Concussive effects of bomb blast on the ear*

By A. G. KERR and J. E. T. BYRNE (Belfast, Northern Ireland)

IT has been known for over 150 years that hearing loss results from excessive stimulation of the inner ear and the first report of deafness due to blast trauma appeared just over 100 years ago (Green, 1872). There has been a tendency in most papers on acoustic trauma to group into one category all cases of stimulation deafness, regardless of the aetiology. In 1958, the IVth Congress of the International Audiological Society accepted a classification proposed by Ruedi and Furrer (1947) that these cases should be grouped under:

1. *Noise-induced deafness*, as a result of long-term exposure to elevated sound intensities;

2. *Report trauma*, occurring in gunners, where the stimulus duration is less than 1·5 m./sec., and the middle-ear damage is unusual;

3. *Blast trauma*, where the stimulation duration is greater than 1·5 m./sec. and where middle-ear damage is not uncommon.

In a typical explosion, the explosive material is changed, suddenly, from a solid to a gaseous form, with a massive increase in volume and consequently in pressure. This results in a positive-pressure blast-wave that spreads outwards from the seat of the explosion, initially faster than the speed of sound. The wave form from an explosion is illustrated in Figure 1 and is called the Friedlander curve. The positive-pressure phase is very short-lived, lasting perhaps 5 m./sec. and can reach pressures of hundreds or even thousands of pounds per square inch; it is followed by a longer negative phase lasting about 30 m./sec. which of course, cannot be greater than atmospheric pressure, which is approximately 15 lb. per square inch.

The amount of energy is represented by the area between the curve and the baseline and is more or less equal for each phase of the explosion.

The important features, from the point of view of damage to ears, to lungs or to any other structures are:

1. The rise time, i.e. the speed with which the pressure builds up.
2. The intensity or height of the peak pressure.
3. The duration of the positive wave.

The Abercorn, explosion

On a Saturday afternoon in March 1972, Belfast suffered a particularly cruel act of terrorism when a 5-lb. bomb exploded in the crowded Abercorn

*Paper read to Section of Otology, Royal Society of Medicine, 1 February 1974.

Restaurant. In this explosion, two girls where killed, four people lost both legs, one of these also losing an arm, and another girl lost one leg. Three people each lost an eye. In addition to these, there were others seriously injured from head trauma, broken bones, burns and lacerations.

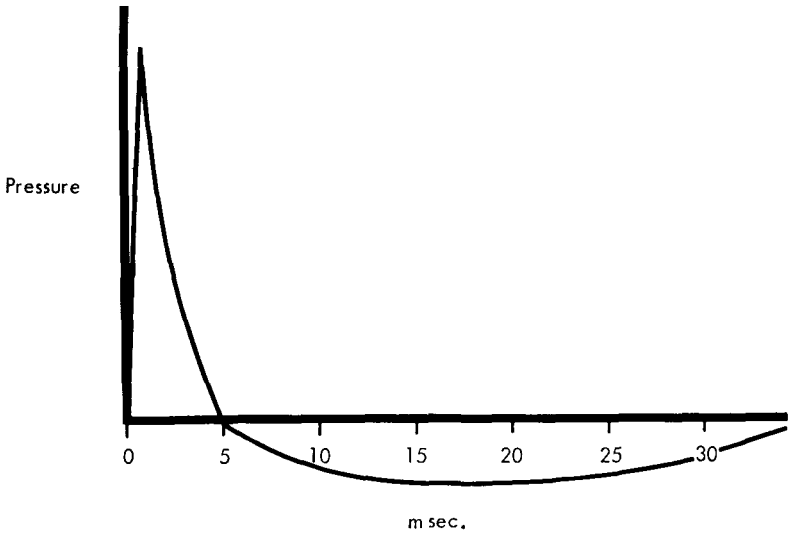

FIG. 1.
Diagrammatic representation of the blast wave.

A sketch plan of the restaurant (Fig. 2) indicates the layout of the tables, the position of the bomb, the seats of those who were killed and the positions of those who lost limbs.

Many of those who suffered ear damage have been under review at the E.N.T. clinics in Belfast, and an effort was made to locate the others who were in the restaurant at the time of the explosion. Up to the time of presentation of this paper it was possible to determine the positions of over eighty persons who were in, or just outside, the restaurant at that time. It is hoped that eventually other victims of this explosion will be contacted for review and consequently any conclusions in this paper must be regarded as being provisional.

