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Blast injuries of the ear as a result of the Peterborough lorry explosion: 22 March 1989

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Abstract

The incidence of blast trauma to the ears in significant numbers is relatively rare in peace time. This paper outlines the results and management of twenty patients injured as a result of the outside explosion of 800 kg of high explosives in Peterborough on 22 March 1989.

Introduction

On 22 March, 1989, a lorry containing 800 kg of high explosives and hundreds of detonators exploded in the Fengate industrial area of Peterborough. The blast resulted in the immediate death of one fireman and injuries to 90 other people (Fig. 1).

All the injured people were taken to the Accident & Emergency department of Peterborough District Hospital. The authors of this paper saw most of the injured patients who complained of any otological symptoms. Subsequently some 20 patients were seen for follow-up in the ENT department, Edith Cavell Hospital, Peterborough. Eight of the 20 patients had identifiable tympanic perforations which were bilateral in seven cases and unilateral in one, indicating an incidence of 40 per cent of all the patients reviewed. This incidence accords well with previous reports of blast injuries, but the circumstances differ in this case in that the explosion took place out of doors. (Kerr and Byrne, 1975a; Walby and Kerr, 1986).

Patients

Table I outlines the symptoms and clinical findings at the time of the initial assessment, some of which were retrospective but all patients were seen within 14 days of the incident. The patients with tympanic perforations had the size and severity of the perforations assessed with the microscope in out-patients. The predominant presenting symptoms were hearing loss and tinnitus which occurred in almost every case but only two patients complained about dizziness or disturbance of balance. There is as one would expect a correlation between the distance from the source of the blast and the severity of the injuries particularly in terms of tympanic perforations. The initial audiometric assessment showed abnormal findings in 87.5 per cent of the cases.

Deafness

Hearing loss was noticed immediately after the blast in nearly every case. In our survey, 18 (90 per cent) patients had bilateral or unilateral hearing loss immediately after the explosion, some of them for less than 24 h and others for a few days.

Ten (11 per cent) out of the original 90 patients who were treated in hospital had hearing problems for more than four weeks. Hadden *et al.* (1978) reported that 4.4 per cent of their patients had hearing problems following an open air explosion. Pahor (1981) in his survey showed that 25.2 per cent of his patients suffered severe hearing loss after an explosion in a confined space.

Sensorineural deafness with a perforation (eight patients)

All the 15 ears with a perforation of their tympanic membranes showed abnormalities in both air and bone conduction. One year after the blast, four patients still complained about persistent hearing loss.

Sensorineural deafness without a perforation

Immediately after the explosion 10 patients complained about hearing loss. Twenty of the remaining 25 ears assessed separately showed abnormalities in their bone conduction. One year after the explosion, only two patients complained about persistent hearing loss.

Tinnitus

Tinnitus was complained of in 29 of 40 ears assessed. The tinnitus tended to be predominantly in the higher frequencies (hissing sounds). There seems to be a close correlation between the complaint of tinnitus and the ear which was most exposed to the force of the blast. The tinnitus tended to diminish as hearing improved and in those cases where tinnitus disappeared it first became intermittent. Review of cases at 12 months after the explosion; 15 of the 29 ears had persistent tinnitus.

