Postoperative Imaging of the Temporal Bone

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The anatomy of the temporal bone is complex, and postoperative imaging evaluation of this bone can be challenging. Surgical approaches to the temporal bone can be categorized didactically into tympanoplasty and ossicular reconstruction, mastoidectomy, and approaches to the cerebellopontine angle and internal auditory canal (IAC). In clinical practice, different approaches can be combined for greater surgical exposure. Postoperative imaging may be required for follow-up of neoplastic lesions and to evaluate unexpected outcomes or complications of surgery. CT is the preferred modality for assessing the continuity of the reconstructed conductive mechanism, from the tympanic membrane to the oval window, with use of grafts or prostheses. It is also used to evaluate aeration of the tympanic and mastoid surgical cavities, as well as the integrity of the labyrinth, ossicular chain, and tegmen. MRI is excellent for evaluation of soft tissue. Use of a contrast-enhanced fat-suppressed MRI sequence is optimal for follow-up after IAC procedures. Non–echo-planar diffusion-weighted imaging is optimal for detection of residual or recurrent cholesteatoma. The expected imaging findings and complications of the most commonly performed surgeries involving the temporal bone are summarized in this review.

Online supplemental material is available for this article.

Abbreviations: CPA = cerebellopontine angle, CSF = cerebrospinal fluid, CWD = canal wall down, CWU = canal wall up, EAC = external auditory canal, IAC = internal auditory canal, OCR = ossicular chain reconstruction, PORP = partial ossicular replacement prosthesis, TORP = total ossicular replacement prosthesis

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- List the most commonly performed temporal bone surgical procedures.
- Describe the expected findings and possible complications seen at postoperative imaging.
- Discuss the role of CT and MRI for postoperative assessment of the temporal bone.

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Introduction

Postoperative imaging evaluation of the temporal bone may be challenging owing to the anatomic complexity of this structure (1) and the variety of procedures that may be performed. The already intricate temporal bone anatomy can be distorted by the combination of surgery and preexisting abnormalities. For accurate interpretation of postoperative imaging studies, it is necessary to understand the surgical procedures that involve the tympanic membrane, middle ear, mastoid, internal auditory canal (IAC), and cerebellopontine angle (CPA).

Tympanoplasty and ossicular chain reconstruction (OCR) may be performed when conductive hearing loss occurs owing to alterations in the tympanic membrane and/or ossicular chain (2,3). These procedures may be performed to establish an effective pathway for conduction of sound in patients with congenital middle ear abnormalities (4), restore ossicular continuity in cases of chronic otitis media or cholesteatoma, or re-establish ossicular mobility in cases of stapes footplate fixation due to otosclerosis (5).

Mastoidectomies are widely used for surgical treatment of chronic otitis media and cholesteatoma and provide surgical access for cochlear implantation, endolymphatic sac surgery, facial nerve decompression surgery, and other indications. Concomitant tympanoplasty and/or OCR—that is, tympanomastoidectomy—may be performed for treatment of chronic otitis media (2,6).

TEACHING POINTS

- Imaging is generally requested after OCR in cases of new or recurrent hearing loss. In these cases, an abnormal audiogram should prompt the radiologist to scrutinize the reconstructed ossicular chain. However, if the audiogram is normal or similar to the postoperative baseline audiogram, then suspicion for complication is low. CT is the best choice for the initial imaging evaluation and can be used to assess the position of the prosthesis, the progression of underlying disease (eg, otosclerosis, chronic otitis media), and other causes of hearing loss that were previously undetected or are related to surgical manipulation.
- Imaging is performed in the postoperative setting to assess for possible complications and recurrent or residual disease. The surgical cavity is expected to be well aerated. However, imaging performed too early may show recent postoperative changes such as variable opacification and fluid levels. Flat soft-tissue material around the mastoid bowl can be seen and is usually related to scar or granulation tissue.
- The presence of lobulated material in the mastoid bowl should raise suspicion for cholesteatoma, cholesterol granuloma, or granulation tissue as a differential diagnosis. CT has high predictive value for ruling out disease when it depicts a clear cavity. However, CT findings are nonspecific, and MRI is the modality of choice for narrowing the diagnosis.
- The retrosigmoid and middle cranial fossa approaches allow the possibility of preserving the patient's hearing at the cost of limited access to the IAC fundus and CPA, respectively. The translabyrinthine approach provides good access to the entire IAC and CPA but at the cost of hearing loss.
- Linear enhancement along the surgical site, particularly the IAC, can be a normal finding in the first 2 years after surgery and is related to inflammatory changes. However, nodular or masslike enhancement or an increase in enhancement between examinations should raise suspicion for residual or recurrent tumor, which requires close follow-up. Inflammatory enhancement in the IAC can appear to be nodular occasionally, but it resolves over time.

Three major approaches generally are used to resect lesions of the IAC and CPA: the middle cranial fossa, translabyrinthine, and retrosigmoid approaches (3). These techniques may be performed in conjunction with mastoidectomy to promote greater exposure of the surgical site. The chosen technique depends on the surgeon's expertise, the patient's hearing status, the characteristics of the tumor (eg, size, location, IAC involvement), and other factors (7).

After a surgical procedure involving the temporal bone has been performed, imaging may be required to monitor for tumor recurrence or evaluate unexpected outcomes and complications. Familiarity with the postoperative radiologic appearances is essential, enabling the radiologist to have an important role in analyzing the surgical results and thereby assist the referring physician with decision making (Table 1) (2,5,6).

In this review, we discuss postoperative changes of the temporal bone with use of numerous examples and describe the more commonly performed otologic and neuro-otologic surgeries, with emphasis on the radiologic features and potential complications of these procedures.

Imaging of the Temporal Bone

Images of the temporal bone are obtained by using CT or MRI. CT should be performed with thin (0.5-mm) sections and a small field of view. Use of intravenous contrast material is usually not indicated, except in cases of a suspected vascular lesion, thrombosis, or abscess. Use of a bone algorithm is optimal for evaluation of osseous structures, particularly to assess the ossicular chain and search for bone erosion (8). Multiplanar reconstruction of CT images enables better depiction of the anatomy of the temporal bone and postoperative changes. Sagittal oblique planes parallel (Pöschl) or perpendicular (Stenvers) to the superior semicircular canals are useful for visualizing the long axes of the malleus and incus. Furthermore, the Pöschl projection provides an excellent view of the incudostapedial joint (9).

MRI is better for evaluation of soft tissue, nerves, and fluid-filled compartments than CT (8). Therefore, it is the technique of choice for expansile tumoral lesions, enabling differentiation of these lesions from fluid and assessment of invasion of adjacent structures. The protocol for temporal bone imaging can be tailored according to the clinical setting. In the context of imaging the temporal bone postoperatively, the following protocol is applied at our institution (Table E1): axial T1- and T2-weighted MRI sequences, a fluid-sensitive volumetric sequence for evaluation of the nerves and labyrinth (eg, fast imaging employing steady-state acquisition, SPACE [sampling perfection with application-optimized contrasts using different flip angle evolution]), a three-dimensional fluid-attenuated inversion-recovery sequence, a contrast-enhanced T1-weighted sequence with fat saturation (optional for evaluation of cholesteatoma), and non–echo-planar diffusion-weighted imaging.

The contrast-enhanced MRI sequence is performed with fat saturation to enable differentiation of a fat graft and fatty bone marrow from enhancement and blood products and is particularly useful in IAC approaches. Three-dimensional contrast-enhanced MR image acquisition can be helpful for evaluating a recurrent or persistent tumor after IAC surgery. A structured report template for postoperative MRI of the IAC is available at *https://www.radreport.org/home/RPT50843*.

Compared with echo-planar sequences, non–echo-planar diffusion-weighted imaging provides higher spatial resolution, enables thinner sections to be obtained, and leads to fewer susceptibility

Table 1: Key Imaging Findings at Postoperative Assessment of the Temporal Bone

Surgical Approach	Key Imaging Findings
Incus interposition	Remodeled incus interposed between manubrium of the malleus and head of the stapes
Stapedectomy and/or stapedotomy and stapes prosthesis	Stapes prosthesis articulates laterally with the long process or lenticular process of the incus and medially with the oval window
PORP	Prosthesis extends from the tympanic membrane, manubrium of the malleus, or long process of the incus to the stapes head
TORP	Prosthesis extends from the tympanic membrane to the stapes footplate
CWU mastoidectomy	Resection of mastoid cortex and air cells; EAC wall is preserved
CWD mastoidectomy	Resection of mastoid cortex and air cells; removal of posterosuperior wall of the EAC
Middle cranial fossa	Temporal craniotomy; resection of superior wall of the IAC*
Translabyrinthine	Mastoidectomy and resection of vestibule, semicircular canals, and posterior wall of IAC
Retrosigmoid	Retrosigmoid craniotomy and resection of posteromedial wall of the IAC

Note.—CWD = canal wall down, CWU = canal wall up, EAC = external auditory canal, PORP = partial ossicular replacement prosthesis, TORP = total ossicular replacement prosthesis.
*Performed in IAC approaches.

artifacts. Non–echo-planar diffusion-weighted imaging also enables accurate detection of residual cholesteatoma after surgery and may enable unnecessary second-look surgery to be avoided (1,10). There are several non–echo-planar diffusion-weighted imaging techniques (eg, half-Fourier single-shot turbo spin echo, periodically rotated overlapping parallel lines with enhanced reconstruction [PROPELLER]). Of these, the most commonly used is the half-Fourier single-shot turbo spin-echo technique, which allows acquisition in the coronal plane and has the advantage of enabling more precise localization of lesions in the epitympanum. Although the PROPELLER technique can be performed only in the axial plane (11), in our opinion use of axial non–echo-planar diffusion-weighted imaging in addition to the remaining sequences of the protocol is sufficient for evaluation of cholesteatoma.