The positions of those whose ears have been examined and whose hearing has been assessed are seen in Figure 3. Generally speaking, those nearest the blast suffered the greatest damage, although there are obvious examples of some who were quite close but unscathed.

Figure 4 indicates those who had bilateral perforations. When both membranes were damaged, the ear facing the blast usually had the bigger perforation.

Figure 5 indicates those with unilateral perforations. In all but one instance, the unilateral perforations occurred in the ear nearer to the blast.

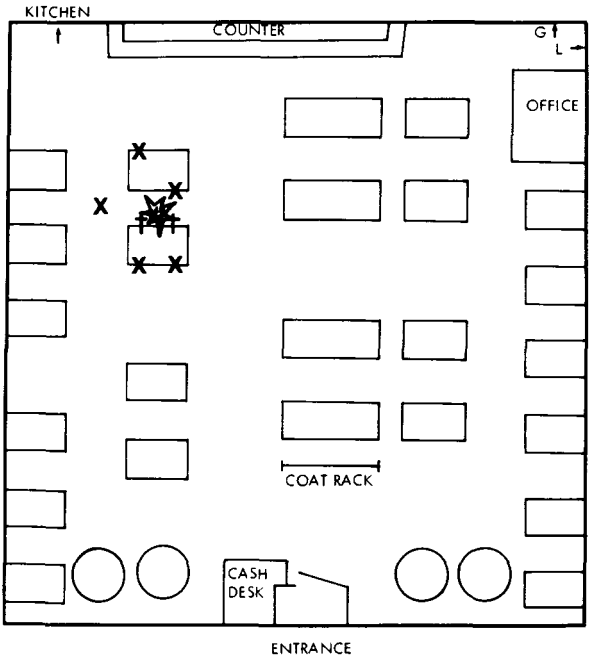

FIG. 2.

Sketch plan of the Abercorn Restaurant, indicating table plan, bomb (exploding star), the dead (†) and those who lost limbs (X). (Dimensions: 40 × 45 × 9 ft.).

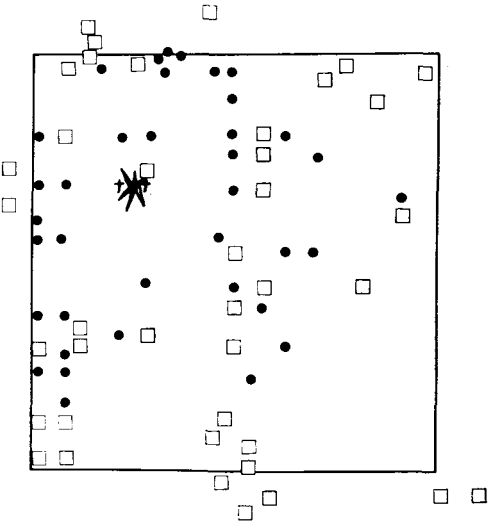

FIG. 3.

The positions of those whose ears have been examined and whose hearing has been assessed. The restaurant tables have been omitted for clarity. (●=perforations; □=non-perforations).

https://doi.org/10.1017/S002221510008018X Published online by Cambridge University Press

In this exception the patient was thrown from right to left against the wall, and presumably the reflected blast was the cause of the perforated left ear drum.

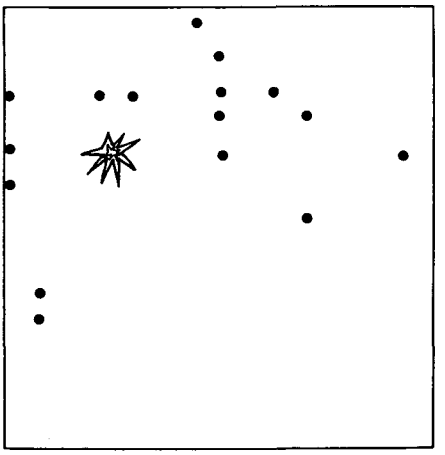

FIG. 4.
Bilateral perforations.

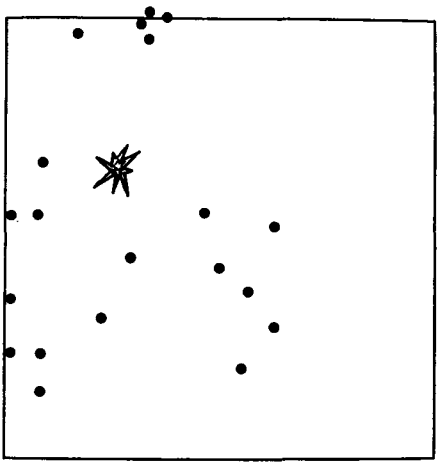

FIG. 5.
Unilateral perforations.

