TYMPANOPLASTY

SAUMIL N. MERCHANT, MD, JOHN J. ROSOWSKI, PhD,
MICHAEL J. McKENNA, MD

We review many aspects of tympanoplasty, including physiologic principles and our philosophy regarding the treatment of chronic otitis media. We then describe the various techniques of tympanoplasty that we currently use and indications for each technique. Hearing results after 388 tympanoplasty procedures in which the middle ear was judged as being aerated postoperatively are presented. The best hearing results occurred after type I tympanoplasty. An intact stapes was a positive prognostic indicator when the ossicular chain had to be reconstructed. There were no differences in hearing outcomes between canal wall-up and canal wall-down procedures.

Tympanoplasty may be defined as a surgical procedure designed to reconstruct the sound transmission mechanism of the middle ear. The modern era of tympanoplasty began in the 1950s with the pioneering work of Wüllstein[1] and Zollner.[2] Subsequently, many other otologic surgeons contributed to the development and refinement of tympanoplasty techniques. Wüllstein classified the operations as types I through V, and we use a modified version of his classification.

The objectives of tympanomastoid surgery for chronic otitis media (COM), in decreasing order of priority, are (1) elimination of disease to produce a safe and dry ear; (2) alteration of anatomy to prevent recurrent disease, and to optimize cleaning and otologic monitoring; and (3) reconstruction of the middle ear to achieve serviceable and stable postoperative hearing.[3] Although this article focuses mainly on the third objective, we point out that our choice of technique of tympanoplasty in a given case is influenced significantly by the first 2 objectives.

The *goal of a tympanoplasty* is to restore sound pressure transformation at the oval window by coupling an intact tympanic membrane (TM) with a mobile stapes footplate via an intact or reconstructed ossicular chain and to provide sound protection for the round window membrane by a closed, air-containing, mucosa-lined middle ear.[4] In the normal ear, most of the middle-ear gain is provided by the area ratio (ie, the TM gathers force over its surface and then couples the gathered force to the smaller footplate of the stapes). It is pertinent to note that mean gain provided by the normal human middle ear is only approximately 20 dB, between 250 and 1,000 Hz, and the gain decreases by 6 to 8 dB per octave at frequencies higher than 1,000 Hz.[4]

We routinely combine tympanoplasty and mastoidectomy when treating ears with COM. Ears with cholesteatoma undergo surgery to remove cholesteatoma (canal wall-down [CWD] mastoidectomy, canal wall-up [CWU] mastoidectomy, or atticotomy) in conjunction with tympanoplasty. Ears without cholesteatoma but with active infection are initially treated medically to control infection and eliminate otorrhea. If the ear remains dry for 6 months, then elective tympanoplasty is considered. If medical treatment fails, then tympanoplasty is combined with mastoidectomy (ie, CWU or CWD). The mastoidectomy is necessary to eliminate infection and granulation tissue in the mastoid air cells, antrum, and epitympanum.

We stage the procedure in tympanoplasty when the stapes is fixed. When the ossicles are mobile, our philosophy is to combine elimination of disease and reconstruction of hearing in one stage. Should the hearing results be unsatisfactory and if the middle ear is well aerated without infection, a revision operation for hearing can be performed. In many cases, revisions are not necessary, and, therefore, the staging procedure is avoided. In our experience, major reconstruction, such as total drum replacement with ossiculoplasty in combination with a mastoidectomy, is successful often enough to challenge the wisdom of planned staging. In cases of COM with cholesteatoma treated with a CWU mastoidectomy in which a second look is planned to be certain there is no residual disease, we will sometimes perform the ossicular reconstruction during the second procedure.

We avoid tympanoplasty in ears with end-stage COM pathology characterized by fibrosis and cyst formation (ie, fibrocystic sclerosis) that obliterates large portions of the tympanomastoid compartment.[5] It is unreasonable to expect that the middle ear will become aerated after surgery in such cases. These patients often present with a history of multiple failed tympanoplasties, TM grafts that are retracted and immobile on pneumatic otoscopy, and computerized tomography (CT) studies showing diffuse soft tissue opacification of the middle ear and mastoid with nonaeration. We also avoid tympanoplasty in ears with

From the Department of Otology and Laryngology, Harvard Medical School, Department of Otolaryngology, Massachusetts Eye and Ear Infirmary, Boston; and Division of Health Sciences and Technology, Harvard University-Massachusetts Institute of Technology, Cambridge, MA.

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Address reprint requests to Saumil N. Merchant, MD, Department of Otolaryngology, Massachusetts Eye and Ear Infirmary, 243 Charles Street, Boston, MA 02114-3096.

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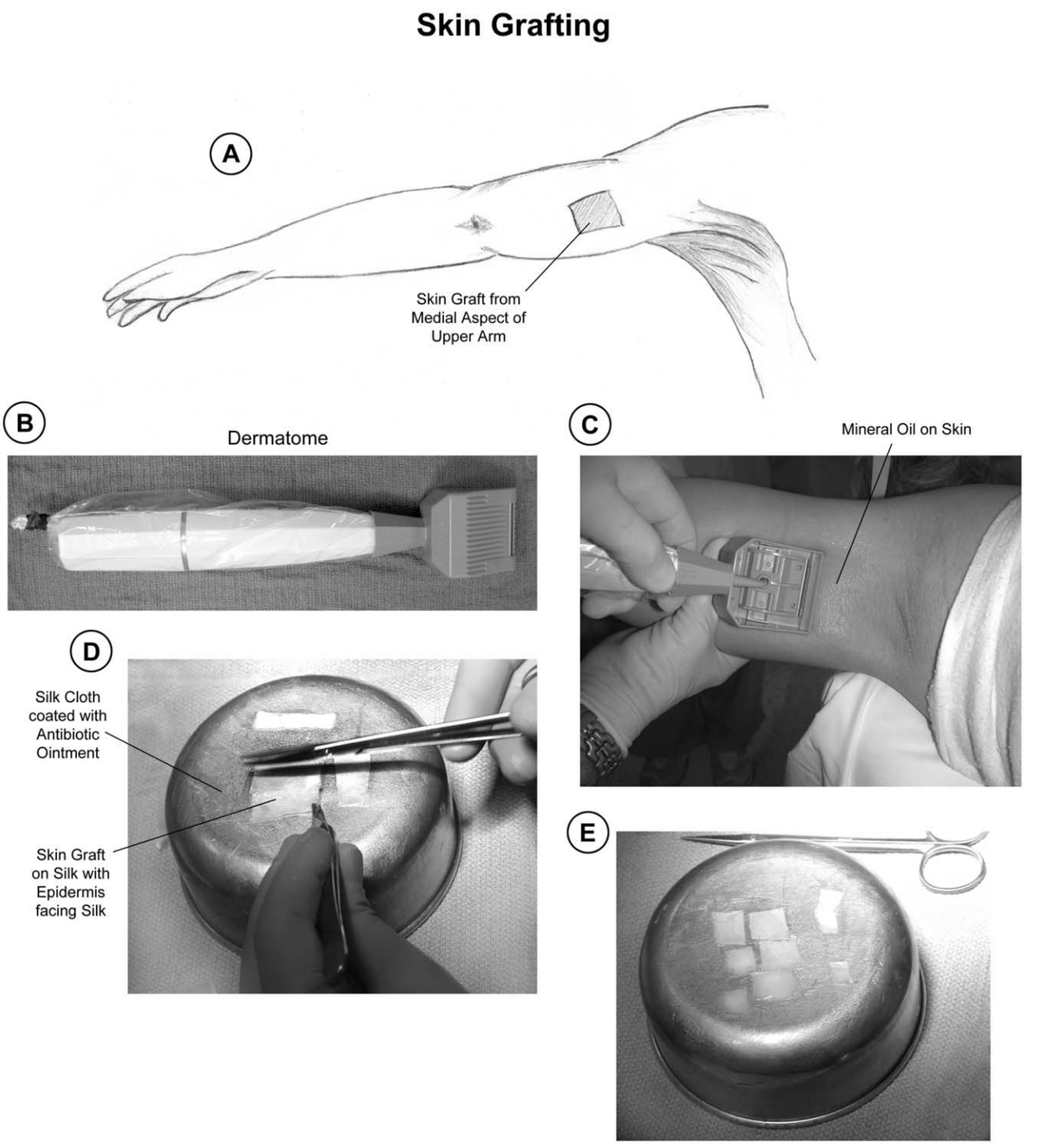

