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Exposure to impulse noise is an important occupational health concern. The risk of injury to auditory structures is well recognized and provides the conerstone for present safety standards. For freefield impulse noise, nonauditory injury is dependent on peak pressure positive phase duration (or impulse), and number of exposures. Trivial laryngeal petechiae are shown to preceed nonauditory injury to more critical organs (ie. pulmonary and gastro-intestial systems). This study identifies the critical impulse noise thresholds causing trivial laryngeal petechial changes resulting from expousre to 5, 25, and 100 repetitions of specific levels of impulse noise. Because of anatomical differences, sheep should be slightly more susceptable to impulse noise laryngeal petechial changes than man; therefore, it seems reasonable to set the absolute limits for human occupational exposure levels below those causing laryngeal petechiae in sheep for persons wearing adequate hearing protection. This study does not address human auditory injury that may occur above or below these exposure limits even with proper hearing protection. Keywords;

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Nonauditory Injury Threshold for Repeated Intense Freefield Impulse Noise

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Exposure to impulse noise is an important occupational health concern. The risk of injury to auditory structures is well recognized and provides the cornerstone for present safety standards. For freefield impulse noise, nonauditory injury is dependent on peak pressure, positive phase duration (or impulse), and number of exposures. Trivial laryngeal petechiae are shown to precede nonauditory injury to more critical organs (ie, pulmonary and gastrointestinal systems). This study identifies the critical impulse noise thresholds causing trivial laryngeal petechial changes resulting from exposure to 5, 25, and 100 repetitions of specific levels of impulse noise. Because of anatomical differences, sheep should be slightly more susceptible to impulse noise laryngeal petechial changes than man; therefore, it seems reasonable to set the absolute limits for human occupational exposure levels below those causing laryngeal petechiae in sheep for persons wearing adequate hearing protection. This study does not address human auditory injury that may occur above or below these exposure limits even with proper hearing protection.

Injury to the auditory system from exposure to high-intensity impulse noise has long been recognized as an occupational medicine problem. Occupational standards for exposure to simple freefield impulse noise environments are limited. Ammunition and explosive safety standards as developed by the Department of Defense that are accepted by the civilian occupational health community list only a single peak pressure of 2.3 psi (15.8 kPa), over which no exposure should occur.[1] Military Standard 1474B lists a much more extensive criterion based on peak pressure, B-duration, number of exposures, and type of hearing protection.[2] (B-duration is the duration of the primary portion of an impulse noise plus the duration of significant subsequent fluctuations. Significant subsequent pressure fluctuations are those for which the summed duration is greater than 10% of the duration of the primary portion.) Single or multiple impulse noise from any source when inadequate aural protectors are used can cause aural effects ranging from no measurable injury to tympanic membrane rupture, disabling pain, vestibular dysfunction, temporary threshold shifts, and, potentially, some degree of permanent hearing loss.[3,4] Until recently, these auditory effects had been the primary occupational medicine concern and the basis of current standards. However, in a military environment, with the development of better aural protection and more energetic weapon systems and their associated intense noise, the potential for injury to nonauditory structures has also become a consideration. Civilian occupational health standards are not well defined for cases in which persons are exposed to ammunition and explosives hazards during industrial, processing, manufacturing, maintenance, renovation, demilitarization, and similar operations.[1]

Nonauditory injury resulting from exposure to impulse noise is confined almost exclusively to the gas-containing structures of the body.[5-9] These organs include the upper respiratory tract, the lungs, and the gastrointestinal tract. The lesions range from trivial surface petechiae to tissue disruption and hemorrhage. Extensive work with simple freefield impulse noise environments has shown that the severity of injury to

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The views of the authors do not purport to reflect the position of the US Department of the Army or the US Department of Defense.

"In conducting the research described in this report, the investigators adhered to the standards set forth in the 'Guide for the Care and Use of Laboratory Animals' (NIH publication 85-23) as promulgated by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council."

