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Surgical Approaches and Complications in the Removal of Vestibular Schwannomas

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Vestibular schwannomas (VS) are benign tumors of Schwann cells that originate on the vestibular portion of the eighth cranial nerve. Found in the internal auditory canal (IAC) and cerebellopontine angle, VS account for nearly 6% of intracranial tumors. Although surgical excision previously had high mortality rates, the advent of the operating microscope and neurotologic and neurologic monitoring has allowed surgical techniques to evolve and morbidity and mortality to be reduced significantly. Currently, complete surgical excision with preservation of facial nerve function is often an achievable goal. The increasing sensitivity of MRI has allowed for diagnosis of smaller tumors and has increased the ability to preserve hearing. Three basic surgical approaches are used for removal of VS: the translabyrinthine, retrosigmoid, and middle cranial fossa (MCF) approaches, which are described in this article. Although many factors influence the choice of surgical approach, personal experience of the surgeon often determines the surgical approach. This article presents the different approaches, their advantages and disadvantages, common complications, and mechanisms to prevent complications.

Surgical history

The first documented case of VS was an autopsy report during the late eighteenth century by Eduard Sandifort [1]. It was nearly 100 years later when Thomas Annandale performed the first complete surgical excision with patient survival. Surgical excision had high mortality rates—in excess of 50%—until the early 1920s, when Harvey Cushing refined techniques and lowered mortality rates to 21% [2]. Cushing's protégé, Walter Dandy, further lowered mortality rates to 10% by the early 1940s [3].

The modern era of tumor dissection began in the early 1960s with the introduction of the operating microscope and the introduction of the translabyrinthine and MCF approaches by William House. Sterile technique, microscopic magnification, and precise otologic drills have continued to lower mortality rates to approximately 1%. Continued earlier diagnosis with the advent of MRI with gadolinium has changed the goals of surgery from complete excision and survival to maintenance of facial nerve function and preservation of hearing when possible [4].

Treatment options

After proper diagnosis, four treatment options are available for VS: observation, stereotactic radiation therapy, complete surgical excision, and subtotal resection with planned radiation therapy.

Observation

The indolent nature of VS has led many physicians to observe tumors that may remain dormant or grow slowly enough to never require treatment. Treatment decisions may be based on patient characteristics, such as age, general health, status of hearing in the contralateral ear, and patient preference, or tumor characteristics, such

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as size, location, and growth rate [5]. Observation is performed via a set schedule of MRI. We scan our patients initially at 6 months and then every year until a general growth rate can be established. If minimal growth has been observed, the MRI every 2 years is possible.

The natural history of VS is enigmatic. The percentage of tumors that grow is generally unknown and has varied widely in studies from 40% to 80% [5–7]. A long-term follow-up of 14 years in more than 1800 patients with observed acoustic neuroma was published recently in which 83% of intrameatal tumors remained intrameatal and 70% of extrameatal tumors did not grow more than 2 mm [6]. All tumors that exhibited growth did so in the first 4 years and maintained consistent growth rates throughout observation [6]. Tumor growth rates can be stratified into slow growing (<2 mm/y) and fast growing (>2 mm/y). Tumors with slower growth rates often do not require treatment [5].

There are difficulties with observation. First, MRI is expensive and patients may be lost to follow-up. Rarely, tumors may undergo accelerated rates of growth after multiple years of stable growth. Patients who require surgery after observation also are older and may suffer from more comorbidities, which makes surgery potentially more risky. Finally, tumors with continued growth may no longer meet criteria for hearing preservation approaches or radiation therapy and may make facial nerve preservation more difficult.

Advantages to observation are the obvious delay and potential elimination of the need for surgical or radiosurgical intervention. Older patients may develop or have exacerbation of existing disease that may take precedence over treatment of the tumor (ie, cancer, stroke, cardiac disease). Younger patients may choose to observe the tumor to determine growth and choose intervention only when growth has been established. Economic reasons, such as retirement, job changes, or insurance issues, may compel a patient to choose observation as an initial option. Family issues, such as a wife/husband or child with an illness or other family issues (child starting school/college), also may compel a patient to choose observation.

Radiation therapy

Although surgical resection has the goal of complete tumor removal, radiation therapy has the primary goal of tumor control. Leksell performed the first stereotactic radiosurgery for VS in 1969. Techniques have evolved and outcomes with fewer side effects are currently possible. Although most tumors are controlled successfully, nearly 9% of tumors exhibit growth after radiation therapy. Surgery after failed radiation therapy is more difficult to perform because intense scarring and fibrosis obscure surgical planes. As a result, facial nerve outcomes are poorer than in patients with nonirradiated tumors [8–10]. Because VS are known to be slow growing, it is difficult to study techniques (radiation therapy) that slow or eliminate tumor growth. Long-term studies are needed to determine the effectiveness of radiation therapy over observation and surgery to treat VS.

Surgery

The goal of surgery is complete tumor removal while preserving neurologic function and hearing, if possible. Each of the three main approaches for surgical removal of VS has advantages and disadvantages (Table 1). The retrosigmoid and MFC are the two surgical techniques most commonly used in VS surgery when attempting to preserve hearing. Hearing preservation may be attempted when the pure-tone average is 50 dB or less and the speech discrimination is more than 70%. Tumor size also determines whether hearing preservation is attempted, because a tumor $\geq$2 cm is rarely amenable to hearing preservation despite initial hearing status. Location also may play a role in hearing preservation because tumors far lateral in the IAC with extension into the cochlea or vestibule may not be amenable to hearing preservation.