Temporal Bone Surgery Techniques

Tympanoplasty and OCR

Tympanoplasty and OCR are performed with the intent of restoring the conductive sound mechanism (3). Although these surgeries are frequently performed together, for didactic reasons, we define *tympanoplasty* as tympanic membrane repair performed with or without bypass surgery for eroded ossicles and with no attempt to reconstruct them, and OCR as the interposition of grafts or prostheses to restore or replace the ossicular chain.

Tympanoplasty.—Tympanoplasty is a surgical procedure that involves the tympanic membrane and possibly the ossicular chain and is performed to restore the conductive hearing apparatus. In 1956, Wullstein (12) proposed an initial classification of tympanoplasty types according to the degree of ossicular bypass, with many modifications proposed in the years that followed (13).

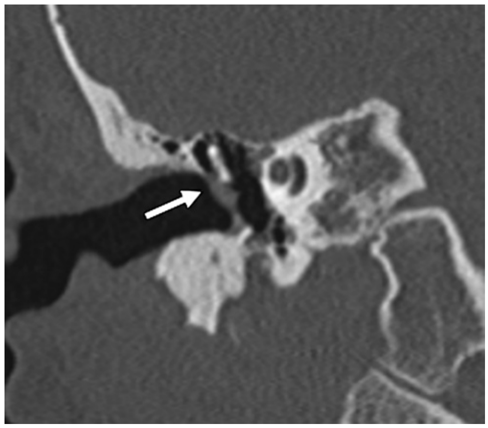
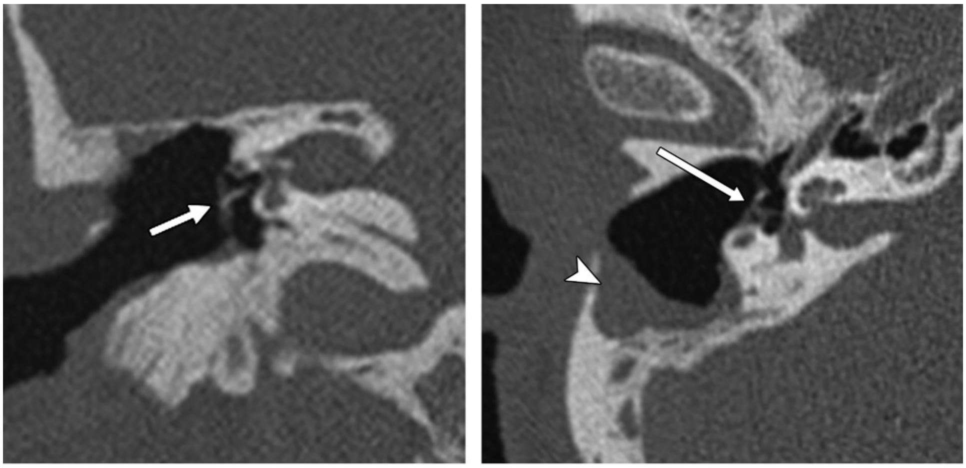


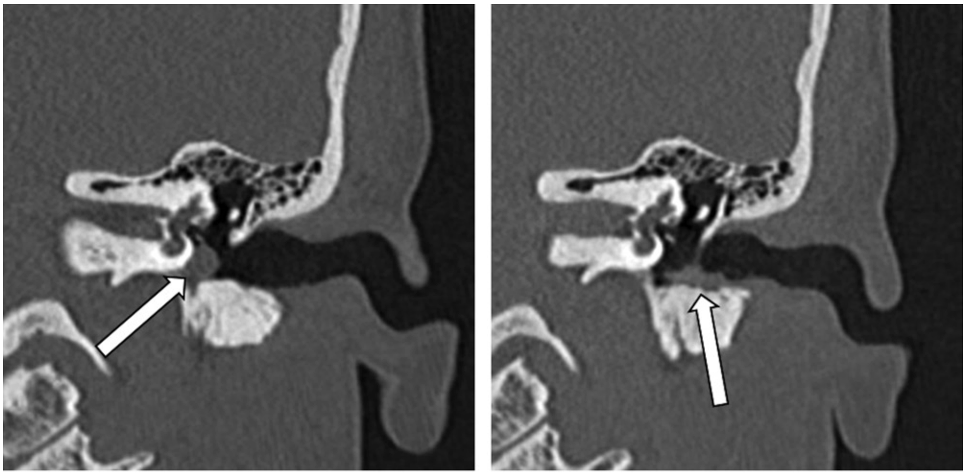
Figure 1. Type 1 tympanoplasty (myringoplasty). Coronal CT image shows expected thickening of the right tympanic membrane (arrow) after repair of its upper portion.

The Wullstein classification is as follows: Type 1 tympanoplasty, referred to as myringoplasty, involves repair of a perforated tympanic membrane, which appears thickened at imaging after the repair (Fig 1) owing to use of different graft types. These grafts are commonly made from temporalis fascia or auricular cartilage. The ossicular chain is intact. Type 2 tympanoplasty is performed in cases with erosion of the malleus. The tympanic membrane is attached to the incus or residual malleus. Type 3 tympanoplasty is performed in cases with extensive erosion of the malleus and incus. The tympanic membrane is attached to the head of the stapes (myringostapediopexy) (Fig 2). Variations of type 3 tym-



a. b.

Figure 2. Tympanomastoidectomy with canal wall down (CWD) modified radical mastoidectomy and tympanoplasty type 3 (myringostapediopexy). Coronal **(a)** and oblique axial **(b)** CT images show the tympanic membrane attached to the stapes head (arrow). The posterosuperior EAC wall is absent, the EAC is enlarged (canaloplasty), and there is nonspecific opacification adjacent to the posterior wall of the mastoid cavity (arrowhead in **b**).



a. b.

Figure 3. Transcanal approach for resection of tympanic paraganglioma. **(a)** Preoperative coronal CT image shows a nodular lesion adjacent to the cochlear promontory (arrow). **(b)** Postoperative coronal CT mage shows soft-tissue thickening and osseous irregularity of the inferior wall of the EAC (arrow) related to the transcanal approach.

panoplasty are performed in conjunction with ossicular reconstruction. Type 4 tympanoplasty is performed in cases with erosion of the malleus, incus, stapes head, anterior crus, and posterior crus, but with a mobile footplate. The tympanic membrane is attached to the stapes footplate. This type of tympanoplasty is usually performed in conjunction with canal wall down (CWD) mastoidectomy (2). Type 5 tympanoplasty is performed in cases with erosion of the ossicular chain and fixation of the stapes footplate. The tympanic membrane is attached to a fenestration of the lateral semicircular canal.

Tympanoplasty types 1 and 3 are the most commonly performed, and type 5 is no longer considered a treatment option (2,14). The transcanal approach is a type of surgery performed entirely through the external auditory canal (EAC) for access to the tympanic membrane and middle ear. Postoperative imaging findings may be subtle, appearing as soft-tissue thickening, bone defects, and flattening of the walls of the EAC (Fig 3). Given that the clinical history frequently is lacking, it is important for the radiologist to be familiar with these expected findings and not mistake them for disease-related erosion (such as cholesteatoma or carcinoma) (15).

Surgical incision (myringotomy or tympanostomy) combined with placement of a tympanostomy tube is a common tympanic membrane

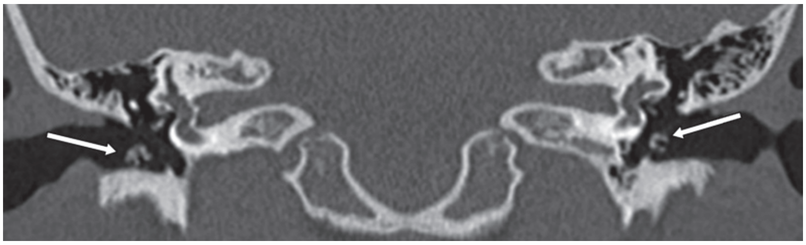
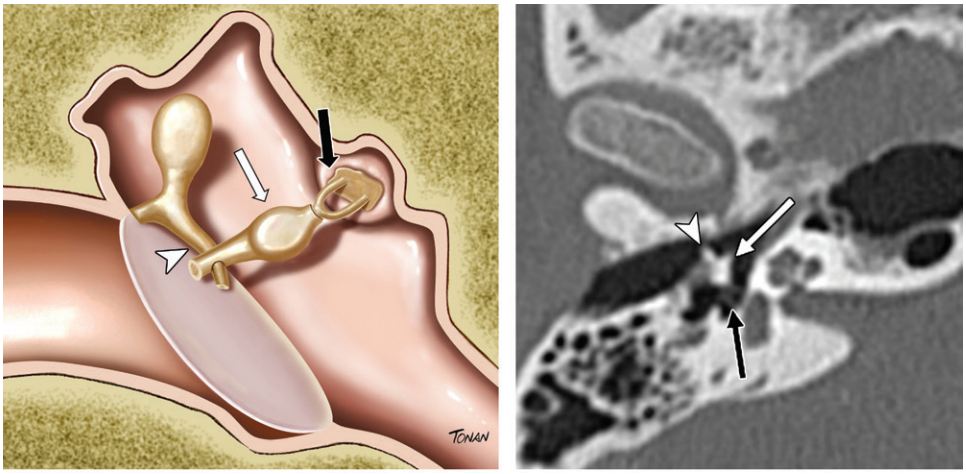


Figure 4. Tympanostomy tubes. Coronal CT image shows bilateral tympanostomy tubes (arrows), which are placed in the inferior portion of the tympanic membrane on the left and displaced to the medial portion of the EAC on the right.



a. **b.**

Figure 5. Incus interposition. **(a)** Drawing of a coronal view of the middle ear shows the sculpted incus (white arrow) between the manubrium of the malleus (arrowhead) and the stapes (black arrow). **(b)** Axial oblique CT image at the level of the oval window shows the contact of the sculpted incus (white arrow) with the stapes (black arrow) and the manubrium of the malleus (arrowhead).