FIGURE 1. Technique of split-thickness skin grafting. (A) Skin graft is harvested from hairless area on medial aspect of upper arm. (B) Dermatome used to harvest skin graft. (C) Skin is lubricated with sterile mineral oil and stretched tightly while using the dermatome. (D) Area of skin $\sim 3 \times 3$ cm is removed and placed onto silk cloth coated lightly with antibiotic ointment. Skin is placed with epidermis down, facing the silk. Excess silk is trimmed away. (E) Final appearance of skin graft cut into smaller pieces, ready for placement in ear.

inactive COM and "epidermization," which refers to a severely atelectatic TM resulting in areas of the middle ear becoming lined with squamous epithelium but without retention of keratin.[5] In our experience, the majority of such ears remain free from infection, although they have varying degrees of conductive hearing loss. Surgical extirpation of all squamous epithelia from the middle ear in cases of epidermization is often impossible and places the ear at risk for future problems with cholesteatoma.

We routinely use intraoperative split-thickness skin grafting for tympanoplasty and mastoidectomy to cover unepithelialized areas of the ear canal and mastoid cavity.[3] The skin grafts promote rapid and controlled healing, reduce fibrosis, and improve functional results. The skin graft is harvested at the beginning of the procedure from a hairless area on the medial aspect of the upper arm (Figure 1A) using a dermatome (Davol/Simon dermatome, CR Bard, Covington, GA) (Figure 1B) or a razor blade. The skin is lubricated with sterile mineral oil (Figure 1C) and a strip of split-thickness skin is removed, measuring approximately 3×3 cm. The skin graft is placed with epidermis down on silk cloth (Otosilk, Boston Medical Products,

Westborough, MA) that has been lightly coated with antibiotic ointment, such as bacitracin (Figure 1D). The graft is covered with moist gauze soaked in normal saline until the end of the procedure at which time excess silk is trimmed away (Figure 1D), and the graft is cut into smaller pieces for placement onto recipient sites (Figure 1E). A "rosebud" packing is used to hold the skin tightly against the recipient sites to prevent accumulation of fluid and subsequent fibrosis underneath the grafts.

TECHNIQUES OF TYMPANOPLASTY

Our choice of technique for tympanoplasty in an individual case is based on the pathology encountered in the TM and ossicular chain, and whether there is an associated CWU or CWD mastoidectomy (Figure 2, Table 1). *In ears undergoing a tympanoplasty alone or a tympanoplasty in conjunction with CWU mastoidectomy:*

1. When the ossicles are intact and mobile, the TM perforation is repaired with a temporalis fascia graft using an underlay technique or total drum replacement technique (type I tympanoplasty) (Figure 2A).

2. If the malleus and/or incus are diseased but the stapes is intact and mobile, we use a type III minor columella reconstruction (Figure 2B) between the stapes head and TM/manubrium using either an autograft ossicle strut, autograft cortical bone strut, or partial ossicular replacement prosthesis (PORP).

3. When the stapes superstructure is missing but the footplate is mobile, we perform a type III major columella reconstruction using a total ossicular replacement prosthesis (TORP) between the footplate and the TM/manubrium (Figure 2C).

4. With a fixed stapes, we use a 2-staged procedure. The first stage consists of repair of the TM perforation and elimination of suppuration. The second stage, which is performed only if the ear is stable and free from disease and the tympanic cavity is well aerated, consists of a stapedectomy with a conventional stapes prosthesis or TORP.

In ears where a tympanoplasty is performed in conjunction with a CWD mastoidectomy:

1. If the stapes is intact and mobile, a type III stapes columella reconstruction is performed by placing a thin cartilage disk and a temporalis fascia graft directly onto the stapes head (Figure 2D). In CWD cases, we prefer this type III stapes columella reconstruction even when the malleus and/or incus is present.

2. When the stapes superstructure is missing but the footplate is mobile, we perform either a type IV tympanoplasty using temporalis fascia and thick cartilage to shield the round window (Figure 2E) or a type III major columella reconstruction using a TORP. A type IV reconstruction is preferred when the oval window niche is shallow and wide, while the TORP technique is better suited for a deep and narrow oval window niche.

3. When the footplate is fixed, a second stage type V tympanoplasty is performed, provided the ear is stable and free from suppuration, and the round window is aerated (Figure 2F).

We now present the individual techniques of tympanoplasty along with results obtained on 388 procedures performed by authors SNM and MJM over the past 10 years (Tables 2 and 3). Results are based on cases in which the middle ear was judged to be aerated postoperatively. Aeration is a prerequisite for successful tympanoplasty. Nonaerated ears caused by middle ear fibrosis, graft atelectasis, or tubal dysfunction show large 40 to 60 dB conductive hearing losses, regardless of the type of tympanoplasty.[4,6] Removing the confounding variable of nonaeration in the analysis of postoperative hearing permits a more meaningful comparison of results among different techniques.

TYPE I TYMPANOPLASTY (± CWU MASTOIDECTOMY)

Our preferred graft material is temporalis fascia. For small posterior perforations, we use the *underlay grafting technique*.[3] The edges of the perforation are freshened with a sharp pick, followed by elevation of a tympanomeatal flap. The medial surface of the TM remnant is inspected under high power to look for and remove squamous epithelium that may have migrated through the perforation onto the undersurface of the TM. The ossicles are inspected, and their mobility is confirmed. The fascia graft is trimmed to approximately double the area of the perforation and then placed medial to the TM with pledgets of Gelfoam (Pharmacia and Upjohn, Kalamazoo, MI), filling the middle ear to support the graft on its undersurface.

For anterior perforations, large posterior perforations, and subtotal/total perforations, we use the technique of *total drum replacement* (Figure 3A). The perforation is approached via an endaural or postauricular incision. The entire remnant of the TM is removed, including the annulus (Figure 3B). A wide-field canalplasty is performed using liberal irrigation to avoid overheating the tympanic bone. If the manubrium is retracted medially, then the tensor tympani tendon is sectioned, and the manubrium is gently forced into its normal position using a spatula, while the incus is restrained with a suction tip held in the opposite hand. Should there be an excessive loss of middle ear mucosa, a Schuknecht Teflon crescent (Gyrus ENT, Bartlett, TN) or a piece of thin Silastic sheeting (SF Medical, Hudson, MA) is introduced into the tympanic space. The temporalis fascia graft is trimmed to an appropriate size that will bridge the entire tympanic space and reflect approximately 3 mm onto the walls of the bony canal (Figure 3C). A slit in the graft enables the graft to be placed medial to the manubrium and wrapped around the neck of the malleus (Figure 3D). Gelfoam may be placed in the tympanic space to support the graft. Placing the graft medial to the manubrium prevents the graft from lateralizing during the process of healing.

