Vestibular schwannomas (VSs) are benign extraxial intracranial tumors that arise from the vestibular portion of cranial nerve VIII. Because of an indolent growth pattern and the capacity for long-term quiescence in up to 50% of them,18 these tumors have prompted a number of management options that include watchful waiting with serial imaging follow-up, microsurgical resection, and stereotactic radiotherapy.2

Recurrence of the VS following gross-total resection (GTR) is uncommon; several large series have reported rates of less than 1% during a 5- to 10-year follow-up period.4,22,26 The majority of patients with recurrent tumors are asymptomatic, and clinicians are left to rely on serial follow-up imaging for detection of early recurrence.3,23 Over the past 2 decades, Gd-enhanced T1-weighted MR
imaging has emerged as the diagnostic modality of choice for VS surveillance. The retrosigmoid craniotomy is one of three commonly used surgical routes for cerebellopontine angle (CPA) and internal auditory canal (IAC) access. While the retrosigmoid approach provides excellent medial exposure, the lateral one-third of the IAC cannot be routinely visualized if the inner ear is to be preserved, leaving the fundus particularly vulnerable to recurrence. Several studies have found that, following GTR, the presence of nodular enhancement within the tumor bed predicts a high likelihood for future recurrence. Over the past 10 years we have observed a number of patients in whom intense nodular enhancement was documented at the fundus of the IAC lateral to the preoperative radiological tumor margin following retrosigmoid GTR. To our knowledge, there are no published data addressing this unique occurrence. We discuss the imaging features, natural history, and clinical significance of such findings.

Methods

After institutional review board approval, a retrospective chart review was performed using the institutional electronic medical record. All patients who underwent microsurgery (between 1/2000 and 1/2010) for VS at our tertiary academic referral center were identified. Initial data including previous treatments (radiotherapy or microsurgery), presence of neurofibromatosis Type 2, surgical approach (retrosigmoid, middle fossa, translabyrinthine), completeness of resection as determined by the operating neurosurgeon and neurotologist, timing and number of postoperative MR imaging studies, and basic demographic information were recorded. We excluded patients with an incomplete resection, those who had undergone previous treatments (radiotherapy or surgery), and those with a history of previous Gd-enhanced MR imaging studies available at the time of review. Additionally, all patients with neurofibromatosis Type 2 were excluded given the possibility of synchronous or metachronous ipsilateral tumors.

At our institution, factors including preoperative hearing status, patient preference, tumor size, and tumor location strongly influence approach selection. The middle fossa approach is commonly used in patients with serviceable preoperative hearing and small lateral (intracanalicular) tumors. A retrosigmoid craniotomy may be used in patients with serviceable preoperative hearing when extrafoidal tumor extension is present or in patients with poor preoperative hearing and large medial based tumors. Finally, a translabyrinthine approach is preferred in patients with poor preoperative hearing in whom the tumor extends to the fundus; the translabyrinthine and retrosigmoid approaches are often used interchangeably for large medial based tumors in patients with nonserviceable hearing.

All radiological examinations were performed using 1.5- or 3.0-T superconducting magnets (General Electric Medical Systems and Siemens Medical Solutions). Imaging sequences included 2D or 3D T1-weighted sequences with and without Gd enhancement (slice thickness varying from 1 to 3 mm) and 3D T2-weighted sequences (FIESTA or T2-weighted SPACE [sampling perfection with application optimized contrasts sequence with different flip angle evolutions] [slice thickness 1 mm]). Fat suppression was used at the discretion of the performing neuroradiologist or ordering physician and was most commonly in patients undergoing a translabyrinthine or middle fossa approach when an autologous fat graft was placed. The preoperative size and location of the tumor were reported according to the 1995 American Academy of Otolaryngology–Head and Neck Surgery published guidelines. The extent of IAC penetration was determined using both T1-weighted Gd-enhanced and T2-weighted MR imaging sequences. Morphology (linear vs nodular), size, and location of enhancement were characterized on serial postoperative MR imaging studies with the contralateral unoperated side serving as a control. Recurrence was defined by progressive enlargement on serial imaging with or without treatment.