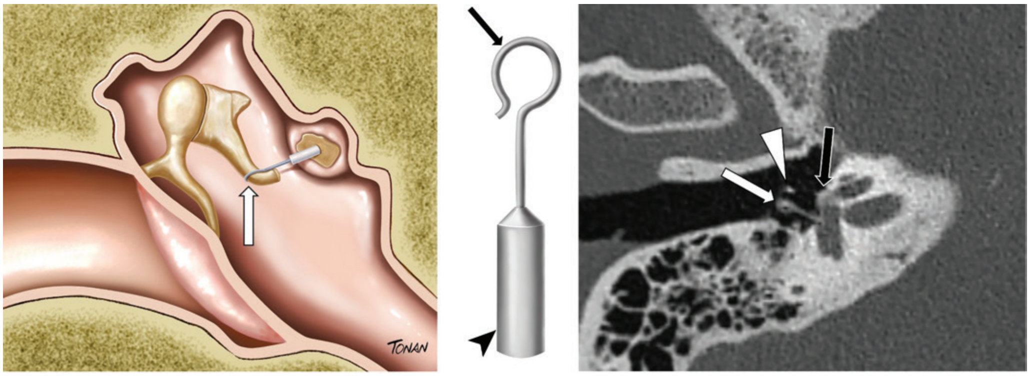
procedure performed in children, with the aim of keeping an open communication between the middle ear and the EAC. The cylindrical tube is made of various materials such as silicone, plastic, or steel. Although imaging is not performed for the purpose of visualizing these tubes, it can provide information about the position of the tube and in some cases depict migration (Fig 4) (16).

Ossicular Chain Reconstruction.—OCR refers to partial or complete reconstruction or replacement of the ossicles with use of a graft or prosthesis, depending on the degree of impairment of the ossicular chain. It is usually performed in patients who have a congenital middle ear deformity, otosclerosis, ossicular discontinuity, or erosion due to chronic otitis media or cholesteatoma (5). Regardless of the method used for OCR, the goal is to re-establish the connection between the tympanic membrane and the stapes footplate. Therefore, it is essential that the radiologist evaluate the integrity of this connection.

Ossicular Interposition.—Ossicular interposition refers to reconstruction of a discontinuous or eroded ossicular chain with use of an ossicular graft (commonly the incus). This type of graft can be autologous (from the patient) or homologous (from a cadaver or donor) (5).

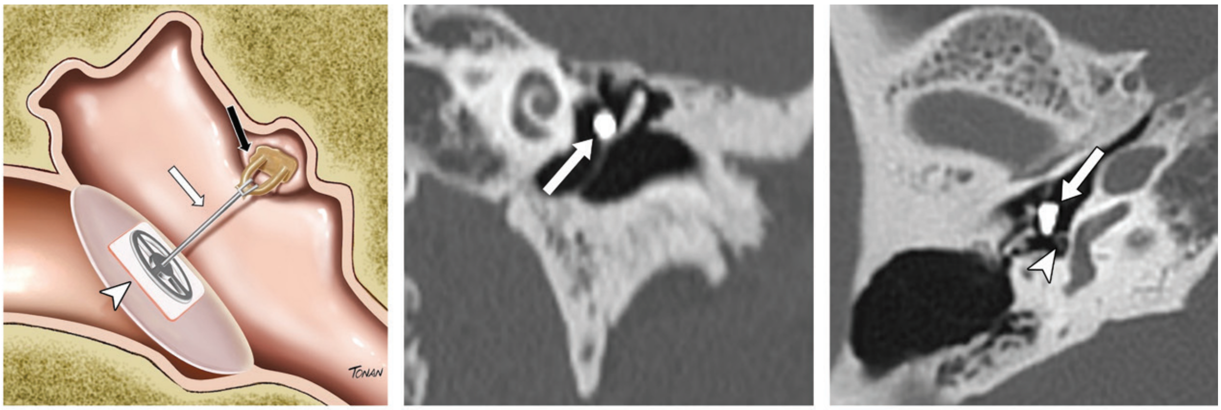
Incus interposition is the main type of autologous OCR and is usually performed in cases of erosion of the lenticular process of the incus due to chronic otitis media or cholesteatoma. The incus is disarticulated from the malleus, the short process of the incus is drilled to receive the manubrium of the malleus, and a groove is created on the incus body to receive the head of the stapes (2). If the incus is absent, the head of the malleus may be used (13). At CT, there is evidence of morphologic alteration of the ossicular chain but with osseous continuity (Fig 5).

Stapes Prosthesis.—In patients with otosclerosis, an osteodystrophy of the otic capsule that becomes involved with spongiotic (hypoattenuating) and sclerotic foci, an important and prevalent consequence of disease progression is fixation of the stapes footplate, which leads to conductive hearing loss. The surgical treatment in these cases may be stapedectomy, which consists of total or partial removal of the stapes, or stapedotomy. At present, the preferred procedure is stapedotomy, in which a small hole is made in the footplate, followed by insertion of



a. b.

Figure 6. Stapes prosthesis. **(a)** Left: Drawing of a coronal view of the middle ear shows the loop of the stapes prosthesis attaching to the long process of the incus (arrow). Right: Drawing of the prosthesis shows the loop (arrow) that will attach to the long process of the incus and the piston (arrowhead) that will articulate with the oval window. **(b)** Axial oblique CT image at the level of the oval window shows the loop of the stapes prosthesis attached to the long process of the incus (white arrow). Also note the manubrium of the malleus (arrowhead) and the otospongiotic foci involving the otic capsule anterior to the oval window (black arrow).



a. b. c.

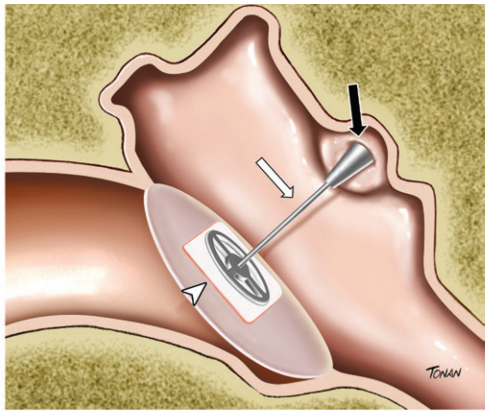
Figure 7. Partial ossicular replacement prosthesis (PORP). **(a)** Drawing of a coronal view of the middle ear illustrates the prosthesis (white arrow) connecting the tympanic membrane with a cartilage graft (arrowhead) to the intact stapes (black arrow). **(b, c)** Coronal **(b)** and axial **(c)** CT images show the intact stapes (arrowhead in **c**) in contact with a metallic PORP (arrow), which is also in contact with the tympanic membrane.

a stapes prosthesis that lies medially on the oval window and articulates laterally with the long process of the incus or less frequently with the lenticular process. Different materials have been used for the prosthesis, including polytetrafluoroethylene and stainless steel (17).

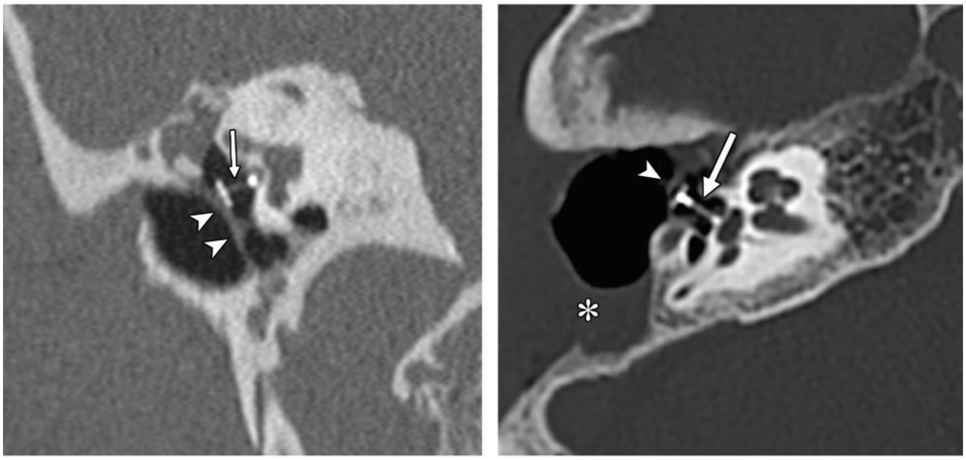
On CT images, whether there is continuity between the malleus, incus, and prosthesis—without any gaps—should be noted, because dislocation of the prosthesis or discontinuity of these structures may lead to conductive hearing loss. The stapes prosthesis generally consists of a loop on the lateral portion that should crimp (attach) over the long process of the incus and a piston on the medial end that is inserted into the oval window (Fig 6) (5,18). CT may yield anatomic information that is useful in surgical planning for patients who will receive a stapes prosthesis, such as oval window status, facial nerve prolapse, and presence of a persistent stapedial artery.

Partial and Total Ossicular Replacement Prostheses.—In cases of extensive discontinuity or lateral fixation of the ossicular chain, partial or total ossicular replacement synthetic prostheses may be used. There are several types of these prostheses, which are adjustable or fixed in length and most commonly made of hydroxyapatite, titanium, or combined materials, including plastic (13).

When the head, anterior crus, and posterior crus of the stapes are intact, a PORP is used to connect the tympanic membrane, malleus, or incus to the stapes head (Fig 7). When the head and crura of the stapes are absent or impaired, a TORP is used to connect the tympanic membrane to the stapes footplate at the oval window (Fig 8). With both techniques, a cartilage graft is usually



a.



b. c.