Split thickness skin grafts are then laid in place to cover the unepithelialized surfaces of the graft and the canal wall (Figure 3D). It is particularly important to use skin grafts in the anterior tympanomeatal angle. The skin and fascia grafts are held in place by a "rosebud" packing (Figure 3E). The rosebud packing consists of overlapping silk strips that are dipped in Cortisporin solution (Burroughs Wellcome, NC) (ie, neomycin, polymixin B, hydrocortisone), followed by pledgets of cotton also soaked in Cortisporin solution that are used to fill the ear canal. The silk strips are then folded over the antibiotic-soaked cotton (Figure 3F). The rosebud packing is left in place for 2 weeks to stent the reconstruction during preliminary healing. It is critical to contour the skin grafts and rosebud packing to recreate a sharp tympanomeatal angle and avoid blunting (Figure 3G). Blunting refers to proliferation of fibrous tissue in the anterior tympanomeatal angle, which will fix the manubrium, resulting in conductive

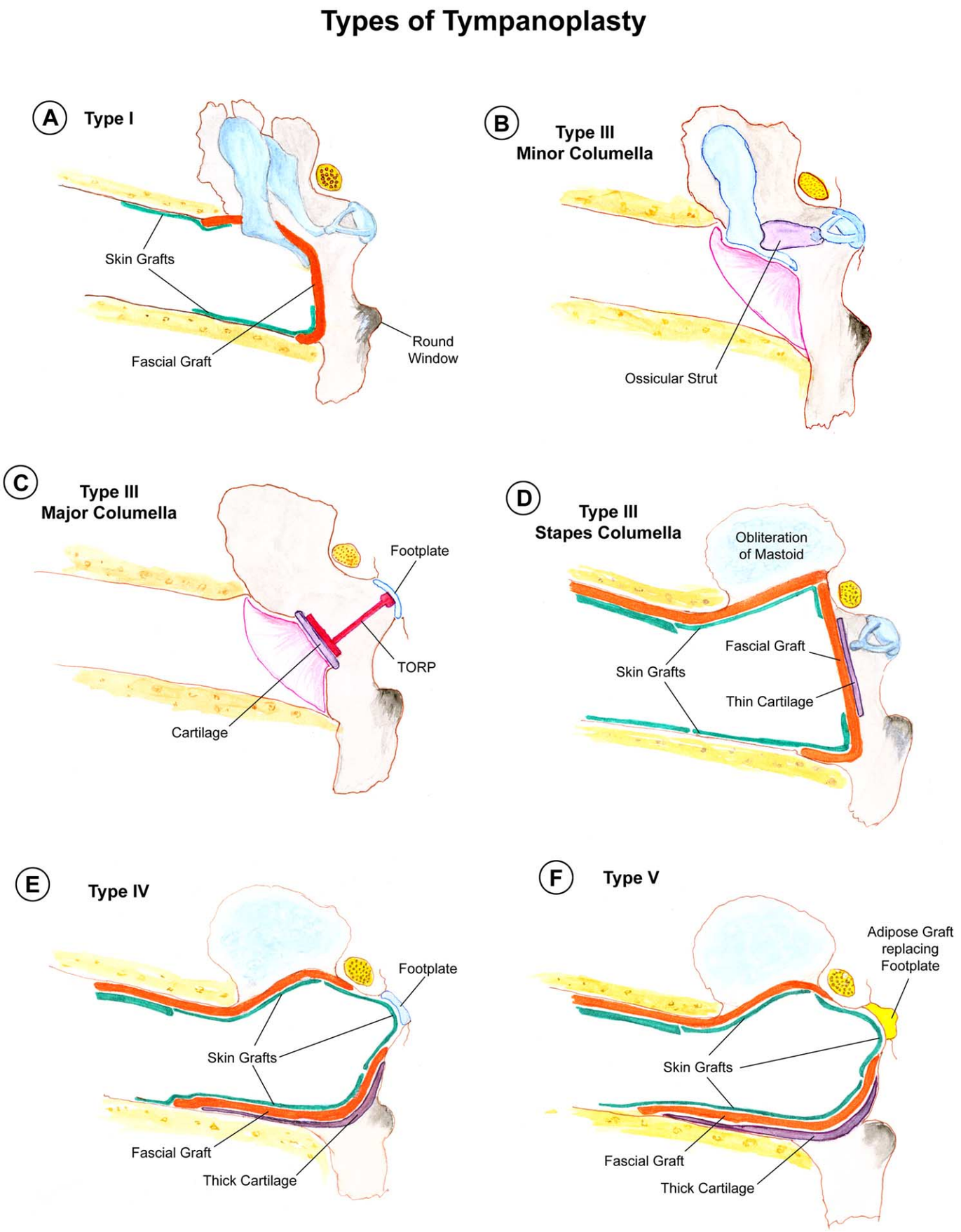

FIGURE 2. Types of tympanoplasty. (A) Type I. Repair of tympanic membrane (TM) with temporalis fascia. (B) Type III: minor columella. Ossicular strut or partial ossicular replacement prosthesis (PORP) is placed between stapes head and manubrium/TM. (C) Type III: major columella. Total ossicular replacement prosthesis (TORP) is placed from stapes footplate to the manubrium/TM. (D) Type III: stapes columella. Performed with canal wall-down (CWD) mastoidectomy and obliteration of mastoid. Thin cartilage disk and temporalis fascia are placed on stapes head. (E) Type IV. Round window is acoustically shielded by thick cartilage and temporalis fascia while footplate is covered with thin skin graft. Also performed with CWD mastoidectomy. (F) Type V. Similar to type IV, except for total stapedectomy and footplate replacement by an adipose graft.

TABLE 1. Tympanoplasty

Type of Tympanoplasty	Middle Ear Pathology	Choice of Grafts
Tympanoplasty ± CWU mastoidectomy:		
Type I	TM perforation, ossicles intact and mobile	Temporalis fascia to repair TM
Type III: minor columella	Malleus or incus diseased, stapes intact and mobile	Graft from stapes head to TM/manubrium: Autograft ossicle or cortical bone strut, or PORP
Type III: major columella	Stapes superstructure missing, footplate mobile	TORP from footplate to TM/manubrium
Tympanoplasty + CWD mastoidectomy:		
Type III: stapes columella	Stapes intact and mobile	Thin cartilage disk + fascia over stapes head
Type III: major columella	Stapes superstructure missing, footplate mobile, OW niche deep and narrow	TORP + thin cartilage + fascia
Type IV	Stapes superstructure missing, footplate mobile, OW niche shallow and wide	Thin skin graft over footplate, thick cartilage + fascia to shield RW
Type V	Fixed stapes footplate	Second stage total stapedectomy with adipose graft and thick cartilage fascia to shield RW

Abbreviations: OW, oval window; PORP, partial ossicular replacement prosthesis; RW, round window; TM, tympanic membrane; TORP, total ossicular replacement prosthesis.

hearing loss (Figure 3H). Blunting is usually the result of a failure to use a skin graft in the angle or the result of loose packing.

RESULTS

We have found the technique of total drum replacement extremely reliable and robust. We regularly use this technique for type I tympanoplasty and in conjunction with simultaneous ossiculoplasty in CWU techniques. It is exceedingly rare for the total drum grafts to fail or perforate, and our success rate is 98%. Of 110 total drum replacement procedures, mean air-bone gap for the 3 frequencies of 500, 1,000, and 2,000 Hz was 10.9 dB. The air-bone gap was closed to within 10 dB in 51% and within 20 db in 96% of these 110 cases. We attribute the good hearing results to the avoidance of blunting and lateralization, both of which are minimized by skin grafts and a well-designed rosebud packing.

TYPE III TYMPANOPLASTY: MINOR COLUMELLA (± CWU MASTOIDECTOMY)

A minor columella is suitable for reconstructing an ear with an intact posterior canal wall and a mobile stapes superstructure (Figure 4). Our preferred reconstructive material is an autologous ossicle, either the body of the incus or the head of the malleus. The ossicular graft is sculpted to suitable dimensions using the operating microscope and small burs along with liberal irrigation with saline to avoid thermal injury. A facet is drilled to accommodate the stapes capitulum, and a groove is created on the opposite side to accept the manubrium (Figure 4A). If the manubrium is missing or too far anterior (regarding the stapes) for a stable assembly, then the strut is brought from the stapes capitulum to the TM (Figure 4B). It is important to make the ossicle strut small enough so that it is not too close to the bony tympanic annulus, promontory, or facial canal, to prevent ankylosis of the strut to these structures.

If autologous ossicles are not available, we will fashion a minor columella from autologous cortical bone or use a PORP. Cortical bone is readily available if the procedure is performed with the endaural or postauricular approach. A small cutting bur is used to fashion a strut from cortical skull bone, again using liberal saline irrigation (Figures 4C and D). After detaching it from the skull, the strut is sculpted in a manner similar to an autologous ossicle. The PORP that we currently use is made of hydroxyapatite or titanium.