Many of the patients experienced pain in the ears, but not all of them had perforations, and some who had perforations did not have any pain. Almost everyone experienced temporary severe deafness and some claimed that, for the first few minutes after the explosion, they were unable to hear at all and said that they could see the ambulance men's lips moving but could not hear them speaking. In most instances, this severe deafness was

short-lived and recovered fairly quickly. Almost all complained of severe tinnitus immediately after the blast.

There is a varied appearance of the tympanic membrane immediately after exposure to blast. The only finding may be injection of the vessels in the attic or along the malleus handle, or there may be contusion of the membrane with subepithelial bleeding. Perforations occur in the pars tensa and may be simple linear tears, cleanly punched holes or may be ragged. They may be small or large and occasionally are double. The edges may be inverted or everted. Usually there is no obvious bleeding although rarely this is marked.

Despite the small bomb, only 5 lb., at least sixty tympanic membranes were perforated. (The total number of perforations represented in Figures 4 and 5, does not come to sixty because the seating positions of some of those known to have had perforations have not yet been established.) The authors are not aware of any other bomb in the current troubles in Northern Ireland that has caused such otological carnage, and the probable explanation lies in the fact that the explosion took place in a confined space.

The rise time in the Friedlander curve is dependent mainly on the nature and the amount of explosive. However, the peak of the curve and the duration of the positive pressure wave are influenced to a considerable extent by the speed with which the pressure can 'get away'. In a confined space the peak is higher and, because of reflection of the blast wave, the duration of the positive pressure wave is increased in some areas; thus, this blast had much more damaging properties than would have occurred in an out-of-doors explosion.

There is a fourth factor determining the number of drums ruptured, which is the strength of the tympanic membrane. It has been shown that the tympanic membranes of young animals are stronger and more resistant to rupture from increased pressure than those of mature animals (Hirsh, 1968). This probably also applies to humans as four children were exposed to the blast and although sitting alongside those who experienced perforations, did not suffer any damage to their tympanic membranes (Fig. 6).

In addition, it is obvious that a drum, weakened by previous ear disease, or indeed, strengthened by previous ear surgery, will be affected in a different way. While there is no record of which ears were weakened by ear disease, one patient involved in the blast had had a tympanoplasty. The operated ear remained intact while the normal tympanic membrane ruptured.

Management of perforated tympanic membranes

Some authors advocate immediate surgery and high success rates have been cited following such an approach. The ruptured drums following the Abercorn explosion were managed expectantly. As a rule the ears were not cleaned out, ear drops and systemic antibiotics were avoided in the absence

of evidence of infection, and the patients were advised to keep water out of their ears. As a result of this regime forty-nine of the sixty perforations healed spontaneously. It would be difficult to justify surgical intervention with a spontaneous healing rate as high as this. Seven of the remaining eleven ears have been operated on so far and of these, six have healed satisfactorily.

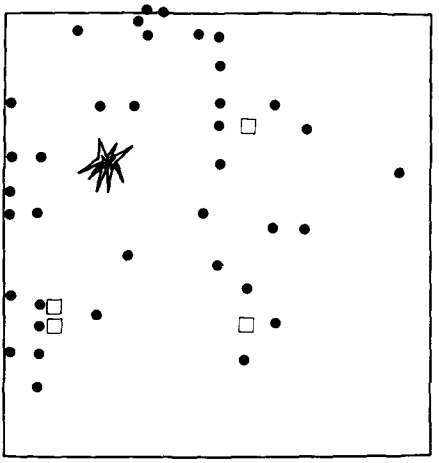

FIG. 6.
Children (□) seated among those with perforations (●).

Complications

Two patients with perforated drums developed squamous epithelial cysts, or pearls, in the middle ear. In one of these the perforation failed to heal and the cyst was removed at tympanoplasty. In the other the drum healed spontaneously but on routine examination an epithelial pearl was seen on the inside of the tympanic membrane. This was symptomless and has been kept under observation but surgical removal probably will be required eventually.

