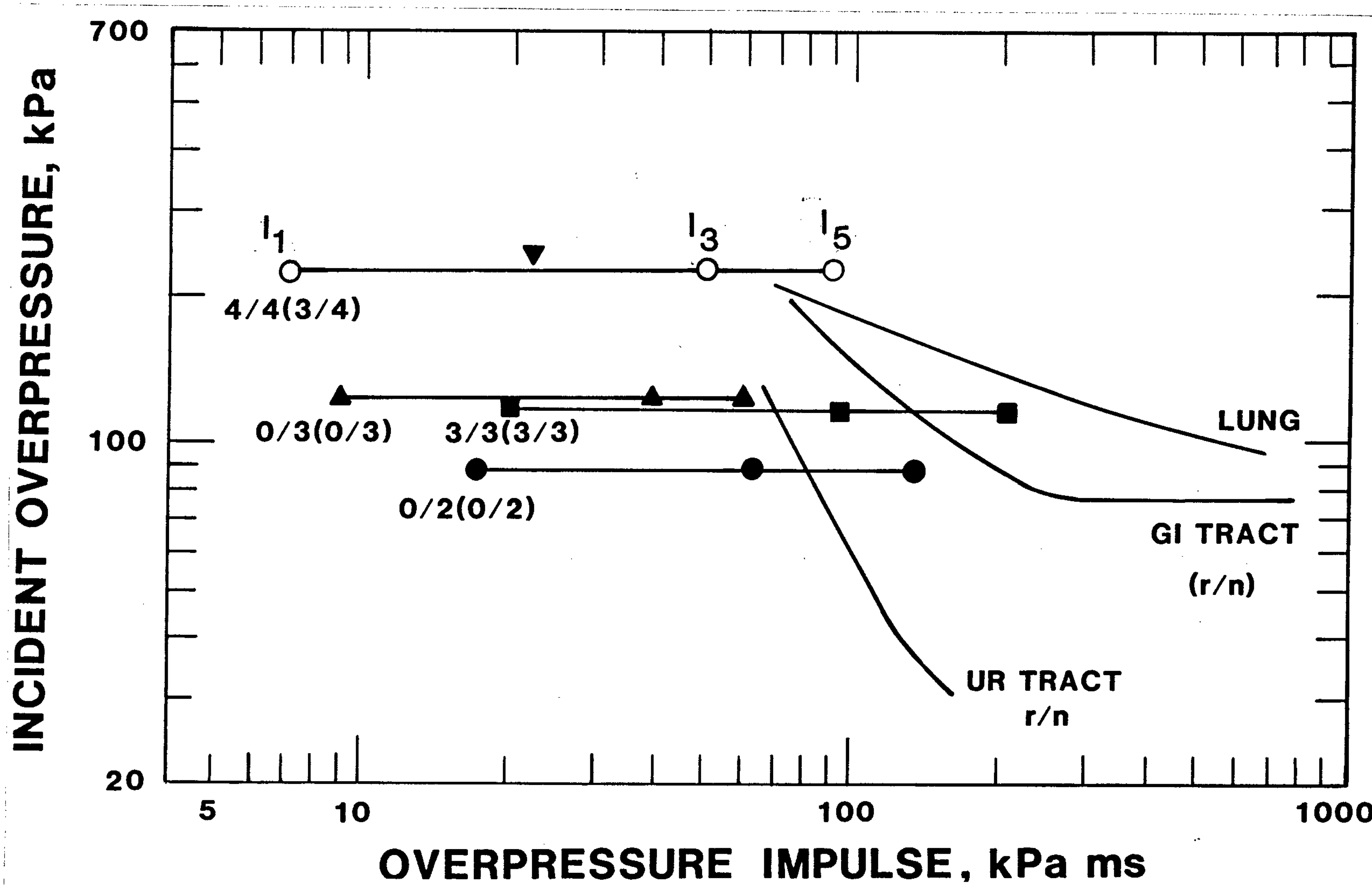


Figure 5. Curves for Threshold Injuries in Sheep Exposed to One Blast in the Open. The data points give the incident overpressures and accumulated impulses at selected times listed in Table 1. I_1, impulse up to about 1 msec; I_3, 2-3 msec; and I_5, 5-6 msec. Inside vehicle: ● 57 g at 122 cm; ▲ 57 g at 91 cm; ■ 113 g at 122 cm; and ○ 113 g at 91 cm. The fractions correspond to the number of animals sustaining injury over the number in the group.