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these susceptible organ systems is determined by some combination of the number of exposures, peak pressure, and A-duration (the time required for the overpressure to rise from ambient to its principal positive peak and return momentarily to ambient pressure) or A-impulse (the integral of peak pressure and A-duration).[2,7,9-13] This interaction of peak pressure, duration (or impulse), and number of exposures holds true only for Friedlander waves, which are characterized by an instantaneous rise in pressure to a peak with a subsequent exponential decay. To define safe human nonauditory exposure limits, a benign injury marker sensitive enough to indicate the earliest nonauditory effects before any injury occurs to critical organ systems is essential. Such a marker could then be used in carefully planned research to establish occupational threshold limits for nonauditory injury in single and repeated impulse noise environments. This marker would also assist medical triage evaluation of injured persons for the likelihood of nonauditory injury to more critical organ systems (ie, pulmonary and gastrointestinal tracts) when exposure to an intense impulse noise environment is suspected. Observations of nonauditory injury have shown upper respiratory tract petechial changes to precede or accompany injury to the pulmonary or gastrointestinal organ systems.[9,11,12,14,15] Although isolated upper respiratory petechial changes are innocuous, they are present in all cases when more significant injury has occurred elsewhere.

The current criteria for nonauditory injury in impulse noise environments is based on the Bowen curves derived by the Lovelace Inhalation and Toxicology Research Institute in 1968.[5] These criteria were established for three physical orientations: body parallel to the propagation of the waveform, body perpendicular to the propagation of the waveform, and the thorax near a reflecting surface perpendicular to the propagation of the waveform. For each of the orientations, three curves are plotted as peak pressure *v* A-duration. The first curve defines threshold lung injury, the second designates 1% lethality, and the third delimits 50% lethality. Neither multiple exposures nor complex waves are addressed by these lethality curves. In military training, the overall levels experienced by soldiers are relatively low in contrast to combat exposure; however, repeated exposures during training may increase the risk of injury. Lovelace investigators and others[7,9,12-14] have demonstrated that the number of exposures has a dramatic effect on reducing the peak pressure and duration or impulse required to induce injury. There is a concern that nonauditory injuries may result from multiple exposure to low-level impulse noise. A safety criterion for nonauditory occupational exposure in impulse noise environments is essential for both military and civilian personnel.

Methods

Columbia-Rambouillet ewes ranging from 40 to 70 kg were procured from a local vendor. The sheep was used because it is similar in size to man and a considerable data base exists that defines the effects of various intensities of shock waves on sheep. All animals were quarantined, assessed as being healthy, and determined to be free of laryngeal injury by fiberoptic laryngoscopy. Each group was exposed either 5, 20 to 25, or 100 times. Twenty exposures were initially chosen but, as the study progressed, it became apparent that 25 exposures were more appropriate. Data from these two groups were combined.

Charge weights and exposure distances were chosen to represent a wide range of occupational overpressure conditions that would be applicable to both military and civilian populations. The overpressures experienced in mortar crew positions have high peak pressures with short durations (low impulse). In contrast, the overpressures experienced by large-caliber artillary crew positions have lower peak pressures with long durations (high impulse). The charges were detonated by a Reynolds FS-10 portable geophysics exploding bridgewire firing set using RP-83 EBW detonators. The maximum interval between exposures was 6 minutes.

Pencil-shaped piezoelectric gauges (PCB model 136A) were used to make the freefield pressure-time measurements. The outputs from the gauges were passed unfiltered through Tektronix differential amplifiers (model AM502) and recorded on an Ampex model PR-2230 magnetic-tape unit. Paper strip chart records were obtained from the magnetic tape using a Honeywell model 1858 fiberoptic visicorder. The signals were played back from the magnetic tapes and digitized on a Gould DASA 9000 waveform recorder. The digitized records were imported into a software program for calibration, analysis, and storage. Peak pressure, A-duration, and A-impulse were calculated from the digitized records. The A-duration was measured from the initial pressure rise, time zero, until the first zero crossing. A-impulse was calculated by integrating the positive phase A-duration curve.

On the day of the test, the animals in the exposure group, varying in number from 4 to 10 depending on the maximum number that could be exposed simultaneously, were fitted in fishnet slings, anesthetized, transported to the exposure pad, slung in a normal standing position so as not to impede respiratory movements, and exposed right-side-on to freefield impulse noise at predetermined distances from a specific weight explosive charge. The impulse noise conditions evaluated in this study were below the known level of consequential nonauditory injury[5] and no pain or discomfort was expected. However, all animals were administered intramuscular xylazine (1.1 mg/kg) and, because of the potential risk of painful ear injury, were fitted with ear protectors (formed ear plugs). Within 1 hour after exposure, animals were transported to the laboratory, further anesthetized with an intravenous barbiturate, and exsanguinated, and autopsies were performed. Gross pathologic findings from the pulmonary and gastrointestinal tract and upper respiratory tract were documented and recorded. Injury to the upper respiratory tract of each animal was graded according to the following scale:

None—no perceptible injury.