Figure 8. Total ossicular replacement prosthesis (TORP). **(a)** Drawing of a coronal view of the middle ear shows the prosthesis replacing the entire ossicular chain (white arrow) and connecting the tympanic membrane with a cartilage graft (arrowhead) to the oval window (black arrow). **(b, c)** Coronal **(b)** and axial oblique **(c)** CT images show the prosthesis (arrow) between the tympanic membrane, which is thickened owing to a cartilage graft (arrowheads), and the oval window. Flat soft-tissue thickening (∗ in **c**) in a CWD mastoidectomy cavity also is seen.

interposed between the prosthesis and underlying tympanic membrane (5,14), giving the tympanic membrane a thickened appearance on CT images.

Complications of OCR.—The audiogram, if available, can be a useful tool for postoperative evaluation. Imaging is generally requested after OCR in cases of new or recurrent hearing loss. In these cases, an abnormal audiogram should prompt the radiologist to scrutinize the reconstructed ossicular chain. However, if the audiogram is normal or similar to the postoperative baseline audiogram, then suspicion for complication is low.

CT is the best choice for the initial imaging evaluation and can be used to assess the position of the prosthesis, the progression of underlying disease (eg, otosclerosis, chronic otitis media), and other causes of hearing loss that were previously undetected or are related to surgical manipulation (19). Careful evaluation of the continuity of the reconstructed ossicular chain is necessary to exclude necrosis or dislocation of the ossicular chain or graft; malpositioning of the prosthesis (Fig 9); and extrusion, subluxation, or fracture. Revision surgery will probably be necessary if any of these complications occur.

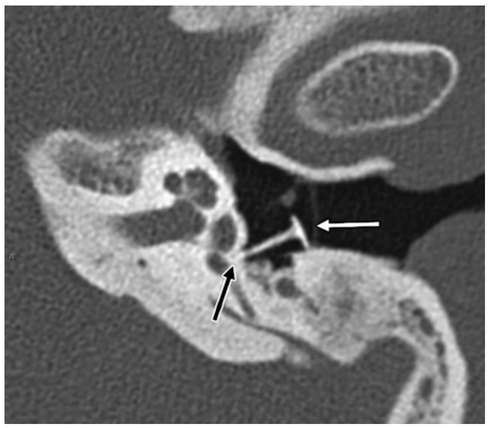


Figure 9. Dislocated prosthesis. Axial oblique CT image shows no contact of the lateral portion of the prosthesis with the tympanic membrane (white arrow). The medial portion of the prosthesis (black arrow) also is dislocated posteriorly.

Granulation tissue may develop as a complication, reducing the mobility of the reconstructed ossicular chain or prosthesis and leading to postoperative conductive hearing loss. At CT, granulation tissue appears as nonspecific soft-tissue material around the prosthesis (Fig 10) 4–6 weeks after surgery (5). There is usually

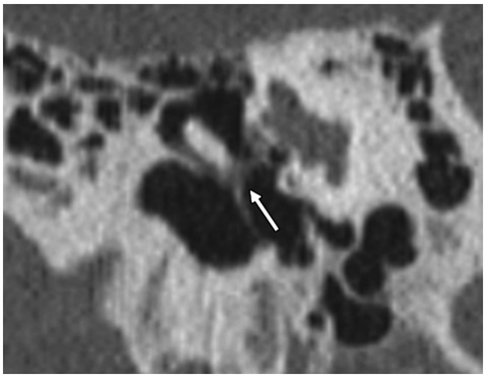


Figure 10. Granulation tissue. Coronal oblique CT image shows soft tissue (arrow) involving the long process of the incus and incudostapedial joint, reducing the mobility of the reconstructed ossicular chain.

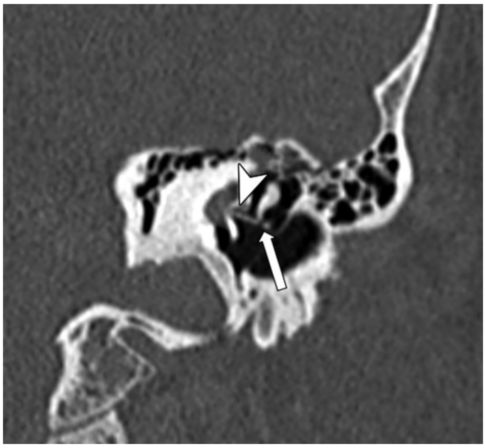


Figure 11. Necrosis of the long process of the incus. Coronal oblique CT image shows a loose loop of a stapes prosthesis (arrow) as a consequence of necrosis of the long process of the incus. The medial portion of the prosthesis (arrowhead) persists in the oval window.

a small amount of this tissue, which may not be visible in cases of suboptimal technique and/or motion artifact (13,19). Owing to the lack of specificity, the imaging finding suggestive of granulation tissue should be carefully correlated with the clinical information and the audiogram, if available. The following aspects should be assessed, particularly in cases of a stapedial prosthesis:

Disarticulation of the prosthesis from the incus may or may not be associated with erosion of the long process due to necrosis (Fig 11) or resorption. Fixation, malpositioning, or dislocation of the medial end of the stapes prosthesis may occur in the presence of granulation tissue or as a consequence of obliterative otosclerosis in the oval window (Fig 12). Obliterative otosclerosis is characterized by bone formation at the oval or round window in association with disease progression (19).

Deep vestibule penetration of the medial extremity of the prosthesis is a complication that is usually accompanied by vestibular symptoms. There are various reports in the literature regarding the accuracy of CT for determining the position of the piston in the vestibule and the acceptable depth of penetration (20,21). Usually, the position may be considered abnormal in a compatible clinical scenario in which the tip of the prosthesis exceeds 50% of the width of the vestibule (Fig 13) (19).

Other causes of a poor OCR outcome include dehiscence of the superior semicircular canal or other labyrinthine structure (the "third window" mechanism), obliterative otosclerosis in the round window, labyrinthitis, intravestibular dislocation of the footplate or an intravestibular foreign body, reparative granuloma, and labyrinthine fistula. A labyrinthine fistula should be suspected in the appropriate clinical context when imaging depicts unexplained middle ear effusion (5,19) and/or a pneumolabyrinth at postoperative follow-up (Fig 14). A certain quantity of air is expected to be found in the labyrinth immediately after stapes prosthesis surgery, but it is usually reabsorbed within 1 week (22).

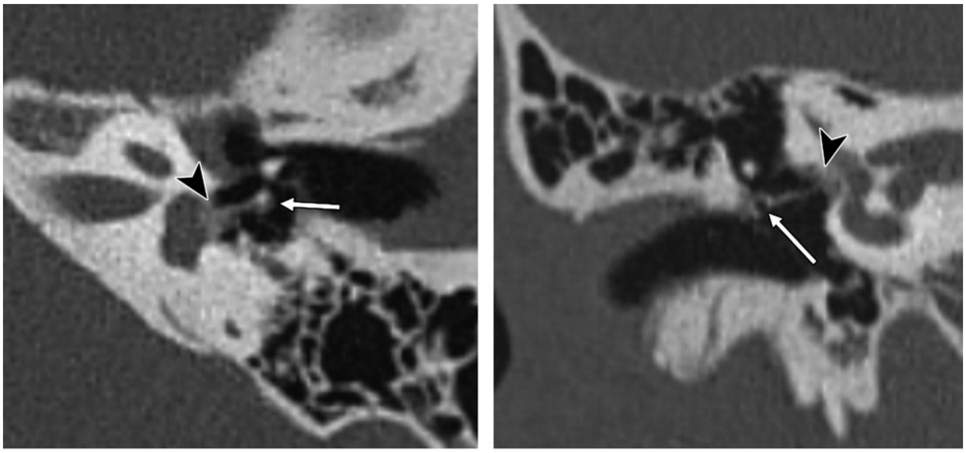
MRI may be helpful when serous or infectious labyrinthitis is suspected. Labyrinthitis manifests as high signal intensity at fluid-attenuated inversion-recovery sequences and contrast enhancement of the labyrinth (23).

Mastoidectomy

Mastoidectomy is a surgical procedure that is frequently performed to treat chronic otitis media and cholesteatoma, but it can also be used for other purposes, including cochlear implantation, endolymphatic sac surgery, and facial nerve surgery. According to the status of the posterosuperior wall of the EAC, mastoidectomy can be classified as a simple (cortical) or canal wall up (CWU) procedure if the wall is left intact or as a CWD procedure if the wall is resected (2). When performed in conjunction with tympanoplasty and/or OCR, this surgery is referred to as tympanomastoidectomy (24).

The term *atticotomy* refers to resection of the lateral epitympanic wall, including the scutum, and results in an enlarged attic, which is better seen on coronal CT images. It can be performed for treatment of attic cholesteatoma but is frequently performed in conjunction with mastoidectomy (3,25).

Preoperative CT can provide relevant information for planning middle ear and mastoid surgery. Intraoperative delineation of the second genu of the facial nerve and the lateral semicircular canal can be difficult in patients with sclerotic mastoid air cells (14). An aberrant or lateralized internal



a. b.

Figure 12. Two cases of stapes prostheses and obliterative otosclerosis. **(a)** Axial oblique CT image shows bone formation at the oval window due to progression of otosclerosis (arrowhead), involving and leading to fixation of the medial portion of the prosthesis. The loop around the long process of the incus (arrow) keeps its normal position. **(b)** Coronal oblique CT image shows bone formation at the oval window due to progression of otosclerosis (arrowhead), which presumably led to dislocation of the lateral end of the prosthesis (the loop) (arrow).

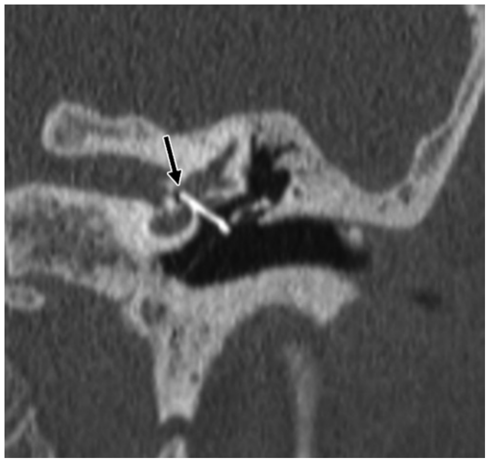


Figure 13. Vestibular penetration of the stapes prosthesis in a patient with postoperative vestibular symptoms. Coronal CT image shows the medial portion of the prosthesis deep in the vestibule (arrow), exceeding 50% of the vestibule's width.

carotid artery, an anteriorly placed sigmoid sinus, and a dehiscent high-riding jugular bulb can increase the risk of a vascular lesion during surgery.