Earache

Even the patients without a perforation experienced

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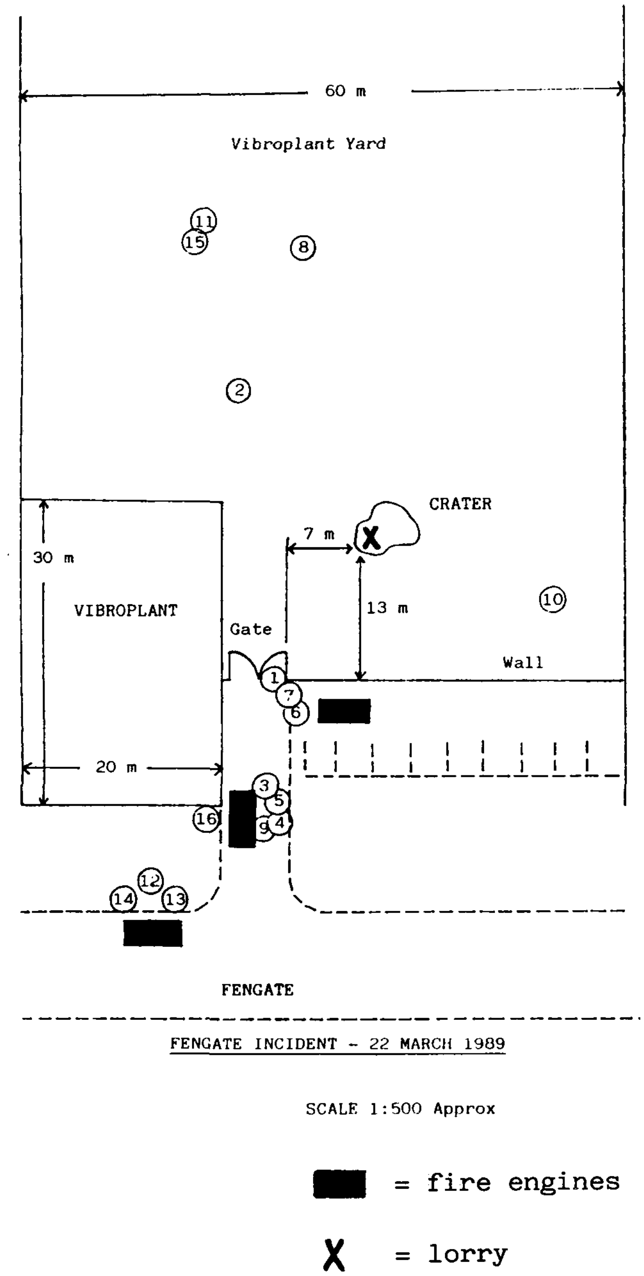

FIG. 1

Fengate
Fengate incident—22 March 1989

some degree of otalgia. In two cases otitis media developed resulting in pain of increasingly severity which resolved after treatment with systematic and topical antibiotics. It is possible that the blast had affected the Eustachian tube mucosa and predisposed to otitis media (Kerr and Byrne, 1975b) or that the otitis media is a direct result from traumatic transplantation of foreign material into the middle ear.

Perforations

Eight patients sustained tympanic perforations in the pars tensa which in seven cases were bilateral (Table II).

The appearances of the perforations were for the most part round and only a few had an oval or bean-shaped appearance.

The edges of the perforations tended to be irregular, sometimes inverted or occasionally everted.

Table III indicates the estimated surface area of the perforation in relation to the total number.

A further observation noted, was the presence of linear lines of trauma, particularly in the tympanic membranes with a perforation but middle ear analysis confirmed the drumhead to be intact. Twelve (80 per cent) of the 15 perforated drumheads healed spontaneously. Two patients, in one case bilateral, were left with persisting perforations which required surgical repair.

Parameters affecting middle ear and inner ear damage

We analysed the relationship between the size of a tympanic perforation in relation to the distance from the site of the blast.

During an explosion solid material is suddenly changed into a gas. This results in a rapidly expanding volume and an increase in temperature and pressure, known as a blast wave (Fig. 2).

Damage to the middle and inner ear from any specific explosion is dependent on many factors. These factors are:

1. The amount of explosives used and the type of explosive charges.
2. The rise time, *i.e.* the time required to reach the peak pressure. The faster the rise time the greater the damage.
3. The peak pressure, the height of the peak pressure decreases in time and with distance. The height of the over-pressure is calculated by an empirically derived formula originally given by Stoner and Bleakney (1948).

   The formula was based upon measurements of blast pressure from cylinders of TNT detonated above the ground. We must stress that figures calculated using the formula are at best approximate, and must be regarded only as a general guide. Factors

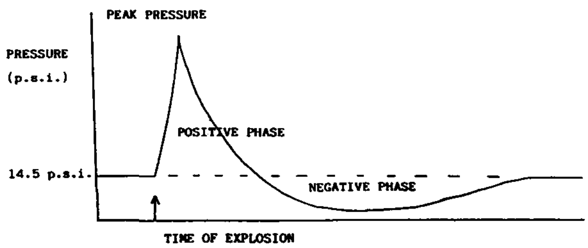

FIG. 2

The form of a blast wave.