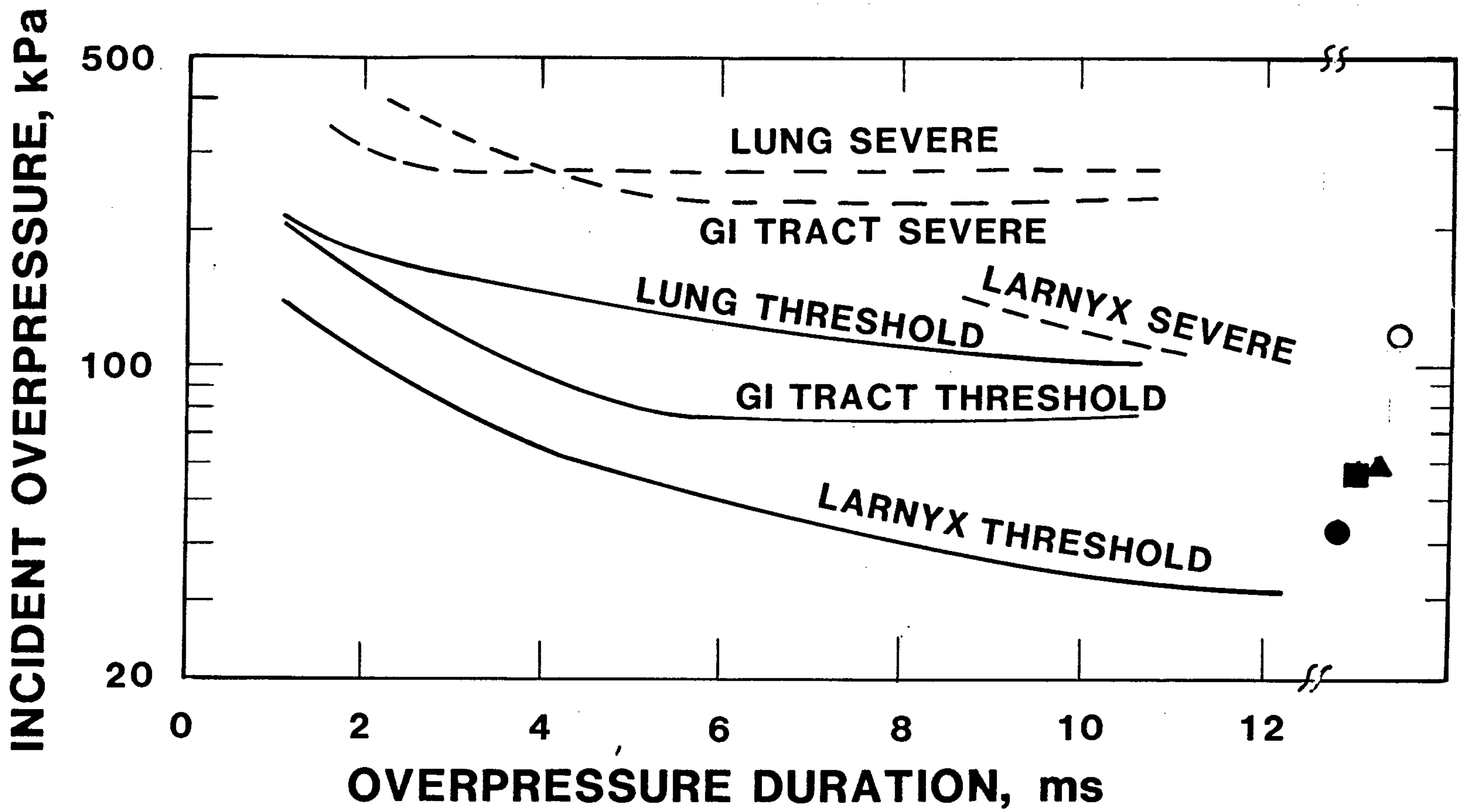


Figure 6. Iso-Damage Curves for Threshold and Severe Injury in Sheep Exposed to One Blast in the Open. The data points, obtained inside the vehicle, give the quasi-static overpressures but the measured overpressure durations were too large to be included on the figure. The animals were exposed to either 57 g at 122 cm (●), 57 g at 91 cm (▲), 113 g at 122 cm (■), or 113 g at 91 cm (○).

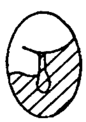
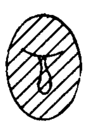
AREA OF EARDRUM DESTROYED	OSSICLES	HEARING LOSS, MINUS dB	BEHAVIORAL EFFECTS
Less than 25% 	Intact	0-15	Minimal transitory disturbance.
	Fracture	10-15	Slight transitory disturbance.
25-50% 	Intact	10-20	Moderate temporary disturbance.
	Fracture	20-40	Immediate transitory disorientation.
50-75% 	Intact	20-40	Immediate transitory disorientation.
	Fracture	30-50	Immediate disorientation; moderate temporary incapacitation.
75-100% 	Fracture	50-70	Immediate transitory disorientation; immediate incapacitation.

Figure 7. Estimated Effects of Blast Injury in Man.

Table 1. Pressure-Time Parameters Grouped According to Charge Weight and Distance from the Charge.

Group	P_0, kPa	I_1.Pa·sec (t_0-t_1, msec)	P_2, kPa	I_3, Pa·sec (t_0-t_3, msec)	P_4, kPa	I_5, Pa·sec (t_0-t_5, msec)	Total Wave, I_6, Pa·sec (t_0-t_6, msec)
I ● 57 g, 122 cm	88	17 (0.8)	100	63 (3.0)	61	138 (6.0)	350 (36)
II ■ 113 g, 122 cm	117	21 (0.7)	141	93 (2.6)	117	204 (5.0)	459 (37)
III ▲ 57 g, 91 cm	121	9 (0.5)	115	38 (2.6)	25	60 (6.0)	219 (40)
IV ○ 113 g, 91 cm	228	7 (0.08)	110	51 (2.0)	63	91 (5.0)	>400 (>40)
V ▼ 113 g, 91 cm	246	22 (0.5)