

Chapter 36

DELAYED OTOLOGICAL TRAUMA

MITCHELL J. RAMSEY, MD,* AND PHILIP D. LITTLEFIELD, MD[†]

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*Colonel, Medical Corps, US Army; Department of Surgery, Landstuhl Regional Medical Center, Geb. 3765, 66849 Landstuhl, Germany

[†]Lieutenant Colonel, Medical Corps, US Army; Department of Surgery, Tripler Army Medical Center, 1 Jarrett White Road, Honolulu, Hawaii 96859-5000; Assistant Professor of Surgery, Uniformed Services University of the Health Sciences

INTRODUCTION

Military service is associated with numerous hazards. Injuries to the ear are generally not what come to mind. However, they are arguably some of the most significant in terms of frequency, cost, and impact. Otolological trauma from the Global War on Terror (GWOT) can range from mild transient hearing threshold shifts to gunshot wounds to the temporal bone. Although the mechanism of injury can be quite variable, noise and blast exposures are by far the most common. Noise-induced hearing loss in the military is a well-known problem, and it has continued to grow during the GWOT. Tinnitus and hearing loss are the most common service-connected disabilities for veterans receiving benefits and represent 18.4% of service-connected disabilities for veterans who began receiving compensation in 2011.¹ Explosions have caused a greater percentage of injuries in Operation Enduring Freedom (OEF) and in Operation Iraqi Freedom (OIF) than in any other large-scale conflict,² and they have caused the majority of combat injuries and deaths in OIF and OEF.^{3,4} The auditory system is particularly sensitive to impulse noise, and several reports have documented the auditory and vestibular injuries following blast exposure, including

- tympanic membrane (TM) perforation,
- implantation cholesteatoma,
- ossicular injuries,
- sensorineural hearing loss (SNHL),
- vertigo, and
- tinnitus.^{5–10}

Noise-induced hearing injury is the most common injury in blast exposure and is primarily due to blast overpressure.³ TM perforation is common with blasts and occurs in 8% to 62% of blast-exposed patients.^{9,11–13} Otolological injury is clearly a highly relevant issue for today's armed forces, and for the physicians and audiologists caring for service members with hearing loss.

Current methods of combat have increased the incidence of otological trauma. One author (PDL) evaluated and managed a large number of soldiers evacuated with combat injuries to Walter Reed Army Medical Center (Washington, DC) from 2007 to 2012. From this experience, there were 87 tympanoplasties for blast-induced perforations, with 29 repaired by the lateral graft technique. Of the tympanoplasties, six required ossiculoplasty, 10 had blast-implanted epithelium removed (usually small pearls), and 3 had fragments removed. There were three perilymph fistula repairs: two at a fractured stapes footplate found during tympanoplasty and one in a dizzy patient with an intact TM. Two patients had surgery for suspected cerebrospinal fluid (CSF)

leaks. There were three facial nerve transections that were treated with interposition grafts: two from gunshot wounds and one from an improvised explosive device (IED) fragment. One patient had a carotid artery, ear canal, and mastoid injuries from an IED fragment (facial nerve uninjured). He also had a Rambo procedure. The petrous carotid artery was treated by endovascular techniques without any neurological complications. There were also three bone-anchored hearing aids for single-sided deafness and a cochlear implant. A 1-year review of TM perforation repairs from this experience has been published, and the major results are included in this chapter. Various military medical facilities have different patterns of disease, but these numbers reflect the breadth and volume of otological trauma at an Army medical center. As previously described, the spectrum of otological injuries is broad, and the management of less frequent, more complex otological trauma is not the focus of this chapter.

Most otolaryngologists will care for patients with traumatic TM perforations, and this chapter emphasizes the definitive surgical management of such ear trauma. Although TM and middle ear injuries are the most common indications for surgery, a small subset of patients may benefit from surgery to rehabilitate a SNHL. Surgery may include a bone conduction device for single-sided deafness or a cochlear implant for bilateral SNHL. An even smaller subset of patients with perilymphatic fistula may benefit from surgery to aid vestibular symptoms and prevent further SNHL. Many of the surgical principles and techniques used for blast middle ear trauma are similar to those applied in the management of chronic otitis media and will be discussed later.

It is important to realize that many blast-injured patients have experienced emotional and physical violence, pain, and injuries that are difficult to comprehend. The effects of hearing loss, tinnitus, posttraumatic stress disorder, and traumatic brain injury should all be appreciated, and extra time should be set aside for detailed repeat counseling. Patients with traumatic brain injury frequently have some degree of organizational and cognitive difficulties. Many patients will require multiple and extensive surgeries. Sridhara and colleagues¹⁴ from Walter Reed Army Medical Center found that 59% of their blast-injured tympanoplasty patients also suffered traumatic amputations. In light of these issues, the recommendation and timing of surgery should be considered carefully. The window of opportunity for reconstruction of the eardrum is wide, so there is no rush in most instances. Amplification may be the best option for some patients until they are physically and emotionally prepared for surgery.

OTOLOGICAL PATHOLOGY OF BLAST/IMPULSE NOISE

Before discussing clinical management, it is worthwhile to review the mechanism of blasts and the associated otological pathology that result from blasts and noise exposure. An explosion results when a liquid or solid chemical undergoes a rapid exothermic reaction generating a high-pressure gas. The expanding gas pushes outward, compressing the surrounding air, and creates a blast wave that travels radially from the source at supersonic velocities. Explosions are characterized by an almost instantaneous rise from atmospheric pressure to a peak overpressure, followed by a longer negative pressure phase. The intense overpressure phase is the most detrimental to the ear. The pressure associated with these events is generally over 140 dB sound pressure level (SPL), creating a very intense acoustic stimulus.

Injuries sustained from a blast are classified as primary, secondary, tertiary, and quaternary. Primary blast injury (PBI) refers to trauma sustained as the blast wave encounters the body. The effect of the crushing overpressure wave varies with different tissue types. Thus, different rates of tissue acceleration and deceleration result in tissue compression and reexpansion causing differential movement, stress, and distortions at tissue interfaces. These detrimental effects are most pronounced at interfaces with air-containing spaces, such as the ear.

The “noise” of combat is extremely harmful. The mechanisms of noise toxicity are still being investigated, but the pathophysiology involves metabolic injury (molecular and cellular changes) at lower intensities, and a combination of metabolic and mechanical injuries in the higher intensities. Clinically, the exposure may result in a temporary threshold shift (TTS) or a permanent threshold shift. The degree of noise-induced injury depends on exposure characteristics (intensity, duration, type of noise, and frequency), as well as individual factors (genetic susceptibility, existing hearing loss, and comorbidities). High-intensity, short-duration noise—from gunfire and explosions—is termed *impulse noise*. Animal and human studies both indicate that impulse noise is more damaging than continuous noise.^{15–17}

The exact mechanism producing a TTS is still being elucidated. It has been assumed that the recovery of a threshold shift after acoustic exposure indicates a pathological process that is completely reversible with no permanent cochlear alterations. This is only a theory. Animal studies suggest that noise-induced TTS arises from cochlear dysfunction resulting from injury to the stria vascularis, the hair cells, the supporting cells, and the spiral ganglion cells.¹⁸ It is unclear which of these alterations is the most important contributor to

threshold shift. In addition, noise exposure produces swelling of the synaptic terminals of cochlear nerve fibers innervating the inner hair cell.¹⁹ Studies reproducing this swelling suggest that the effect is a result of glutamate excitotoxicity.²⁰ Recent work by Kujawa and Liberman²¹ has shown that TTS-producing noise exposure can cause dramatic loss of hair cell synapses without any hair cell loss.¹⁸ This pathological process may produce a clinical picture similar to auditory neuropathy and may explain a phenomenon of hidden hearing loss in which patients with noise exposure have subjective hearing difficulty despite normal audiometric thresholds.