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TABLE I

Case	Sex	Age	Distance from blast (metres)	Perforation		Hearing problems		Tinnitus		Previous occupational acoustic trauma	Tears		Facing	Abnormal audiogram	
				L	R	L	R	L	R		L	R		L	R
1	M	41	15	●	●	●	●	●	●	●	●	●	front	●	●
2	M	30	19	5%	5%	+	+	+	+	+	–	+	front	+	+
3	M	32	26	50%	50%	+	+	+	+	–	+	+	back	+	+
4	M	48	29	5%	80%	+	+	–	+	–	–	–	R side	+	+
5	M	45	26	10%	10%	+	+	+	+	+	–	–	L side	+	+
6	M	30	17	20%	5%	+	+	+	+	–	+	+	L side	+	+
7	M	27	16	60%	10%	+	+	+	+	–	–	+	L side	+	+
8	M	33	30	–	5%	–	+	–	+	+	–	–	R side	+	+
9	M	35	29	5%	80%	+	+	+	+	+	–	–	R side	+	+
10	M	33	20	–	–	–	+	–	+	+	–	+	front	+	+
11	M	27	36	–	–	–	+	–	+	–	–	–	R side	+	+
12	M	54	40	–	–	–	–	–	–	+	–	–	L side	+	+
13	M	43	40	–	–	24 h	24 h	f.d.	f.d.	–	–	–	back	–	+
14	M	36	41	–	–	+	–	f.d.	–	+	–	–	L side	+	+
15	M	31	36	–	–	f.d.	f.d.	f.d.	+	+	–	–	L side	+	+
16	M	58	30	–	–	–	–	+	+	+	–	–	back	+	+
17	F	53	±35	–	–	f.d.	–	+	+	–	+	–	L side	+	+
18	M	38	±100	–	–	–	f.d.	–	+	+	–	–	front	+	+
19	M	29	±35	–	–	24 h	–	+	–	–	–	–	L side	–	–
20	F	34	±35	–	–	–	f.d.	+	+	–	–	–	R side	–	–
21	M	31	±100	–	–	–	f.d.	–	–	–	–	–	L side	+	+

24 h = 24 hours.
f.d. = few days.

including the type of explosive charge, the height of the charge above ground and the detailed topography of the location will influence the actual pressures generated.

We have ignored the contribution of the detonators which typically each contain only 2 g of explosives. The formula is:

$$\text{Scaled distance } Z = \frac{\text{distance s}}{(\text{charge mass m})^{1/3}}$$

$$\text{Pressure} = \left(\frac{11.34}{z} - \frac{185.9}{z^2} + \frac{19210}{z^3} \right) \frac{101.3}{6.9}$$

$$(1 \text{ p.s.i.} = 6.9 \text{ KPa})$$

The equation was derived using units of centimetres for distance and grammes for charge mass and gives the results for pressure in p.s.i. (Fig. 3).

Tympanic membranes begin to rupture at an overpressure of 5 p.s.i., about 50 per cent of the tympanic membranes will rupture when the pressure reaches 15 p.s.i. (Kerr, 1978; Strohm, 1986).

In our survey however, none of the tympanic membranes ruptured below an overpressure of 10 p.s.i. Hearing was affected, at least temporarily, at pressures well below those required to rupture the tympanic membrane namely from pressures as low as 1 p.s.i.

4. The duration of the positive pressure phase. The greater the height of the overpressure and the longer the duration of the overpressure, the greater the damage to middle and inner ear.
5. The topography of the location.

Figure 4 shows that there is only a moderate relation between the size of a perforation and the overpressure of a blast wave or the size of a perforation and the distance from the site of the blast. Only nine of the 15 perforations were the size expected.

Figure 4 shows that the perforations of patients 3, 4 and 9 were much larger than expected. These three patients were not only hit by the direct blast wave but also by the indirect blast wave, reflected from the fire engine. This phenomenon is called reflection (Fig. 1 & Table I).

6. The position of the ear in relation to the blast. The ear facing the blast has usually the larger perforation (Table I).
7. The size and shape of the pinna, the diameter and length of the external meatus, the amount and position of cerumen and squamous material in the external meatus also influences the amount of damage to the middle and inner ear (Kerr, 1987).
8. Patient 5 was also very near the fire engine, his left ear was facing the explosion. His tympanic perforations were the size expected. It is clear therefore that people who are standing next to each other can

TABLE II

	Number	%
anterior inferior	7	46.7
anterior superior	0	–
posterior inferior	2	13.3
posterior superior	3	20
subtotal	3	20

TABLE III

surface areas of the perforations	Number	%
5%	6	40
10%	3	20
20%	1	6.7
50%	2	13.3
60%	1	6.7
80%	2	13.3

have widely differing sizes of perforation.

This suggests that the size of a perforation is also dependent on the individual susceptibility of a tympanic membrane to blast wave trauma.