Seaman and Newell (1971) described similar cysts in Vietnam war veterans in a paper entitled 'Another Aetiology of Middle Ear Cholesteatoma'. While only two such cases have been found following this explosion and the authors have seen only one other case from other blasts, it is possible that further cases will be detected with the passage of time. The findings of large numbers of such cysts would necessitate a reappraisal of the passive management of perforations due to blast injury.

Secretory otitis media was seen in two cases, a child and an adult, shortly after the explosion. Individual cases of secretory otitis media, especially in children, are unremarkable but the authors are aware of one other case in an adult, in a different explosion, and it is possible that the blast has affected the Eustachian-tube mucosa and predisposed to secretory otitis media.

While cases of dislocation of the incus have been seen following other blast injuries in Belfast, there were no cases of ossicular damage in this particular explosion.

The inner ear

Initially most of those exposed to the blast had some sensorineural loss. This recovered rapidly in most, more slowly in others and did not recover in some. A twenty-one-year-old girl was sitting two tables from the bomb and her audiogram (Fig. 7) shows her hearing two days following the explosion, after she had already experienced some improvement in her hearing.

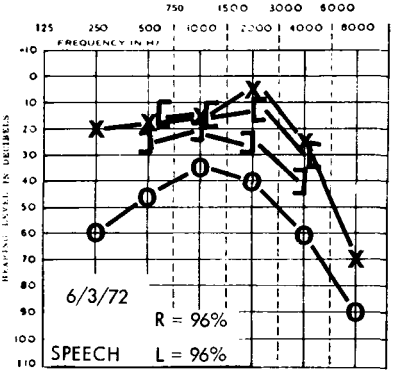

FIG. 7.
Audiogram of B. D. two days after explosion.

She had a subtotal perforation on the right side and a small hole on the left side. She did not have any active treatment. Both drums healed spontaneously, and while slightly scarred, were not remarkable in appearance. The audiogram eighteen months after the explosion showed excellent recovery (Fig. 8).

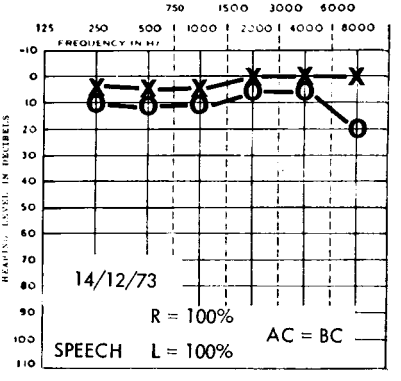

FIG. 8.
Audiogram of B.D. eighteen months after explosion.

https://doi.org/10.1017/S002221510008018X Published online by Cambridge University Press

Teter *et al.* (1970) reported four typical audiometric patterns in patients with sensorineural hearing loss following blast injury. In this series there was a massive predominance of high frequency loss but the other cases were not readily classifiable.

Those with high-frequency sensorineural loss averaging greater than 30 dB for 4,000 and 8,000 Hz in one or both ears are shown in Figure 9. This represents almost one-third of all the patients but the majority of these did not have any significant hearing problem although many had some tinnitus.

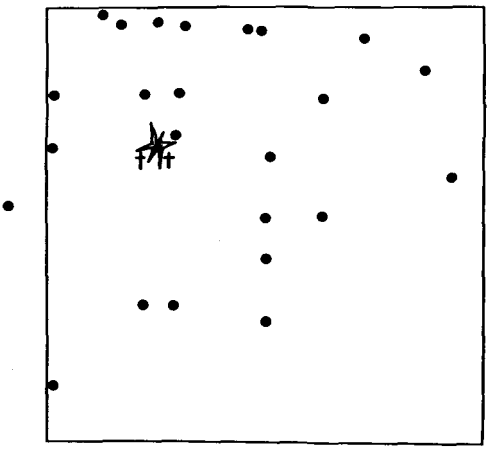

FIG. 9.
High-frequency sensorineural hearing loss (average greater than 30 dB for 4,000 and 8,000 Hz).

Many of those with high frequency hearing loss were not even aware of deafness, and to be more meaningful, the chart should indicate only those who also had involvement of the speech frequencies, that is, those with hearing loss greater than shown in the audiogram in Figure 10. Figure 11 shows the position of those with such deafness; just over 10 per cent of the patients therefore have significant sensorineural deafness. However, not all of these are aware of a handicap and in some only one ear is affected. If a bilateral sensorineural loss of 40 dB or greater for the speech frequencies is assumed to be a serious deafness, those who have persistent serious loss are seen in Figure 12.

