MRI of the Internal Auditory Canal, Labyrinth, and Middle Ear: How We Do It

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MRI is firmly established as an essential modality in the imaging of the temporal bone and lateral skull base. It is used to evaluate normal anatomic structures, evaluate for vestibular schwannomas, assess for inflammatory and/or infectious processes, and detect residual and/or recurrent cholesteatoma. It is also extensively used in pre- and postoperative evaluations, particularly in patients with vestibular schwannomas and candidates for cochlear implantation. Nevertheless, despite the widespread use of MRI for these purposes, many radiologists remain unfamiliar with the complex anatomy and expected imaging findings with such examinations. The purpose of this review is to provide an overview of the most useful MRI sequences for internal auditory canal and labyrinthine imaging, review the relevant anatomy, and discuss the expected appearances of the most commonly encountered pathologic entities. In addition, the features at pre- and postprocedural MRI will be discussed to help ensure that diagnostic radiologists may be of greatest use to the ordering physicians.

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Learning Objectives:
- After reading the article and taking the test, the reader will be able to:
  - Identify the major anatomic structures visible on MRI within the internal auditory canal (IAC), labyrinth, and middle ear
  - Describe the key prognostic imaging features of vestibular schwannomas
  - Describe the typical MRI appearance of acute labyrinthitis and labyrinthitis ossificans

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MRI of the temporal bone and lateral skull base has become a mainstay of neuroradiology to delineate anatomic structures and to investigate neoplastic or infectious processes affecting this complex space. Common applications of MRI include diagnostic evaluation of sensorineural hearing loss, assessment of cochlear implant candidacy, monitoring for residual or recurrent cholesteatoma within the tympanomastoid space, and monitoring for vestibular schwannoma within the inner auditory canal or cerebellopontine angle. In many cases, MRI is complementary to CT in the evaluation of surgical candidates, such as individuals being considered for pediatric cochlear implantation, where the labyrinth may be malformed and the facial nerve may take an anomalous course through the temporal bone.

Radiologists who interpret such imaging studies should be well-versed in the expected appearances of the most common pathologic entities. Herein, we outline the most useful MRI sequences, review the imaging characteristics of the most frequently encountered pathologic entities, and describe the use of MRI in the postoperative follow-up of vestibular schwannomas and cholesteatomas.

MRI Technique
Our institution conducts the vast majority of internal auditory canal (IAC) MRI examinations with 3-T magnets, which allow for a superior signal-to-noise ratio and higher spatial resolution compared with 1.5-T imaging. In addition, 3-T imaging can be completed with shorter acquisition times. Such benefits are not without costs, as 3-T images contain more banding and susceptibility artifacts, particularly with gradient-recalled echo sequences (1). In recent years, pioneering work has introduced 7-T imaging for IAC evaluations. Such imaging yields further increases in signal-to-noise ratio and spatial resolution at the expense of even more degradation by susceptibility artifacts (2,3). The use of parallel transmit techniques may help overcome the signal drop-off in the posterior fossa and IAC on 7-T images; we are currently assessing the capabilities of this technique.

Our institution uses multichannel phased-array coils to substantially increase the signal-to-noise ratio of acquired images. Currently, we use either a 32- or 64-channel head coil, depending on what is available for each scanner’s platform. A dedicated multichannel head coil achieves an excellent signal-to-noise ratio of the cerebellopontine angle. It is also capable of producing high spatial resolution of cranial nerves VII and VIII, even with 1.5-T scanners.

Like most other institutions, ours has made small field-of-view T2-weighted cisternography the workhorse MRI sequence for imaging the IAC and associated anatomic...
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Summary
MRI of the inner auditory canal, middle ear, and labyrinth is complex and requires a detailed knowledge of the regional anatomy, the most common pathologic entities, and the expected postsurgical findings.

Essentials
- MRI of vestibular schwannomas has prognostic value and is used to guide surgical approaches.
- Preoperative examinations of candidates for cochlear implants should be closely scrutinized for anatomic and pathologic conditions relevant to surgery.
- Non–echo-planar diffusion-weighted imaging is highly accurate in the diagnosis of residual and recurrent cholesteatomas.
- Early detection of labyrinthitis is crucial so that cochlear implantation can be performed if indicated, before labyrinthitis ossificans ensues.