All procedures are performed under general anesthesia with neurophysiologic monitoring. Facial EMG electrodes are inserted into the obicularis oris and occuli muscles for continuous facial nerve monitoring. Auditory brainstem response is used in hearing preservation cases with an acoustic ear insert in the external auditory canal, a recording electrode placed at C0 on the vertex, a reference in the ipsilateral ear lobule, and a ground in the shoulder. Perioperative antibiotics and steroids are used. Mannitol (1 g/kg) is given just before opening the dura in all cases.

The translabyrinthine approach provides wide access to the posterior fossa with little or no need for brain retraction. The anatomy is familiar for the neurotologist but often is unfamiliar to the neurosurgeon. The facial nerve is identified early in the case laterally at the fundus of the internal IAC and medially at the brainstem. This lateral surgical approach allows for the facial nerve to be

Table 1
Advantages and disadvantages of surgical approaches for removal of vestibular schwannoma

	Translabyrinthine	Middle fossa	Retrosigmoid
Advantages	Consistent facial nerve identification No tumor size limitation No intradural drilling Wide exposure posterior Fossa Low recurrence rates ABI placement possible Low rate of headaches	Best hearing preservation No intradural drilling Low rate of headaches	No tumor size limitation Hearing preservation possible Wide exposure brainstem ABI placement possible Consistent facial nerve identification Neurosurgeon familiarity
Disadvantages	Complete hearing loss Neurosurgeon unfamiliarity Abdominal fat graft	Limited tumor size Temporal lobe retraction Limited exposure posterior Fossa Increased risk of recurrence of tumor in an unfavorable position related to the facial nerve	Limited exposure of lateral IAC Intradural drilling Postoperative headaches Cerebellar retraction Facial nerve identification is relatively late in the dissection

Abbreviation: ABI, auditory brainstem implant.

in a favorable place deep in the IAC and places the vestibular nerves laterally, where the surgeon encounters the vestibular nerves initially on IAC dissection. The main disadvantage of this approach is the lack of ability to preserve hearing.

The MFC approach was seldom used for tumors until recently because most tumors remained undiagnosed until they were too large to be removed by MCF. Its popularity has increased recently as imaging technology has allowed for detection of small tumors and tumors with up to 1 cm in the cerebellopontine angle are amenable to this technique. Although this approach has the most favorable hearing preservation rates, the technique is challenging because the facial nerve lies between the surgeon and the tumor and the principal anatomic landmarks for identification of the IAC are less reliable and may be obscured. The superior approach to the IAC makes the facial nerve and the superior nerve the first encountered by the surgeon on dissection through the temporal bone. Elevation and retraction of the temporal lobe also carry the risk of brain injury, including aphasia, seizures, and stroke.

The retrosigmoid approach traditionally has been the most widely used approach because of its popularity among neurosurgeons and its wide versatility. It affords wide exposure of the posterior fossa, can be used for excision of small and large tumors, and offers an opportunity for hearing preservation. Intradural drilling of the IAC is required. Like the translabyrinthine approach, lateral surgical approach allows for the facial nerve to be in a favorable position deep in the IAC and places the vestibular nerves laterally, where the surgeon encounters the vestibular nerves initially on IAC dissection.

Surgical approaches

Retrosigmoid approach

The patient is positioned in a modified park bench position, lying supine with the ipsilateral shoulder and hip bumped with rolls and padding. The patient's head is flexed and rotated toward the opposite shoulder and secured with Mayfield pinions. This simple and straightforward position enables excellent visualization of the contents of the posterior fossa. Extreme rotation and flexion may cause venous occlusion and should be avoided. Somatosensory evoked potentials are monitored throughout the case. Potential changes in the waveforms may indicate compromise of the vascular system or spinal compression. Hair is prepped with betadine solution and shaved for four finger breadths behind the ear.

As shown in Fig. 1, a curvilinear "C" incision is made into the posterior scalp down onto the neck. The incision is approximately 4 cm posterior to the ear canal. The incision is carried through

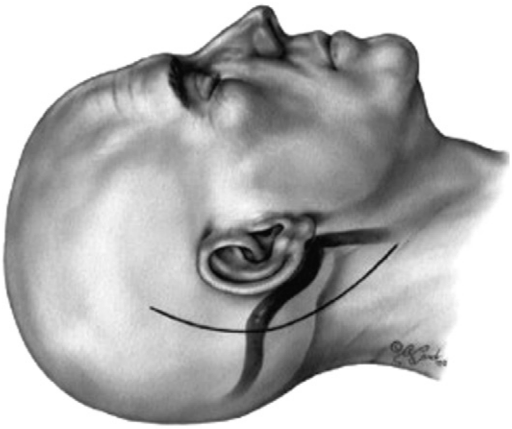

Fig. 1. Skin incision for retrosigmoid approach.

the skin and subcutaneous tissues and an anterior flap is dissected for nearly 1 cm. Electrocautery is used to incise the musculoperiosteum down to the bone. Offset incisions allow for overlapped closure and a reduced incidence of incisional cerebrospinal fluid (CSF) leaks.