Results

Over the past 10 years, 350 patients have undergone microsurgical excision of a VS at our institution. Eighty patients met initial inclusion criteria. In this group, the first postoperative MR imaging study in 16 (20.0%) of the 80 patients revealed postsurgical Gd enhancement in the IAC lateral to the radiological limits of the preoperative tumor margin (37.5% women, median age 45 years) (Table 1).

Of the 16 patients, the initial postoperative MR imaging study was obtained a mean of 3.1 months following surgery (range 2.0–3.9 months), and the mean radiological follow-up period was 39.8 months (range 16.4–101.9 months; mean number of postoperative MR imaging scans 2.4). The mean tumor size was 1.6 cm (range 0.6–2.5 cm), and 4 tumors had partial cystic components. The mean distance from the lateral tumor margin to the IAC fundus on preoperative MR imaging was 5.3 mm (median 5.5 mm, range 2.5–8 mm); thus, this tumor population excluded those with extension to the distal IAC. All 16 tumors were approached via a retrosigmoid craniotomy. None of the patients in whom a middle fossa or translabyrinthine approach was used had the imaging enhancement pattern under investigation. In all cases, the tumor could be removed under direct visualization; none of the tumors required blind dissection of the distal IAC, although indirect mirror-assisted visualization was routinely used at the end of dissection to confirm complete removal. Surgicel (Johnson & Johnson Medical), Tisseel (Baxter Healthcare Corp.), and bone wax were used in various combinations in 15 patients for occlusion of exposed petrous air cell tracts. One patient with minimal pneumatization did not require air cell tract occlusion. No patient underwent autologous tissue (fat or muscle) packing of the surgical defect.

The first postoperative MR imaging study demonstrated nodular enhancement in 13 patients (Fig. 1A and B), whereas thin linear enhancement was revealed in 3 (Fig. 1C). The mean maximum dimension of nodular enhancement was 4.7 mm (median 5.0 mm, range 2.0–7.0
Enhancement in the IAC after retrosigmoid VS resection

Each successive scan demonstrated diminished size and/or loss of enhancement in 11 patients, whereas in 5 patients radiological findings remained stable. None of the 16 patients developed enlarging nodular enhancement suggestive of recurrence during follow-up.

**Discussion**

The goal of VS management remains long-term tumor control with a high priority placed on preserving neurological function. Microsurgical resection of VS provides definitive cure for the majority of patients in whom the clinical recurrence rate following GTR is less than 1%. Typically, recurrent VS must become large before patients exhibit any suggestive symptoms or examination findings, particularly in the setting of absent ipsilateral vestibular function and hearing resulting from the initial operation or tumor. Therefore, T1-weighted Gd-enhanced MR imaging has become the imaging modality of choice for postoperative tumor surveillance. Several studies have found that the presence of nodular enhancement within the operative bed of baseline postoperative MR imaging predicts a high risk (up to 66%) for future recurrence. In the current report, we describe the novel finding of nodular enhancement at the fundus of the IAC lateral to the preoperative radiologically delineated tumor margin, following retrosigmoid resection. In contrast to other patterns of enhancement reported in the literature, our data support the contention that these MR imaging abnormalities do not appear to predict future recurrence.

Currently no uniform standard exists regarding the timing and frequency of follow-up MR imaging after GTR of VSs, and there is tremendous practice variation among neurosurgeons and neurotologists. We typically obtain a baseline MR image approximately 3 months following GTR and then again at 2 and 7 years to try to capture any early or late tumor recurrence. If the 7-year MR imaging study appears satisfactory, in young patients we recommend a follow-up MR imaging 1 decade thereafter. In the rare cases that the 3-month MR image reveals nodular enhancement in the tumor bed, we may follow the lesion more closely with yearly MR imaging studies for the first 2–3 years until we are confident that the tumor has achieved radiological stability. An argument could be made to forego such an early imaging study at 3 months and only obtain the first MR image 1 or 2 years following GTR, but with serial follow-up MR imaging we have found the resolution or diminution of the distal IAC enhancement, and often even intratumoral bed enhancement, reassuring in such cases.