Simple (Cortical) Mastoidectomy.—Simple mastoidectomy is a less invasive type of mastoidectomy that includes resection of the mastoid cortex and lateral air cells, classically preserving the Koerner septum without extension to the antrum or epitympanum (6). However, some variations with access to the antrum have been described.Because access to the mastoid and middle ear is limited with this procedure, it can be used to treat acute or chronic mastoiditis and subperiosteal abscess (26).

CWU Mastoidectomy.—CWU mastoidectomy involves removing the mastoid cortex and air cells while preserving the posterosuperior wall of the EAC. Unlike cortical mastoidectomy, CWU mastoidectomy includes resection of the Koerner septum and communication of the mastoid cavity with the antrum and epitympanum (Fig 15) (27). The intact EAC wall protects the mastoid cavity from the external environment, avoiding the long-term problems associated with CWD procedures (26). However, this comes at the expense of limited access to the tympanic cavity and higher rates of residual or recurrent cholesteatoma (28).

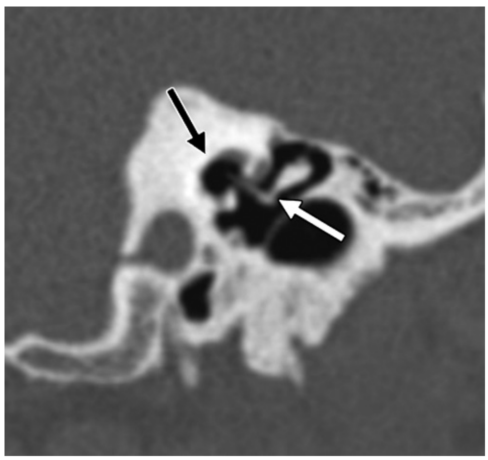
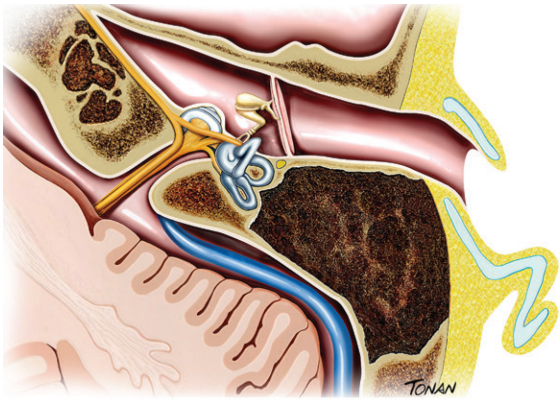
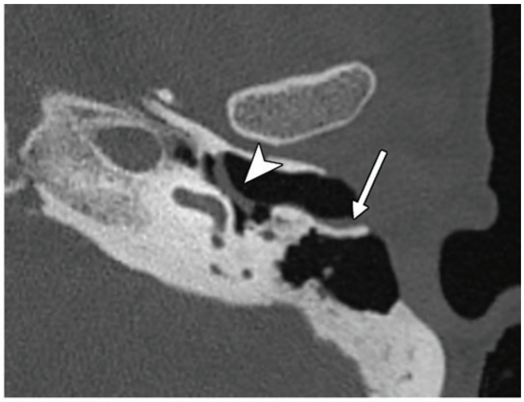


Figure 14. Stapes prosthesis and pneumolabyrinth. Coronal oblique CT image shows the loop of the prosthesis attached over the long process of the incus (white arrow). The medial end of the prosthesis is inserted into the oval window and insinuates into the vestibule, which is filled with air (black arrow), suggesting a perilymphatic fistula.



a.



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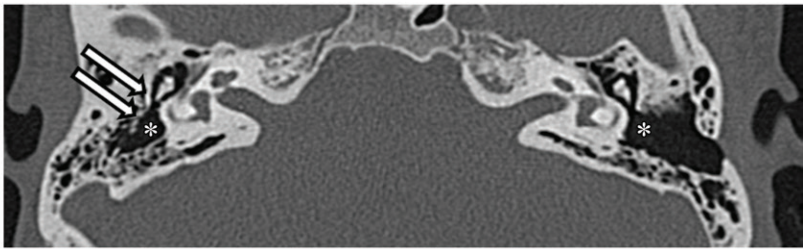
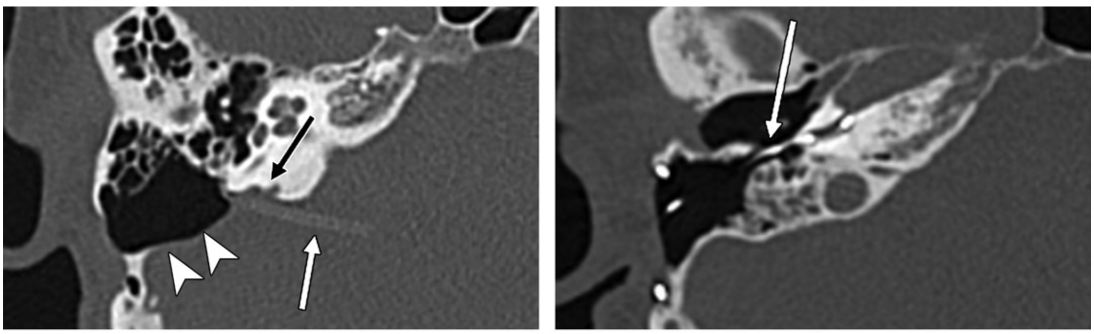


c.

Figure 15. CWU mastoidectomy. **(a)** Drawing depicts CWU mastoidectomy, with removal of the mastoid cortex and air cells. **(b)** Axial CT image shows mastoidectomy, with preservation of the posterior EAC wall (arrow). Graft repair of the tympanic membrane (arrowhead) also is seen. **(c)** Axial CT image at the level of the antrum shows removal of the left mastoid air cells and Koerner septum, connecting the surgical cavity with the mastoid antrum (*). The preserved right Koerner septum (arrows) delineates the mastoid antrum.



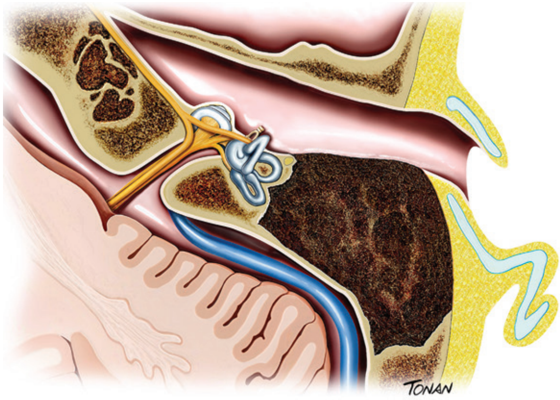
a. b.

Figure 16. Variations of CWU mastoidectomy. **(a)** Axial CT image shows right-side mastoidectomy for endolymphatic sac surgery, with removal of the medial mastoid cortex (arrowheads) and the bone adjacent to the vestibular aqueduct for endolymphatic sac exposure (black arrow). In addition, a Silastic tube (Dow Corning) (white arrow) has been inserted to keep the endolymphatic sac open. **(b)** Axial CT image shows a right facial recess approach. The cochlear implant electrode is passed through the dissected facial recess (arrow) and into the basal turn of the cochlea by means of cochleostomy.

CWU mastoidectomy is also performed in endolymphatic sac surgery (shunt or decompression) (Fig 16a), with subsequent access to the retrolabyrinthine dura through an osteotomy in the posteromedial wall of the mastoid (29). This defect should not be mistaken for an iatrogenic lesion.

A variation of CWU mastoidectomy is the facial recess approach, with dissection of the facial recess (lateral to the mastoid segment of the facial nerve canal). This approach provides better access to the tympanic cavity. In addition to treatment for middle ear disease, the facial recess approach is also used for facial nerve surgery and cochlear implantation, with introduction of the electrode into the cochlea through the round window or by means of cochleostomy (Fig 16b) (30).

CWD Mastoidectomy.—CWD mastoidectomy is a more extensive type of mastoidectomy that is characterized by resection of the posterosuperior wall of the EAC and scutum. This resection leads to creation of a surgical cavity that communicates with the antrum, middle ear, and EAC. Another step in this procedure is meatoplasty with widening of the EAC, which enables the surgeon to clean and visualize the surgical



a. b.

Figure 17. CWD mastoidectomy. **(a)** Drawing depicts radical mastoidectomy involving removal of the posterior EAC wall and the ossicles. **(b)** Axial CT image shows the take-down of the posterior canal wall and occlusion of the eustachian tube with a fascial graft and fragments of the ossicles (arrow).

cavity postoperatively (13). Furthermore, the middle ear opening of the eustachian tube can be occluded to prevent exposure of the cavity to the nasopharynx (Fig 17) (6,24).

CWD mastoidectomy enables excellent intraoperative visualization of the tympanic cavity, with low rates of residual cholesteatoma. However, this approach has disadvantages, such as the need for periodic cleaning of the cavity, possible infection, and lifestyle adjustments (28).

CWD mastoidectomy can be further subdivided into modified radical mastoidectomy and radical mastoidectomy procedures. Modified radical mastoidectomy includes tympanoplasty and/or OCR (Fig 2) (27). Radical mastoidectomy is usually reserved for treatment of extensive middle ear disease and resection of tumors (26). The ossicles are removed, with preservation of the stapes, if possible, and there is no attempt to reconstruct the ossicular chain or tympanic membrane.