Summary of Parameters for 3-T MRI of the Internal Auditory Canal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Axial T2-weighted FLAIR with Fat Saturation</th>
<th>Axial T2-weighted SPACE</th>
<th>Axial T1-weighted SPACE with Gadolinium-based Contrast Material</th>
<th>Axial T2-weighted FLAIR SPACE with Gadolinium-based Contrast Material</th>
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<tr>
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<td>Imaging duration</td>
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<td>3 minutes 55 seconds</td>
<td>4 minutes</td>
<td>4 minutes</td>
</tr>
</tbody>
</table>

Note.—FLAIR = fluid-attenuated inversion recovery, FOV = field of view, SPACE = sampling perfection with application-optimized contrasts by using flip angle evolution, TE = echo time, TR = repetition time.
To assess for residual or recurrent cholesteatomas, we add axial and coronal diffusion-weighted imaging to our IAC imaging protocol, as the lesions demonstrate intense restricted diffusion due to their high keratin content. Specifically, non–echo planar diffusion-weighted imaging is used, which is less prone to susceptibility artifact and is capable of thin-slice imaging, and consequently outperforms echo-planar imaging (10,11). Focal restricted diffusion is highly specific for recurrent cholesteatomas, and lesions as small as 2 mm in diameter can be detected. Lower-resolution diffusion sequences can be coregistered with higher-resolution MRI sequences or multidimensional CT to better delineate the anatomic location of the cholesteatoma recurrence (12).

Normal IAC Anatomy
The anatomy of the IAC is best demonstrated on high-resolution T2-weighted images, reformatted in a parasagittal oblique plane perpendicular to the IAC. The IAC contains the facial nerve, vestibulocochlear nerve, nervus intermedius, and labyrinthine artery. The vestibulocochlear nerve exits the brainstem as a single large nerve just posterosuperior to the facial nerve and then divides into the cochlear, superior, and vestibular nerves near the porus acusticus. In the majority of patients, 3-T imaging will also demonstrate the nervus intermedius that exits the brainstem lateral to the motor root of the facial nerve and travels along the posterior aspect of cranial nerve VII until joining the facial nerve just proximal to the mental foramen at the fundus of the IAC (Fig 2) (13). Within the lateral IAC, a transverse segment of bone named the falciform crest bisects the canal along its horizontal axis. The vertical segment of bone, termed the Bill bar, separates the facial nerve from the superior vestibular nerve. A loop of the anterior inferior cerebellar artery also enters the IAC in 20%–40% of individuals and is generally of no clinical significance (14). The numerous small osseous foramina that arise from the IAC, such as the singular and fallopian canals, cochlear aperture, and tiny openings of the fundal cribiform plate, are typically better evaluated with CT (15).

The aptly named labyrinth is anatomically complex. The otic capsule is comprised of the dense temporal bone that forms the structure of the inner ear and is segmented into the semicircular canals, vestibule, and cochlea. This bony capsule contains the membranous labyrinth, which is made up of endolymph-containing ducts and sacs that are separated from the surrounding bone by perilymphatic fluid (16). Within the osseous vestibule are two membranous sacs that detect linear acceleration. One is called the utricle, which is located adjacent to the semicircular canals and innervated by the superior vestibular nerve. This sac detects horizontal linear acceleration. The other is the smaller saccule, which is located near the cochlea and innervated by the saccular branch of the inferior vestibular nerve. This sac detects vertical linear acceleration.

Within the semicircular canals are ducts by the same names. The superior and lateral semicircular ducts are innervated by the superior vestibular nerve, whereas the posterior semicircular canal is innervated by the inferior vestibular nerve. Despite the lateral semicircular canal being commonly referred to as the horizontal semicircular canal, its plane actually rests approximately 30° off the true horizontal. The ducts are follicularly dilated at one end in a region named the ampulla. Each ampulla contains a crista ampullaris, a cone-shaped sensory structure that deflects during movement of endolymph within the ducts, thereby sensing rotational movements. The crista ampullaris is sometimes detectable on high-resolution T2-weighted images and appears as a small low-signal-intensity focus within the ampulla.