The retrosigmoid approach is extremely versatile, permitting wider posterior fossa exposure and the potential for transmeatal access. Because the retrosigmoid approach utilizes an extralabyrinthine route, hearing function may be preserved in select patients. Despite its many advantages, access to the fundus of the IAC is limited by the medial extent of the inner ear (the apex of the posterior semicircular canal and vestibule) during attempts to preserve hearing. Anatomical studies have demonstrated that while the retrosigmoid approach provides excellent access to the medial IAC, the distal 3–6 mm cannot be directly visualized (if the labyrinth is preserved), leav-

### TABLE 1: Clinical, surgical, and radiological characteristics in 16 patients with postoperative enhancement at the fundus of the IAC lateral to the preoperative radiologically delineated tumor margin*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Preop Tumor Size (cm)</th>
<th>Tumor Margin to Fundus Distance (mm)</th>
<th>Imaging Follow-Up (mos)</th>
<th>No. of Postop MRI Studies</th>
<th>Morphology</th>
<th>Lesion Size (max diameter [mm]) Baseline MRI</th>
<th>Most Recent MRI</th>
<th>Change in Size (mm)</th>
<th>Change in Enhancement</th>
<th>Substrates Used for Occlusion of Air Cells</th>
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<tr>
<td>1</td>
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<td>1.2</td>
<td>6.5</td>
<td>31.8</td>
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<td>linear</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>diminished</td>
<td>BW, S</td>
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<td>2</td>
<td>29, F</td>
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<td>2.5</td>
<td>52.3</td>
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<td>unchanged</td>
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<td>3</td>
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<td>BW</td>
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<td>8.0</td>
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<td>—</td>
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<td>BW, S, T</td>
</tr>
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<td>72.8</td>
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<td>6</td>
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<td>BW, S</td>
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<td>BW, S, T</td>
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<tr>
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<td>BW, S, T</td>
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<tr>
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<td>5.0</td>
<td>70.2</td>
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<td>nodular</td>
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<td>4</td>
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<td>diminished</td>
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<td>4.7</td>
<td>3.9</td>
<td>—0.8</td>
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<td>BW, S, T</td>
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* BW = bone wax; S = Surgicel; T = Tisseel.
Fig. 1. Preoperative and serial postoperative T1- and T2-weighted MR images, before and after Gd administration, in 2 patients undergoing VS GTR via a retrosigmoid approach.  

A: Images obtained in 69-year-old man with a 1.9-cm left-sided VS. Five months following retrosigmoid resection, a nodular enhancing lesion was seen filling the lateral third of the IAC (white arrow). Twenty-nine months following surgery, the lesion had diminished in size and intensity, leaving only a very small enhancing remnant at the very apex of the IAC (black arrow). 

B: Images obtained in a 36-year-old man with a 1.5-cm right-sided VS. Four months following surgery, a nodular enhancing mass (white arrow) was seen filling the fundus on T1-weighted Gd-enhanced sequences. Twenty-nine months following surgery the lesion had completely resolved leaving only a thin rim of linear enhancement (black arrow). 