Slight—at least one but not more than four identifiable minor petechial hemorrhages.

Moderate—single ecchymotic hemorrhage or more than four petechial hemorrhages.

Severe—ecchymotic or petechial hemorrhages.

Each exposure group was assigned an injury ranking according to the following scale:

None—no injury in any animal.

Trivial—less than 34% of the group's animals having slight upper respiratory tract injury and no pulmonary or gastrointestinal tract injury.

Unacceptable—(1) any animal in a group with pulmonary or gastrointestinal tract injury, (2) greater than 33% of the group's animals with slight upper respiratory tract injury, or (3) any animal in a group with moderate or severe upper respiratory tract injury.

Results

Tables 1, 2, and 3 present the data for the 5-, 25-, and 100-shot exposure groups, respectively. The data are presented according to increasing peak pressure. As evidenced by these tables, there was no grossly detectable lung or gastrointestinal injury discerned when no laryngeal and tracheal petechiae were noted. There were no conditions tested in which any animal showed any gross injury to the pulmonary tract. However, in seven cases, upper respiratory tract petechial changes occurred in conjunction with gastrointestinal tract contusions.

The average measured peak pressure was plotted against the average measured A-duration for each group. The threshold curves for each of the exposure scenarios in which upper respiratory tract petechial changes were induced were determined by drawing a curve through the lowest peak pressure/A-duration point where the onset of trivial injury was detected. Similar curves were drawn for the onset of trivial laryngeal petechial changes using peak pressure and A-impulse. These curves represent the lowest impulse noise levels that caused detectable petechial changes in the larynx and/or trachea in the absence of pulmonary or gastrointestinal injury (Fig. 1). For each sequence of multiple exposures, the resultant threshold curves

TABLE 1
Peak Pressure, Impulse, Duration, and Observed Injury for Five Freefield Exposures

Pressure, kPa	Impulse, kPa·ms	Duration, ms	Charge Weight	HOB,* ft	Range, ft	Animals with Injuries† Lar	Tra	GI	N	Injury
22.8	66.2	7.0	8 lb TNT	5	39.5	0	0	0	10	None
27.6	116.5	10.8	32 lb TNT	9.7	58.8	0	0	0	6	None
29.7	80.0	6.0	8 lb TNT	3.2	31.3	0	0	0	6	None
35.2	85.5	5.1	8 lb TNT	3.2	29.0	0	0	0	6	None
36.5	82.7	6.2	8 lb TNT	5	29.5	0	0	0	6	None
37.9	89.0	6.0	8 lb TNT	5	29.5	0	0	0	7	None
40.0	91.7	5.7	8 lb TNT	3.2	27.0	0	0	0	6	None
40.7	84.8	5.9	8 lb TNT	5	27.4	0	0	0	4	None
41.4	46.9	3.0	1 lb Pentolite	2.7	14.6	0	0	0	6	None
45.4	159.8	9.2	32 lb TNT	9.7	45.2	2	0	0	6	Trivial
46.9	90.3	5.4	8 lb TNT	5	25.5	0	0	0	6	None
49.6	37.2	2.0	.5 lb C-4	1	10.2	0	0	0	7	None
51.0	37.2	2.0	.5 lb C-4	1	9.8	0	0	0	6	None
53.8	38.6	2.0	.5 lb C-4	1	9.7	0	0	0	7	None
53.8	97.2	5.1	8 lb TNT	5	23.9	2	3	0	6	Unacceptable
54.5	53.8	2.7	1 lb Pentolite	2.7	12.8	0	0	0	6	None
56.5	165.5	8.2	32 lb TNT	9.7	40.3	5	3	1	6	Unacceptable
58.6	54.5	2.6	1 lb Pentolite	2.7	12.4	0	0	0	6	None
60.0	41.4	1.9	.5 lb C-4	1	9.3	0	0	0	4	None
60.7	41.4	1.9	.5 lb C-4	1	9.3	0	0	0	7	None
62.0	42.1	1.9	.5 lb C-4	1	9.3	0	0	0	7	None
68.3	45.5	1.9	1 lb Pentolite	1	8.5	2	0	0	6	Trivial
68.3	64.1	2.7	1 lb Pentolite	1	11.4	1	0	0	6	Trivial
73.1	35.9	1.2	24 ft 100 g PC‡	0.08	4.6	0	0	0	6	None
75.2	35.9	1.2	24 ft 100 g PC	0.08	4.6	0	0	0	6	None
82.7	24.8	0.8	.125 lb C-4	5	3.8	0	0	0	5	None
100.0	24.8	0.8	.125 lb C-4	5	3.4	0	0	0	4	None
103.4	24.1	0.8	.125 lb C-4	5	3.4	0	0	0	4	None
103.4	39.3	1.1	24 ft 100 g PC	0.08	3.5	0	0	0	6	None
105.5	36.5	1.0	24 ft 100 g PC	0.08	3.5	0	0	0	6	None
113.8	40.0	1.1	24 ft 100 g PC	0.08	3.5	0	0	0	3	None
115.8	38.6	1.0	24 ft 100 g PC	0.08	3.5	0	0	0	6	None
121.1	46.0	1.4	24 ft 100 g PC	0.08	3.4	2	0	0	6	Trivial
127.6	37.9	1.0	24 ft 100 g PC	0.08	3.3	1	1	1	6	Unacceptable
148.9	42.8	0.8	24 ft 100 g PC	0.08	2.8	3	3	0	6	Unacceptable