Several cochlear changes have been observed in noise-exposed ears with permanent threshold shift. The most vulnerable elements to noise damage in the cochlea are the organ of Corti in general and the hair cells in particular.¹⁸ Ultrastructural analysis with electron microscopy shows that damage to the stereocilia bundles is a widespread consequence of acoustic overexposure.²² The stereociliary bundle is key in the mechanoelectric transduction; and widespread disarray, fusion, or loss of stereocilia can be associated with dramatic threshold elevations, even when virtually all hair cells remain intact.¹⁸ In humans, outer hair cells (OHCs) are the most susceptible to injury or loss, but degeneration involves both OHCs and inner hair cells with progressive or more intense acoustic exposure. Current evidence suggests that the metabolic mechanism of hair cell loss involves increased cellular stress, generation of reactive oxygen species, and the activation of apoptotic pathways.

Acoustic trauma can also cause mechanical injury to the cochlea. Short-duration, high-intensity impulse noise can literally blow the organ of Corti off of the basilar membrane. Roberto et al²³ performed a series of experiments to study the effects of blast wave exposure on the auditory system of chinchillas, sheep, and pigs. Chinchillas were exposed to a single impulse of 160 dB SPL. Histological evaluation showed separation of the organ of Corti from the basilar membrane. Sheep and pigs were exposed to single explosive detonations in a hard-walled enclosure (generating a mean peak SPL of 194 dB SPL for sheep and 193 dB SPL for pigs), and this caused a variety of TM, ossicular, and inner ear injuries. Histological preparations showed mechanical separation of the organ of Corti from the basilar membrane, as well as extensive immediate hair cell loss. Middle ear pathology was also assessed, and the majority of animals sustained both middle ear and inner ear damage. A few animals had normal middle ears and no TM injuries, but all animals were found to have significant inner hair cell loss and/or OHC loss

despite normal-appearing middle ear structures. Data suggest that an injury sufficient to cause middle ear damage will also cause inner ear damage.

A few animal and human studies have specifically evaluated the physical limits of the TM. The earliest studies, by Zalewski,²⁴ evaluated TM tolerance to gradual pressure increases and found the following:

- the minimum pressure required to rupture a TM was 5.4 pounds per square inch (psi) (185 dB SPL), and
- the pressure at which 50% of TMs ruptured was 23 psi (198 dB SPL).

OTOLOGICAL BLAST INJURIES

The TM is highly susceptible to injury from explosions. Several studies have evaluated the otological sequelae from blast events and tried to quantify the incidence of TM injuries. But, each event is unique, and quantifying the blast parameters is extremely complex. A few studies provide data from the current GWOT. A study of 652 British servicemen serving in Iraq and Afghanistan found TM rupture in 8% of those evacuated with blast injuries.⁹ A review of 436 explosion-wounded US soldiers treated at Brooke Army Medical Center (Fort Sam Houston, TX) found that 15% had TM perforations.¹² A separate review of 257 US soldiers treated at Walter Reed Army Medical Center found that 32% had a history of perforation.¹¹ Table 36-1^{27,28} is a collection of studies evaluating TM injury from terrorist bombings and combat blast exposure. Although the rate varies, each study shows a high incidence of TM injury.

Certain factors influence the likelihood of TM injury. Injury is most dependent on the characteristics of the explosion, the proximity of the patient to the blast, and if a blast occurs in open or confined spaces. The patency of the external auditory canal (EAC) and the health of the TM and middle ear may alter susceptibility to blast injury. Observations suggest that a canal occluded with cerumen can mitigate the blast effect if an air space exists lateral to the TM. This would suggest that an earplug might function in a similar manner. Pathology of the TM, middle ear, or eustachian tube has an unclear influence and has not been systematically studied. Yetiser and Ustun²⁹ studied Turkish soldiers exposed to blasts and found that the only patients who did not have perforations had otitis media with effusion and retracted TMs with poorly pneumatized mastoids. Their findings suggested that a small mastoid volume may be protective, but this was not supported in a subsequent study.³⁰

Blake et al²⁵ conducted experiments in a shock tube, presumably using a sharp-rising overpressure and found that the minimum pressure required to produce a TM rupture was 2.2 psi (178 dB SPL). Hirsch²⁶ reviewed the effects of overpressure from published material, as well as his own unpublished data, and estimated that the threshold pressure for damage to the eardrum was about 5 psi (185 dB SPL), and that overpressure near 15 psi (194 dB SPL) will rupture 50% of eardrums. TM injury is more likely the result of a blast that rapidly reaches its peak pressure, has a high pressure, and has a long duration.

Considering the huge number of variables involved in explosions, it is no surprise that blasts produce perforations of all shapes and sizes. Perforations uniformly occur in the pars tensa. They may be linear and result in flaps folded into the middle ear but, more frequently, an area of the eardrum is simply missing. Pahor³¹ described the distribution of perforations in 29 patients and found that 60% were central, 25% anterior, and 15% were posterior. Kronenberg et al³² characterized 210 perforations and found that 49% were inferior, 48% were superior, 13% were central kidney shaped, 15% had a combination of superior and inferior involvement, and 6.6% were marginal. He found two thirds were no larger than one quadrant, 27% involved half of the eardrum, and 7.1% were subtotal. Other reports indicate a higher rate of total and near total perforations, ranging from 65% to 81%, but these reports are from the surgical series and have a selection bias for larger or nonhealing perforations.^{14,33} Bilateral perforations are common and occur in 49% to 62% of blast victims.^{12,14,34} Figures 36-1 and 36-2 represent findings from six soldiers injured in an attack from a vehicle-borne IED. This vehicle-borne IED was detonated at the entrance to a small military compound and resulted in the death of seven soldiers. Survivors were evaluated at Landstuhl Regional Medical Center (Landstuhl, Germany) 10 days after the event. All survivors complained of severe acute hearing loss, 4 had tinnitus, 1 had some limited positional vertigo, and 1 had otorrhea.

Traumatic perforations, regardless of the etiology, generally have a high rate of spontaneous healing. Kronenberg et al³² evaluated the natural history of TM perforations in 147 military patients (210 ears) injured by artillery fire, aerial bombing, or gunfire. Spontaneous healing was seen in 155 ears (74%). Of these, 131 ears (62%) healed within the first 3 months, and 145 ears (69%) healed within 10 months.³² From the "Abercorn" explosion, Kerr and Byrne¹⁰ found

TABLE 36-1

FREQUENCY OF BLAST-RELATED TYMPANIC MEMBRANE PERFORATION

Author, Year, & Study Group	No. of Patients Exposed or Injured in Explosion*	% Patients with TM Perforation†
Breeze et al, 2011 ¹ British soldiers evacuated following blast injury	657	8
Cave et al, 2007 ² US soldiers with blast injury at Walter Reed Army Medical Center	250	32
Mellor and Cooper, 1989 ³ Soldiers killed or injured in Northern Ireland	828	61
Radford et al, 2011 ⁴ Victims of London subway bombs	148	48
Leibovici et al, 1999 ⁵ Israeli survivors of terrorist bombings	647	22
Ritenour et al, 2007 ⁶ US soldiers injured by explosion	436	15
Tungsinmunkong et al, 2007 ⁷ Victims of terrorist bombings in Thailand	110	20

*Each study group differs; some groups include patients injured, whereas other groups include those exposed.

†A large percentage of patients had bilateral perforations.