The cochlea is made up of the scala media (also known as the cochlea duct) bordered by two perilymphatic channels called the scala tympani and scala vestibuli. The scala vestibuli transmits fluid waves from the oval window, whereas the scala tympani allows the pressure to decompress by propagating the wave to the round window; these meet at the helicotrema within the cochlea apex. Along the inner wall of the cochlear
Figure 2: Normal inner auditory canal and labyrinthine anatomy in a 37-year-old woman. A, B, Axial and, C, reformatted oblique sagittal T2-weighted sampling perfection with application-optimized contrasts by using flip angle evolution (SPACE) MRI scans at 3 T show the expected appearance of the regional anatomic structures. A, On axial image, the facial nerve (long straight black arrow), cochlear nerve (curved black arrow), and inferior vestibular nerve (short black arrow) are all identified. Components of the cochlea, such as the intercalar septa (dashed white arrow) and modiolus (curved white arrow) are easily visualized. The crista ampullaris of the posterior semicircular canal (solid straight white arrow) is also seen. B, Within the cochlea, the spiral lamina/basilar membrane complex (short straight arrow) is seen as a clear border between the scala vestibuli (curved arrow) and scala tympani (long straight arrow), particularly within the basal turn of the cochlea. C, The nerves are often best seen on reformatted images. The facial nerve is located within the anterosuperior cerebellopontine angle (long straight solid arrow), while the cochlea nerve is located anteroinferiorly (curved arrow). The nervus intermedius is located just posterior to the facial nerve (dashed arrow). The superior and inferior divisions of the vestibular nerve are often indistinguishable at this point of the canal (short straight arrow).

Figure 3: Illustration of fluid alterations within the membranous labyrinth in the setting of a vestibular schwannoma. The left image shows normal endolymphatic and perilymphatic fluid; the right image demonstrates a vestibular schwannoma extending into the inner auditory canal, with abnormal labyrinthine fluid. (Image used with permission of Mayo Foundation for Medical Education and Research, all rights reserved.)

spiral, the spiral lamina is usually discernable on 3-T images as a landmark between the scala vestibuli and tympani. Along the outer wall, however, the scala media lies between these structures, bordered by the Reissner membrane ventrally, the basilar membrane dorsally, and the spiral ligament and otic capsule laterally. Although the membranous borders of the scala media have been identified on high-resolution ex vivo MRI scans, they are not typically visualized on clinical 3-T images (17).

Recently it has been noted that gadolinium accumulates over time within the perilymph, leaving the endolymph visible as an unopacified fluid compartment within the bony labyrinth. A few studies have investigated the use of this technique to diagnose endolymphatic hydrops (18,19). Most of these imaging protocols used 3D FLAIR sequences 4–8 hours after intratympanic or intravenous gadolinium administration. However, the use of these techniques remains largely investigational, and they are not routinely employed in clinical practice at most institutions.

Vestibular Schwannomas

Imaging Characteristics

Vestibular schwannomas are benign nerve sheath tumors that arise from the vestibular portion of the eighth cranial nerve. Approximately 95% of tumors are unilateral and sporadic, while the rest of cases typically occur in the setting of neurofibromatosis type 2, which is a condition hallmarked by the development of bilateral vestibular schwannomas (20). Vestibular schwannomas comprise 6%–8% of intracranial tumors and
more than 90% of cerebellopontine angle tumors. Owing to more widespread access to head MRI and greater adherence to screening protocols for asymmetric sensorineural hearing loss, the incidence of vestibular schwannomas has risen from 1.5 to 4.2 per 100,000 population per year in the past half-century (21, 22). Approximately half of tumors will not grow for an extended period of time after initial diagnosis, and the average growth rate among growing tumors is approximately 1–2 mm per year (23). This slow growth rate has imaging implications in that detection of tumor growth will often require comparing the current study to images obtained at more than just one prior annual examination. In addition, volumetric assessment of tumor growth has been demonstrated to be a more sensitive measure of tumor growth than linear diameter assessment (23).

In general, vestibular schwannomas are easily recognizable on images. Compared with adjacent parenchyma, vestibular schwannomas are typically T1 isointense, T2 hyperintense, and avidly enhance with contrast agents. Intralesional cysts and hemorrhage are common, which may contribute to signal heterogeneity and blooming foci with T2*-weighted gradient-echo sequences. Larger tumors often lead to bony remodeling and/or enlargement of the IAC and/or porus acusticus and compression of the adjacent cerebellum, cerebellar peduncles, or brainstem (Fig 3).

Many imaging features of vestibular schwannomas have prognostic value. Not surprisingly, patients with smaller and slower-growing tumors fare better in terms of maintaining serviceable hearing (24). The presence of cerebrospinal fluid located lateral to the tumor within the IAC is associated with better hearing outcomes after surgery (25). Vestibular schwannomas arising from the superior vestibular nerve also have more favorable prognoses in terms of hearing preservation. Cystic tumors, which are composed primarily of large coalescent cysts, are generally faster growing with a shorter clinical history and often treated as more aggressive lesions (26).