9. Other factors reducing the resistance of the tympanic membrane to pressure are ageing, scarring, thinning of the tympanic membrane and inflammation in the middle ear or tympanic membrane (Kerr, 1987).

Audiometric findings

Audiograms were carried out on all the patients within two weeks of the incident and five of the eight patients with a perforation had audiometric assessment within 24 h. Because of shock and injuries bone conduction assessments were made at a later time. From the 40 ears assessed, 35 had an abnormal audiogram.

Interpretation of the audiometric findings needs careful evaluation and were complicated by:

1. limitations of audiometric time, so that full frequency testing is not always done (*i.e.* including 3000 Hz and 6000 Hz) and also bone conduction has not always been carried out in every case;
2. the rapid changing pictures of audiometric loss which occurs in the first few days;
3. pre-existing deafness due to previous acoustic trauma or other causes;

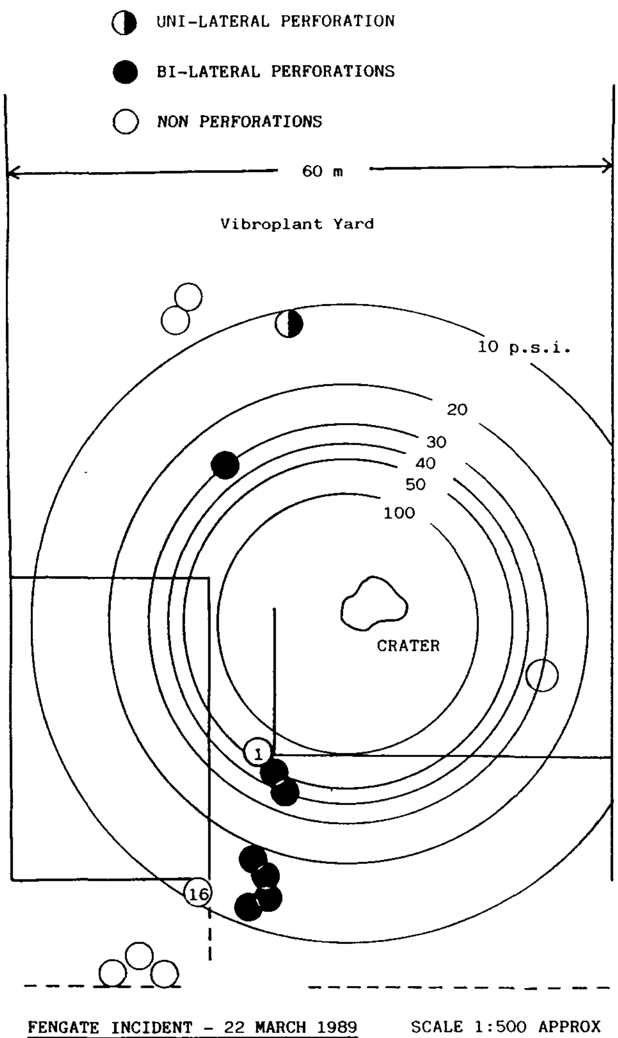

FIG. 3

Fengate incident—22 March 1989

4. slight abnormal changes in audiometric patterns but overall lying within normal limits, *i.e.* better than 20 dB;
5. the presence of non-organic hearing loss.

In the interpretation of our audiograms we have considered thresholds better than 20 dB to lie within normal limits.

A fairly wide variation of abnormal audiograms was found and is outlined below:

a. **trough-shaped hearing losses** occur where three or more adjacent frequency thresholds are abnormal;
b. **dip** occurs where there is a one frequency loss of hearing threshold;
c. **sloping** losses may occur at any frequency from above 1000 Hz and involve all subsequent higher frequencies;
d. **low freqency hearing loss**, only the frequencies <2000 Hz are involved and are predominantly conductive in type.

Finally in some cases there may be combined abnormalities of hearing loss.

We detected 41 abnormal audiometric findings in a total of 35 ears. Table IV illustrates the strong preponderance of high frequency sensorineural hearing losses in 61 per cent of the cases.

Table IV illustrates the relatively small number of low frequency hearing losses all of which were conductive and associated with the perforation of the drumhead; recovery of hearing took place as the perforation healed.