TM: tympanic membrane

Data sources: (1) Breeze J, Cooper H, Pearson CR, Henney S, Reid A. Ear injuries sustained by British service personnel subjected to blast trauma. *J Laryngol Otol*. 2011;125:13–17. (2) Cave KM, Cornish EM, Chandler DW. Blast injury of the ear: clinical update from the Global War On Terror. *Mil Med*. 2007;172:726–730. (3) Mellor SG, Cooper GJ. Analysis of 828 servicemen killed or injured by explosion in Northern Ireland 1970–84: the hostile action casualty system. *Br J Surg*. 1989;76:1006–1010. (4) Radford P, Patel HD, Hamilton N, Collins M, Dryden S. Tympanic membrane rupture in the survivors of the July 7, 2005, London bombings. *Otolaryngol Head Neck Surg*. 2011;145:806–812. (5) Leibovici D, Gofrit ON, Shapira SC. Eardrum perforation in explosion survivors: is it a marker of pulmonary blast injury? *Ann Emerg Med*. 1999;34:168–172. (6) Ritenour AE, Wickley A, Ritenour JS, et al. Tympanic membrane perforation and hearing loss from blast overpressure in Operation Enduring Freedom and Operation Iraqi Freedom wounded. *J Trauma*. 2008;64(2 Suppl):S174–S178; discussion S178. (7) Tungsinmunkong S, Chongkolwatana C, Piyawongvisal W, Atipas S, Namchareonchaisuk S. Blast injury of the ears: the experience from Yala Hospital, southern Thailand. *J Med Assoc Thai*. 2007;90:2662–2668.

that 82% (49 of 60) healed. Ritenour et al¹² reported spontaneous healing in 48% (35 of 75). In general, the odds of spontaneous repair are good.

TM injuries occur at blast levels much lower than required to cause internal injuries. It would then make sense that the likelihood of other PBIs is low if the TMs are spared in a blast and that perforations may serve as a biomarker for other PBIs. Unfortunately, these assumptions are not valid. Leibovici et al²⁸ evaluated 647 survivors of terrorist bombings and found that 193 (29.8%) of them had PBIs, including 142 with isolated TM perforations. No patient with an isolated eardrum perforation developed later signs of pulmonary or intestinal blast injury, and nearly 10% of cases had pulmonary blast injury with intact TMs. They concluded that isolated TM perforations in explosion survivors

do not appear to be a marker of concealed pulmonary blast injury or a poor prognosis.²⁸ Richmond and colleagues³⁵ had already realized this while researching the physical limits of the TM in animals. They stressed, “the tympanic membrane has such a wide range of tolerance that pressure high enough to damage the lung severely and pose a serious threat to life may, on occasion, not even rupture either eardrum.”³⁵

Blast-induced ossicular injuries are uncommon, but they do occur. A few series have reported the incidence of ossicular injuries, which ranges from 0% to 18%.^{14,33,36} These series can include disruption of the incudostapedial joint, displacement of the incus, malleus fracture, and fracture of the stapes superstructure. Chandler and Edmond³⁷ presented an unusual case in which 4 of 5 soldiers had ossicular damage after a

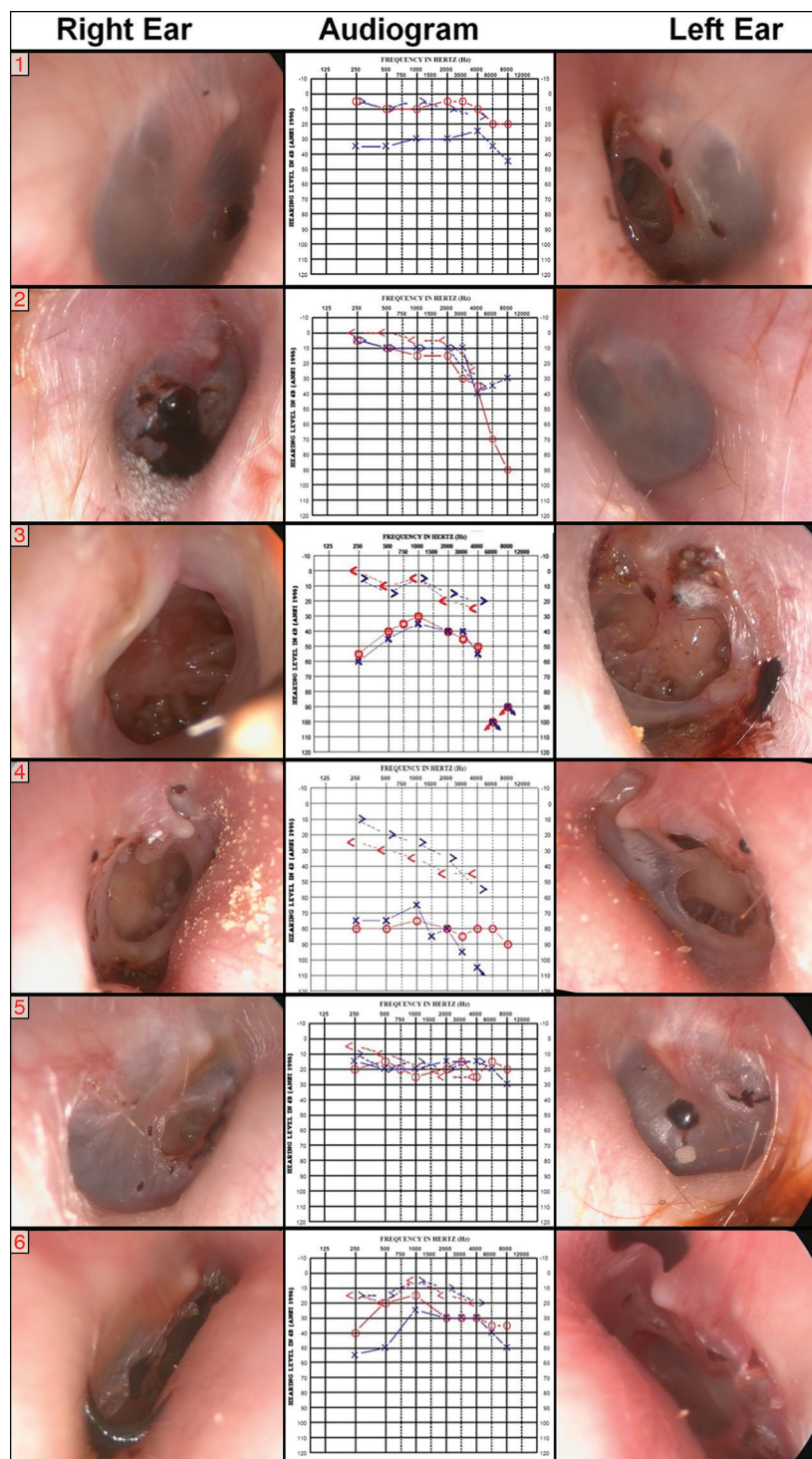


Figure 36-1. Examinations and audiometric findings of six vehicle-borne improvised explosive device blast patients. Each row is numbered by patient and shows the right ear, the audiogram, and then the left ear. This series illustrates some of the variation seen with tympanic membrane blast injuries. It is interesting to note that patients 1 and 2 had unilateral injuries, which also correlated to the ears facing the blast. Patients 3 and 4 were both facing the blast and had bilateral perforations. Patient 3 was the most exposed and had the most severe injury. Patient 5 sustained a perforation on the right side, which was facing the blast. Patient 6 was furthest from the blast, and his left ear was facing the blast yet he sustained bilateral perforations. The right perforation likely resulted from pressure reflected from the barrier to his right. A review of their audiograms shows mostly mixed losses, indicating significant inner and middle ear injury. These patients did not have any other primary blast injuries. ANSI: American National Standards Institute