Signal intensity alterations exist within the ipsilateral inner ear in patients with vestibular schwannomas. Specifically, FLAIR signal intensity is increased within the perilymphatic fluid, which normally is suppressed with such sequences (Fig 4) (27). The perilymph has long been known to have elevated protein levels in the presence of vestibular schwannomas (labyrinthine taps were used to test for this before nonenhanced CT and MRI), and this proteinaceous fluid has been hypothesized...
as the explanation for such signal intensity abnormalities (28). The clinical significance of the increased FLAIR signal intensity remains uncertain. Some studies have failed to demonstrate an association between the change in signal intensity and the severity of hearing loss (29). Others have found such an association and have suggested that high signal intensity portends a poor prognosis for regaining hearing (30,31). Nevertheless, because intralabyrinthine FLAIR signal intensity changes remain a notable ancillary finding and a topic of continued interest, our institution routinely incorporates 3D FLAIR sequences into our IAC protocol partly to assess for such changes.

Preoperative Evaluation
The goal of microsurgery is maximal resection with preservation of neurologic function (32). Historically, gross total resection was highly prioritized. However, in more recent years aggressive subtotal resection has been used with increasing frequency to preserve facial nerve function. Three types of surgical approaches are used to resect vestibular schwannomas: translabyrinthine, middle cranial fossa, and retrosigmoid (Fig 5). The primary determinants of surgical approach choice are baseline hearing capacity, tumor size, tumor location, and patient age. The middle cranial fossa approach is generally reserved for small intracanalicular tumors in patients with good preoperative hearing levels. In contrast, the retrosigmoid approach can be used for any size tumor, ranging from a small medial-based intracanalicular tumor to a large 5-cm tumor. Although controversial, there are some nuances when choosing

Figure 5: Illustrations and corresponding postoperative MRI scans of the three primary surgical approaches used for resection of vestibular schwannoma. A, The retrosigmoid (suboccipital) approach is performed through an occipital craniotomy placed just posterior and inferior to the sigmoid-transverse junction. The cerebellum is retracted and then bone is removed over the medial two-thirds of the internal auditory canal. B, Postoperative scan demonstrates surgical absence of the posterior wall of the right inner auditory canal (straight arrow); the contralateral side is shown for comparison (curved arrow). Extra-axial fluid related to surgical retraction (*) overlies the right cerebellar hemisphere. C, The translabyrinthine approach entails a wide mastoidectomy, decompression of the sigmoid sinus, labyrinthectomy, and bone removal over the internal auditory canal and presigmoid posterior fossa dura to expose the tumor. D, Postoperative T1-weighted image demonstrates the fat graft within the postoperative site (arrows). E, The middle cranial fossa approach involves a temporal craniotomy with subtemporal extradural brain retraction. The bone overlying the internal auditory canal is then drilled to access the tumor. F, Coronal postoperative image demonstrates the fat graft laid along the roof of the right inner auditory canal (arrows). [Image used with permission of Mayo Foundation for Medical Education and Research, all rights reserved.]
Preoperative imaging helps to both aid in the decision of surgical approach and assess the regional anatomy. In retrosigmoid approach operations, the IAC is accessed by drilling through the posterior meatal lip and decompressing the medial two-thirds of the IAC. Preprocedural planning for this depends on assessing the relationship between the dural sinuses, labyrinth, and tumor. As a general rule, the lateral third of the IAC cannot be directly visualized with the retrosigmoid approach when attempting to preserve hearing; drilling more lateral will risk entry into the vestibule and posterior semicircular canal with resultant hearing loss. Some surgeons advocate using the endolymphatic duct as a reliable surgical landmark while decompressing the IAC for tumor resection when hearing preservation is being attempted. Specifically, if the surgeon is able to stay just medial to the endolymphatic duct, surgical exposure can be maximized without inadvertently drilling into the labyrinth and causing profound hearing loss. Remarkably, most data indicate that drilling along the medial edge of this structure does not incur substantial risk of hearing loss (35).

Preoperative imaging reports should contain information pertinent to future treatment planning. A high-riding jugular bulb should be noted, as it may impede surgical access to the between these two approaches, such as a greater short-term headache risk with the retrosigmoid approach and a greater short-term risk of facial paralysis with the middle cranial fossa approach. In contrast, the translabyrinthine approach by definition sacrifices hearing because the semicircular canals and vestibule are drilled through during the approach. The translabyrinthine approach is often used to resect the vestibular schwannoma in patients with poor baseline hearing or in those with large tumors, where hearing preservation surgery is not realistically feasible.