C: Images obtained in a 29-year-old woman with a 1.5-cm right-sided VS. Four months following surgery, an area of thin linear enhancement was seen outlining the fundus and anterior meatal wall (white arrow). Subsequent imaging 2 years later demonstrated lesion involution with a small remnant of enhancement at the fundus (black arrow).
Enhancement in the IAC after retrosigmoid VS resection

ing the fundus particularly vulnerable as a place of recurrence. Several authors have recommended the use of angled endoscope to explore the fundus during retrosigmoid surgery, but there are no long-term large-study data to show the superiority of this tool with regard to disease control over conventional techniques. Clinical studies have confirmed that of the 3 commonly used surgical approaches, the retrosigmoid route has the highest risk that unintentional tumor will be left behind, especially in the lateral one-half to one-third of the IAC. Furthermore, in contrast to small remnant disease left along the facial nerve in the midcistern, tumor at the fundus is well vascularized, and therefore, it may be more apt to demonstrate continued growth and clinically significant recurrence.

Several studies have examined postoperative MR imaging enhancement patterns following retrosigmoid VS resection, but all studies to date have not investigated the location of enhancement in relation to the extent of preoperative tumor. Millen and Daniels reported on postoperative MR imaging findings following retrosigmoid craniotomy for removal of a heterogeneous group of benign CPA tumors (VS 28 [77.7%] of 36). In all patients some degree of enhancement was demonstrated in the operative field on the initial 1-year postoperative MR imaging study. Internal auditory canal enhancement took on 2 distinct patterns: in 15 of 36 patients imaging demonstrated thin linear enhancement along the anterior IAC wall, and in 7 of 36 patients imaging demonstrated nodular enhancement at the fundus (≤ 4 mm). In Millen and Daniels’ series, 1 of the 7 patients with nodular enhancement was diagnosed with recurrence 1 year after surgery; a large enhancing masslike lesion completely filled and extended out of the IAC. Cerebellopontine angle enhancement occurred in 19 (of 36) patients and was observed both anterior and posterior to the porus acusticus.

Smith and colleagues examined the MR imaging characteristics in 31 patients who underwent VS GTR via a retrosigmoid approach. They found 16 patients in whom there was thin linear IAC enhancement. Seven of these had a follow-up MR imaging at 1–2 years; in 6 there were no interval changes, whereas in 1 there was decreased enhancement. Five patients were found to have nodular enhancement within the IAC on initial baseline MR imaging; after 1 year, imaging revealed stable enhancement in 4 patients and nodular enhancement in 1 patient in whom recurrent disease was discovered, as demonstrated by progressive enlargement. Similar to the first study, the one patient who developed recurrence was found to have a large globular lesion filling the entire IAC. This study was limited in that only 14 (of 31) patients underwent follow-up MR imaging after baseline postoperative imaging.

Finally, Mazzoni et al. reported on the radiological and surgical findings in 104 consecutive cases of VS in which the patients underwent a retrosigmoid surgery with the aim of hearing preservation. Eighty-one percent of patients had no detectable enhancement following surgery, whereas in the remaining 19 cases some degree of enhancement was seen in the operative field. Of the latter group, 11 patients had thin linear enhancement along the VII and VIII cranial nerve complex or meatal wall, whereas 8 demonstrated a round nodular mass (range 1–15 mm) at the fundus or filling the IAC. Reoperation was performed in 7 patients (4 with nodular and 3 with linear enhancement); all 4 patients with nodular enhancement were found to have histologically verified recurrence, whereas in the 3 patients with linear enhancement, imaging demonstrated only “thin connective tissue” without any residual VS identified. The remaining 4 patients with nodular enhancement did not undergo revision surgery because imaging revealed stable findings.