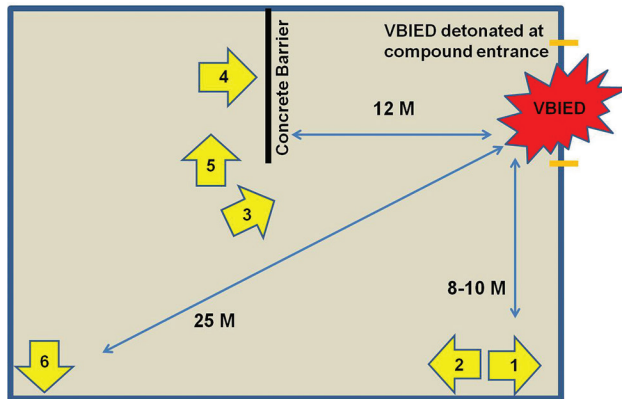


Figure 36-2. This schematic demonstrates the compound and the approximate position of the patients at the time of the blast. Each soldier is designated with a *yellow arrow* and *numbered 1 to 6*. The arrows point in the direction the soldiers were facing at the time of the blast, indicate their relative positions, and show the estimated distances from the vehicle-borne improvised explosive device (VBIED). Soldiers 4 and 5 were sheltered behind a concrete barrier.

large explosion of 200 dB (85 psi). Ossicular injuries may go undiagnosed because the outpatient assessment provides limited visualization. These injuries are often suggested by a residual conductive hearing loss (CHL) with an intact TM or are identified during surgery. Any patient undergoing tympanoplasty should have an intraoperative ossicular assessment with a detailed description of the findings. Figure 36-3 is from a patient injured by a grenade blast. His TM looked normal, but his clinical and audiometric examinations demonstrated a CHL. Exploration revealed a fracture of the anterior and posterior stapes superstructure. This was repaired with a total ossicular replacement prosthesis. Although there was good closure of the air bone gap, the patient had a residual high-frequency SNHL bilaterally.

Cholesteatoma is another important sequelae of blast injury. The mechanism involves displacement of the epithelium into the middle ear and subsequent growth. The cholesteatoma may present as a small keratin pearl, which is relatively easy to recognize and manage, or may be an open epithelial “carpet” that is less distinct and more difficult to remove. The incidence of cholesteatoma following PBI of the middle ear ranges from 8% to 12%.^{14,38,39}

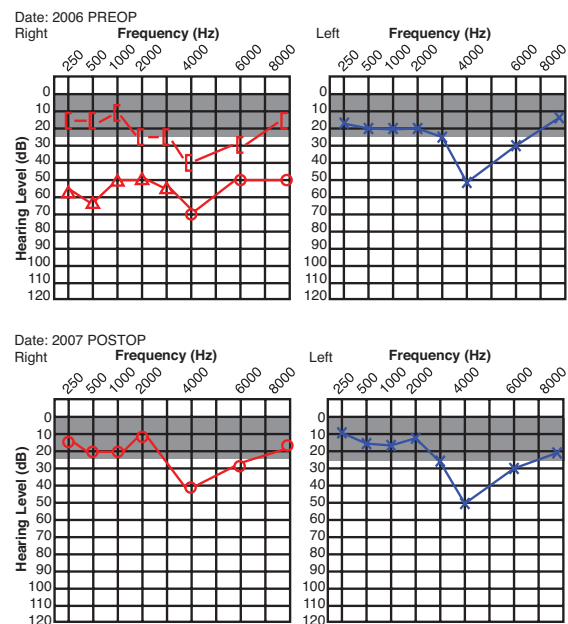
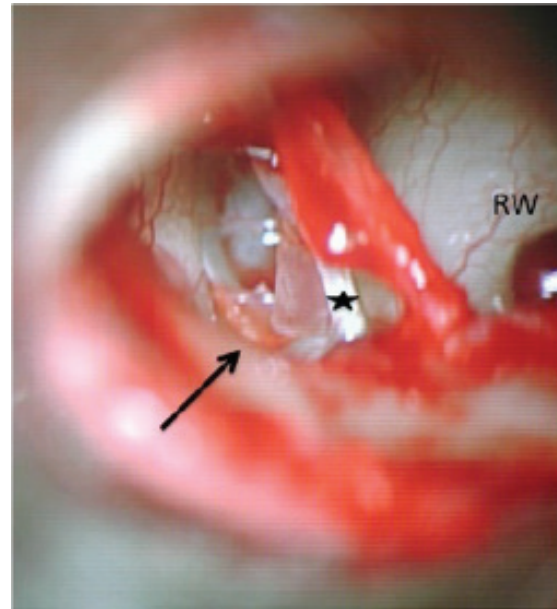


Figure 36-3. This surgical photograph shows a fracture of the right stapes in a patient injured by a grenade blast. The *black arrow* points to the fractured posterior crura, the *black star* is on the stapedius tendon, and RW identifies the lip of the round window. The preoperative and postoperative audiograms are indicated in the graphs below the photograph. *Red markings* = right ear hearing. *Blue markings* = left ear hearing. Pre-op: preoperative; POSTOP: postoperative

SURGICAL OUTCOMES

Tympanoplasty techniques are effective for residual TM perforations. Sudderth³³ reviewed tympanoplasty outcomes for soldiers injured by blasts in Vietnam. He studied 93 patients with 107 perforations, 81% of which

were total perforations. The medial graft technique was used in 42.2% and the lateral graft technique in the rest. Surgery resulted in an intact TM in 86.9% of cases. Sprem et al³⁴ studied blast injuries from the conflict in

Croatia. Tympanoplasty was done for 161 TM perforations using temporal fascia in 81, perichondrium in 61, and heterograft (bovine collagen) in 19. Repair of the TM was successful using temporal fascia in 91%, perichondrium in 92%, and heterograft in 89% of the cases. The report does not indicate the specific technique

used. One author of this chapter (PDL) and colleagues studied tympanoplasty outcomes in US soldiers with perforations from IED or grenade blasts, and 65% of their patients had total or near total perforations. They found that both lateral graft and medial graft techniques were effective 83% and 82% of the time, respectively.

MANAGEMENT

The initial management of blast perforations was outlined in Chapter 7, *Impact of Body Armor on Head and Neck Injuries: Preventive Measures*. Delayed management may consist of further conservative measures or definitive repair. Conservative measures consist of water precautions and a paper patch for small perforations. A period of observation is recommended because the majority of small and medium perforations will heal spontaneously. Kronenberg et al³² monitored perforations for the longest period and found that the majority of TMs that would heal spontaneously did so in the first 3 months. Anecdotally, total and subtotal perforations are less likely to heal spontaneously. In general, a minimum of 6 weeks of observation is recommended. We recommend proceeding to surgery if there is no change after 6 weeks. However, further observation is warranted if the perforation is improving. This recommendation is based on our observations that a perforation without change in the first 6 weeks is less likely to heal spontaneously. Furthermore, service members are frequently lost to follow-up over longer observation periods because of discharge, transfer, or medical separation. Individual factors should be considered and may justify a shorter observation period. A temporary hearing aid may be very beneficial while considering tympanoplasty, open fit aids are less associated with otorrhea, and many service members with mixed loss will continue to benefit from hearing aids even after tympanoplasty. Most patients who suffer a traumatic perforation will have good eustachian tube function, and a history of normal function preinjury is the best “test” of function. As always, an up-to-date audiogram is mandatory. Imaging depends on the situation, but is not necessary for most patients.