As shown in Fig. 2, a 4 × 4 cm craniectomy is performed. The anterior and superior limits of the craniotomy are the sigmoid and transverse sinuses, respectively. As a general rule, the external ear canal approximates the level of the transverse sinus. Laterally exposed mastoid air cells near the sigmoid sinus are occluded with bone wax to prevent transgression of CSF at initial opening and again at the end of the case. The dura is then opened, as shown along the dashed lines in Fig. 2, and the dural flaps are reflected laterally and secured with sutures. The dural flaps are routinely irrigated throughout the case to avoid desiccation. Moist cottonoid pledgets are placed over the cerebellum to avoid intraoperative injury and prevent desiccation throughout the case. The cisterna magna is opened anteroinferiorly to the cerebellum with a right angle pick to allow CSF egression, which maximizes posterior fossa relaxation and minimizes the need to retract the cerebellum during the case.

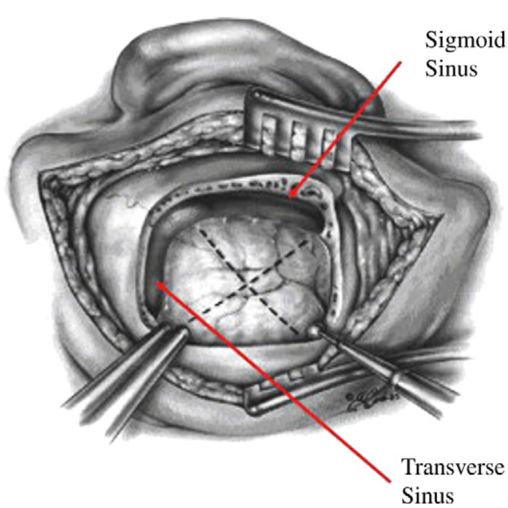

Fig. 2. Craniotomy for retrosigmoid approach.

The tumor and the seventh to eighth nerve complexes are identified at the brainstem and dissection is performed in a cooperative fashion between the neurosurgeon and neuro-otologist. The lateral surface of the tumor is examined for a rare lateral displacement of the facial nerve or major vascular structure. Visual inspection of the IAC is often difficult until large tumors are internally debulked. If still difficult to visualize, the IAC can be palpated with blunt instrumentation. The dura above the IAC is coagulated with bipolar cautery in an arc several centimeters above the posterior lip of the IAC before making a similar incision. The dura is then elevated down to the porus acousticus of the IAC and reflected over the tumor. Several cotton balls are placed medially to the IAC to prevent bone dust from accumulating in the cerebellopontine angle.

Dissection begins with an otologic drill and medium-sized cutting burs until the IAC is approached. Diamond burs are then used to create superior and inferior troughs closer to the IAC until nearly 180° to 270° of bone is removed around the posterior IAC (Fig. 3). Exposure of the IAC continues laterally until the IAC appears normal and the end of the tumor is encountered. For hearing preservation to be accomplished, the common crus of the bony labyrinth and the vestibule must not be injured during dissection. Drilling continues until a thin layer of bone remains over the IAC dura. This bone is removed with careful dissection and the IAC dura is then opened. It is preferred to gain exposure of the IAC lateral to the tumor before opening the dura. Keeping the dura intact provides a protective layer to the contents of the IAC during drilling. Opening the dura too early requires further drilling laterally to gain tumor control with an open IAC. The superior vestibular nerve, inferior vestibular nerve, and tumor are identified in the posterior aspect of the canal. Gentle retraction

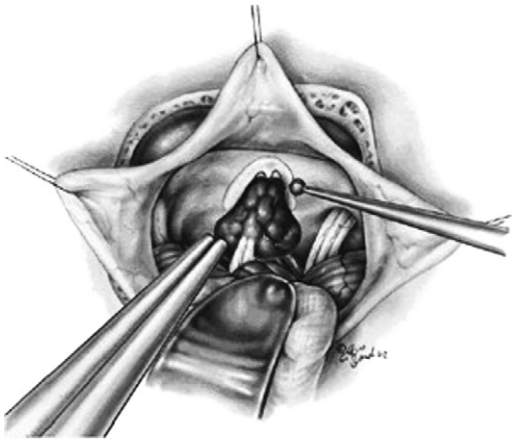

Fig. 3. IAC dissection in retrosigmoid approach.

of the superior vestibular nerve reveals the facial nerve, which is identified physiologically with a stimulator at minimal settings (0.05 mA). The vestibular nerves are sectioned laterally, and tumor dissection is performed in the plane between the tumor and the facial and cochlear nerves in a lateral to medial fashion. Endoscopic assistance with a 30° endoscope also may be valuable to inspect the lateral IAC and reduce the risk of residual disease.

Once the tumor dissection is complete, the operative field is copiously irrigated and hemostasis is achieved with bipolar cautery. The entire bone surrounding the IAC is sealed with bone wax applied with a cotton pledget. Gelfoam is then placed over the remaining seventh and eighth nerve complex and fibrin glue is used to reinforce the seal of the IAC. The dura is then closed with running 3-0 nylon closure. Fibrin glue is placed over the closure of dura. The subcutaneous tissues and skin are closed in several layers with absorbable 2-0 and 3-0 vicryl sutures and staples are placed in the skin. A compressive dressing is placed over the wound to apply pressure in the postoperative period. The patient is kept in the neurointensive care unit for 24 to 48 hours and kept on steroids and antibiotics.