Following intracranial surgery, nonspecific postoperative radiological enhancement is common, and the difficulty of surveillance lies in our inability to accurately differentiate recurrence from nonneoplastic postoperative changes. In the normal state, Gd is held to the intravascular space by tight endothelial junctions of the blood-brain barrier, and it is only under pathological conditions such as infection, tumor, or hemorrhage that meningeal or parenchymal enhancement occurs. Surgery produces an iatrogenic alteration of the blood-brain barrier, which may result in enhancement of the meninges, parenchyma, or cranial nerves. Free extravascular contrast extravasation and granulation tissue formation may create early postoperative enhancement, and autologous grafting materials such as fat and muscle may result in persistent nodular enhancement. Histological studies have confirmed that Gelfoam, Surgicel, fibrin glue, and bone wax may induce an inflammatory reaction and neovascularization that may result in contrast enhancement. Additionally, subarachnoid blood may precipitate a locoregional arachnoiditis, resulting in increased vascular permeability. The patients in our series are unique in that the enhancement was located lateral to the extent of tumor resection, making postoperative granulation tissue unlikely, and importantly, none of the 16 patients in the present series underwent fat or muscle packing of the IAC. A combination of bone wax, Tisseel, and Surgicel was used in 15 of the 16 patients to occlude opened petrous air cell tracts to reduce the risk for postoperative CSF leakage, but it was only applied to exposed bone and never blindly placed in the fundus. While not histologically proven, we hypothesize that retracted dura mater or sectioned nerve remnants may account for the unique enhancement pattern seen. It is also possible that increasing MR imaging resolution and evolving imaging techniques may be partly responsible for these findings.

A final possibility includes tumor being iatrogenically implanted in the lateral IAC during surgery. There are numerous reports in the English-language literature describing local and distant seeding of benign primary intracranial tumors. While most reports blame spontaneous dispersion along CSF tracts, intracranial seeding along stereotactic biopsy pathways or iatrogenic surgical implantation along the surgical route has also been described. In our review, most reports involving benign disease have included craniopharyngiomas and meningiomas, whereas there has been only one report describing iatrogenic VS implantation. In the latter case, there was no evidence of ectopic tumor implantation on the first postoperative MR imaging study, and it was only ap-

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proximately 10 years following initial surgery that a tumor was identified in the parenchyma of the ipsilateral inferior cerebellum, far from the original tumor extent. The rarity of reported VS tumor seeding, combined with the fact that none of the patients in our series have had enlarging nodular enhancement, argues against this phenomenon being one of tumor implantation.

It is worth noting that none of the patients who underwent a translabyrinthine or middle fossa approach were found to have postoperative enhancement at the fundus beyond the original tumor margin. There is likely a strong selection bias that accounts for this finding because those tumors extending to the fundus were not evaluated by nature of the study design. Patients with medial tumors, sparing the lateral one-half to one-third of the IAC received retrosigmoid surgery based on surgeon philosophy (see Methods).

In the current study we do not have definitive histological proof that the areas of enhancement are not in fact quiescent tumor remnants. Recurrence following VS resection is most commonly detected within the first 5 years, but the radiological follow-up in our study was limited to a mean of 40 months. Because demonstrated diminution of the tumor was documented in 11 patients and stable size was documented in 5 on serial MR imaging, future recurrence is unlikely but remotely possible.

Conclusions
Vestibular schwannoma recurrence is uncommon following GTR. Given the anatomical constraints of lateral IAC dissection with the retrosigmoid approach, nodular enhancement at the fundus should be carefully scrutinized. In contrast to previous publications reporting a high rate of recurrence with nodular enhancement within the original tumor bed, postoperative enhancement within the fundus, lateral to the original tumor margin, appears to carry a minimal risk for recurrence. As such, clinicians should have very strong proof of recurrence prior to recommending additional treatment. These findings may be helpful in patient counseling and postoperative MR imaging surveillance schedule determination.

Disclosure
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Link, Carlson, Driscoll, Neff, Lane. Acquisition of data: Carlson, Van Abel, Schmitt, Lane. Analysis and interpretation of data: Carlson, Van Abel. Drafting the article: Link, Carlson, Van Abel, Driscoll, Neff, Lane. Critically revising the article: Link, Carlson, Schmitt, Driscoll, Neff, Lane. Reviewed submitted version of manuscript: Carlson. Administrative/technical/material support: Link. Study supervision: Link, Driscoll, Neff, Lane.

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 Enhancement in the IAC after retrosigmoid VS resection


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