Persistent perforations should be repaired using techniques that work well for the surgeon. Both lateral graft and medial graft techniques are successful. Cartilage tympanoplasty techniques are not necessary because most patients with blast perforations have good eustachian tube function. Small posterior perforations are easily repaired through standard medial graft techniques, which are quick and easy, but have limited exposure. Larger total or near total perforations generally require greater exposure to optimize graft placement and frequently require a lateral graft

or modifications of medial graft techniques. These procedures require more time and technical skill, but they optimize exposure. Several variations of tympanoplasty exist. The keys to success are to stick with what works, optimize exposure, ensure good graft placement, and be meticulous.

The lateral graft technique is not complicated, but success requires certain steps to be performed to achieve adequate exposure for reconstruction. Many variations exist, but we will describe the basic technique described by Sheehy.⁴⁰ It starts with meatal and canal incisions to create a vascular strip. Next, a postauricular incision allows harvest of a temporalis fascia graft and exposure of the mastoid and EAC. The anterior skin of the EAC is removed and preserved for later replacement. A canaloplasty is performed to enlarge the EAC anteriorly and inferiorly so that the entire annulus is visible in one view. In addition, a shallow ledge is created immediately lateral to the anterior annulus. This is performed using a 2-mm diamond burr. This small ledge provides additional support for the anterior graft and reduces the chances of blunting. Adequate irrigation during drilling is important to prevent devitalizing the bone, which can impair reepithelialization of the canal. With exposure optimized, the remnant TM is meticulously deepithelialized by separating the epithelial layer of the TM from the fibrous layer. The long process of the malleus must be separated from the fibrous layer anteriorly and posteriorly to allow placement of the fascia graft, which will be anchored under the malleus. The ossicles are inspected, and abnormalities are repaired or carefully noted for a staged procedure.

The middle ear should be copiously irrigated to remove debris, bone dust, and blood clots to prepare a clean and dry field for reconstruction. The fascia graft is trimmed into an ovoid shape, and a slit is placed where it will fit under the malleus. It is absolutely essential that the graft is anchored underneath the malleus or it will lateralize during healing. Once under the malleus, the graft is manipulated into position to repair the defect, ensuring that it is supported by bone circumferentially. Care is taken to minimize the amount of fascia extending laterally onto the anterior EAC because this can predispose it to blunting. The native anterior canal

skin is replaced. The authors frequently utilize several small pieces of split-thickness skin graft to cover any exposed bone or fascia. The authors also prefer a silk rosebud dressing for packing. The surface tension created between the silk strips and tissue helps hold the grafts in place, and prevents granulation tissue growth into the packing material. Finally, the vascular strip is packed into its native position, and the postauricular incision is closed.

Medial graft techniques are familiar to most otolaryngologists, but modifications may be necessary for anterior, large, or total perforations. The anterior tab pull-through variation has been very useful for both authors and is described. The soft-tissue approach consists of a combination of meatal vascular strip incisions and a postauricular incision through which temporalis fascia (or the loose areolar tissue) is harvested for use as a graft. A unique step in the technique is exposure of the anterior EAC bone and anterior annulus. To expose these, the anterior canal skin is transected near the prominence of the temporomandibular joint bulge. The lateral skin is elevated to the bone-cartilaginous junction, whereas the medial skin is elevated to the annulus. A posterior tympanomeatal flap is also elevated and joined with the medial anterior skin flap so that a much wider area of skin is elevated than with a typical tympanomeatal flap. This allows exposure of the anterior, inferior, and posterior bony canals. Bone is removed from the inferior, anterior, and superior EAC. Similar to the lateral graft technique, the goal of canaloplasty is to see all of the annulus in one view. This is a very important step to ensure proper graft placement and should not be skipped. The margin of the perforation is freshened once it is entirely visible. Anteriorly, the exposed annulus is lifted from the groove to create a gap several millimeters long that will allow a tab of fascia to be pulled through.

Next, the posterior annulus is identified and lifted out of the groove from the Notch of Rivinus superiorly to 6 o'clock inferiorly. The entire annulus can be elevated, but it is best to leave a part of it anchored inferiorly to prevent lateralization of the TM. The middle ear and ossicles are inspected, and the field is cleared of any debris. The fascia graft is trimmed, but modified to include a small anterior tab that will be grasped and pulled through the anterior annulus gap. The graft is inset, and then looking through the anterior annular gap, the tab is grasped (usually with an alligator forceps) and pulled laterally to rest on the anterior EAC bone. This maneuver supports the anterior aspect of the fascia graft by anchoring it under the annulus and utilizing the surface tension between the graft and the EAC. When standard medial graft techniques fail anteriorly, they often result from inadequate support and

the greater depth of the middle ear space anteriorly. The remainder of the graft is manipulated into the ideal position and supported with Gelfoam and/or Gelfilm (Pfizer, New York, NY) medially. In contrast, the lateral graft does not require packing in the middle ear space because the surface tension between the graft and the EAC provides support. Gelfilm, however, is placed between the umbo and promontory to prevent adhesions. The tympanomeatal flap is then placed into its native position and supported by additional packing in the EAC, the postauricular incision is closed, and the vascular strip is replaced.

The ossicular chain is occasionally interrupted, most commonly at the incudostapedial joint. The separation can be subtle, so it is important to do a careful assessment of ossicular mobility during every tympanoplasty. Sometimes it is not recognized, and a residual CHL (especially high frequency) is noted postoperatively. It is managed by reconstructing the joint or by replacing the incus. The joint can be repaired with a joint prosthesis that bridges the gap between the incus and stapes, or hydroxyapatite cement if the gap is small. Cement is also useful for reinforcing the prosthesis. If the incus requires replacement, an autologous or synthetic incus interposition—or synthetic partial ossicular replacement prosthesis—can be used with good success. An incus interposition requires a favorable angle between the malleus and the stapes to stay in position, and it is difficult to do at the same time as tympanoplasty because it interferes with any graft near the malleus. Use of a partial ossicular replacement prosthesis is a technically easier alternative because it is simple to manipulate without disrupting the graft. If a synthetic prosthesis is used, the platform is best covered with a thin sheet of cartilage to minimize extrusion. The technique and prosthesis choice are surgeon dependent. A careful assessment of the operative findings should be recorded and is especially useful in cases of residual CHL.

Fracture of the stapes superstructure can be a subtle yet significant injury that is difficult to identify. The ossicular chain will appear to be intact and mobile even though the stapes is fractured. The stapes superstructure is challenging to examine, even with magnification. Palpation of the incudostapedial joint will show movement of the superstructure, but limited movement of the footplate. Management includes placing a prosthesis from the footplate to the TM, using a bucket handle prosthesis from the incus to the footplate, or performing a stapedectomy/stapedotomy (as a staged procedure when a perforation is present).

Postoperative care varies widely, but may become important to facilitate optimal healing. The ability to distinguish between a graft that is healing and wound-

related problems (eg, mucosalization, blunting, and stenosis) is critical to optimize outcomes. Many types of packing techniques are successful. When a lateral graft is performed, both authors prefer to actively remove the rosebud packing 2 to 3 weeks after surgery. The graft has started to incorporate by this time and is safe from accidental removal. After medial graft procedures, the absorbable packing can be removed after a couple of weeks or may be left to dissolve for a month or more. This is based on surgeon preference. To aid in identifying the plane between packing and the underlying tissue, silk strips, thin Silastic (Dow Corning Corporation, Midland, MI), or Gelfilm are placed lateral to the reconstructed TM. Their iden-

tification during packing removal signals the limit and helps ensure adequate packing removal. Water precautions are implemented until the entire EAC and graft are well epithelialized. A postoperative audiogram is usually obtained 2 to 3 months after surgery. Long-term assessment is necessary to monitor for late graft failures, canal stenosis, postoperative mucosalization or myringitis, and identification of epithelial pearls. Follow-up can be tailored, but should be every 4 months for the first year, then every 6 months for the next year. The transient nature of the military population makes this difficult. Therefore, long-term postoperative care should be carefully outlined to all patients.