Canal wall reconstruction with mastoid obliteration can be attempted to minimize the disadvantages of CWD mastoidectomy. The mastoid cavity can be obliterated by bone, fat, cartilage, muscle flaps, or hydroxyapatite (Fig 18) (31).

Complications of Mastoidectomy.—Imaging is performed in the postoperative setting to assess for possible complications and recurrent or residual disease. The surgical cavity is expected to be well aerated (24). However, imaging performed too early may show recent postoperative changes, such as variable opacification and fluid levels (3). Flat soft-tissue material around the mastoid bowl can be seen and is usually related to scar or granulation tissue. Opacification of the mastoid cavity may be due to active inflammation, which occasionally manifests as hazy osteogenesis in the cavity walls (Fig 19) (14).

The presence of lobulated material in the mastoid bowl should raise suspicion for cholesteatoma, cholesterol granuloma, or granulation tissue as a differential diagnosis (24). CT has high predictive value for ruling out disease when it depicts a clear cavity. However, CT findings are nonspecific, and MRI is the modality of choice for narrowing the diagnosis (32). At MRI, cholesteatoma classically has low T1 signal intensity and high T2 signal intensity, with no enhancement.

Diffusion-weighted imaging is considered the most accurate imaging technique for detection of cholesteatoma, which manifests as restricted diffusion (33) (Fig 20). The non–echo-planar sequence should be used for diffusion-weighted imaging owing to the associated lack of susceptibility artifact, thinner sections, and higher imaging matrix and enables detection of lesions as small as 2 mm (10,34). Abscess also can manifest as restricted diffusion (35), but the clinical setting can help guide the diagnosis. Conversely, cholesterol granulomas appear as high T1 signal intensity (Fig 21), and granulation tissue shows contrast enhancement (Table 2) (1,24,36).

The osseous margins should be carefully evaluated to exclude new areas of erosion (if prior imaging studies are available), which raise suspicion for expansile lesions such as residual or recurrent cholesteatoma. It is also important to assess the integrity of the osseous labyrinth, tegmen tympani, and tegmen mastoideum to exclude a cerebrospinal fluid (CSF) leak or perilymphatic fistula. Patients who are found to have a lesion that is contiguous with a tegmen defect at CT should undergo MRI, with special attention paid to coronal T2-weighted image findings to rule out meningoencephalocele (Fig 22) (37).

Automastoidectomy and autoatticotomy are imaging pitfalls. Occasionally, cholesteatomas

a. b. c.

Figure 18. CWD surgical cavity obliteration. **(a)** Axial bone window CT image shows hydroxyapatite granules obliterating the mastoid bowl (black arrow), with foci of gas (white arrow) permeating the cavity. **(b, c)** Axial soft-tissue window **(b)** and bone window **(c)** CT images show signs of infection of the surgical site: gas in the cavity, fragmentation of the material, and fistulous communication with the skin (arrowheads). There is also thickening and stranding of the soft tissues (arrow in **b**) adjacent to this process.

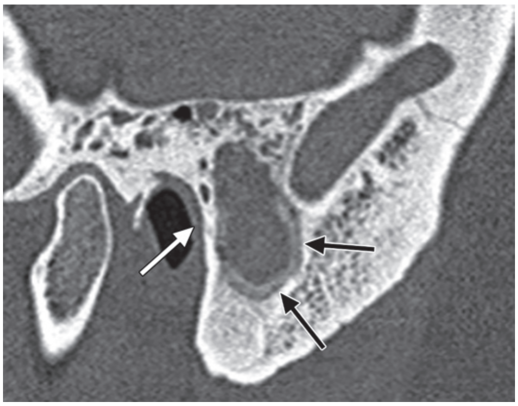


Figure 19. CWU mastoidectomy with chronic inflammation. Sagittal CT image shows hazy bone formation (black arrows) in the walls of the mastoid cavity. Note the preserved EAC wall (white arrow).

spontaneously drain through the EAC as a result of erosion of the adjacent structures, leaving behind the cholesteatoma matrix (mural cholesteatoma). In a patient with no history of surgery, the resulting cavity resembles a surgical mastoidectomy cavity or atticotomy (38,39).

Approaches to the IAC and CPA

Surgery involving the IAC and CPA is mainly performed for resection of a tumor; vestibular schwannomas account for 85% of the tumors in this region (40). There are three main surgical approaches: the middle cranial fossa, translabyrinthine, and retrosigmoid approaches. These techniques may also be used in conjunction with mastoidectomy to gain greater exposure. Many factors affect the choice of surgical technique, including the surgeon's expertise, the patient's hearing status, the tumor size, and the location and depth of IAC penetration (7).

The retrosigmoid and middle cranial fossa approaches allow the possibility of preserving the patient's hearing at the cost of limited access to the IAC fundus and CPA, respectively. The translabyrinthine approach provides good access to the entire IAC and CPA but at the cost of hearing loss.

Preoperative evaluation of the patient's anatomy aids in surgical planning. With the retrosigmoid and translabyrinthine approaches, a high-riding jugular bulb or jugular bulb diverticulum limits access to the IAC. Pneumatization of the posterior IAC wall may predispose the patient to CSF leakage (41). Anterior or posterior placement of the sigmoid sinus can make the translabyrinthine or retrosigmoid approach technically more difficult (7).

Middle Cranial Fossa Approach.—With the middle cranial fossa approach, temporal craniotomy is performed and the temporal lobe is elevated, providing access to the floor of the middle cranial fossa, the arcuate eminence, and the superior aspect of the IAC (Fig 23) (40). This approach is used for resection of small intracanalicular tumors, with little (<1 cm) or no CPA extension (40). It can also be used to repair temporal lobe cephaloceles (42) and superior semicircular canal dehiscence (Fig 24) (43) and to access the labyrinthine and upper tympanic segments of the facial nerve.

Coronal images are optimal for evaluation of postoperative changes. Titanium mesh, bone, hydroxyapatite cement, fascia, and muscle grafts may be used to reconstruct the floor of the middle cranial fossa (44). Bone and hydroxyapatite have high attenuation at CT, while fascia and muscle are hypoattenuating and generally imperceptible (40).

The main advantages of using the middle cranial fossa approach are the possibility of hearing

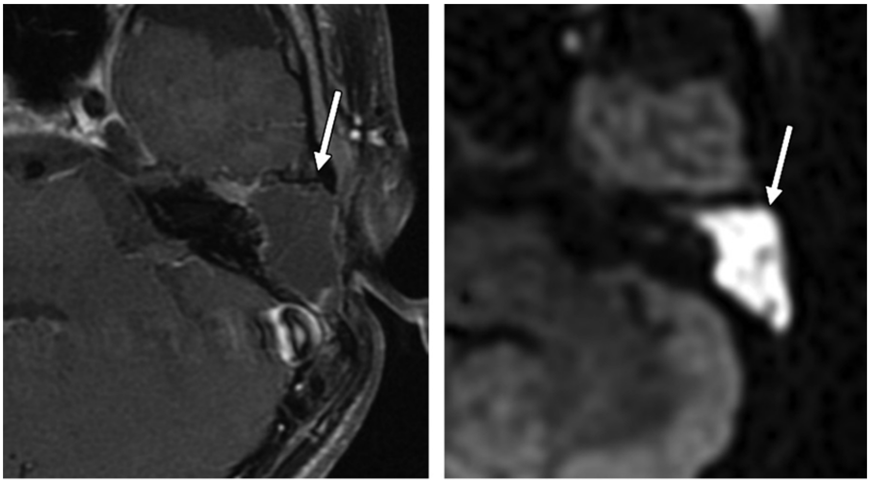


Figure 20. Recurrent cholesteatoma. Axial contrast-enhanced T1-weighted fat-suppressed **(a)** and non–echo-planar diffusion-weighted **(b)** MR images show a large lesion (arrow) with low signal intensity and thin peripheral enhancement **(a)** and restricted diffusion **(b)** occupying the left mastoidectomy cavity.

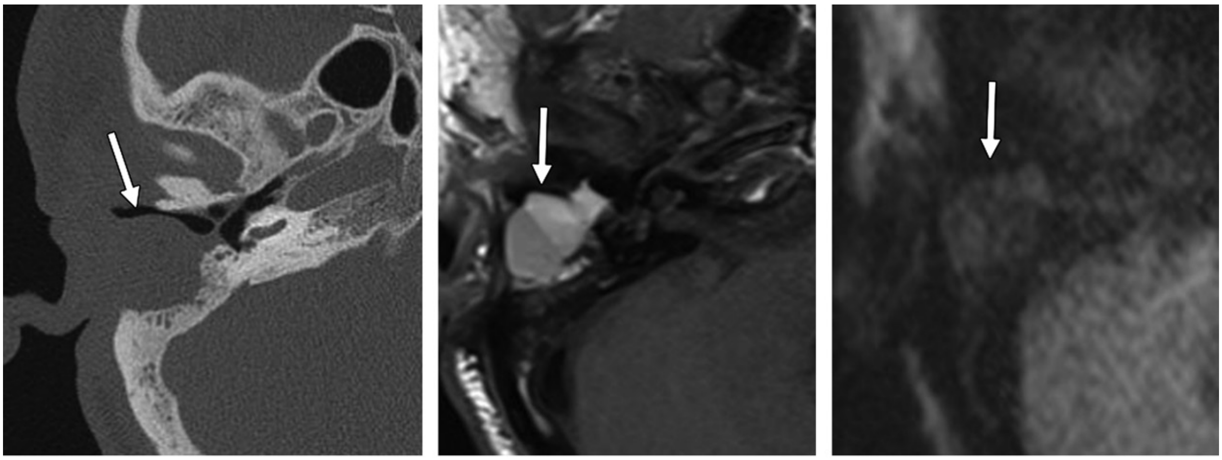


Figure 21. Cholesterol granuloma. **(a)** Axial CT image shows a lobulated lesion (arrow) occupying the right mastoidectomy cavity. **(b, c)** Axial T1-weighted **(b)** and non–echo-planar diffusion-weighted **(c)** MR images show the lesion (arrow) with predominantly high signal intensity **(b)** and no restricted diffusion **(c)**.