In Table V we analysed the subgroup of 10 patients with a previous history of occupational acoustic trauma. This clearly illustrates the predominance of sloping and trough shaped hearing losses which showed virtually no signs of recovery in the months after the injury. However, we did observe that the initial dip in hearing at 6000 Hz in nearly all the cases recovered by six months after the original injury. This finding stresses the importance of testing specifically for 6000 Hz in cases of acute blast trauma.

Failure to test for 6000 Hz in cases were there is pre-existing deficit at adjacent frequencies due to past acoustic trauma gives the false impression that there has been no specific evidence of damage to the cochlea.

We considered the relationship between subjective deafness and abnormal audiometric findings. A poor correlation was found in many cases either because patients had suffered previous acoustic trauma although they felt hearing was normal or alternatively quite a few patients complained of subjective hearing loss although their audiograms showed no evidence of this.

We found no evidence of a flat hearing loss as described by Singh and Ahluwalia (1968) or type A (single 1000 Hz Dip) and type B (1000 Hz and 4000 Hz Dip) hearing losses as described by Teter *et al.* (1970). Our trough-shaped hearing loss >2000 Hz is the same as Teter's type C (4000 Hz Dip with recovery at 8000 Hz). We decided to call it a trough-shaped hearing loss >2000 Hz because there was evidence of hearing loss at the frequencies immediately above and below 4000 Hz.

Management of the perforations

All the patients with tympanic perforations had their ears examined in the outpatients clinic under the micro-

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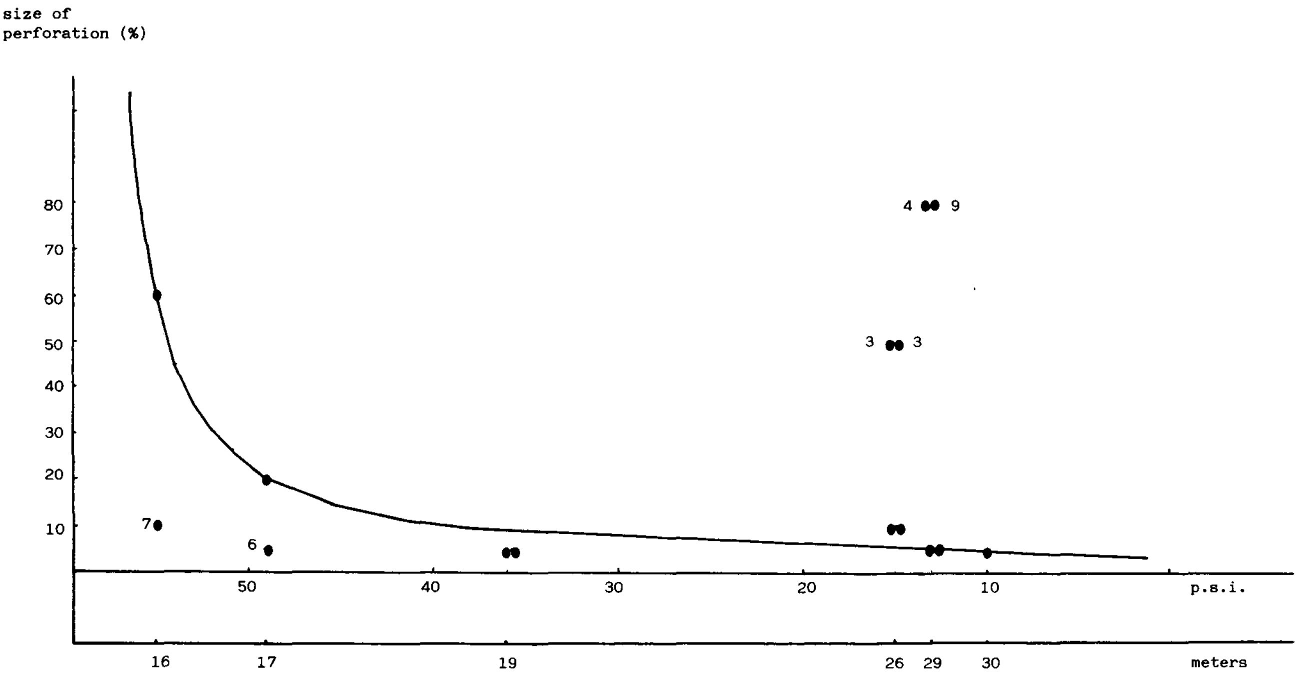

FIG. 4

The relation between the size of a perforation (%), the overpressure (p.s.i.) and the distance (m).

scope. Any significant degree of wax and debris was removed but no active measures were taken with regard to the tympanic perforations. All patients were treated with oral antibiotics and given advice regarding measures to keep the ears dry. At subsequent follow-up 80 per cent of the perforations healed spontaneously within a period of four months.