Furthermore, decisions regarding the treatment of vestibular schwannomas are complex and multifaceted beyond those of surgical approaches. The most common management options—observation, stereotactic radiosurgery, and surgical resection—must be considered in the context of existing neurologic function, tumor size, patient age, comorbidities, and patient preference (33). Conservative management is often initially employed for tumors smaller than 1.5 cm in the cerebellopontine angle (34). Tumors larger than 1.5 cm or those that exhibit growth at serial imaging are frequently treated with either radiosurgery or microsurgical resection, whereas resection is preferred for those larger than 2.5 cm. Familiarity with these treatment approaches is essential for radiologists to play a role in the multidisciplinary management of vestibular schwannomas.

Preoperative radiology reports should contain information pertinent to future treatment planning. A high-riding jugular bulb should be noted, as it may impede surgical access to the...
intrameatal components of a vestibular schwannoma during retrosigmoid operations. Similarly, a high-riding jugular bulb or anteriorly located sigmoid sinus may limit the surgical corridor with the translabyrinthine approach. Intracranial hemorrhage should be described, as hemorrhagic vestibular schwannomas are prone to causing abrupt changes in neurologic function (Fig 6) (36). Finally, preprocedural imaging can help assess for findings that put patients at higher risk for postoperative complications (37). Pneumatization of the temporal bone adjacent to the IAC is a risk factor for cerebrospinal fluid leak, whereas a loop of anterior inferior cerebellar artery adherent to the posterior petrous dura may risk vascular injury. In addition, the presence of chronic ear disease should make surgeons wary of seeding deeper infections (37).

**Postoperative Evaluation and Follow-up**

The expected postoperative imaging findings are dependent on the surgical method employed. Middle cranial fossa approach surger-
ies require intraoperative retraction of the temporal lobe, which may lead to encephalomalacia, gliosis, and, much less commonly, symptomatic seizures or aphasia. In addition, surgeons access the IAC during a middle cranial fossa approach resection by drilling down through its roof. A fat or muscle graft is then often set at the site of the drilling, which is conspicuous on postoperative T1-weighted images. Fat packing after a translabyrinthine surgery, conversely, will be far more extensive and centered within the mastoidectomy cavity. Retrosigmoid surgeries require medial retraction of the ipsilateral cerebellar hemisphere and, consequently, can often be recognized by the ensuing characteristic encephalomalacia that often develops within the retracted tissue.

Currently, our standard postoperative protocol employs gadolinium to assess for residual, recurrent, and/or progressive tumor after vestibular schwannoma resection. Nodular enhancement within the postoperative IAC or cerebellopontine angle is suggestive of recurrent or residual tumor, whereas linear enhancement is presumed to represent postoperative granulation tissue (38). In the setting of subtotal resection, correlation with the operative report, if available, is crucial. Some investigators have suggested that high-resolution 3D T2-weighted sequences are sufficient for such follow-up evaluations (39,40). Kim et al (41), in a recent meta-analysis, found no significant difference between the sizes of recurrent tumors measured on contrast-enhanced and high-resolution T2-weighted images. Furthermore, normal postoperative enhancement can sometimes be confused for residual tumors (42). It is therefore possible that we may ultimately adjust our protocol to exclude the use of contrast material in some cases, particularly as concerns about gadolinium deposition are raised by referring providers and patients.

Figure 10: A, Axial contrast-enhanced MRI scan of the brain shows labyrinthitis ossificans in an 8-month-old boy who developed streptococcal meningitis, which was complicated by subdural empyemas. B, C, MRI scans obtained 1 month later demonstrate avid enhancement and decreased T2 signal intensity within the labyrinthine structures, including the cochlea (arrow in B) and lateral semicircular canal (arrow in C). D, Temporal bone CT scan obtained after MRI demonstrates resorption of the walls of the lateral semicircular canal with faint internal ossification (*). E, Temporal bone CT scan of the normal left side is shown for comparison.
Close attention should be paid to the membranous laboratory in the postoperative setting. Early changes may include T1-hyperintense fluid, typically representing blood products or proteinaceous fluid. FLAIR hyperintensity might suggest the presence of proteinaceous fluid or inflammatory changes. The major concern, however, is that of cochlear luminal obliteration in light of recent interest in cochlear implant following vestibular schwannoma resection (43,44). Patients are prone to such changes after surgery, particularly after those performed with a translabyrinthine approach. Similar to labyrinthitis ossificans that develops from other causes (see the following section), cochlear obliteration appears as decreased, and ultimately absent, signal intensity with heavily T2-weighted sequences. Ossification can be confirmed with CT (45). Enhancement often precedes obliteration in the postoperative setting, often by a substantial period of time. Intense enhancement is seen a median of 5.4 months after surgery (interquartile range, 2.8–7.2 months); obliteration occurs a median of 16 months after vestibular schwannoma resection (interquartile range, 12.0–18.9 months) (46,47).