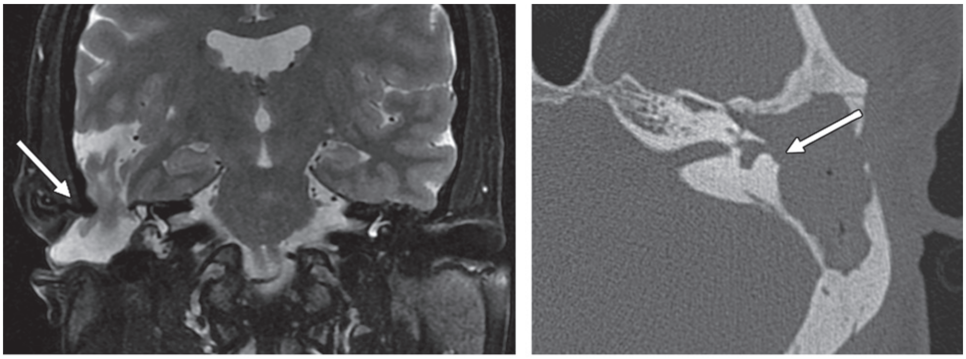
Table 2: MRI Appearances of Temporal Bone after Surgery for Chronic Otitis Media or Cholesteatoma

Tissue Type	T1-weighted Appearance	T2-weighted Appearance	Enhancement	Diffusion Restriction
Cholesteatoma	Hypointense	Hyperintense	No	Yes
Granulation tissue	Hypointense	Hyperintense	Yes	No
Scar tissue	Low or intermediate signal intensity	Low or intermediate signal intensity	None or delayed	No
Cholesterol granuloma	High signal intensity	High or intermediate signal intensity	No	Variable

Note.—Reprinted, with permission, from reference 1.

preservation and complete exposure of the lateral portion of the IAC, particularly the fundus, without manipulation of the inner ear structures. Moreover, this is the only technique that provides direct access to the superior semicircular canal. The main disadvantage is the limited exposure of the CPA (7,40).

Translabyrinthine Approach.—With the translabyrinthine approach, CWU mastoidectomy and labyrinthectomy are performed, with resection of the semicircular canals and the posterior, superior, and inferior walls of the IAC. This approach provides wide access to the CPA and complete exposure of the IAC, including the fundus (Fig



a. b.

Figure 22. Complications of mastoidectomy in two patients. **(a)** Coronal T2-weighted MR image shows an osseous defect in the tegmen tympani and a meningoencephalocele occupying the surgical cavity, with herniation of the temporal lobe (arrow). Widening of the right sylvian fissure corroborates the diagnosis. **(b)** Axial CT image in a different patient shows signs of fenestration of the lateral semicircular canal (arrow) and fluid filling the mastoid cavity, compatible with a perilymphatic fistula at surgical exploration.

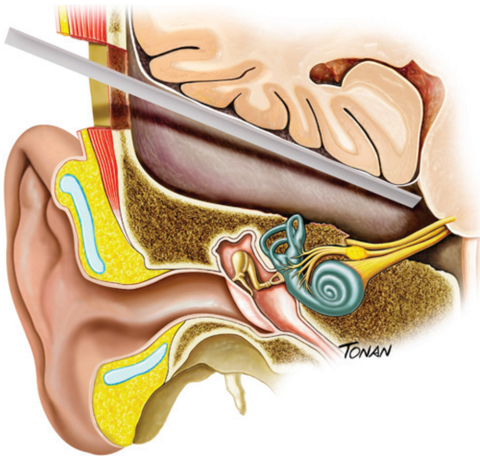


Figure 23. Drawing illustrates the middle cranial fossa approach, with temporal craniotomy and removal of the superior wall of the IAC to access a small lateral schwannoma.

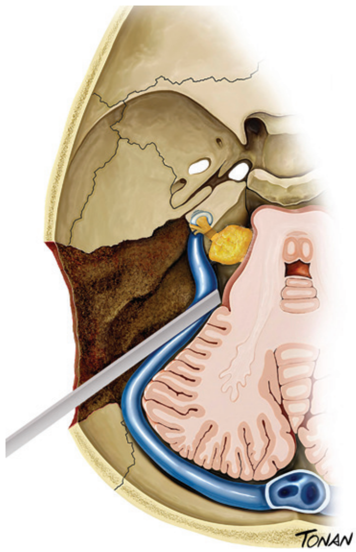


Figure 25. Drawing illustrates a translabyrinthine approach, with removal of the mastoid air cells, vestibule, semicircular canals, and posterior wall of the IAC.

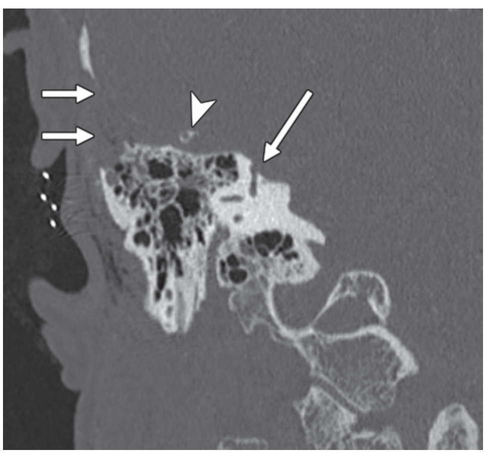


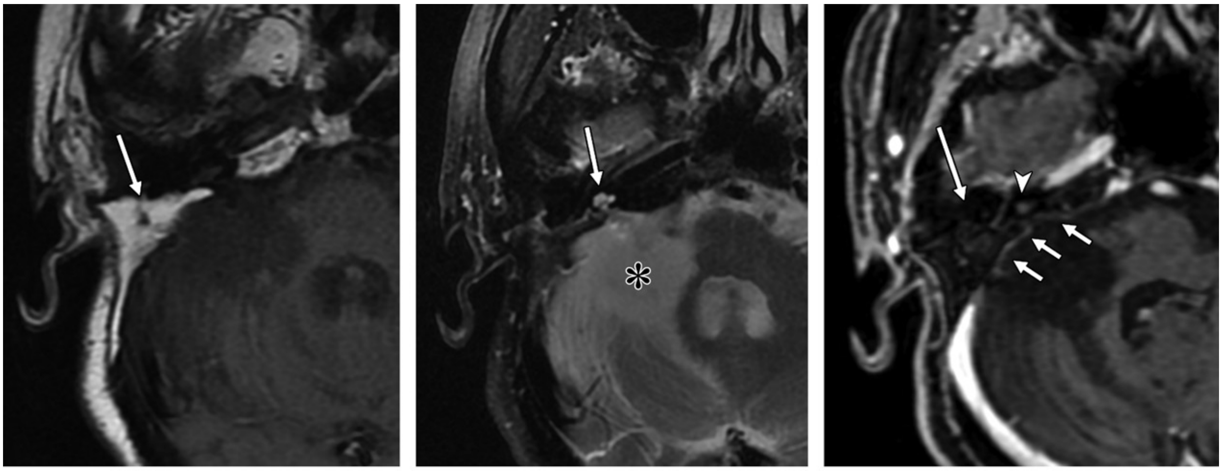
Figure 24. Middle cranial fossa approach for repair of superior semicircular canal dehiscence. Coronal bone window CT image demonstrates right temporal craniotomy (short arrows), which provides access to the arcuate eminence. The bone graft (arrowhead) used to cover the dehiscence is laterally displaced, while the fascial graft plugging the superior semicircular canal (long arrow) is imperceptible.

25). The access site is anterior to the sigmoid sinus, and often there is little cerebellar retraction (6,45). The translabyrinthine approach is generally used for resection of intralabyrinthine and vestibular schwannomas, in patients with no serviceable hearing, or as part of a combined approach for other skull base neoplasms.

To prevent CSF leakage, the surgical cavity is obliterated, usually by using fat or other materials such as bone powder, fascia, or fibrin glue. Use of fat-suppression MRI techniques is important for distinguishing between fat and residual tumor at postoperative assessment (Fig 26) (40).

The main advantage of using the translabyrinthine approach is the wide access to the IAC and CPA, without tumor size limiting this accesss (46). The main disadvantage is permanent hearing loss.

Retrosigmoid Approach.—With the retrosigmoid approach, a craniotomy is performed (posterior



a. b. c.

Figure 26. Right translabyrinthine approach with fat graft placement. **(a)** Axial T1-weighted MR image shows the typical high signal intensity of the fat graft (arrow). **(b)** Axial T2-weighted fat-suppressed MR image shows the preserved contours of the cochlea (arrow) and absence of the vestibule and semicircular canals. There is also encephalomalacia of the right cerebellar hemisphere due to traction of the parenchyma (*). **(c)** Axial contrast-enhanced T1-weighted fat-suppressed MR image shows the fat-graft saturation (long arrow) and expected linear enhancement along the periphery of the fat graft and IAC walls (short arrows). Note the faint cochlear enhancement (arrowhead), which is probably related to fenestration of the labyrinth.

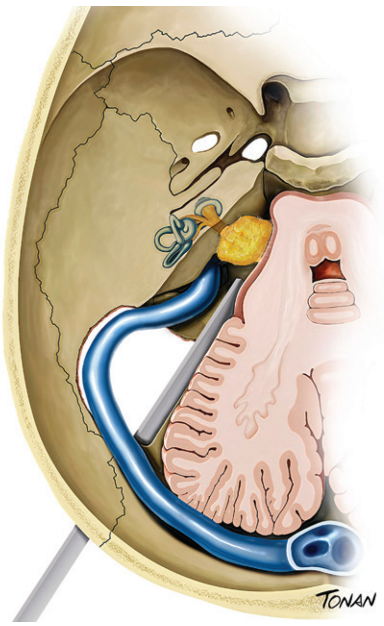


Figure 27. Drawing shows a retrosigmoid approach, with access to the cerebellopontine angle (CPA).

to the sigmoid sinus) and the cerebellar hemisphere is retracted. The medial portion of the posterior wall of the IAC is removed, providing access to the canalicular segment of the facial, cochlear, and vestibular nerves (Fig 27) (6,27). Access to the IAC fundus is limited owing to the risk of fenestration of the labyrinth, the posterior semicircular canal in particular (40).