* HOB, height of burst.
† Lar, laryngeal; Tra, tracheal; GI, gastrointestinal.
‡ PC, primacord.

TABLE 2

Peak Pressure, Impulse, Duration, and Observed Injury for 25 (20) Freefield Exposures

Pressure, kPa	Impulse, kPa·ms	Duration, ms	Charge Weight	HOB,* ft	Range, ft	Animals with Injuries†			N	Injury
						Lar	Tra	GI		
22.8	66.2	7.0	8 lb TNT	5.0	39.5	0	0	0	10	None
27.6	116.5	10.8	32 lb TNT	9.7	58.8	0	0	0	6	None
29.7	80.0	6.0	8 lb TNT	3.2	31.3	0	0	0	6	None
35.2	85.5	5.1	8 lb TNT	3.2	29.0	0	0	0	6	None
36.5	82.7	6.2	8 lb TNT	5.0	29.5	0	0	0	6	None
37.9	89.0	6.0	8 lb TNT	5.0	29.5	0	0	0	7	None
40.0	91.7	5.7	8 lb TNT	3.2	27.0	0	0	0	6	None
40.5	84.5	5.3	8 lb TNT	5.0	27.0	1	2	0	7	Trivial
40.7	84.8	5.9	8 lb TNT	5.0	27.4	0	0	0	4	None
41.4	46.9	3.0	1 lb Pentolite	2.7	14.6	0	0	0	6	None
41.5	84.8	5.4	8 lb TNT	5.0	27.0	0	1	1	7	Unacceptable
45.4	159.8	8.7	32 lb TNT	9.7	45.2	2	0	0	6	Trivial
45.5	42.2	2.0	.5 lb C-4	1.0	9.8	1	0	0	6	Trivial
47.0	96.9	4.8	8 lb TNT	5.0	25.5	1	0	0	6	Trivial
49.6	37.2	2.0	.5 lb C-4	1.0	10.2	0	0	0	7	None
51.0	37.2	2.0	.5 lb C-4	1.0	9.8	0	0	0	6	None
53.8	38.6	2.0	.5 lb C-4	1.0	9.7	0	0	0	7	None
54.5	53.8	2.7	1 lb Pentolite	2.7	12.8	0	0	0	6	None
59.2	54.9	2.8	1 lb Pentolite	2.7	12.4	1	0	0	6	Trivial
60.0	41.4	1.9	.5 lb C-4	1.0	9.3	0	0	0	4	None
60.1	43.1	1.9	.5 lb C-4	1.0	9.3	0	1	0	6	Trivial
60.7	41.3	1.9	.5 lb C-4	1.0	9.3	0	0	0	7	None
62.1	42.1	1.9	.5 lb C-4	1.0	9.3	0	0	0	7	None
64.1	48.1	2.0	.5 lb C-4	1.0	9.3	1	1	0	6	Trivial
68.3	45.5	1.9	.5 lb C-4	1.0	8.5	4	4	0	6	Unacceptable
68.3	64.1	2.5	1 lb Pentolite	3.2	14.5	3	5	4	6	Unacceptable
72.4	31.7	1.2	24 ft 100 g PC‡	0.08	4.6	0	5	0	6	Unacceptable
73.1	35.9	1.2	24 ft 100 g PC	0.08	4.6	0	0	0	6	None
82.7	24.8	0.8	.125 lb C-4	5.0	3.8	0	0	0	5	None
100.0	24.8	0.8	.125 lb C-4	5.0	3.4	0	0	0	4	None
101.5	33.2	1.1	.125 lb C-4	0.67	4.5	0	1	0	5	Trivial
103.4	26.2	0.8	.125 lb C-4	5.0	3.4	0	2	0	4	Unacceptable
103.4	39.3	1.1	24 ft 100 g PC	0.08	3.5	0	0	0	6	None
103.4	24.1	0.8	.125 lb C-4	5.0	3.4	0	0	0	4	None
103.6	27.4	0.8	.125 lb C-4	5.0	3.4	0	1	0	4	Trivial
113.8	40.0	1.1	24 ft 100 g PC	0.08	3.5	0	0	0	3	None
115.8	38.6	1.0	24 ft 100 g PC	0.08	3.5	0	0	0	6	None
120.0	35.9	1.1	24 ft 100 g PC	0.08	3.4	2	5	0	6	Unacceptable
127.6	37.9	1.0	24 ft 100 g PC	0.08	3.3	2	3	0	6	Unacceptable
142.7	45.5	0.9	24 ft 100 g PC	0.08	2.8	5	5	0	6	Unacceptable