Labyrinthitis

Labyrinthitis refers to inflammation of the inner ear and a vast majority of cases are infectious, in which the offending agent may enter the inner ear by direct spread (ie, through adjacent structures such as the middle ear [tympanicogenic] or meninges [meningogenic]) or through hematogenic seeding from a remote source (48). Among children, Streptococcus meningitis is the most common cause of labyrinthitis, and meningitic labyrinthitis is the most common cause of acquired sensorineural hearing loss (49). Meningitic labyrinthitis can spread into the inner ear through multiple routes, including by the cochlear aqueduct and modiolus (50). The associated labyrinthitis is usually bilateral. Tympanicogenic infections, conversely, enter the inner ear through the oval and round windows and result in unilateral symptoms (51).

Detection of labyrinthitis is of utmost importance because of its proclivity to progress to labyrinthitis ossificans, a condition that may preclude successful cochlear implantation (discussed later) (52). Classically, MRI demonstrates increased FLAIR signal intensity, decreased T2 signal intensity, and enhancement within the affected areas of the labyrinth (Fig 7) (51,53). Faint intrinsic T1-hyperintense signal may also be seen, likely related to proteinaceous fluid. This is easily differentiated from hemorrhage, which does not demonstrate enhancement. However, results of early imaging may be negative; a normal examination does not exclude the clinical diagnosis of labyrinthitis. Nevertheless, enhancement does have prognostic value. In patients with meningitic labyrinthitis, the presence of enhancement is predictive of future hearing loss, with a sensitivity of 87% and a specificity of 100% (54).

The major imaging differential consideration is that of an intralabyrinthine schwannoma, which demonstrates similar characteristics. Some investigators have sought to use quantitative signal analysis to differentiate between these entities, although this technique is not used in our practice (55,56). Instead, we rely more on clinical and imaging findings. Intralabyrinthine schwannomas demonstrate more focal enhancement than labyrinthitis, have a soft-tissue filling defect on high-resolution T2-weighted images, and tend to enhance more avidly (Fig 8) (57).

Intrinsic T1-hyperintense signal within the labyrinth, conversely, represents presumed intralabyrinthine hemorrhage, also known as hemorrhagic labyrinthitis (Fig 9) (58,59). Often, the T1 signal intensity is patchy and lacks nodularity. Such cases tend to occur in specific clinical situations, such as in the context of trauma, surgery, disseminated intravascular coagulation, systemic lupus erythematosus, sickle cell disease, or the use of anticoagulants (60,61). Intralabyrinthine hemorrhage may also result from bacterial labyrinthitis. Patients typically present with profound sudden sensorineural hearing loss, from which they generally do not recover (62).

Autoimmune labyrinthitis is a known, albeit rare, subtype of labyrinthitis. Patients typically present with steroid-responsive fluctuating bilateral asymmetric sensorineural hearing loss and/or vestibular symptoms and often have other known autoimmune diseases such as ulcerative colitis. Contrary to Meniere disease,
which is usually unilateral, autoimmune labyrinthitis often affects both ears at once (63). MRI findings are similar to those of other causes of labyrinthitis, with avid enhancement of the labyrinthine structures and/or vestibular nerves (64). Although it is often a diagnosis of exclusion, some laboratory tests may support autoimmune labyrinthitis as a clinical consideration, including C-reactive protein level, erythrocyte sedimentation rate, and rheumatoid factor. Autoimmune labyrinthitis, like other forms of labyrinthitis, can progress to labyrinthitis ossificans (65).

**Labyrinthitis Ossificans**

As mentioned earlier, labyrinthitis ossificans results from inner ear inflammation, in which the membranous labyrinth is filled with osseous material (51). Although infection is the most common cause, numerous processes may result in labyrinthitis ossificans. Trauma, surgery, and inflammatory, autoimmune, and sickle cell disease have all been implicated (66,67). Patients often present with sensorineural hearing loss, which can be profound.

Classically, the progression to labyrinthitis ossificans occurs in a predictable pattern. Bacteria and/or leukocytes within the peri-lymphatic spaces are associated with a serofibrinous exudate, which leads to the proliferation of fibroblasts followed by the formation of osteoid matrix (68). These histopathologic changes are categorized into three distinct phases: acute, fibrous, and ossifying. The fibrous and ossifying phases can occur as early as 2 weeks and 2 months after infection, respectively (69).