SUMMARY

Otological injury from impulse noise remains a major problem for service members and is a substantial cause of morbidity for current as well as future conflicts. Animal and clinical research have provided some insight into the otological pathology associated with impulse noise, but much more research is necessary. The nature and scope of the clinical problem have led to the development of the Department of Defense Hearing Center of Excellence (Lackland Air Force Base, TX). The Hearing Center of Excellence works through advocacy and leadership in the development of initiatives focused on the prevention, diagnosis, mitigation, treatment, rehabilitation, and research of hearing loss and auditory-vestibular injury. Efforts like these will help expand prevention and treatment options for otological injury.

All patients with blast injuries returning from the

combat theater should have otolaryngology and audiology evaluations to screen for injury of the middle or inner ear. Patients with TM perforations generally benefit from a period of observation because the majority will heal spontaneously. Large total and near total perforations have a poorer prognosis, and this may influence the period of observation. Patients who have persistent TM injuries can be treated with safe and effective tympanoplasty techniques. Medial and lateral graft techniques are both successful, and selection should depend on surgeon preference and experience. Surgeons should monitor for epithelial implantation, ossicular injury, and remain vigilant during surgery in the event that they encounter unexpected findings. Lastly, a significant number of patients with a mixed hearing loss preoperatively may also benefit from amplification postoperatively, even with good closure of the air-bone gap.

CASE PRESENTATIONS

Case Study 36-1

Presentation

A male in his twenties was massively injured by an IED in Iraq in 2006. This included pelvic and abdominal injuries, bilateral lower extremity amputations, and a hip disarticulation. He had more than 60 surgeries by the time otolaryngology was consulted for bilateral TM perforations. Figure 36-4 shows his initial audiogram. He had a right underlay tympanoplasty by another provider 5 months after his injury. Although the perforation was closed, his hearing was worse, and he was fitted with a hearing aid. On examination, his right TM was intact but opaque, whereas his left TM had a total perforation that appeared clean. The right ear was the worse hearing ear.

Operations and Outcomes

The patient had a right middle ear exploration with lysis of adhesions 11 months after the first right tympanoplasty. The ossicles appeared normal. This nearly completely closed the air-bone gap. Subjectively, he noted a mild improvement in his hearing because he still had a sloping SNHL, but he stopped using the hearing aid.

This was followed by a left lateral graft tympanoplasty. There was a small CSF leak during drilling of the tympanosquamous suture line, which was from an undiagnosed temporal bone fracture. It was controlled with a Gelfoam EAC packing and bed rest. A postoperative CT (computerized tomography) scan confirmed a longitudinal temporal bone fracture in the same area. Despite this, he had closure of the

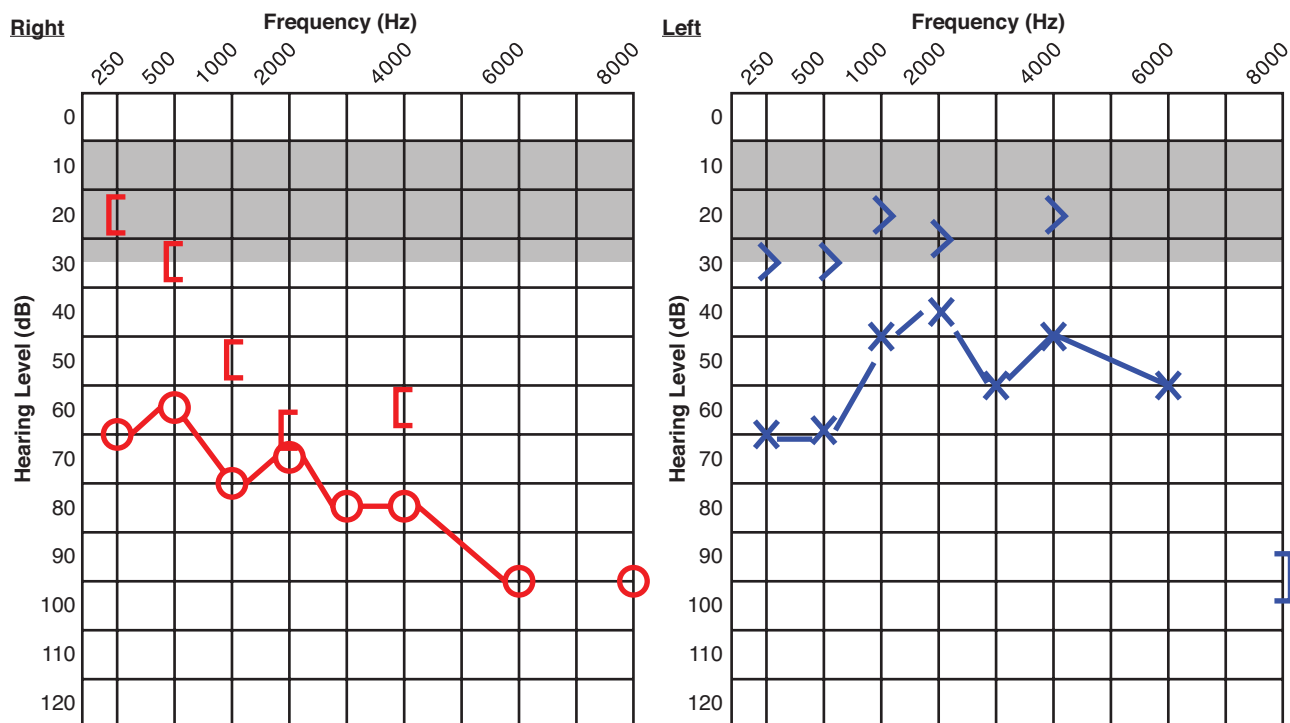


Figure 36-4. Preoperative hearing, early 2007. Red markings = right ear hearing. Blue markings = left ear hearing.

perforation and an excellent hearing result (his air line was 10 dB in the low frequencies, 15 dB in the mid frequencies, and sloped to 50 dB at 6 kHz because of the SNHL). Unfortunately, a cholesteatoma was identified at the 10-month follow-up visit. A left revision tympanoplasty, with removal of hypotympanic and peritubal cholesteatoma, was performed. The ossicles appeared normal during surgery. Postoperatively, he had an intact TM, but a poor hearing result secondary to blunting and lateralization. He had a revision lateral graft 5 months later. The TM was only partially attached to the malleus, and there was a small pearl of cholesteatoma lateral to the handle (it was lateral to where the TM should have been). The pearl was removed, and the entire TM was replaced with a new graft that healed well. His air-bone gap was closed, and he only had high-frequency SNHL.

The right ear remained stable with closure of the air-bone gap for several years. However, the right ear developed progressive SNHL. It was near normal at 250 Hz and 500 Hz, but then declined to 85 dB to 110 dB in the mid and high frequencies. He eventually developed a new perforation in the posterior-inferior quadrant 4 years after the first revision. A second revision lateral graft (with cartilage reinforcing the posterior two quadrants), canalplasty, and canal-wall-up mastoidectomy were performed outside

the military. Surgeons found adhesions around the incudostapedial joint, but the ossicles were otherwise normal and the mastoid was healthy with no cholesteatoma present. His hearing at 500 Hz and 1 kHz decreased by 10 dB and 15 dB, respectively, but then showed an average improvement of 30 dB through 4 kHz. There remained no measurable response at 6 kHz to 8 kHz.