RESULTS

Mean air-bone gap for the 3 frequencies (ie, 500, 1,000, and 2,000 Hz) was 15.5 dB in 115 ears with minor columellae. The air-bone gap was closed within 10 dB in 27%, to

TABLE 2. Results of Tympanoplasty in 388 Ears

Type of Tympanoplasty	No. of Cases	No. 0-10 dB (%)	No. 0-20 dB (%)	No. 0-30 dB (%)
Tympanoplasty ± CWU mastoidectomy:				
Type I (total drum replacement)	110	56 (50.9)	105 (95.5)	110 (100.0)
Type III: minor columella				
Autograft ossicle	71	19 (26.8)	63 (88.8)	70 (98.6)
PORP	44	12 (27.3)	31 (70.5)	41 (93.2)
Type III - Major Columella				
TORP	38	7 (18.4)	23 (60.5)	33 (86.8)
Tympanoplasty + CWD mastoidectomy:				
Type III: stapes columella				
Fascia alone	53	5 (9.4)	25 (47.2)	49 (92.5)
Fascia + thin cartilage	17	1 (5.9)	15 (88.2)	17 (100.0)
Type III: major columella				
TORP	27	2 (7.4)	12 (44.4)	20 (74.1)
Type IV				
Fascia alone	13	1 (7.7)	4 (30.8)	10 (76.9)
Fascia and thick cartilage	9	0 (0.0)	6 (66.7)	9 (100.0)
Type V	6	1 (16.7)	3 (50.0)	5 (83.3)

NOTE. Average postoperative air-bone gap at 500, 1,000, and 2,000 Hz. All 388 ears were judged to be aerated postoperatively.

TABLE 3. Results of Tympanoplasty in 388 Ears

		250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	3-Frequency Mean (500, 1,000, 2,000 Hz)	5-Frequency Mean (250-4,000 Hz)
Tympanoplasty ± CWU mastoidectomy:								
Type I (total drum replacement, N = 110)	Mean gap	15.7	11.7	15.1	6.0	17.6	10.9	13.2
	Range	−5-35	−20-30	−5-35	−15-20	−10-35	−3.3-21.7	−3.0-23.0
	SEM	0.0	0.8	0.8	0.7	0.9	0.5	0.5
Type III: minor columella								
Autograft ossicle (*N* = 71)	Mean gap	19.6	14.9	20.1	8.3	22.4	14.6	17.1
	Range	0-75	−10-60	0-40	−10-40	−5-45	0.0-46.7	3.0-52.0
	SEM	1.4	1.2	1.0	1.1	1.4	0.8	0.9
PORP (*N* = 44)	Mean gap	23.4	17.1	21.8	12.3	26.0	17.0	20.0
	Range	0-60	−5-55	0-45	−10-45	5-65	3.3-46.7	5.0-51.0
	SEM	1.8	1.9	1.4	1.7	2.1	1.3	1.3
Type III: major columella, TORP (*N* = 38)	Mean gap	26.5	23.6	25.0	16.1	30.8	21.6	24.4
	Range	−5-60	0-60	0-60	−5-45	10-55	1.7-51.7	5.0-52.0
	SEM	2.8	2.4	2.3	1.9	2.1	2.0	1.9
Tympanoplasty + CWD mastoidectomy:								
Type III: stapes columella								
Fascia graft alone (*N* = 53)	Mean gap	30.5	23.6	27.3	11.6	24.0	20.8	23.3
	Range	−10-50	0-45	0-40	0-30	−5-65	3.3-38.3	3.8-41.0
	SEM	1.6	1.4	1.2	1.2	1.9	1.0	1.0
Fascia and thin cartilage (*N* = 17)	Mean gap	29.4	18.8	22.9	8.5	23.8	16.8	20.7
	Range	10-50	5-30	5-30	−5-20	10-45	6.7-23.3	9.0-26.0
	SEM	2.5	1.7	1.6	1.7	2.3	1.0	1.0
Type III: major columella, TORP (N = 27)	Mean gap	34.4	28.0	29.3	16.3	34.6	24.5	28.3
	Range	5-75	10-65	10-55	−10-45	5-60	8.3-53.3	13.0-59.0
	SEM	3.8	2.7	2.3	2.4	2.6	2.1	1.0
Type IV:								
Fascia alone (*N* = 13)	Mean Gap	25.0	28.5	25.8	15.0	24.6	23.7	24.1
	Range	−10-50	10-40	5-40	0-30	10-40	10.0-40.0	10.0-37.5
	SEM	5.2	2.7	2.9	3.3	2.4	2.5	2.2
Fascia and thick cartilage (*N* = 9)	Mean Gap	33.3	27.8	25.0	10.0	22.8	20.9	22.9
	Range	35-40	15-40	20-30	−5-25	0-35	13.3-30.0	17.5-33.0
	SEM	2.8	2.9	0.8	3.7	3.7	2.1	1.8
Type V (*N* = 6)	Mean Gap	38.3	29.2	22.5	15.8	32.5	22.5	27.7
	Range	30-50	15-45	10-45	0-25	10-55	10-36.7	18.0-42.0
	SEM	3.3	4.7	5.0	3.8	7.2	3.9	3.9

NOTE. Post operative air-bone gaps in dB at various frequencies. All 388 ears were judged to be aerated after surgery. SEM, standard error of the mean.

within 20 dB in 82%, and within 30 dB in 97%. Air-bone gaps with autograft ossicles (71 ears) were 1 to 4 dB smaller than with PORPs (44 ears), and these differences were significant ($P < 0.05$) at 250 and 2,000 Hz. Autologous grafts (ie, incus, malleus, or cortical bone) maintain their morphologic contour, size, shape, and physical integrity for long periods, more than 20 years (Figure 4E).[5,7] They do not incite formation of new bone, and they do not undergo resorption (in the absence of infection). They have an extremely low incidence of extrusion, even in the face of chronic tubal dysfunction and TM atelectasis. The aforementioned features combined with low cost make them our preferred first choice for minor columellar reconstruction.

TYPE III TYMPANOPLASTY: MAJOR COLUMELLA (± CWU MASTOIDECTOMY)

A major columella is interposed between the stapes footplate and the TM or manubrium in cases in which the stapes crura are missing, and the footplate is intact and mobile (Figure 2C). In our experience, it is difficult to fashion a major columella from autologous ossicles or cortical bone so that it can be placed into the oval window niche with precision. Furthermore, an ossicular or cortical bone strut has a risk of delayed ankylosis of the strut to the fallopian canal or promontory. For these reasons, we prefer to use a synthetic material (ie, TORP) as a major columella. In ears where the manubrium is anatomically favorable regarding the stapes, we prefer to use a hydroxyapatite TORP (Wehr design, Gyrus ENT) placed between the center of the footplate and the manubrium. When the manubrium is absent or in an anatomically unfavorable position, we prefer to use a titanium TORP (Kurz, Germany) from the center of the footplate to the TM (Figure 2C). A thin slice of cartilage is placed between the TORP and the TM to decrease the chance of extrusion. If necessary, Gelfoam is placed around the TORP for stabilization. In general, we prefer titanium TORPs because (1) they are lighter, and the center of gravity is closer to the medial (lower) end (versus TORPs made of other materials), making them less likely to topple over; and (2) one can visualize the medial end of the TORP during its positioning because the lateral end is a ring of titanium rather than an opaque platform.