Nonenhanced CT is useful in end-stage labyrinthitis ossificans, in which the osseous material is easily visualized. However, MRI can play a crucial role in the diagnosis of earlier and/or developing labyrinthitis ossificans, when CT imaging remains normal. Specifically, inner ear fibrosis can be detected with heavily T2-weighted sequences, which demonstrate decreased signal intensity within the affected labyrinthine structures (70). Inner ear enhancement may also be seen in the fibrous stage, though less avidly than that seen during acute labyrinthitis (71). During the ossifying phase, the affected structures are classically devoid of signal intensity on T2-weighted images and will no longer enhance (Fig 10). However, some overlap in imaging features can be seen, particularly between the fibrous and ossifying phases at MRI. CT may be useful in such cases to assess for inner ear ossification.

Labyrinthitis ossificans typically starts within the scala tympani in the basal turn of the cochlea, near the round window (72). This is because the cochlear aqueduct enters the basal turn near the round window and represents a conduit for spread of infection from the subarachnoid space in meningitis. From there, it progresses to the cochlear apex (73). However, any part of the membranous labyrinth can be involved. Postoperative labyrinthitis ossificans most commonly affects the basal turn of the cochlea,

![Figure 12: Recurrent cholesteatoma in a 49-year-old woman who underwent a canal wall up tympanomastoidectomy and ossicular chain reconstruction 10 years earlier for resection of a cholesteatoma. The patient has had recurrent pressure and a sensation of fluid in her ear. A, Axial and, B, coronal diffusion-weighted half-Fourier acquisition single-shot turbo spin-echo images demonstrate a focus of restricted diffusion (arrow) in her operative site, compatible with a recurrent cholesteatoma. C, Axial T2-weighted sampling perfection with application-optimized contrasts by using flip angle evolution (SPACE) image and, D, axial contrast-enhanced T1-weighted SPACE image show nonspecific soft-tissue signal intensity with faint peripheral enhancement (arrows), highlighting the usefulness of diffusion-weighted imaging.](image-url)
vestibule, and semicircular canals. Mineralization patterns of labyrinthitis ossificans resulting from other risk factors are nonspecific and are not useful for determining the etiologic origins (74).

Cochlear Implantation Evaluation

Preprocedural imaging is crucial before placement of a cochlear implant. Temporal bone CT scans are primarily used to assess the bony structures, such as ensuring that the course of the facial nerve is not aberrant, particularly in patients with CHARGE syndrome, branchio-oto-renal syndrome, or dysplasia of the semicircular canals. The IAC diameter should also be noted at CT. A narrowed IAC (<3 mm) or cochlear aperture should alert radiologists to the possibility of vestibulocochlear nerve aplasia or deficiency (75,76). Nevertheless, MRI must be used for confirmation.

As mentioned earlier, the cisternal and canalicular segments of the vestibulocochlear and facial nerves are best scrutinized by using 3D high-resolution T2-weighted images acquired in an oblique plane perpendicular to the IAC. This is particularly important to evaluate in children with bilateral profound congenital hearing loss. Both absence and deficiency, which are generally defined as reduction in nerve caliber, are associated with sensorineural hearing loss. Absence of the nerve is almost always congenital and is generally viewed as an absolute contraindication to cochlear implantation (Fig 11). Deficiency, conversely, is only a relative contraindication, as such nerves can still sometimes successfully transmit neuronal impulses for hearing (77). Small or deficient nerves are typically congenital (hypoplasia) in nature. The average diameter of a normal cochlear nerve in the mid-to-distal IAC is 1.2 mm, similar in caliber to the facial nerve, and is larger than the superior and inferior vestibular nerves in the vast majority of cases (75,78). Comparison to the contralateral nerve can also be useful.

Preprocedural imaging should also be used to closely evaluate for cochlear anatomic variants, especially of cochlear aplasia and types of incomplete partition. Patients with all subtypes of incomplete partition may be candidates for cochlear implant. However, the deformities place them at risk for cerebrospinal fluid “gushers” and electrode misplacement during cochlear implantation and, consequently, at higher future risk for cerebrospinal fluid leak and meningitis. Incomplete partition type III, an anomaly present in X-linked congenital deafness, has the highest risk of potential complications; such cochleae are particularly prone to severe cerebrospinal fluid gushers and have a high likelihood of electrode misplacement. Incomplete partition type III deformities are characterized by complete absence of the modiolus and intact intercalar septa (79). Incomplete partition type I cochlea, in comparison, lack both the modiolus and intercalar septa; incomplete partition type II deformities are limited to the apical aspect of the modiolus and are commonly associated with enlarged vestibular aqueduct.

