Long-Term Hearing Outcomes Following Stereotactic Radiosurgery in Vestibular Schwannoma Patients—A Retrospective Cohort Study

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BACKGROUND: An understanding of the hearing outcomes is needed for treatment counseling for patients with vestibular schwannomas (VS).

OBJECTIVE: To determine long-term hearing results following stereotactic radiosurgery (SRS) for VS and identify any influential variables.

METHODS: Tertiary hospital retrospective cohort.

RESULTS: There were 579 tumors (576 patients) treated with SRS. Eighty-two percent (473) of tumors had ≥ 1 yr and 59% (344 ≥ 3 yr follow-up). In the 244 tumor ears, with measurable hearing before SRS who were followed ≥ 1 yr, 14% (31) had improved hearing, 13% (29) unchanged hearing, and 74% (158) had worsened hearing. In 175 patients with ≥ 3 yr follow-up and who had measurable hearing pretreatment, 6% (11 ears) improved hearing, 31% (54 ears) unchanged hearing, and 63% (110 ears) had worsened hearing. Patients with tumors with larger target volumes ($P = .040$) and with neurofibromatosis type 2 (NF2; $P = .017$) were associated with poorer hearing ($P = .040$). Patients with word recognition scores (WRS) of 50% or poorer had tumors with a larger volume ($P = .0002$), larger linear size ($P = .032$), and NF2 ($P = .045$). Traditionally reported hearing outcomes using the Gardner Robertson maintenance of PTA ≤ 50 dB or WRS $\geq 50\%$ were 48% at 3 yr, which overestimates hearing outcomes compared to the above reporting standards.

CONCLUSION: Hearing declines over time in VS treated with SRS in a high proportion of cases. The frequency and magnitude of long-term hearing decline following SRS argues against prophylactic radiation for small tumors in hearing ears with undetermined growth behavior.

KEY WORDS: Vestibular schwannoma, Hearing, Radiosurgery, Stereotactic

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Vestibular schwannomas (VS) are benign, slow-growing tumors originating from the eighth cranial nerve's vestibular division. The main focus of managing VSs is tumor control and preservation neurological function.

Weighing the probability of hearing preservation is a key factor in deciding among

management option including observation, microsurgery, and radiation.^{1–4} Stereotactic radiosurgery (SRS) has been defined by several consensus statements as stereotactic radiation therapy in 1 to 5 fractions.^{5,6} The objective is to evaluate long-term hearing outcomes following SRS for VS using contemporary methods and identify the variables that influence the probability of preservation.

METHODS

A retrospective cohort study of patients undergoing SRS for VS between 1992 and 2013 (576 patients, with 579 tumors) who had both pre- and posttreatment audiometric evaluation and ≥ 1 yr follow-up. With Institutional Review Board approval (IRB-26568), a waiver of consent was obtained. Patients who had not attended recent follow-up were

ABBREVIATIONS: AAO-HNS, American Academy of Otolaryngology–Head and Neck Surgery; **GR**, Gardiner–Robinson; **NF2**, neurofibromatosis type 2; **PTA**, pure tone average; **SRS**, stereotactic radiosurgery; **VS**, vestibular schwannomas; **WRS**, word recognition scores

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posted a reminder letter and/or phone called to attend for imaging and hearing tests or to post in outside imaging and hearing tests appropriate.

Patients were classified as primary SRS (SRS only) for those who had a single course of SRS, adjuvant SRS for those who had primary surgical resection followed by SRS within 6 mo, without documented tumor growth on follow-up, salvage SRS for those who had nontotal surgical resection, followed by SRS following documented tumor remnant growth on follow-up, and salvage surgery for those who had primary SRS, followed by surgical resection following documented tumor growth.

Tumor growth before SRS was defined as documented imaging evidence of interval enlargement of the tumor preceding SRS. Many patients in the study were treated with SRS shortly after diagnosis without documented imaging evidence of tumor growth. In such cases, these were categorized as growth “undetermined.”

Posttreatment hearing was assessed by comparing pre- and posttreatment audiograms. Either audiograms were interpreted directly or the audiometric data were taken from the treating clinician notes. Where available, the hearing results were recorded according to the guidelines provided by the Hearing and Equilibrium Committee of the American Academy of Otolaryngology–Head and Neck Surgery (AAO-HNS)^{7,8} hearing results were grouped into the following categories: Maintained hearing if there was a <10 db change in pure tone average (PTA) or $<20\%$ change in word recognition scores (WRS), better hearing if there was an increase of ≥ 10 db of PTA or $\geq 20\%$ of WRS, and worse hearing (hearing decline) if there was a decrease of ≥ 10 db of PTA or $\geq 20\%$ of WRS.

Summary statistics are expressed as counts for categorical variables and means for continuous variables. Proportional hazards regression models were used to examine the impact of age at baseline, sex, follow-up time (years), NF2, tumor side, growth before SRS, coverage isodose, treatment isodose (%), D max (Gy), target volume and tumor size both as a continuous predictor in mm and stratified into 3 categories (<10 mm, 10 mm to <20 mm, ≥ 20 mm), on time to four separate dichotomous responses: worsened hearing, worsened hearing $\geq 50\%$, worsened PTA and worsened PTA ≥ 50 dB. Univariate and multivariate odds ratios were performed and if statistically significant were retained in the final multivariate models. These statistics were performed using STATA version 13 (StataCorp. 2013. Stata Statistical Software: Release 13. College Station, Texas).