* HOB, height of burst.

† Lar, laryngeal; Tra, tracheal; GI, gastrointestinal.

‡ PC, primacord.

for the upper respiratory tract petechial changes for 5, 25, and 100 exposures were plotted as peak pressure *v* A-duration (Fig. 2) and peak pressure *v* A-impulse (Fig. 3). A point lying on the lower side of the threshold injury curve for a given number of exposures would be associated with the absence of any nonauditory injury. In contrast, any point lying on the upper side of the threshold injury curve would be associated with the potential for some degree of injury with the likelihood of more serious injury increasing for each more intense exposure condition.

Discussion

Sheep have proven to be a reasonable human surrogate model for characterizing the occurrence, type, location, and severity of nonauditory injury produced in impulse noise environments.[9,12,14] In this study, sheep were used to develop threshold curves for nonauditory injury from 5, 25, and 100 repeated exposures. Previous studies have shown that petechial changes in the upper respiratory tract precede trivial injury in other susceptible nonauditory organ systems and coexist with more severe levels of pulmonary and gastrointestinal injury.[9,12–15] The results of this study support this observation. In the exposure scenarios tested, no detectable gross pulmonary injuries were observed in the necropsied animals. As seen in Tables 1, 2, and 3, trivial upper respiratory tract petechial changes primarily occurred in the absence of any other nonauditory injury. In five of the seven cases in which increased levels of impulse noise caused unacceptable nonauditory laryngeal petechial changes in the exposure group, gastrointestinal tract injury was observed. For two remaining cases in which gastrointestinal injury was evident (5 exposures,

TABLE 3
Peak Pressure, Impulse, Duration, and Observed Injury for 100 Freefield Exposures

Pressure, kPa	Impulse, kPa·ms	Duration, ms	Charge Weight	HOB,* ft	Range, ft	Animals with Injuries†			N	Injury
						Lar	Tra	GI		
22.8	66.2	7.0	8 lb TNT	5	39.5	0	0	0	10	None
33.1	77.9	5.9	8 lb TNT	5	31.5	2	10	1	10	Unacceptable
39.3	85.5	5.7	8 lb TNT	5	29.0	3	10	1	10	Unacceptable
52.7	44.4	2.1	.5 lb C-4	1	10.2	1	0	0	6	Trivial
49.6	37.2	2.0	.5 lb C-4	1	10.2	0	0	0	7	None
52.7	44.4	2.1	.5 lb C-4	1	10.2	0	2	0	7	Trivial
53.8	38.6	2.0	.5 lb C-4	1	9.7	0	0	0	7	None
53.8	37.9	2.0	.5 lb C-4	1	9.7	1	4	0	7	Unacceptable
57.2	40.0	1.9	.5 lb C-4	1	9.7	1	6	1	6	Unacceptable
58.6	40.0	1.9	.5 lb C-4	1	9.3	1	3	0	6	Unacceptable
60.0	40.7	1.9	.5 lb C-4	1	9.3	0	5	0	6	Unacceptable
82.7	24.8	0.8	.125 lb C-4	5	3.8	0	0	0	5	None
85.5	26.5	0.8	.125 lb C-4	5	3.8	1	1	0	5	Trivial
86.9	36.6	0.8	.125 lb C-4	5	3.8	0	1	0	5	Trivial
90.3	27.1	0.8	.125 lb C-4	5	3.8	0	1	0	5	Trivial
111.0	37.9	1.0	24 ft 100 g PC‡	0.08	3.5	5	6	0	6	Unacceptable

* HOB, height of burst.
† Lar, laryngeal; Tra, tracheal; GI, gastrointestinal.
‡ PC, primacord.