Translabyrinthine approach

The patient is placed in the supine position and the head is turned away from the operative side. The initial positioning is much simpler with this approach than with the retrosigmoid approach—no pins, head holders, or park bench positioning is required. The hair is prepped with betadine solution and four fingerbreadths of hair are shaved above and behind the auricle. As shown in Fig. 4, a C-shaped incision is made extending from one finger breadth above the ear and two finger breadths behind the postauricular crease down to one finger breadth posteroinferiorly to the mastoid tip. The incision is made through the skin and a skin flap is elevated for 1 cm toward the ear through the entire incision. The stepped incision allows for easier closure and prevention of CSF leak. A large superficial temporal fascial graft is harvested and placed on a block. As shown in Fig. 4, a C-shaped musculoperiosteal incision is made with electrocautery from just above the temporal line to the mastoid tip. This incision is offset from the cutaneous incision by 1 cm throughout the incision. The periosteum is elevated to the external auditory canal and retracted with dura hooks. Several large pieces of digastric or sternocleidomastoid muscle are harvested for later use in packing the middle ear.

The bony exposure is performed in three stages: complete mastoidectomy, labyrinthectomy, and IAC dissection. Most of the drilling is performed with cutting burs; however, diamond burs are used when dissection is around critical areas. A complete mastoidectomy is performed, skeletonizing the bone overlying the sigmoid sinus and the tegmen. As shown in Fig. 5, the facial nerve is identified throughout its mastoid course with a large diamond bur. In previous reports the facial recess was opened, the incudostapedial

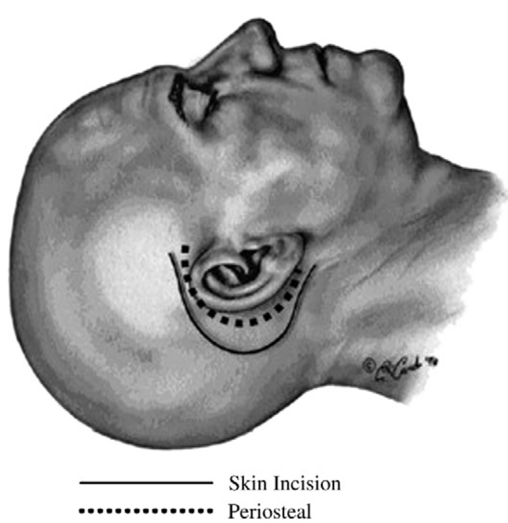

Fig. 4. Skin and periosteal incisions for translabyrinthine approach.

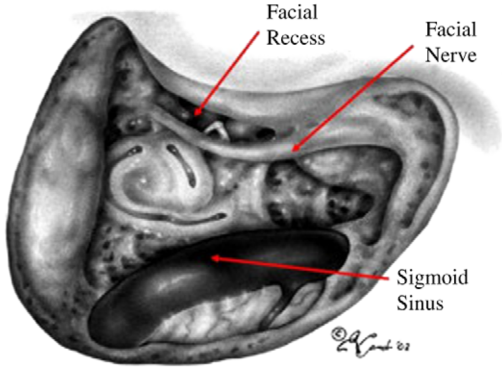

Fig. 5. Mastoidectomy and start of labyrinthectomy.

joint was separated, and the incus was removed. Currently, the senior author does not open the recess or remove the incus unless needed for exposure, leaving less exposed area to seal from CSF leak. All bone is removed from the middle fossa dura, sinodural angle, sigmoid sinus, and posterior fossa down to the level of the labyrinth. Nearly 1 cm of bone is also removed from the posterior fossa dura behind the sigmoid to allow for sinus retraction if necessary.

A complete labyrinthectomy is performed using a diamond bur after the labyrinth is skeletonized and the jugular bulb is identified. The three semicircular canals are removed starting with the horizontal canal. The posterior canal is then opened from its midportion to the common crus. The superior canal is removed and the inferior portion of the posterior canal is removed. The vestibule is opened widely.

Bone from the inferior, posterior, and superior aspects of the IAC is removed with diamond burs. The orientation of the IAC is roughly parallel to the external auditory canal. All bone surrounding the IAC is skeletonized to an eggshell thickness from the middle and posterior fossa dura onto the IAC before removing any bone or opening the dura. The inferior border of the IAC is skeletonized before the superior as the facial nerve is in the superior IAC. The fundus of the canal is exposed just medial to the vestibule, and the transverse crest that separates the vestibular nerves is identified.

The dura of the IAC is then sharply opened. The transverse and vertical crests in the lateral aspects of the IAC are identified with a right angle pick. The superior vestibular nerve is gently displaced while palpating the vertical crest or "Bill's bar" to allow visualization of the facial nerve, which is confirmed electrophysiologically with stimulation at minimal settings (0.05 mA) (Fig. 6). A small right angle hook is used to avulse the superior vestibular nerve laterally and expose the facial nerve. The inferior vestibular nerve and cochlear nerves are then separated laterally. The contents of the IAC are dissected from the facial nerve in a lateral to medial fashion. The posterior and middle fossa dura surrounding the IAC is opened for visualization of the cerebellum, brainstem, and cerebellopontine angle component of the tumor. Internal debulking of the tumor is performed with ultrasonic aspiration or a laser to allow for infolding of the tumor and dissection away from the facial nerve and brainstem. The remainder of the tumor is dissected from the facial nerve and brainstem until completely removed.