The retrosigmoid technique is mainly performed to resect vestibular schwannomas located predominantly in the CPA, with or without a medial intracanalicular component, and to address other CPA tumors such as meningiomas and epidermoid cysts (40,41).

The advantages of using this procedure are the potential for preserving hearing and the wide access to the CPA, which allows resection of larger tumors. However, this technique does not provide access to the lateral portion of the IAC (fundus) (Fig 28), and there is a potential risk of residual tumor or tumor recurrence. Other disadvantages include possible parenchymal injury due to prolonged cerebellar retraction and early postoperative headache (40,41).

Complications of IAC and CPA Approaches.— Postoperative complications include cerebellar or temporal lobe retraction injury (Fig 26), intracranial hemorrhage (Fig 29), facial nerve paresis, meningitis, vascular injury, and dural venous sinus or jugular vein thrombosis (Fig 30). Potential CSF-related complications include CSF leakage (more common with the retrosigmoid approach) and mild temporary postoperative hydrocephalus from transitory disruption of CSF resorption (27,47).

Contrast-enhanced fat-suppressed MRI is better for follow-up evaluation, especially in cases where a fat graft was used to close the dural defect. Linear enhancement along the surgical site, particularly the IAC, can be a normal finding in the first 2 years after surgery and is related to inflammatory changes (Fig 26). However, nodular or masslike enhancement or an increase in enhancement between examinations should raise suspicion for residual or recurrent tumor, which requires close follow-up (Fig 31). Inflammatory

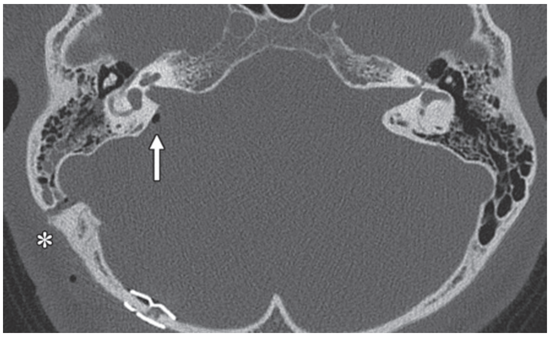


Figure 28. Retrosigmoid approach. Axial bone window CT image shows a retrosigmoid craniotomy (*) posterior to the sigmoid sinus and resection of the medial portion of the posterior IAC wall (arrow). The mastoid cells and labyrinthine structures are intact.

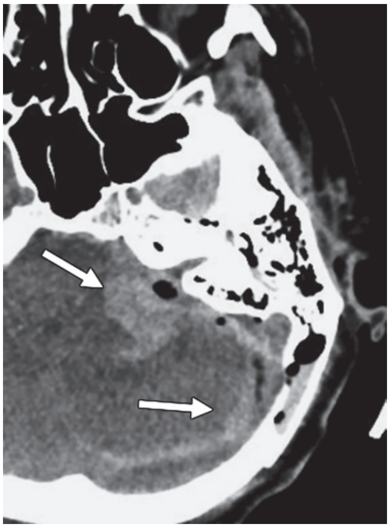


Figure 29. Complication of postoperative retrosigmoid approach. Axial soft-tissue window CT image 24 hours after the surgery shows hyperattenuating material compatible with subarachnoid hemorrhage in the left CPA and cerebellar hemisphere sulci (arrows), with rightward deviation and mass effect on the pons and cerebellar hemisphere.

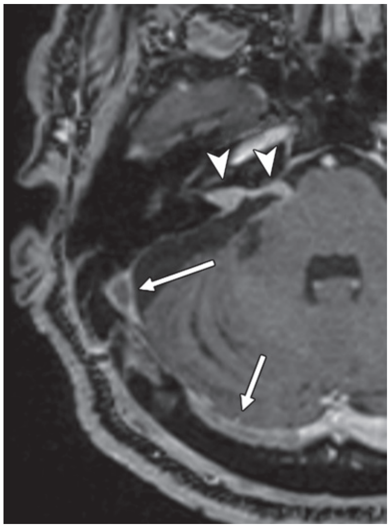


Figure 30. Postoperative dural venous sinus thrombosis and residual tumor. Axial contrast-enhanced T1-weighted fat-suppressed MR image shows thrombosis of the right transverse and sigmoid sinuses (arrows). Residual tumor (schwannoma) (arrowheads) is left in the IAC and CPA adjacent to the facial and trigeminal nerves intentionally to preserve their function.

enhancement in the IAC can appear to be nodular occasionally, but it resolves over time (Fig 32) (48). Furthermore, it is important to note that subtotal resection of the tumor may be needed to preserve function of the facial and trigeminal nerves (Fig 30) (47).

Labyrinthine enhancement can also be a normal finding in the early postoperative period, especially after a translabyrinthine approach (Fig 26), and usually resolves after the 1st year. However, labyrinthine enhancement is not usual after a retrosigmoid or middle cranial fossa approach and can be related to inflammatory changes, vascular injury, or labyrinthine fenestration (27,40).

Conclusion

Postoperative temporal bone evaluation can be challenging owing to the different types of procedures that can be performed. CT is optimal for assessment of tympanoplasty and OCR, with capability to depict gaps in the reconstructed ossicular chain that would manifest clinically as conductive hearing loss. CT is a good method for excluding disease in the postoperative mastoid; a structured report template for postoperative CT of the mastoid and middle ear is available at *https://www.radreport.org/home/RPT50844*.

However, when there is opacification of the mastoid bowl, MRI is a better choice for narrowing the diagnosis. Non–echo-planar diffusion-weighted imaging should be performed in suspected cases of cholesteatoma. MRI is the best choice for follow-up of IAC and CPA approaches, and a contrast-enhanced fat-suppressed MRI sequence can be useful, particularly in cases where a fat graft was used.

Linear enhancement along the surgical site (frequently in the IAC) can be related to inflammatory changes; however, nodular enhancement

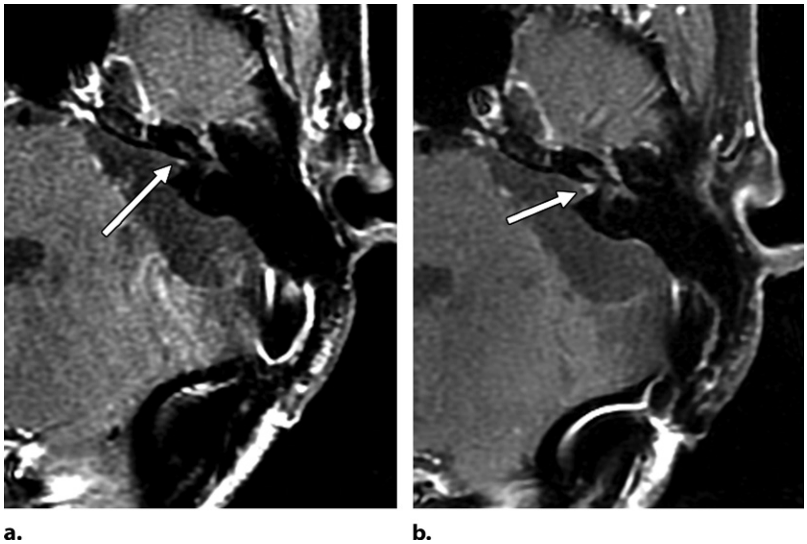


Figure 31. Follow-up after retrosigmoid surgery for resection of left vestibular schwannoma. Axial contrast-enhanced T1-weighted fat-suppressed MR images show nodular enhancement in the IAC fundus (arrow) that increases between the early postoperative examination **(a)** and the 4-year follow-up examination **(b)**, indicating a recurrent lesion. There is also enlargement of the left CPA, which is commonly seen after a retrosigmoid approach, with traction of the cerebellar hemisphere.

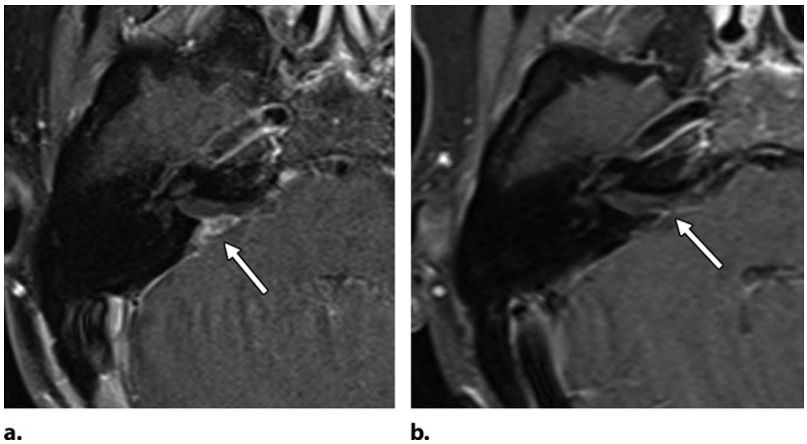


Figure 32. Follow-up after retrosigmoid surgery for resection of right vestibular schwannoma. Axial contrast-enhanced T1-weighted fat-suppressed MR images show nodular enhancement adjacent to the medial portion of the IAC (arrow in **a**) that has resolved by the time of the 1-year follow-up examination (arrow in **b**), indicating inflammatory changes.

should raise suspicion for residual or recurrent tumor. Familiarity with the expected findings after temporal bone surgeries can help diagnose possible complications.

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