RESULTS

Of 38 procedures, the 3-frequency air-bone gap was closed to within 10 dB in 18%, within 20 dB in 61%, and within 30

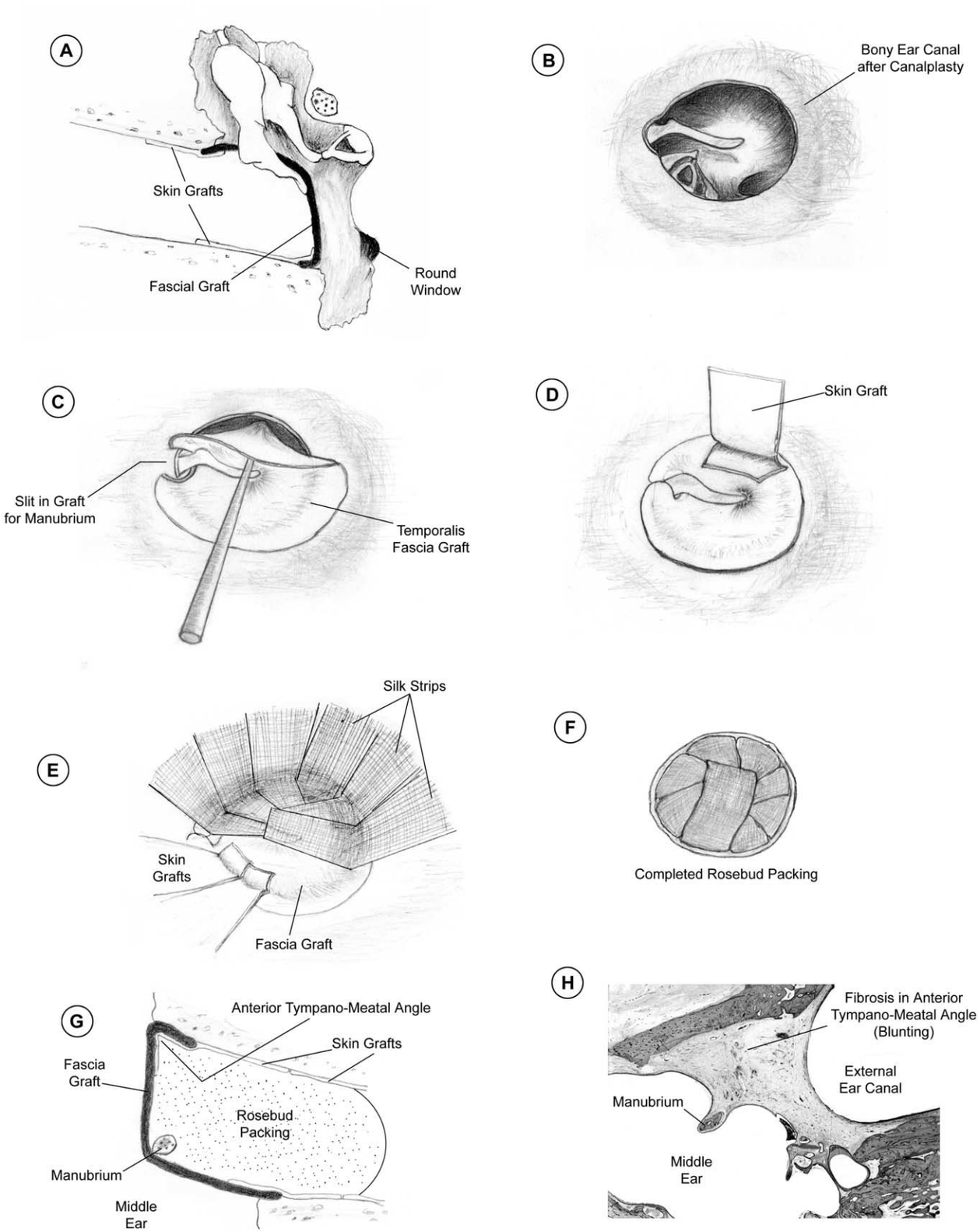

FIGURE 3. Technique of type I tympanoplasty: total drum replacement. (A) Total drum replacement. (B) All remnants of the tympanic membrane (TM), including annulus, have been removed. Skin of bony ear canal has been excised and a canalplasty performed. (C) Graft of temporalis fascia is placed medial to the manubrium. Slit in graft enables graft to be draped around neck of malleus. Note that graft extends onto bony canal wall for only 2 to 3 mm. (D) Skin graft placed to cover unepithelialized surfaces of canal wall and part of fascia graft. (E) Rosebud packing is used to hold fascia and skin grafts in place. Overlapping strips of silk dipped in Cortisporin solution are placed, followed by pledgets of cotton also soaked in Cortisporin. (F) Silk strips are folded over antibiotic-soaked cotton. Rosebud packing is left in place for 2 weeks. (G) How skin grafts and rosebud packing are contoured to recreate the normal tympanomeatal angle. The packing and skin grafts are critical to prevent blunting. (H) Histopathologic section illustrating fibrous proliferation within the anterior tympanomeatal angle (blunting) after failed tympanoplasty for a central perforation. Reduced from $\times$4.7.

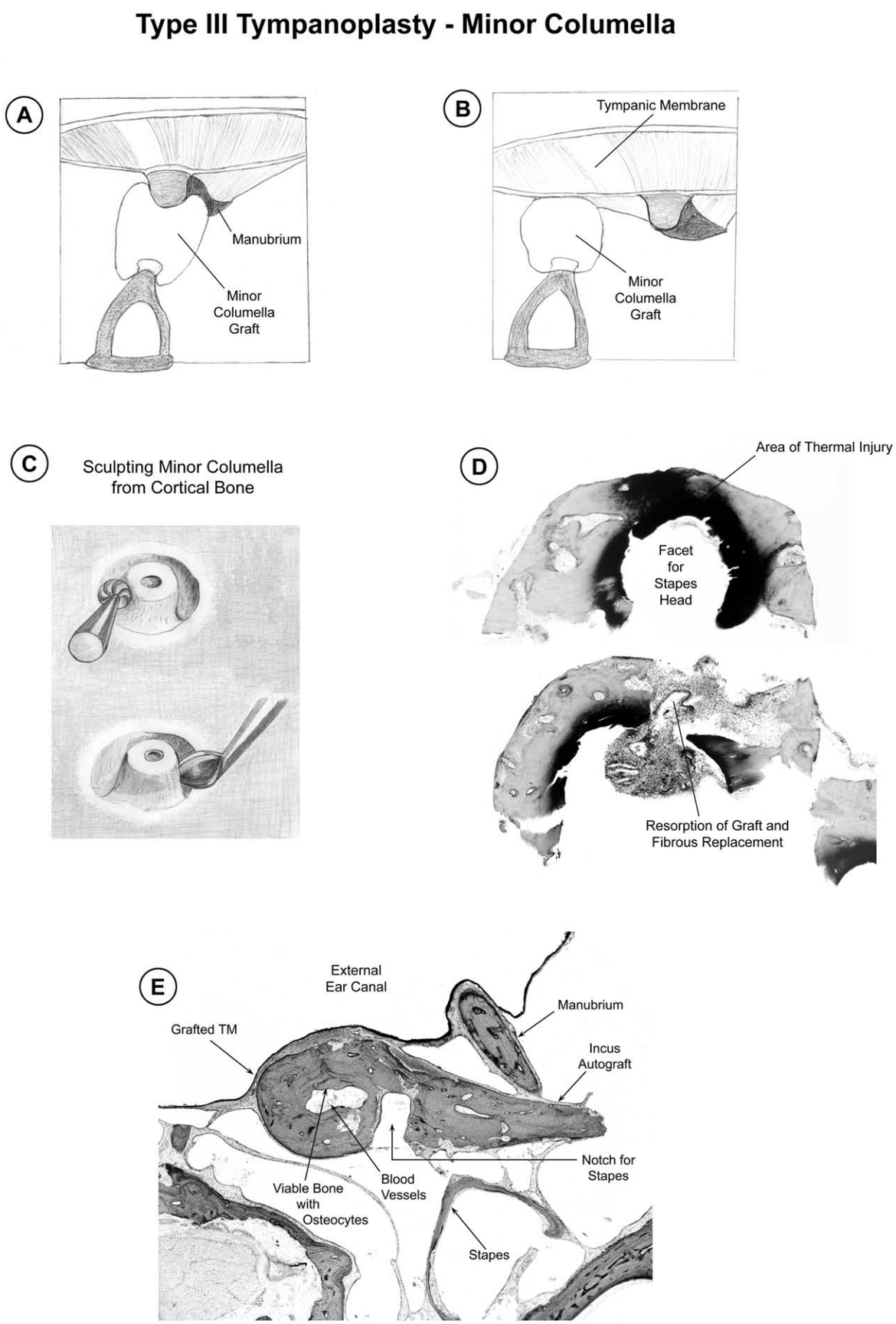

FIGURE 4. Type III tympanoplasty: minor columella. (A) Minor columellar graft placed between stapes head and manubrium. The graft is sculpted to fit snugly and be in a stable position. (B) When manubrium is missing or too far anterior in relation to stapes, then the graft is brought from stapes head to tympanic membrane (TM). (C) Fashioning minor columella from cortical bone. Liberal irrigation with saline is important to avoid thermal injury while drilling. (D) Effects of heat trauma. Histologic section of incus that was sculpted as a graft between stapes head and TM. Top figure shows intense, dark staining secondary to thermal injury. Bottom figure is an adjacent section where the injured bone has been resorbed and replaced by fibrous tissue. Reduced from ×30. (E) Temporal bone section showing successful incus autograft placed 28 years before death. The graft has retained its size and shape. It is enveloped by a layer of mucosa, and blood vessels have penetrated its core. Some areas of graft show the replacement of nonviable bone by deposition of new bone. Reduced from ×13.