The surgical field is then copiously irrigated. Meticulous attention to closure is important for preventing CSF leak. The packing of the eustachian tube orifice and the middle ear is important in that regard. The bone of the promontory is abraded with a small right angle pick and the middle ear, vestibule, and eustachian tube are occluded with previously harvested muscle. The fascia graft is then used to cover the antrum. No attempt at primary reconstruction of the opened posterior fossa dura is performed at our institution because it is removed at initial opening. Abdominal fat is cut into strips and used to pack the mastoid defect down to the level of the IAC. The mastoid periosteum is then closed with interrupted 2-0 vicryl sutures. The skin is closed watertight with 3-0 vicryl sutures and staples externally. A compressive dressing is placed on the incision.

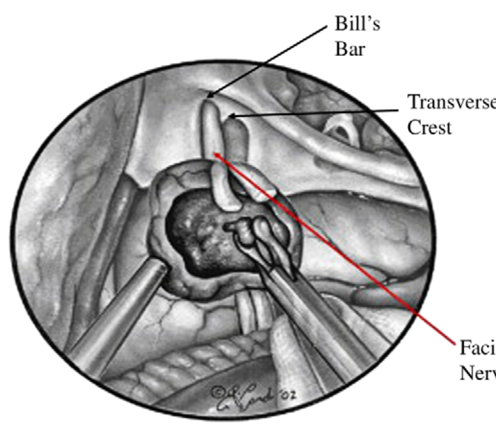

Fig. 6. IAC dissection in translabyrinthine approach.

Middle fossa approach

The patient is placed in a supine position with the head turned to expose the ear of interest. The hair is prepped with betadine solution and four fingerbreadths of hair are shaved above the auricle. The patient is then prepped and draped in the usual fashion. Unlike other surgeries, the surgeon sits at the head of the bed. Although some surgeons prefer a vertical incision through the skin, a broad, posteriorly based, U-shaped skin flap is designed. The anterior aspect of the incision should be left posterior to the natural hairline to camouflage the scar. As shown in Fig. 7, an anteriorly based U-shaped incision is made through the musculoperiosteal layer to skull after the entire skin flap is elevated posteriorly. A Lempert elevator is used to elevate the periosteum to the anterior limit of the incision.

Careful palpation with blunt instrumentation allows identification of the external auditory canal. A 4 × 4 cm craniotomy is performed with the opening roughly two-thirds anterior to the external auditory canal and one-third posterior. A 4-mm cutting bur is used for most bone removal, but a diamond bur is used to remove the last layers of bone over the dura. The bone flap is dissected free from the underlying dura and preserved for reconstruction at the end of the case. The bone inferior to the craniotomy is removed down to the level of the external auditory canal.

Using the microscope and a freer elevator, the middle fossa dura is then elevated off the temporal bone medially to the petrous ridge. Dissection proceeds in a posterior to anterior direction to avoid trauma to the geniculate ganglion and greater superficial petrosal nerve, which may be dehiscent in up to 15% of patients. Anteriorly, dissection stops short of the foramen spinosum and middle meningeal artery.

As shown in Fig. 8, a House-Urban retractor facilitates retraction after dural elevation. Pressure from CSF is relieved with hyperventilation to lower pCO_2 and mannitol. The temporal floor is inspected for clues to identifying the IAC, including the arcuate eminence overlying the superior semicircular canal, the greater superficial petrosal nerve, and the external auditory canal. The semicircular canal is blue-lined in an anterolateral direction to expose the lateral extent of the canal near the IAC.

Although there are several methods available to identify the IAC, we prefer to identify the IAC medially away from the labyrinth and cochlea at the porus acousticus. The plane of the IAC can be approximated by bisecting the angle between the greater superficial petrosal nerve and superior semicircular canal. Drilling along the petrous ridge helps localize the IAC safely. As drilling is extended laterally toward the fundus, smaller diamond burs are used and dissection is performed directly over the canal to avoid injury to the underlying cochlea anteriorly and labyrinth posteriorly. The facial nerve is traced laterally to expose the geniculate ganglion and the labyrinthine segment of the facial nerve.

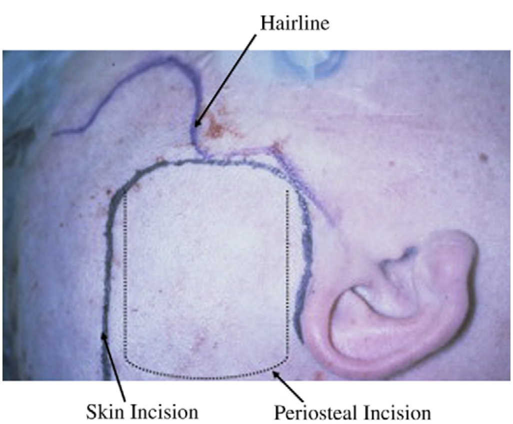

Fig. 7. Skin and periosteal incisions in middle fossa approach.

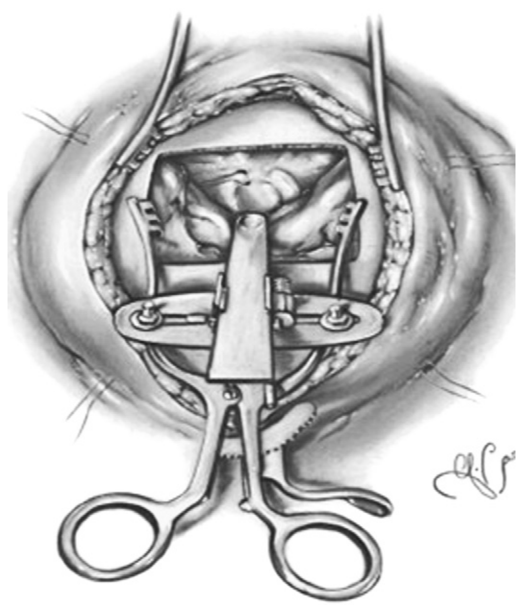

Fig. 8. Middle fossa exposure after dura retraction.