His current examination demonstrates expected postoperative changes and intact epithelialized TMs without blunting or lateralization. Figure 36-5 shows his final hearing result. The conductive component of his hearing loss has gone back and forth over 7 years, but ultimately it was closed for the left ear and improved for the low to mid frequencies in the right ear. Meanwhile, the bone line has deteriorated in the right ear. This may be attributed to surgical trauma. However, we are unaware of any specific event, and the loss appears incrementally over several audiograms. Another possibility is that the cochlear function has continued to deteriorate after the initial blast trauma. Fortunately, the bone line for the left ear is stable. He currently does not use amplification because he says he hears adequately from the left, and a hearing aid on the right is more annoying than helpful. This is substantiated by the fact that he is doing well in a prestigious professional school.

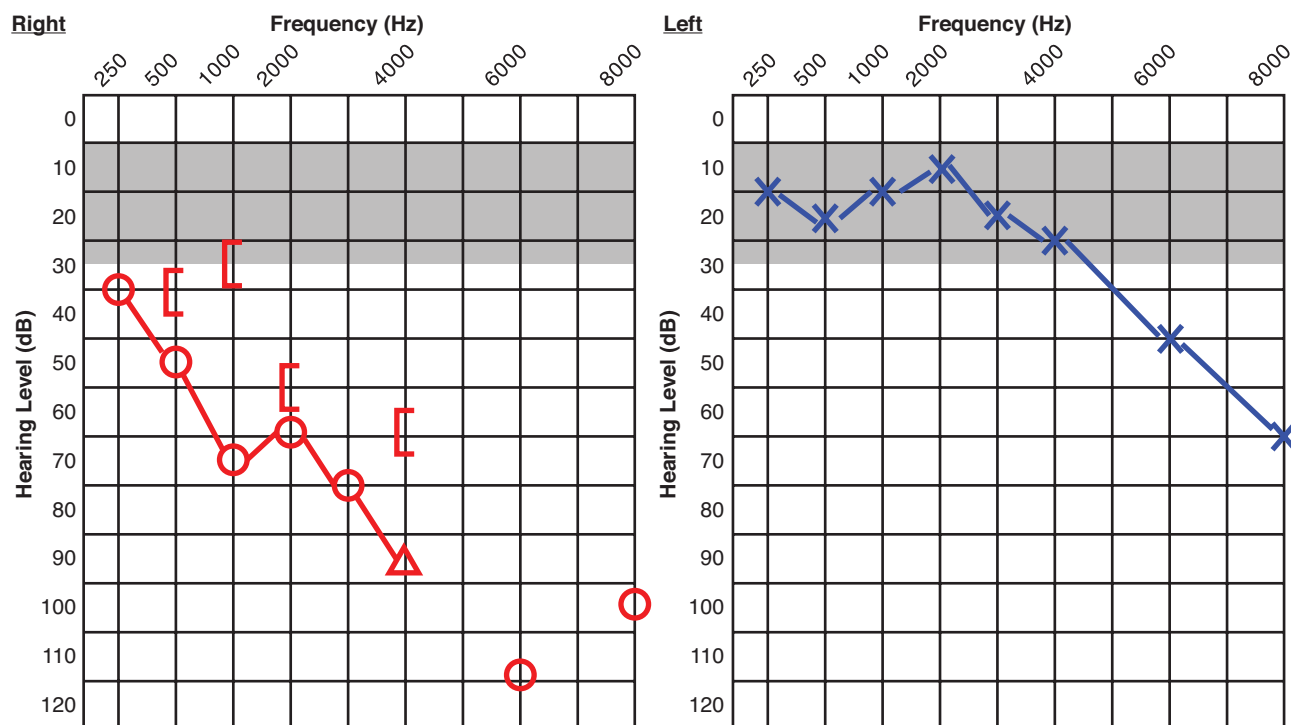


Figure 36-5. Postoperative hearing, mid-2013. Red markings = right ear hearing. Blue markings = left ear hearing.

Lessons Learned

This case was humbling. It looked straightforward at the outset, but ended up being the most challenging of more than 60 patients operated on by the author (PDL) for blast-induced TM perforations while at Walter Reed Army Medical Center. No other ear required more than two revisions, but he ended up having two revisions on *each* ear. The left ear was also complicated by cholesteatoma, which was either not recognized at the initial surgery or was iatrogenic and required additional surgery. This emphasizes the need to aggressively look for it during any tympanoplasty after a blast and the need for consistent long-term follow-up. Another unusual aspect of this patient's injury was the CSF leak from an unrecognized temporal bone fracture, which fortunately stopped with simple ear packing. There probably was nothing to do differently about it, but it was a reminder to stay alert during surgery.

Anterior blunting and lateralization are known complications of lateral graft tympanoplasty. This complication is thought to have been in part due to a robust granulation response with Gelfoam packing that matured and epithelialized. This case—and a couple others—converted the author from Gelfoam packing over Gelfilm disks to the silk rosebud dressing for all lateral grafts. There were no cases of blunting or lateralization in 20 consecutive lateral grafts following this switch.

The author (PDL) had extensive experience in otological surgery by the time he met this patient, but these procedures were among his early experience with blast trauma. Although the surgical techniques required are the same as for chronic otitis media, it seems that they are often less forgiving in these patients. This case also emphasized the need for vigilance in assessing blast patients for the unexpected (cholesteatoma, ossicular abnormalities, CSF leaks, etc). Although humbling, the lessons learned in caring for this patient helped many subsequent patients. Part of what makes this case memorable is the patient. He is an incredible individual, and although horrendously injured, his attitude, character, energy, and influence were deeply inspiring. It was an honor to take care of him, and the doctor definitely benefited the most from the relationship.

Case Study 36-2

Presentation

A male in his twenties was injured by an IED in Iraq in early 2008. His injuries included bilateral lower extremity amputations, an arm amputation, and urological trauma. He had multiple surgeries prior to otolaryngology consultation for bilateral TM perforations and difficulty hearing. Examination showed a

clean but total perforation on the right, whereas the left had a small, clean perforation that was about 25% of the posterior-inferior quadrant. He had an extremely difficult time communicating, even with the aid of a “pocket talker” personal amplifier. Figure 36-6 shows his initial audiogram 2 months after the blast.

Operations and Outcomes

He had bilateral tympanoplasties 7 weeks after his initial injury. Although it is unusual to operate on both ears simultaneously, the smaller perforation was managed with a stuff graft myringoplasty, which would expedite his care and pose little risk of complication. The right total perforation was repaired with a medial graft anterior tab pull-through technique. This required a wide canalplasty to see the anterior and inferior annulus. There was a piece of fragment in the middle ear, and this was removed. The incus and stapes superstructure were absent, but the stapes footplate and round window membrane appeared normal and without fistula. The left ear had a much smaller perforation, and this was repaired by rimming the perforation, filling the middle ear with Gelfoam, and then tucking a piece of fascia (harvested from the contralateral side) under the edges of the perforation via a stuff graft myringoplasty technique.