It has been said in the past that rupture of the tympanic membrane appears to have a protective effect on the inner ear and that sensorineural hearing loss tends to be greater if the drum remains intact. The impression gained from this explosion suggests that this is not the case. Every one of the patients indicated in Figure 12 had ruptured tympanic membranes and in three of these the perforations were bilateral.

Concussive effects of bomb-blast on the ear

Vertigo

Dizziness is uncommon following exposure to blast. It probably is significant that most of those who have complained of vertigo also have had an associated head injury. Either they have been hit by flying debris or falling masonry or rafters, or they have become part of the flying debris,

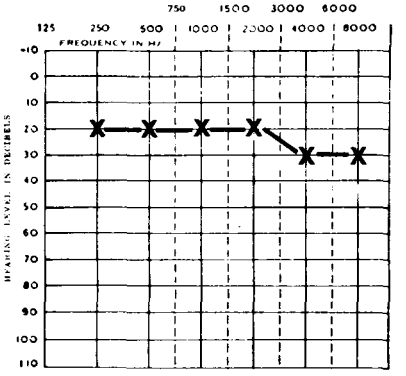

FIG. 10.

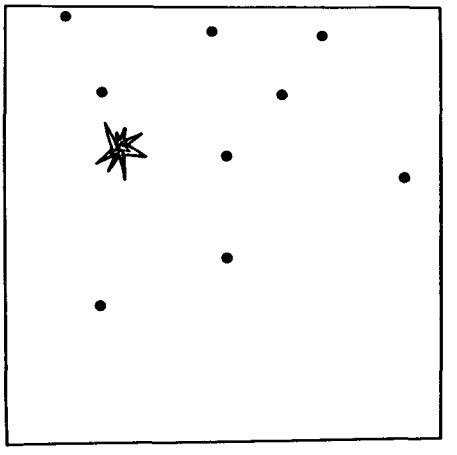

FIG. 11.

Positions of those who sensorineural deafness was greater than indicated in audiogram shown in Figure 10.

injuring their heads on landing. On the whole, the nature of the dizziness has been similar to that which one finds in the post-head injury patient and it seems reasonable to attribute the dizziness to this in most cases. A very small number of cases of Benign Positional Vertigo have been seen following other explosions where the patients have been quite certain they did not suffer any head injury.

Strong (1973) has described a case of perilymphatic fistula in the oval window following a blast injury to the ear. The authors have not diagnosed such a fistula either following this particular explosion or to date in any of the victims of other explosions.

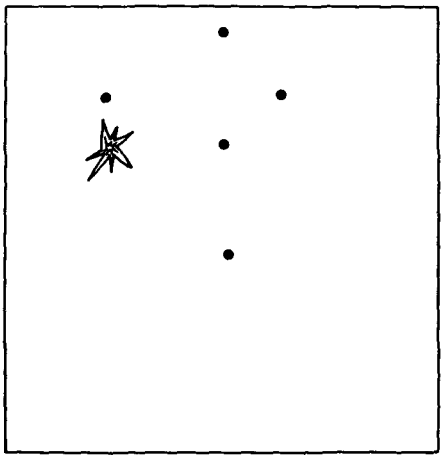

FIG. 12.
Positions of those with serious sensorineural deafness.

Pathology

Many people have been killed by other bombs and ten temporal bones have become available for histological examination. While a detailed description of the findings will be the subject of a further report some points are illustrated.

Bleeding into the tympanic membrane (Fig. 13) and the ragged edges of a perforation (Fig. 14) can be seen. Squamous epithelium has been found in the middle ear (Fig. 15). Ruptures of the saccule (Fig. 16), utricle and basilar membrane also have been seen.

Ruedi and Furrer (1947) have described a case of dislocation of the stapes but this has not been seen in any of the temporal bones examined. In fact, the ossicles in all the specimens have been normal.