The dura of the IAC is then opened parallel to the long axis of the IAC. The facial nerve is identified in the anterior aspect of the IAC and physiologically with a facial nerve stimulator on minimal settings. The tumor is dissected from the facial nerve throughout the IAC. Once the facial nerve is separated, a small right angle hook is used to avulse the superior and inferior vestibular nerves laterally. As shown in Fig. 9, the tumor and vestibular nerves are then dissected free from the facial and cochlear nerves in a lateral to medial fashion. The dissection may be extended medially along the petrous ridge for larger tumors. Once the tumor is dissected free from the IAC, the vestibular nerve is sharply sectioned medially and the tumor is removed.

The surgical field is then copiously irrigated. The peri-IAC air cells are sealed with bone wax to avoid postoperative CSF leak. Muscle or fat is placed in the lateral IAC. The temporal lobe is then released. The craniotomy is replaced and secured with small titanium reconstruction plates. The musculoperiosteal flap is then secured with interrupted 2-0 vicryl sutures and the skin with 3-0 vicryl sutures. The skin is reinforced with staples, and a compressive dressing is placed.

Complications

Although complications rates are reduced with increasing experience, they still occur at a predictable rate [11]. The key to managing complications is twofold. First, prevent complications from occurring with meticulous technique and attention to detail. Second, detect problems early and initiate appropriate therapy in a timely fashion.

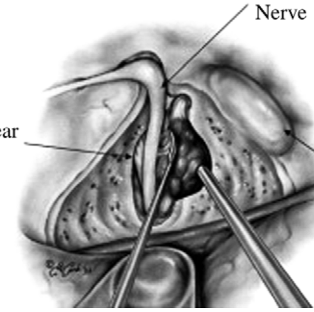

Fig. 9. IAC dissection in middle fossa approach.

Recurrence

Recurrent tumor is usually the result of regrowth of residual tumor fragments. Despite total removal of all microscopically visible tumor, remnants of nerves may contain undetectable tumor cells. Because recurrent tumors do not cause symptoms until they become extremely large, imaging with gadolinium-enhanced MRI is the primary way to detect a recurrence [12]. Because imaging protocols can be used to suppress the signal from fat (fat suppression protocols) and other reconstruction materials, including muscle and fascia, may become indistinguishable from tumor, fat should is best used to reconstruct surgical defects [12]. Linear enhancement of the dura is consistent with inflammation or scar, whereas nodular enhancement is suspect for recurrent or residual tumor [13]. Postoperative MRI within the first year often shows contrast enhancement of dura in involved surgical resection secondary to inflammation and scar. If the image shows an abnormality such as dural enhancement, we proceed with imaging 2 years later. If the first image is normal, a single follow-up scan is obtained at 5 years, with the exception of patients with NF2 who require continuing surveillance.

Subtotal removal of tumor is sometimes necessary to preserve the integrity of the facial nerve or brainstem. Rigorous hemostasis during surgery reduces the vascularization of the remaining tumor and may stop regrowth of tumor [12].

Shelton reported 0.3% recurrence rate on more than 1500 translabyrinthine approaches. No predictive factor of recurrence has been identified for recurrence, including tumor size or patient age [14]. Recurrences are rare after 10 years, regardless of the approach. One disadvantage of the hearing preservation approaches is that the dissection in the lateral IAC dissection is often performed blindly and tumor may be missed in the fundus of the IAC. Blevins and Jackler [15] demonstrated that the lateral one third of the IAC must be left unexposed to avoid injury to the underlying labyrinth in the retrosigmoid approach. In the middle fossa approach, Driscoll and colleagues [16] found that the lateral 14% to 34% of the inferior IAC is obscured by the transverse crest. This would only present a problem in lateral tumors that originate on the inferior vestibular nerve. The translabyrinthine approach allows visualization of the entire IAC and allows dissection of tumor from facial nerve from the fundus of the IAC to the brainstem. The cochlear nerve is usually removed, which reduces the risk of residual tumor cells being left behind.

Recently, there has been growing interest in the use of endoscopes during surgery to see beyond the limits of the microscope and "to look around the corner." Endoscopes offer outstanding illumination and allow for dissection of neoplasm in the most lateral aspect of the IAC without disruption of the labyrinth [17]. Difficulties passing angled scopes without damaging vital structures and concerns over increased local temperature caused by the light have limited its use [18].

Medical complications

The mortality for VS surgery is approximately 1% in most large series and usually is the result of neurovascular insult [19]. A preoperative medical evaluation by an internist who follows patients postoperatively helps minimize nontumor complications, including myocardial infarction, pneumonia, pulmonary embolus, and deep venous thrombosis, that occur in frequencies similar to other major surgical procedures [20].

Tinnitus

Although more than half of patients without tinnitus preoperatively experience it postoperatively, nearly 50% of patients with preoperative tinnitus experience a significant reduction in their tinnitus postoperatively [21]. Most patients compensate well to the tinnitus and rarely are distressed by symptoms.