Finally, as earlier, labyrinthitis ossificans can make electrode placement challenging or even impossible and often leads to partial electrode array insertion (80). MRI is predictive of intraoperative cochlear obstruction, with a sensitivity of 94.1% and specificity of 87.5% (81). In patients with labyrinthitis, the urgency with which cochlear implantation is completed remains somewhat contentious. Some authors have argued for the use of regular MRI follow-up in patients with labyrinthitis, whereas others have opined that some patients should instead be directed to early cochlear implantation (80). Nevertheless, preprocedural MRI is typically recommended to optimize surgical preparation (82).

Cholesteatomas

Cholesteatomas are nonneoplastic expanding accumulations of keratinized squamous epithelium (83). Lesions are locally invasive and are capable of causing substantial destruction to the middle ear and adjacent structures. Complications include conductive hearing loss, facial paralysis, invasion of the labyrinth with subsequent sensorineural hearing loss, and a host of intracranial infection complications (84,85). Resection is typically used for treatment, by means of either canal wall down or canal wall up mastoidectomy. However, cholesteatomas are notoriously prone to reappear, with reported recurrence rates exceeding 7%–10% (86,87).

Nonenhanced CT is the modality most frequently used for initial diagnosis and preoperative planning. Although CT is highly sensitive for the detection of cholesteatomas, it is difficult to differentiate lesions from other soft-tissue attenuation abnormalities such as granulation tissue or mucosal thickening (88,89). Preoperatively, the presence of associated osseous erosion is a useful finding and is the hallmark CT finding of cholesteatomas. Postoperatively, however, nonenhanced CT suffers as a diagnostic tool. A well-aerated tympanomastoid cavity, which is rare in the postprocedural setting, is necessary to exclude residual lesions on a CT scan (90).

For many institutions, including ours, MRI is now the mainstay modality used to assess for residual or recurrent cholesteatomas. This technique is particularly useful in following up patients with prior canal wall up procedures that often include the construction of opaque cartilaginous tympanoplasties, precluding adequate clinical inspection of the middle ear. Previously, MRI evaluations depended on delayed contrast-enhanced images. Cholesteatomas are either nonenhancing or demonstrate thin peripheral enhancement, whereas postoperative and/or inflammatory tissue demonstrates homogeneous enhancement (91,92). In recent years, there has been a substantial rise in the use of non–echo planar diffusion-weighted imaging, which demonstrates conspicuous intratemporal diffusion restriction (Fig 12). This had made MRI a powerful modality when assessing for recurrent lesions, with sensitivity, specificity, and accuracy reported to be 91%–94%, 88%–100%, and 92%–95%, respectively (82,91,93). As such, many institutions have now abandoned the use of delayed contrast-enhanced imaging (94). Others have even questioned whether MRI obviates a second-look surgery following canal wall up mastoidectomies, although diffusion-weighted imaging is limited in its ability to depict small (<3 mm) lesions and those with thin mural growth patterns (95).

False-positive findings do exist and are usually attributed to cerumen, abscesses, and scar tissue (96). Here, review of multiple other sequences is useful to supplement the evaluation for such mimickers. On apparent diffusion coefficient images, cholesteatomas tend to have lower signal than fluid and postoperative granulation tissue (97). On precontrast T1-weighted images, cholesteatomas demonstrate hypointense T1 signal, whereas cholesterol...
granulomas are often hyperintense (98). T1- and T2-weighted images are also useful in anatomically localizing the signal abnormalities seen on diffusion-weighted images. Finally, the morphologic characteristics of any abnormalities should be considered. Wax in the external auditory canal, for example, tends to be linear and/or parallel in configuration (95).

Conclusion

MRI of the inner auditory canal and inner ear is characterized by a diverse array of pathologic conditions. Interpretation of such examinations requires optimized imaging protocols and a sound knowledge of the intricate anatomy. Radiologists must therefore familiarize themselves with the relevant anatomic variants and the diverse array of pathologic conditions that can be seen on these MRI scans. Furthermore, to optimize their usefulness to the ordering providers, radiologists should be well-versed in the expected pre- and postoperative findings related to the most commonly performed surgeries.


References

MRI of the Internal Auditory Canal, Labyrinth, and Middle Ear: How We Do It