dB in 87%. Mean air-bone gap for the 3 frequencies was 21.6 dB. There were insufficient numbers of procedures with titanium TORPs to test for differences in results between hydroxyapatite and titanium TORPs.

TYPE III TYMPANOPLASTY: STAPES COLUMELLA (IN CONJUNCTION WITH CWD MASTOIDECTOMY)

We use the type III stapes columella reconstruction whenever we perform a CWD mastoidectomy, and the stapes is intact and mobile (Figure 5A). A complete CWD mastoidectomy with meatoplasty and canalplasty is performed with a postauricular approach, with thorough exenteration of all mastoid air cells along with lowering of the facial ridge to the level of the facial nerve (Figure 5B). Bone dust (pate), collected from uninfected lateral cortical bone with a Sheehy pate collector (OtoMed, Lake Havasu City, AZ), is used to obliterate the mastoid cavity (Figure 5C). The pate is completely covered by an inferiorly based periosteal-pericranial flap (Figure 5D). A temporalis fascia graft is used to bridge the middle-ear air space. The graft is placed in contact with the stapes capitulum, and then draped over the facial canal and facial ridge (Figure 5E). In recent years, we have interposed a thin disk (0.3 to 0.5 mm thickness and 6 mm in diameter) of meatal or tragal cartilage between the fascia graft and the stapes head (Figure 5D), which serves to increase the effective, vibrating surface area of the TM graft that is coupled to the stapes head, with improved postoperative hearing results.[8] Split-thickness skin grafts are used to cover unepithelialized surfaces of the canal wall, mastoid cavity, and parts of the fascia graft and periosteal flap (Figure 5F). The grafts are held in place by rosebud packing, which is removed 2 weeks postoperatively, and the patient is maintained on antibiotic-steroid drops, such as Cortisporin solution, until healing is complete.

As alluded to earlier, when we perform a CWD procedure and the stapes is intact and mobile, we prefer to remove remnants of the TM, malleus, and incus, and proceed with placing the cartilage-fascia graft directly on the stapes head. When we had opted to retain the ossicles or place a strut between the stapes head and manubrium, some ears showed atelectasis or retraction of the TM graft around the ossicles, with retention of debris and formation of granulation tissue. Such problems caused by TM retraction are minimized with the cartilage-fascia technique.

RESULTS

In 53 ears with only a fascia graft, the 3-frequency air-bone gap was closed to within 10 dB in 9%, within 20 dB in 47%, and within 30 dB in 93%, while mean gap for these same 3 frequencies was 20.8 dB. Interposing a thin disk of cartilage between the fascia graft and stapes head (17 ears) improved hearing results by ~4 to 5 dB, with a mean 3-frequency gap of 16.8 dB, and with closure of the gap to within 10 dB in 6%, within 20 dB in 88%, and within 30 dB in 100%. The improvement observed in the cartilage-fascia group over the fascia-alone group was significant ($P < 0.05$) for 500 Hz, 1,000 Hz, the 3-frequency average and the 5-frequency average, respectively. The improvement was consistent with what was observed experimentally using a cadaveric temporal bone preparation of the type III procedure, and we believe that the cartilage disk increased the effective vibrating area of the TM graft that was coupled to the stapes head.[9] Although not directly germane to the present discussion, we have been very satisfied with the control of disease and infection afforded by the technique of tympanomastoidectomy, described previously. More than 90% of ears have a small, dry, trouble-free mastoid cavity.[10] The incidence of residual cholesteatoma is 5%.

TYPE III TYMPANOPLASTY: MAJOR COLUMELLA WITH TORP (IN CONJUNCTION WITH CWD MASTOIDECTOMY)

We have used TORP reconstruction in conjunction with CWD mastoidectomy when the stapes superstructure is missing, but the footplate is mobile. The TORP reconstruction is an alternative to type IV tympanoplasty, and is especially suitable when the oval window niche is deep and narrow. The procedure is similar to the type III stapes columella technique except that a TORP (either hydroxyapatite or titanium) is placed between the footplate and TM graft. A thin slice of cartilage is introduced between the TORP and the fascia graft. It is important to shorten the length of the TORP so that its lateral extent is at about the level of the facial canal. A longer TORP results in tenting of the TM by the TORP, with an increased potential for extrusion.

RESULTS

Of 27 ears, the air-bone gap was closed to within 10 dB in 7%, within 20 dB in 44%, and within 30 dB in 74%, with the mean 3-frequency gap being 24.5 dB. The results were comparable to type IV procedures (no significant differences except at 4,000 Hz where type IV was superior, $P = 0.01$) but were inferior to results after type III stapes columellae at 500, 2,000, and 4,000 Hz ($P < 0.05$), as well as the 3-frequency and 5-frequency average ($P < 0.01$).

TYPE IV TYMPANOPLASTY (WITH CWD MASTOIDECTOMY)

We perform the type IV procedure when there is a CWD mastoidectomy, the stapes superstructure is missing, the footplate is mobile, and the oval window niche is shallow. A deep or narrow oval window niche makes it problematic for skin grafts to adhere to the footplate, in which case we prefer a TORP. The principles of a type IV are to exteriorize the footplate and cover it with a very thin split thickness skin graft, acoustically separate the oval window from the round window, and to shield the round window with a sufficiently stiff tissue graft (Figure 6A).[4,6] The initial part of the procedure consists of a CWD mastoidectomy, and obliteration of the mastoid with bone pate and a periosteal-pericranial flap, similar to the type III stapes columella reconstruction. Following this procedure, mucosa around the oval window niche is removed, and bone is exposed to allow the tissue graft, which will shield the round window, to adhere to the margins of the oval window niche (Figure 6B).

A small piece of fascia is rolled up and placed in the sinus tympani between the 2 windows to help in acoustically isolating the round window from the oval window (Figure 6B). The round window and hypotympanum are then covered by a crescent-shaped piece of tragal or meatal cartilage (at least 1 mm in thickness), or a piece of thick Silastic sheeting (1 mm thickness) (Figure 6C). The perichondrium is elevated from one surface of the cartilage and reflected onto the canal wall as a hinged flap that helps to stabilize the cartilage. A large piece of temporalis