Two patients with persistent perforations underwent reparative surgery. One patient with bilateral perforations had both repaired at one operation with successful closure on one side, necessitating a revision myringoplasty which was successful. The other patient had a successful primary closure of his unilateral perforation. The results obtained from awaiting spontaneous closure reinforced the previous studies of Kerr (1980), Pahor (1981) and Kronenberg *et al.* (1988). They all showed a high percentage of spontaneous healing.

Early intervention

There may be a case for rather more active management of the perforation on an outpatients basis soon after the trauma has occurred. It is clear in some cases that there may well be a flap of drum which is inverted and in some cases it is possible to evert this and approximate the edges of the perforation which may encourage earlier healing.

TABLE IV
AUDIOMETRIC FINDINGS

Audiometric findings	Previous occupational acoustic trauma	No History of occupational acoustic trauma	Total	%
6000 Hz dip	7	4	11	26.8
Sloping > 6000 Hz	–	1		
Sloping > 4000 Hz	4	2	14	34.2
Sloping > 2000 Hz	1	5		
Sloping > 1000 Hz	1	–		
Trough > 2000 Hz	6	–	7	17.1
Trough > 1000 Hz	1	–		
Low frequency	–	6	6	14.6
2000 Hz dip	–	3	3	7.3
	20	21	41	100

Cholesteatoma

The formation of a cholesteatoma in the middle ear due to traumatic transplantation of epithelial cells has been recorded by Kronenberg *et al.* (1988). They found 10 (4.8 per cent) cholesteatoma formations and six (2.8 per cent) epithelial pearls among 210 ears with a perforation, one to four years after the ears had been exposed to a blast. We have found no evidence up to the present time of any cases of cholesteatoma formations or epithelial pearls in any of the perforated ears.

Protection of the cochlea

It is clear that the contraction of the stapedius and tensor tympani muscles is too slow to protect the cochlea from blast injury. The Eustachian tube may in theory act as a potential safety valve; however, Korkis (1946)

TABLE V
THE AUDIOMETRIC FINDINGS OF THE TEN PATIENTS WITH PREVIOUS OCCUPATIONAL ACOUSTIC TRAUMA

	Immediately after the blast	6 months	12 months
6000 Hz dip	7	1	1
Sloping > 4000 Hz	4	5	4
Sloping > 2000 Hz	1	–	–
Sloping > 1000 Hz	1	1	1
Trough > 2000 Hz	6	5	5
Trough > 1000 Hz	1	1	1

investigated this and came to the conclusion that this mechanism was also too slow. Sound energy may be absorbed by the tympanic membrane and ossicular chain (Jahrsdoerfer, 1979) but it is clear from our series that all patients with tympanic perforations also had evidence of cochlear damage. This would indicate that blast pressure sufficient to rupture the drum will in every case lead to some degree of cochlear damage.

In practical terms the use of gunfender earplugs should in theory protect both drumhead and cochlea from damage but to our knowledge these have never been tested in the situation under present discussion (Kerr 1978, 1987).

Conclusion

1. There is a correlation between the proximity to the blast and the severity of injury to both drumhead and cochlea.
2. There is a high incidence of spontaneous tympanic perforation closure and recovery of cochlea deficit, suggesting that active early intervention is not indicated.
3. There is nothing to suggest from this series of patients that tympanic perforation protects the cochlea from damage in blast trauma.
4. Audiometric assessment of cochlear damage should always include the 3000 Hz and particularly the 6000 Hz frequencies as in some cases these were the only frequencies which showed abnormalities.
5. This series did not confirm the variety of abnormal audiograms previous reported. We have found more than a quarter of the ears assessed had an isolated loss of hearing at 6000 Hz, which has not been reported in previous literature.
6. There is little or no further improvement in recovery of cochlea hearing after six months.
7. A careful occupational history should always be taken. It is clear that a significant number of patients in this series had pre-existing occupational acoustic trauma and presumably abnormal audiograms. This is of particular importance when assessing patients in the preparation of medical reports for the purpose of assessing damages.
8. We are of the opinion that gunfender earplugs may provide some degree of protection from blast trauma but to our knowledge these have never been tested in the situation under present discussion.

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