Equilibrium

Most patients experience acute vertigo after surgery for VS. The severity of postoperative vertigo is directly proportional to the preoperative vestibular function seen on preoperative electronystagmography. Preoperative electronystagmography also identifies patients with bilateral vestibular hypofunction who may have more difficulty compensating after surgery. Patients begin vestibular rehabilitation early in the postoperative period and are encouraged to participate in activities that challenge their vestibular system after discharge. Recovery of balance is nearly universal by 6 to 9 months after surgery.

Cerebrospinal fluid leak

CSF leak is the most common postoperative complication after VS resection, and it occurs in approximately 10% of patients [22]. The MCF approach has a slightly lower rate than the other two approaches [22]. CSF leaks complicate the postoperative course because they can lead to meningitis, increased hospital stay, and reoperation. CSF leaks increase the risk of meningitis. Although the overall risk of meningitis is between 1% and 3%, a CSF leak raises the risk to roughly 14% [22]. Leaks may be evident immediately after surgery or after discharge from the hospital.

CSF may escape through the skin or the nose via the eustachian tube. Although most leaks after the translabyrinthine and MCF approaches present as rhinorrhea, rhinorrhea and incisional leaks are nearly equal after the retrosigmoid approach. CSF leaks through the incision are secondary to failure to obtain a watertight closure. They generally respond to conservative therapy, such as bedside placement of a suture, pressure dressings, and bed rest, in 60% to 70% patients [23]. Rarely is a lumbar drain or operative intervention required. CSF rhinorrhea is the result of spinal fluid gaining access to the middle ear cleft or eustachian tube, and it usually requires more invasive measures because spontaneous resolution occurs in only approximately 10% to 20% of cases [19]. An additional 30% to 70% of cases may resolve with the placement of a lumbar drain [23]. Typically, lumbar drains are used for 2 to 5 days. The drain is then clamped and, if the leak does not recur, it is removed. Patients must be closely monitored, which often necessitates a prolonged intensive care unit course. Although lumbar drains are successful in most patients, operative intervention has the highest success rate (80%–90%) [23].

Closure of the middle ear and eustachian tube with temporalis muscle creates a significant conductive hearing loss, which is insignificant after the translabyrinthine approach or other nonhearing conservation procedures. Although opening a facial recess affords better visualization of the eustachian tube, it also opens a larger route to the middle ear cleft. The vestibule is also packed with muscle and sealed with fibrin glue to prevent CSF from leaking through the vestibule and stapes footplate into the middle ear. If a CSF leak occurs in the immediate postoperative period, conservative therapy with head-of-bed elevation and a pressure dressing may be successful. Persistent drainage requires a lumbar drain or re-exploration of the surgical field. If the CSF leak persists, eustachian tube obliteration may be necessary.

The lateral dura contracts and hardens during the case, which often makes a water-tight closure difficult after the retrosigmoid approach. Reinforcement with synthetic dura lateral to the dural closure helps reduce incisional leaks. CSF also may present as rhinorrhea after the retrosigmoid approach. CSF may enter the middle ear cleft through nonoccluded peri-IAC air cells directly or mastoid air cells near the craniotomy site. The lateral cells should be occluded with bone wax initially after the craniotomy and again at closure. The peri-IAC cells are more difficult to obliterate and require diligent application of bone wax after tumor dissection in the IAC. Sealing this area with fibrin glue also helps to reduce the incidence of CSF leak. Postoperative CSF rhinorrhea is usually controlled with conservative measures, including bed rest and lumbar drain placement. Recalcitrant cases may require reoperation with resealing of the mastoid and peri-IAC air cell system. If the CSF leak persists, a mastoidectomy, packing of any retrosigmoid-mastoid fistula, or obliteration of the middle ear and eustachian tube may be indicated.

CSF leaks after MCF almost exclusively present as rhinorrhea. CSF may leak through peri-IAC air cells or defects between the IAC and middle ear. The defects and air cells around the IAC are occluded with bone wax and fat is used to plug the lateral IAC defect at the end of the case. If a leak develops postoperatively, observation, bed rest, and lumbar drainage are often successful. Recalcitrant cases may require exploration through a transmastoid approach to identify the problem. If no useful hearing is present, obliteration of the middle ear and eustachian tube often stops the CSF rhinorrhea.

Meningitis

Increased survival after VS surgery is in no small part secondary to the dramatic reduction in bacterial meningitis since the advent of antibiotics. Meningitis occurs in 1% to 8% of cases and may be either bacterial or aseptic [24]. Aseptic meningitis occurs more commonly than bacterial and is usually secondary to inflammation from bone dust or blood. Meningitis rates are several folds higher in the presence of a postoperative CSF leak [22]. The diagnosis is difficult because most patients already have symptoms of headache, neck pain, and low-grade fevers in the immediate postoperative period. Any suspicion necessitates a lumbar puncture and aggressive therapy with broad-spectrum antimicrobial therapy and steroid prophylaxis while awaiting cultures. Although spinal fluid analysis is often difficult because of contamination with normal postoperative inflammatory mediators and blood, protein counts >200 mg/dL, glucose <40 mg/dL, and white blood cell counts $>1000/\text{mm}^3$ are important clues in making the diagnosis of bacterial meningitis [25]. Aseptic meningitis responds quickly to steroids, which are slowly tapered over 3 to 4 weeks to prevent recurrent symptoms.

Facial nerve

Standard universal reporting of outcomes with the House-Brackmann facial nerve scale allows for easy comparison between studies. Generally, grade I or II is defined as good postoperative facial nerve function, grade III or IV as intermediate, and grade V or VI as poor. The importance of neurophysiologic monitoring toward facial nerve outcomes cannot be stressed enough in skull base cases.