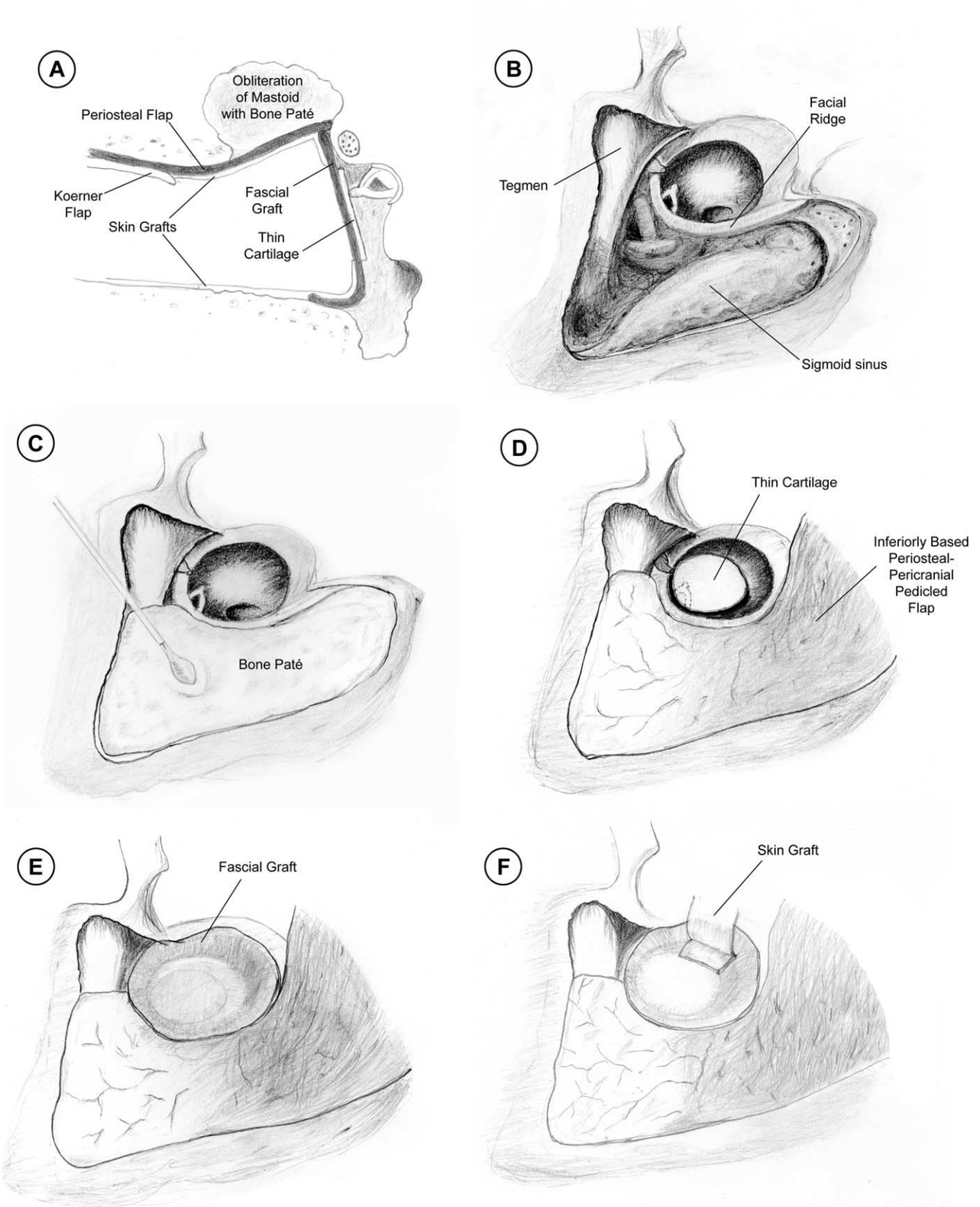

FIGURE 5. Type III tympanoplasty: stapes columella. (A) Placement of thin disk of cartilage plus fascia onto stapes head. The procedure is performed in conjunction with canal wall-down (CWD) mastoidectomy, and obliteration of the mastoid with bone pate and an inferiorly based periosteal flap. (B) CWD mastoidectomy has been completed, with the removal of all disease from middle ear and mastoid. (C) Bone pate is used to obliterate mastoid cavity. Pate is contoured into mastoid tip, sinodural angle, antrum, and area superior and posterior to lateral semicircular canal. (D) Bone pate is covered fully by inferiorly based, periosteal-pericranial pedicled flap. Thin disk of cartilage (0.3 to 0.5 mm in thickness and 6 mm in diameter) is placed onto stapes head. (E) Large graft of temporalis fascia is used to bridge middle ear and placed lateral to cartilage disk. (F) Split-thickness skin grafts are used to cover unepithelialized surfaces of canal wall, mastoid cavity and parts of fascia graft. Grafts are held in place by rosebud packing.

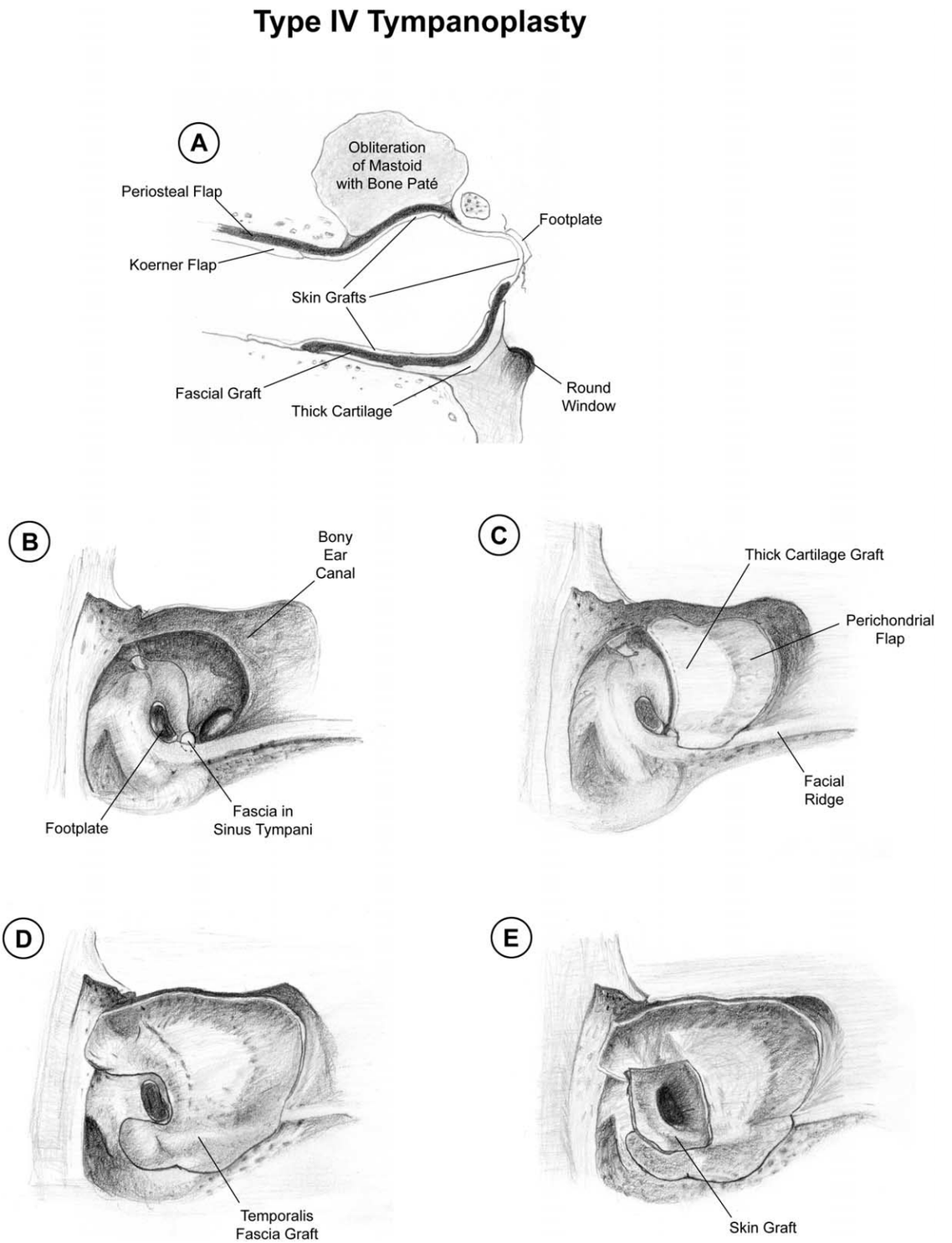

FIGURE 6. Type IV tympanoplasty. (A) Type IV tympanoplasty. Stapes footplate is covered with a very thin skin graft, while round window (RW) is acoustically shielded by graft of thick cartilage and temporalis fascia. Procedure is performed in conjunction with canal wall-down (CWD) mastoidectomy, with obliteration of mastoid by bone pate and inferiorly based periosteal flap. (B) Mucosa over stapes footplate and surrounding oval window (OW) niche is removed, so that bone is exposed to allow fascial graft to adhere to margins of OW niche. Mucosa is preserved in protympanum, hypotympanum, and RW niche. Small piece of fascia is rolled up and placed in sinus tympani between the 2 windows to help in acoustically isolating RW from OW. (C) Hypotympanum and RW are covered by a crescent-shaped piece of cartilage, 1 mm in thickness. Perichondrium from one surface of cartilage graft is elevated and reflected onto canal wall to help in stabilizing cartilage. (D) Large piece of temporalis fascia is placed superficial to cartilage graft with U-shaped opening made in fascia to keep OW exposed. (E) Footplate is covered with very thin split-thickness skin graft that is invaginated into OW niche. Skin graft is made to overlap fascia graft anteriorly and inferiorly.