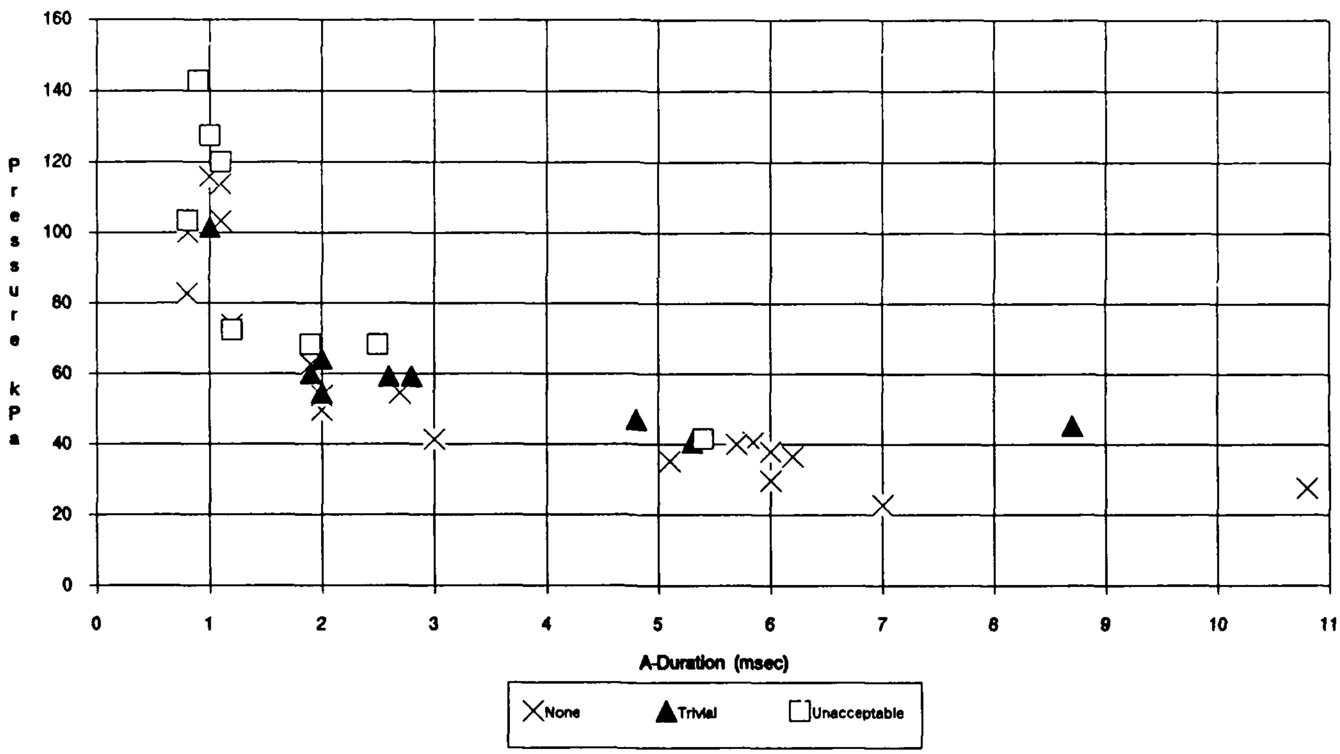

Fig. 1. Representative scatter plot for pressure/A-duration for 25 exposures.

127.65 kPa peak pressure at 37.9 kPa·ms; 20 exposures, 40.0 kPa peak pressure at 84.1 kPa·ms), the impulse noise levels were equal to or more intense than exposures from which no gastrointestinal injury or only trivial upper respiratory tract petechial changes were noted. Because gastrointestinal injury was observed along with trivial laryngeal petechial changes at levels slightly more intense than the threshold curves generated and because the absolute threshold for gastrointestinal injury in repeated exposure scenarios is unknown, it is crucial that exposure to impulse noise levels above the thresholds for trivial laryngeal petechia presented in this paper not be exceeded during occupational exposure.