Conclusions

As a result of this study the following conclusions have been drawn:

1. The shock front of a blast wave is irregular and some people, close to the blast, escaped without any ear damage;

2. Perforations due to blast may occur anywhere in the pars tensa;

3. The perforations probably are caused by the positive phase of the blast, as indicated by the histological finding of squamous epithelium in the middle ear and the formation of epithelial pearls. The everted edges that

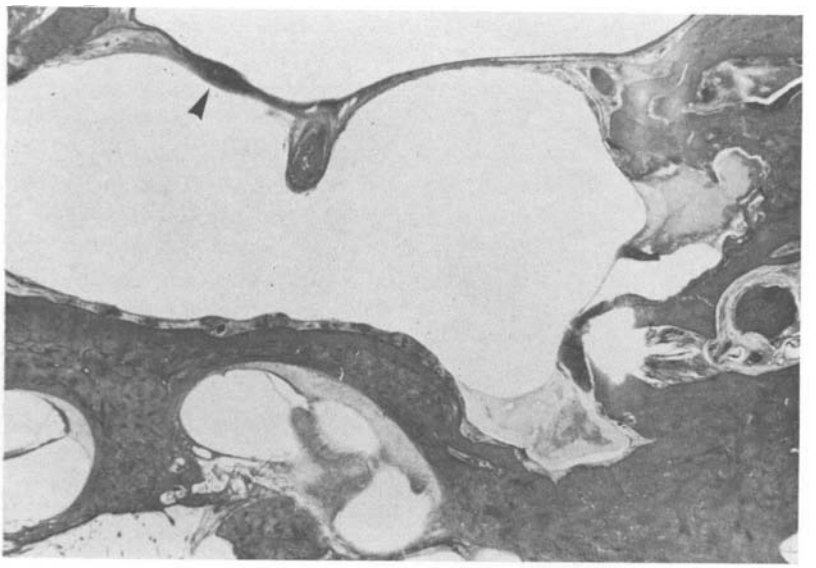

FIG. 13.
Bleeding into the tympanic membrane.

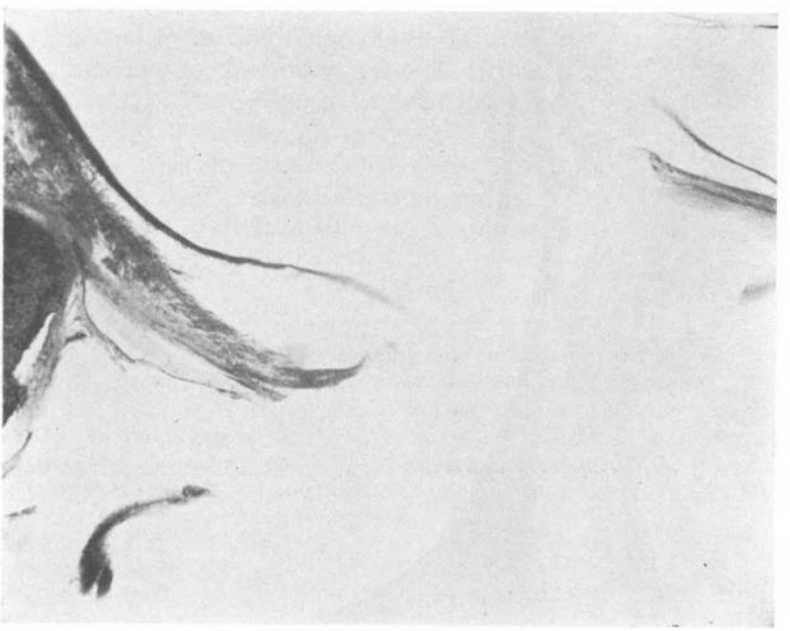

FIG. 14.
The ragged edges of a perforation.

https://doi.org/10.1017/S002221510008018X Published online by Cambridge University Press

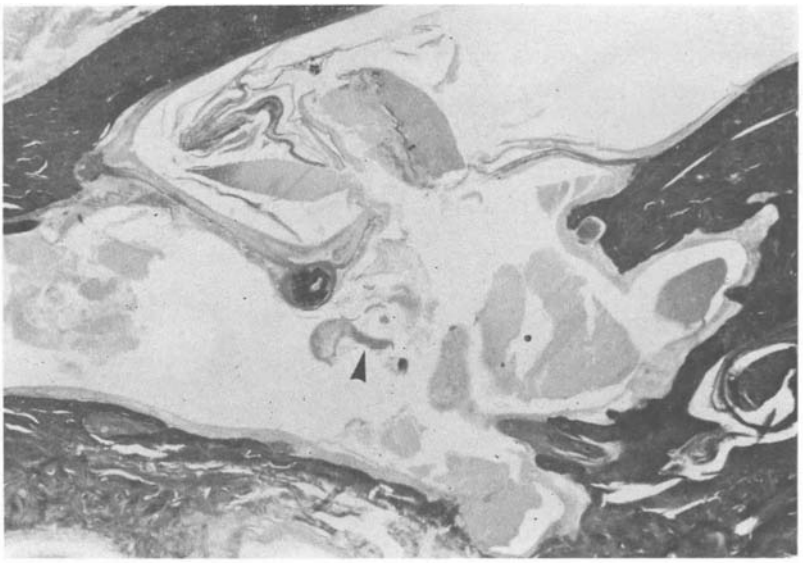

FIG. 15.
Squamous epithelium and keratin in the middle ear.