fascia is then placed superficial to the cartilage graft, and a U-shaped aperture is cut in the fascia to keep the oval window niche exposed (Figure 6D). The footplate is covered with a very thin, split-thickness skin graft that is invaginated into the oval window niche (Figure 6E). The skin graft overlaps the fascia graft anteriorly and inferiorly. The skin is maintained in proper position by a small cotton plug soaked in antibiotic, such as bacitracin ointment. The cotton plug remains in place for at least 3 weeks under the rosebud packing. The skin graft over the footplate should be very thin, which helps to ensure that the footplate remains mobile. Covering the footplate with a fascia graft instead of a skin graft carries the risk of healing by fibrosis, resulting in the impairment of mobility of the footplate.

RESULTS

Of 13 procedures performed with only a fascia graft to shield the round window, the mean 3-frequency air-bone gap was 23.7 dB, with 8% showing closure to within 10 dB, 31% within 20 dB, and 77% to within 30 dB. The mean 3-frequency gap in 9 ears with a cartilage-fascia shield was 20.9 dB, with 67% showing closure of the gap to within 20 dB, and all 9 to within 30 dB. Previous theoretical and experimental analyses had indicated that stiffer shields, such as cartilage-fascia, would provide better hearing.[6] Although the results with the cartilage-fascia shield appear better than the fascia-alone group, the differences were not statistically significant. Also, the type IV results were similar to results after CWD type III TORP, except at 4,000 Hz, where type IV was superior ($P = 0.01$).

TYPE V TYMPANOPLASTY (WITH CWD MASTOIDECTOMY)

If the footplate is fixed during a CWD procedure, a type V tympanoplasty can be contemplated as a second stage procedure (Figure 2F). In anticipation of this later staged procedure, the oval window niche is filled with an adipose tissue plug, and the remainder of the procedure is performed as in the case of a type IV tympanomastoidectomy, including the use of a cartilage-fascia graft to shield the round window and a split thickness skin graft to cover the fat in the oval window niche. We contemplate a second stage type V procedure if (1) there is a clean and dry tympanomastoid cavity with no infection or recurrent disease; and (2) the hypotympanum and round window niche become aerated, which can be confirmed, if necessary, by CT. The type V procedure is performed with a transmeatal approach. A small flap is elevated to expose the footplate. A stapedectomy is performed to remove the fixed footplate, the oval window is covered with the previously placed adipose graft (or with a new adipose graft harvested from the ear lobe), and the overlying flap is thinned or replaced with a split thickness skin graft to cover the adipose tissue.

RESULTS

Only a few ears meet the conditions for a type V procedure. The mean 3-frequency air-bone gap was 22.5 dB in our series of 6 ears. The hearing results were similar to type IV procedures, except at 250 Hz, where type IV was superior ($P < 0.03$).

RESULTS OF TYMPANOPLASTY AND DISCUSSION

We conducted a retrospective review of 950 tympanoplasty procedures performed by authors MJM or SNM over the last 10 years. All of the following criteria had to be met for inclusion: (1) the ear was healed and dry with an intact graft, (2) the ossicles were mobile at surgery, (3) the middle ear had become aerated after surgery, and (4) postoperative audiogram was available. An ear was considered "aerated" if the graft moved on pneumatic otoscopy or on autoinflation, or if a postoperative CT or tympanometry showed an aerated middle ear space. An ear was considered "nonaerated" if the fascia graft was atelectatic, and without motion on pneumatic otoscopy and autoinflation, or when a postoperative CT showed soft tissue filling the middle ear space. In many cases, the status of aeration could not be determined ("unknown" aeration), and these cases were also excluded. Only 388 ears met the inclusion criteria and are presented (Tables 2 and 3). The majority of exclusions were due to unknown aeration status. Because nonaerated ears result in a 40 to 60 dB air-bone gap regardless of the tympanoplasty reconstruction, restricting our analysis to ears that were judged as being aerated allows for a more meaningful comparison among different types of tympanoplasty.

The ages of the 388 ears at surgery ranged from 5 to 78 years, with a mean of 36.3. Mean time interval from surgery to postoperative audiogram was 11 months. In each ear, postoperative air-bone gaps were calculated using postoperative air conduction, and postoperative bone conduction thresholds at frequencies 250, 500, 1,000, 2,000, and 4,000 Hz. The average 3 frequency (ie, 500, 1,000, 2,000 Hz) and 5-frequency (250 to 4,000 Hz) air-bone gaps were also calculated. Results among various subgroups were compared using the Student *t*-test.

INFLUENCE OF STATUS OF THE OSSICULAR CHAIN

The best hearing results occurred when the ossicular chain was intact and mobile, a fact that has been noted in many previous studies.[3,11,12] Results after total drum replacement in our series were clearly better than all other types of reconstructions, being superior to minor columellae by approximately 5 dB ($P < 0.003$ at all frequencies) and by approximately 10 dB compared with major columellae ($P < 0.001$ at all frequencies). When the ossicular chain was diseased, the presence of an intact stapes superstructure was a positive prognostic indicator. For example, in CWU ears, results using minor columellae were approximately 5 dB better than with major columellar reconstructions ($P < 0.05$ at all frequencies). In CWD ears, stapes columella reconstructions were superior to major columella TORP reconstructions by approximately 5 dB ($P < 0.05$ at most frequencies). Other studies have also shown better results when the stapes superstructure is intact.[11-14]

EFFECT OF CANAL WALL-DOWN (CWD) MASTOIDECTOMY ON HEARING RESULTS

We found no significant differences in hearing results whether the canal wall was intact or not. We compared hearing results between ears in the canal wall-up (CWU) and CWD groups for comparable ossicular pathology: (1) there were no significant differences at any frequency between CWU-TORP and CWD-TORP; (2) there were no significant differences between CWU-TORP and CWD

type IV reconstructions, except at 4,000 Hz, where type IV was superior ($P = 0.01$); and (3) there were no significant differences between CWU type III minor columellae and CWD type III stapes columellae using fascia and thin cartilage, except at 250 Hz, where CWU minor columella was superior ($P < 0.03$). The comparable results between CWU and CWD procedures, which has also been reported by other otologic surgeons,[14-17] is consistent with predictions we made using theoretical models[18] and with measurements made in experiments using cadaveric temporal bones by our group[19] and by others.[20]

FACTORS RESPONSIBLE FOR PERSISTENT CONDUCTIVE HEARING LOSS AFTER TYMPANOPLASTY

It is noteworthy that there was a large range of air-bone gaps (0 to 60 dB) in our series, even though all ears were aerated. The only exceptions were the type I tympanoplasties, where the gaps were ≤35 dB. Our clinical observations have suggested multiple factors that can account for the observed postoperative air-bone gaps, including problems with mechanics of the TM (eg, blunting), problems with mechanics of ossicle grafts, and negative static pressure in the middle ear. Some of these factors were due to faulty surgical technique, while many were the result of unwanted healing responses of the ear (eg, fibrosis) or the result of continued biological abnormalities caused by chronic ear disease. An improved understanding of these factors would provide fruitful avenues for future research.

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