Use of animals to estimate human consequences is always subject to uncertainty because of differences between species. For example, man stands erect, whereas the sheep stands horizontal. Man's upper respiratory tract has a relatively short and protected extrathoracic course in contrast to the sheep's long,

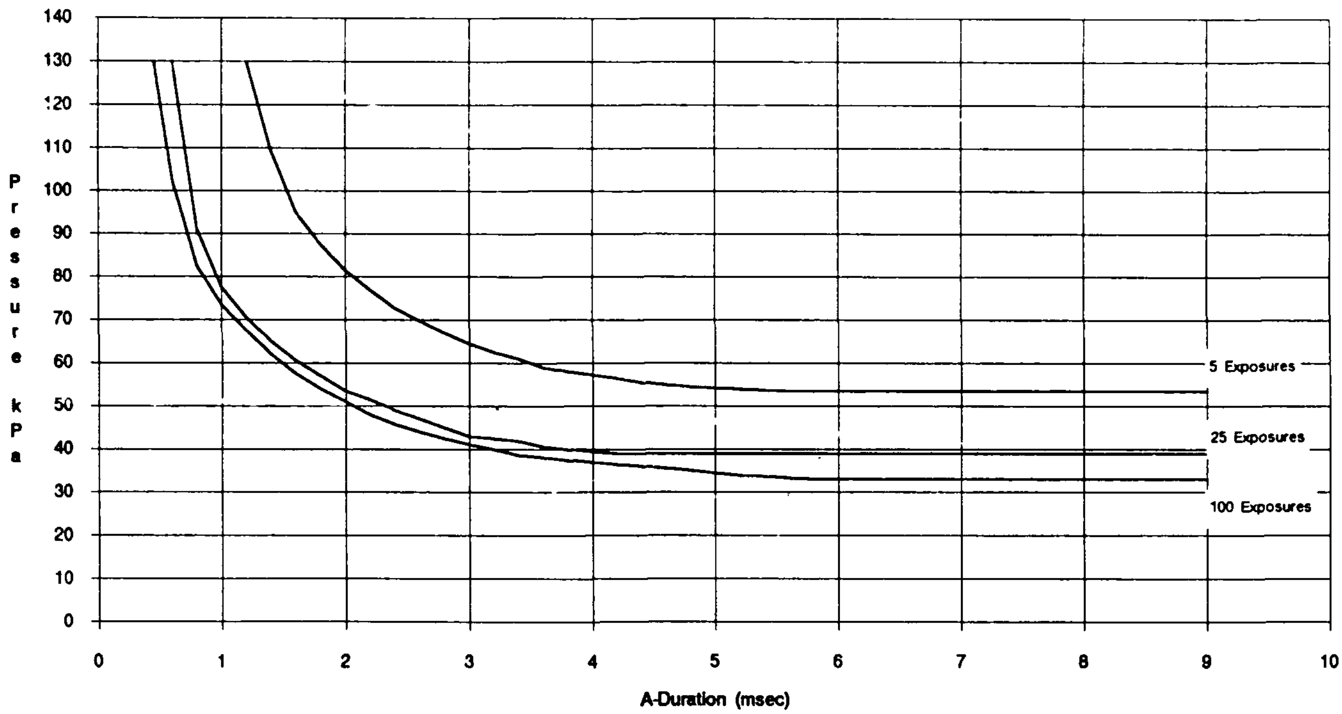

Fig. 2. Peak pressure/A-duration plot for threshold laryngeal petechial changes for 5, 25, and 100 exposures.