The facial nerve is thinned with tumor growth, which reduces the nerve's resilience to manipulation. In studies with large series, facial nerve outcomes are reduced with increasing tumor size or preoperative nerve dysfunction [19]. Tumors may be defined by the size of the tumor in the cerebellopontine angle as intracanalicular (none), small (<15 mm), medium (15–30 mm), and large (>30 mm). The facial nerve is anatomically preserved in 95% to 100% of cases and nerves that stimulate with minimal settings have a 90% chance of grade I-II outcomes at 1 year [26]. In the event of facial nerve transaction, immediate repair should be accomplished; postoperative care with artificial tears, lubricant, and gold weight insertion are encouraged while the facial nerve regains function. Good facial nerve outcomes should be seen in at least 95% of intracanalicular tumors, 85% of small tumors, 75% of medium tumors, and 40% of large tumors [19]. Although a surgeon's experience correlates directly with facial nerve outcomes, there does not seem to be a difference among the surgical approaches [7,27,28]. Tumors resected by a retrosigmoid or MFC approach are more likely to have immediate facial nerve weakness because of neuropraxic injury from intraoperative manipulation. At 1 year there was no difference between approaches, however [29–40].

Delayed facial nerve dysfunction may occur in up to 40% of cases [41]. Similar to Bell's palsy, the delayed weakness has been attributed to edema of the facial nerve or reactivation of virus molecules in the geniculate ganglion. Fortunately, steroids reduce this edema; most patients (90%) recover completely and the remaining patients regain most of their facial nerve function.

Hearing preservation

The three most important factors in determining hearing preservation are preoperative hearing thresholds, tumor size, and the distance between the lateral extension of tumor and the vestibule [42–44]. Two surgical approaches allow for hearing preservation by leaving the labyrinth and cochlear nerves intact: the MCF and the retrosigmoid. Intraoperative monitoring allows for detection of hearing function and preservation. Alterations in the intraoperative auditory brainstem responses should prompt cessation of surgical manipulation until tracings return to baseline. Although there are various classification systems, the American Academy of Otolaryngology–Head and Neck Surgery system is the most universally adopted system. The system is useful to help gauge overall hearing, but useful hearing depends on preoperative hearing and more importantly the status of the contralateral ear. This classification scheme is particularly misleading in patients who fall near division lines because clinically insignificant changes may result in class changes (Table 2).

The overall rate of serviceable hearing preservation, class A or B, for tumors <2 cm is 40% to 50% [24]. The MFC yields better hearing preservation than the retrosigmoid approach. The MFC yields hearing preservation rates between 50% and 70%, whereas the retrosigmoid approach yields hearing preservation between 30% and 40% [24,45]. The better results of the MFC route may be related to better preservation of the vascular supply to the cochlea and cochlear nerve or smaller tumors generally removed through this approach. The internal auditory artery runs in the anterior IAC between the facial and cochlear nerves and is protected by the facial nerve from manipulation in the MCF approach. One advantage of the retrosigmoid approach is the unique possibility of real-time intraoperative monitoring via direct recordings from the eighth nerve at the brainstem.

Table 2
American Academy of Otolaryngology—Head and Neck Surgery hearing classification scheme

Class	Pure-tone threshold (dB)	Speech discrimination (%)
A	≤ 30	≥ 70
B	>30 but ≤ 50	≥ 50
C	>50	≥ 50
D	any	<50

The likelihood of hearing preservation also depends on the distance between the tumor and the IAC fundus. Generally, if the distance from the IAC fundus is <3 mm, the likelihood of hearing preservation is lowered [46]. Hearing is vulnerable when the tumor extends laterally for two reasons: (1) The cochlear nerve is vulnerable to avulsion from the modiolus when dissecting tumor laterally, which is the precise reason for sharp and not blunt dissection. (2) The labyrinth or cochlea also may be injured in extending exposure laterally.

Headaches

The incidence of headache that lasts beyond the initial postoperative period ranges from 0% to 65% [47–50]. It does not seem to be correlated with age, gender, and operative time. Patients with smaller tumors tended to have more headaches. Persistent headaches are not common in patients undergoing resection of VS via either MFC or translabyrinthine approaches [47,49]. Initial discomfort after surgery is expected and related to the incision, reduced CSF pressure, dural irritation, and muscle spasm [50]. Fortunately, most headaches resolve over subsequent months to years, and only 10% of patients continue to experience headaches.

Several mechanisms have been proposed for headache after retrosigmoid excision of acoustic neuroma. Tight dural closure may result in excess tension and irritation of the dura. Dural adhesions to nuchal muscles also may result in intermittent stretching and traction of the dura with head movements or straining. Finally, intradural drilling results in bone dust, which may be the source of aseptic meningitis and associated headache. The surgeon must attempt to prevent the incidence of headaches when possible. First, careful placement of Gelfoam in the posterior fossa may collect bone dust during drilling and reduce postoperative inflammation. Second, periodic moistening of the dural flaps helps prevent dessication and allows easier closure. Finally, replacement of bone flap at the end of surgery significantly reduces postoperative headaches [50–53]. Most headaches can be controlled with anti-inflammatory medicines, including aspirin, acetaminophen, and ibuprofen. Pain that requires narcotic analgesia necessitates a neurologist–headache specialist referral.

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