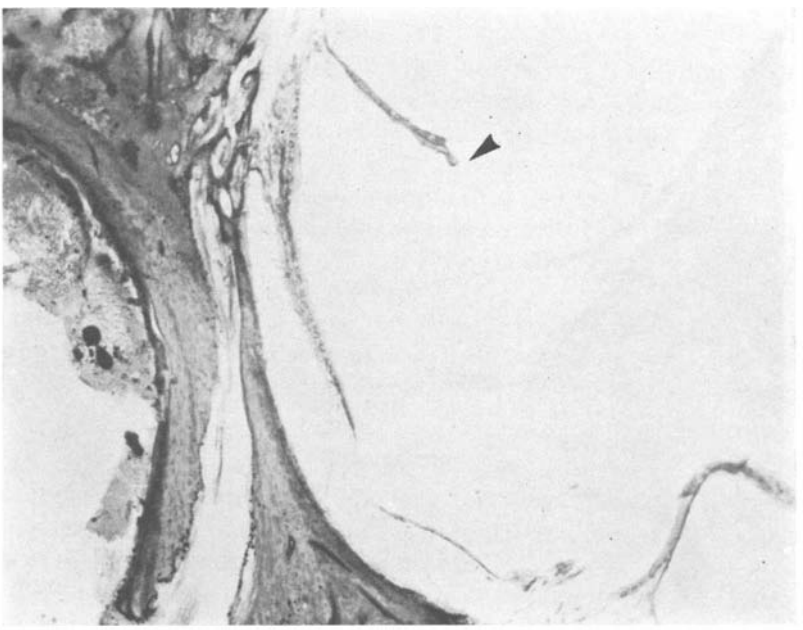

FIG. 16.
Rupture of the saccule.

https://doi.org/10.1017/S002221510008018X Published online by Cambridge University Press

sometimes are seen are caused secondarily by the suction effect of the negative phase;

4. A conservative approach will result in spontaneous healing in the majority of cases;

5. Contrary to general teaching, rupture of the tympanic membrane does not appear to have a protective effect on the inner ear;

6. Sensorineural hearing loss for the speech frequencies tends to, but does not always, recover spontaneously;

The authors have been most impressed by the ability of the ear to recover from blast injury.

Acknowledgements

We have become indebted to so many people in the preparation of this paper that it would not be possible to acknowledge all of them. We wish to mention the staff of the Casualty Departments of Royal Victoria and Belfast City Hospitals, and the Photographic and Pathology Departments of the Royal Victoria Hospital.

We wish to acknowledge the help given by Dr. R. R. A. Coles of Southampton, and Professor T. K. Marshall of Belfast.

We also have been assisted in our investigations by the Police and the Army.

Our E.N.T. colleagues in Belfast, who have treated many of the patients referred to in this report have, as ever, been generous and co-operative, agreeing to the review not only of their notes but also of their patients. Some E.N.T. surgeons in England have examined and done audiograms on patients who have left Belfast.

Finally, we wish to acknowledge the contributions of the Medical Research Council and Medical Education and Research Committee of the Northern Ireland Hospitals Authority, in providing the facilities for the sectioning of temporal bones.

REFERENCES

GREEN, J. O. (1872) *Transactions of the American Otological Society*, **5**, 88.
HIRSCH, F. G. (1968) *Annals of the New York Academy of Science*, **152**, 147.
RUEDI, L., and FURRER, W. (1947) *Das Akustische Trauma*. S. Karger, Basle.
SEAMAN, R. W., and NEWELL, R. C. (1971) *Archives of Otolaryngology*, **94**, 440.
STRONG, S. (1973) *Proceedings of the Irish Otolaryngological Society* (in press).
TETER, D. L., NEWELL, R. C., and ASPINALL, K. B. (1970) *Laryngoscope*, **80**, 1122.

Eye and Ear Clinic,
Royal Victoria Hospital,
Belfast BT12 6BA,
Northern Ireland.