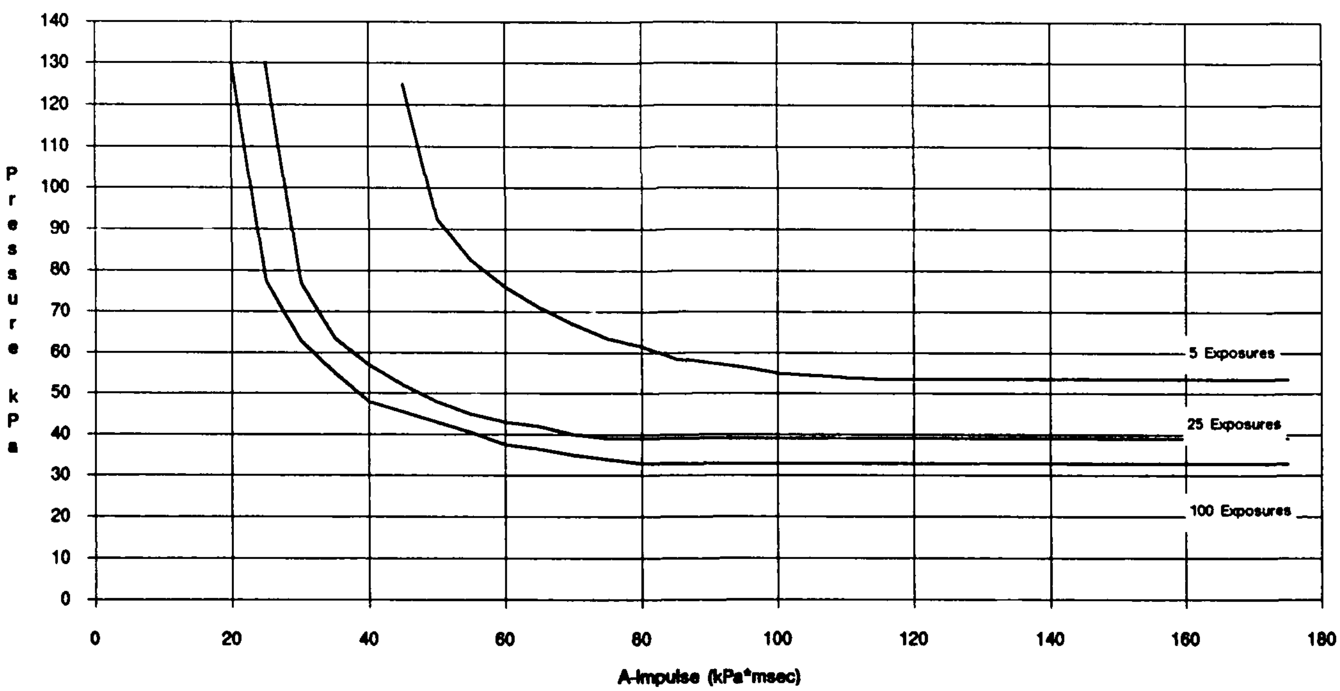

Fig. 3. Peak pressure/A-impulse plot for laryngeal petechial changes for 5, 25, and 100 exposures.

ventrally located extrathoracic trachea. The most probable mechanism of injury to the upper respiratory tract is the direct concussive effect of the shock wave, which produces some degree of deformation and collapse of soft structures adjacent to relatively firm cartilaginous regions, resulting in tissue disruption and hemorrhage. This is borne out by the location of the upper respiratory tract injury on the side of the extrathoracic trachea facing the wave in areas where soft tissue opposes cartilaginous tissue. Because of basic anatomic differences, the sheep should be more sensitive to impulse noise-related upper respiratory tract injury than man. Consequently, man should be less likely to develop upper respiratory tract petechial changes than sheep at any level of impulse noise. Laryngeal examinations performed on 103 German soldiers following exposure to 22 to 36 kPa peak pressures with a 2-millisecond A-duration showed no related abnormalities.[11] Sixty US soldiers also failed to show any evidence of laryngeal, pulmonary, or gastrointestinal injury after being subjected to 12 blasts with a 24-kPa peak and an 8- to 9-millisecond A-duration.[16]

The prevention of nonauditory injury for humans must depend on keeping impulse noise exposure conditions below some threshold level. This is necessitated by the occurrence of gastrointestinal injury at levels only slightly above the threshold curves presented. Considering the difficulty of noninvasively evaluating pulmonary or gastrointestinal injury in man, it seems reasonable to set conservative limits for human exposure in impulse noise environments at the threshold conditions that cause sheep upper respiratory tract petechial changes. Because of normal variability in any population, it is possible that some humans may develop upper respiratory tract petechial lesions during occupational exposure to impulse noise environments even when the limits proposed here are conscientiously followed. Such lesions are benign and asymptomatic, produce no discomfort to the person, are self-healing, require no medical treatment, and pose no serious consequence to the person's overall health. We offer the impulse noise limits defined in this paper as a conservative and sensitive nonauditory occupational exposure standard, above which humans should not be exposed.

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