The right TM healed well, but the left graft failed. He was fitted with bilateral hearing aids, but still could not communicate effectively and was evaluated for a cochlear implant. His performance on the Hearing in Noise Test was 0% in quiet and with noise at 60 dB SPL. On the Abbreviated Profile of Hearing Aid Benefit test, he reported having difficulty 93% of the time in quiet environments, 99% of the time in reverberant environments, and 97% of the time in background noise. He had a right transmastoid cochlear implant 3 months after his tympanoplasties (Cochlear, Nucleus, and Freedom; Cochlear Limited, Sydney, Australia). Figure 36-7 shows him at a follow-up appointment 1 week after his initial activation, for which he had a very favorable response. His Hearing in Noise Test in quiet score was 100% six months after surgery, and his reported difficulties on the Abbreviated Profile of Hearing Aid Benefit test decreased to 5.4%, 29.3%, and 60.2%, respectively.

He attempted to use a left hearing aid for his residual low-frequency hearing, but this made him very prone to otorrhea. A bone-anchored hearing aid was also considered to take advantage of the left ear's residual low-frequency hearing to provide an acoustic supplement to the right cochlear implant (bimodal stimulation). However, the patient declined this option. He had a left revision transcanal medial graft tympanoplasty 14 months after the first surgery for

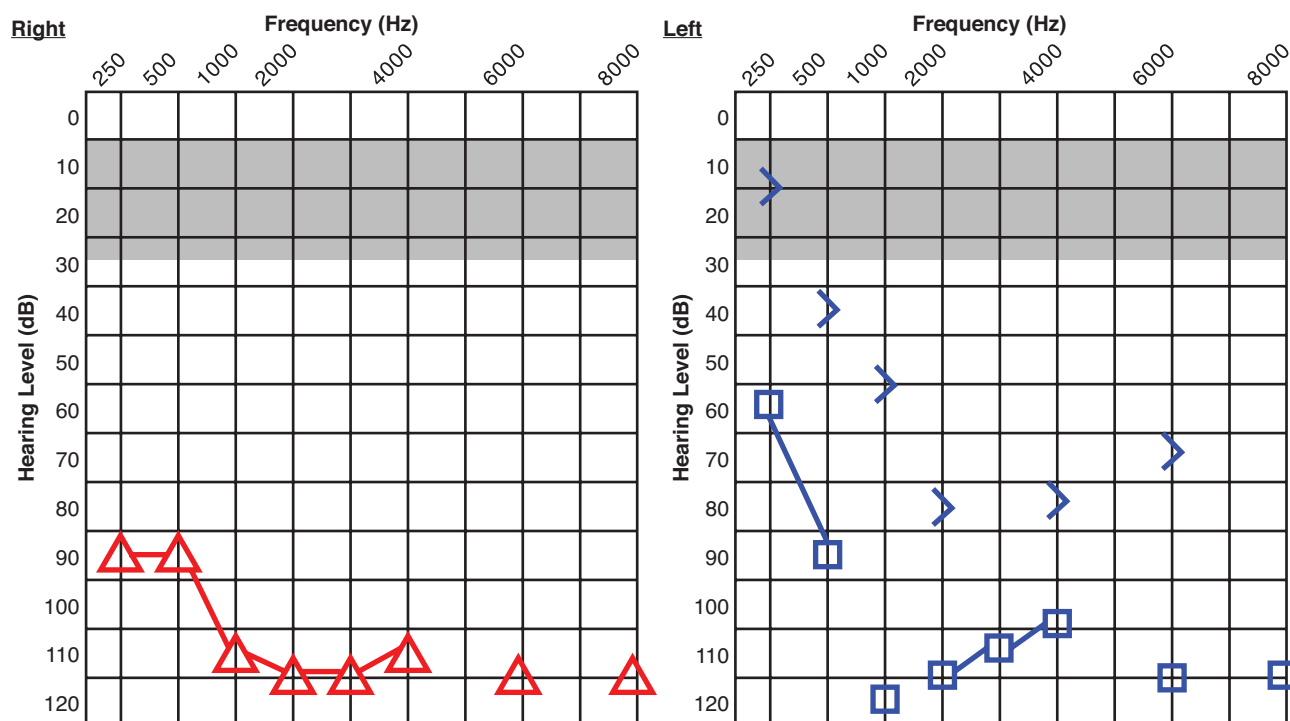


Figure 36-6. Preoperative hearing, mid-2008. Red markings = right ear hearing. Blue markings = left ear hearing.



Figure 36-7. Implant use 1 week after activation.

a small inferior perforation. The graft was successful in closing the perforation, but he still developed intermittent otorrhea from mucosalization of the EAC and TM. The final hearing result is shown in Figure 36-8. The right ear was not included because he did not have any residual hearing in the implanted ear. There is some improvement in the left low-frequency air-bone gap; but, as in the prior case, the sensorineural hearing has continued to decline years after the blast. The audiograms demonstrate a gradual decline in threshold. Considering there was minimal (if any) trauma to the inner ear during the tympanoplasties, we conclude that this is a delayed effect of the blast. He is satisfied with his cochlear implant and has used it successfully for 4 years.

Lessons Learned

It is hard to comprehend how much this soldier has suffered, but his conduct throughout his recovery was inspiring. The cochlear implant made his case unique. The cochlear implant program at Walter Reed Army Medical Center was initially founded in 2002 when it was thought that there would be a flood of soldiers with profound SNHL from blasts. This turned out not to be the case, and only two cochlear implants were performed for otological trauma in more than a decade. These appear to be the only such cochlear implants

done in military medical centers during OIF/OEF, but it is possible that more were performed at Veterans Affairs hospitals.

A bilateral tympanoplasty seemed like a good idea in this situation, but the technique on the left side failed. It probably would have been better to take the time to elevate a tympanomeatal flap and place a proper underlay graft. The patient would have benefited even more if he also had a canalplasty. His EAC was too narrow in retrospect, and enlarging it probably would have prevented much of the otorrhea and myringitis that has troubled him.

This patient is also a candidate for a cochlear implant on the left side, especially since his sensorineural hearing continues to decline. He is not committed to this yet or to any revision surgery on his ear canal. He does receive some sound quality advantage from the residual low-frequency hearing, which he finds very important for music appreciation, and he would potentially lose this with a second cochlear implant. If he elects to have a cochlear implant on the left side, tympanomastoid obliteration would be recommended because of the otorrhea.

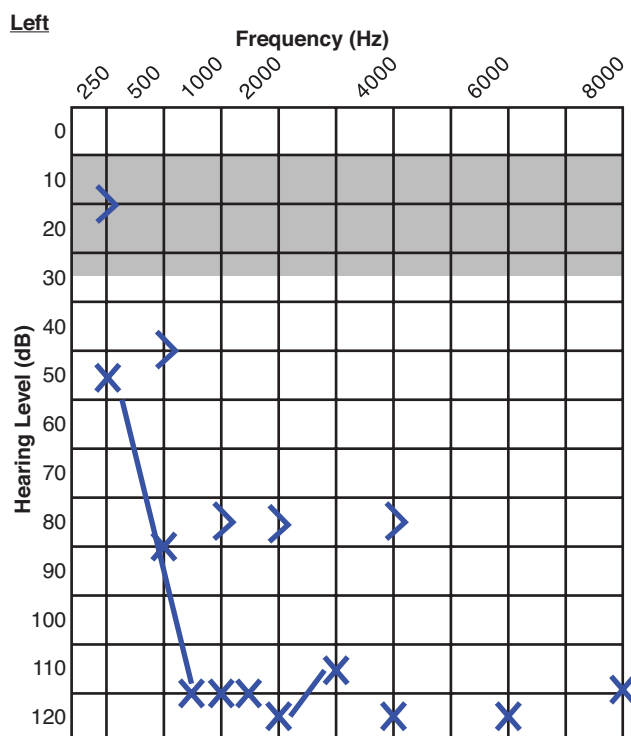


Figure 36-8. Postoperative hearing for the left ear, late 2011. Blue markings = left ear hearing.

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