The raw data for the cohort are included in **Data File, Supplemental Digital Content 1**.

RESULTS

Demographics

The total treated cohort consisted of 576 patients with a total of 579 tumors. Four hundred seventy-three tumors (82%), those with more than 1 yr of follow-up, were included for analysis. Average follow-up was 5.5 yr (range from 1.0 to 18.8 yr). Of these tumors, 344 (73%) had follow-up of ≥ 3 yr. There were 21 (4%) tumors in 18 patients with neurofibromatosis type 2 (NF2). The study tumor cohort consisted of 238 male (50%) and 235 female (50%). Tumors treated were left ($n = 215$), right ($n = 257$), and bilateral ($n = 6$). The mean age at SRS was 53.9 yr (range 13–91 yr). Tumors were classified as primary radiation in 90% ($n = 426$), salvage radiation in 6% ($n = 30$), adjuvant radiation in 2% ($n = 11$) with 3 cases of bilateral radiation

(6 tumors). One patient had two further SRS treatments after initial post-SRS growth and another patient had two treatments of SRS that were both followed by growth leading to salvage surgery. One patient had salvage SRS followed by growth after previous surgery, had another SRS treatment and then grew again after this second SRS treatment. The remaining tumors were single cases of patients who received multiple treatments of both surgery and/or SRS in differing orders and combinations. Of the 473 tumors, 135 (29%) demonstrated growth prior to SRS. There were 72% of tumors (340 of 473) that were treated with SRS with undetermined growth behavior prior. Tumors that received multiple treatments of SRS were only counted once, as a single case.

SRS Details

The most commonly prescription was an 18Gy marginal dose in 3 fractions (87% of tumors) using the Cyberknife (Accuray, Sunnyvale, California), with the remainder receiving a single fraction most commonly of 14 Gy (2%), or 13 Gy (3%), or 21 Gy (5%) given in 3 fractions. The mean target volume was 2.2 cc (range 0.01–22.1 cc) and the mean tumor size was 16.2 mm (<1 cm $n = 86$, 1 to ≤ 2 cm $n = 262$, 2 to ≤ 3 cm $n = 108$, >3 cm $n = 14$, unknown size $n = 3$, range 1–47 mm) in maximal dimension. The SRS prescription was reported as coverage isodose line (mean 75%, range 53%–100%), treatment isodose line (mean 80%, range 62%–98%) and dose maximum (mean 22.5 Gy, range 15–32).

Hearing Outcomes of SRS

The hearing results are displayed for patients with follow-up for ≥ 1 yr ($n = 319$; see Table 1). Those with ≥ 3 yr follow-up are displayed in Table 2 ($n = 235$). Tables 1 and 2 display a deterioration of the majority over time with greater deterioration occurring in those with ≥ 3 yr follow-up. Tables 3A and 3B show the outcomes for the subset of tumor ears that began with WRS $\geq 70\%$.

In patients with ≥ 1 yr of follow-up and who had at least 10% WRS ($n = 244$), 31 ears (13%) had improved hearing, 29 ears (12%) had unchanged hearing, and 158 ears (65%) had worsened hearing (see Table 1C). The remainder already had a WRS below 10% and were not considered as unchanged hearing as no change was possible. Among ears with worsened hearing ($n = 158$), 70 (44%) had worsening of $\geq 50\%$.

A larger target volume ($P = .028$), lower coverage isodose line ($P = .020$), and lower treatment IDL ($P = .045$) were all significantly related to worsened hearing using univariate analysis. Furthermore, in patients with tumor size <10 mm, 65% had worsened hearing, increasing to 68% (tumor size 10 mm to <20 mm) and 87% (tumor size ≥ 20 mm). However, using multivariate analyses only the target volume was statistically significant in the final model ($P = .040$). The presence of NF2 ($P = .017$), tumor volume ($P < .001$), tumor growth prior to SRS ($P = .042$) and a lower treatment IDL ($P < .001$) was predictive of hearing loss of a WRS of less than 50%.

TABLE 1. SRS Hearing Results in Patients With More Than 1 yr of Follow-up

A—Pre-SRS Hearing Levels in Tumor Ears Among Patients With > 1 yr of Follow-up (n = 319)											
PTA (db)	Word recognition score (%)										
	100-90	89-80	79-70	69-60	59-50	49-40	39-30	29-20	19-10	9-0	
0-10	20	3	0	2	0	0	0	0	0	0	
11-20	34	3	3	1	1	0	0	1	0	0	
21-30	22	8	2	0	0	0	0	1	0	0	
31-40	18	5	4	5	2	1	1	1	1	1	
41-50	8	7	2	2	3	3	1	0	2	2	
51-60	3	2	0	6	2	2	2	1	0	4	
61-70	1	2	1	0	2	2	1	0	0	2	
71-80	0	2	0	0	0	0	2	3	0	4	
81-90	0	0	0	0	0	0	1	0	0	4	
>90	0	0	0	0	0	0	1	0	1	58	
Unknown	12	8	3	3	4	2	1	2	2	3	
B—Post-SRS Hearing Levels in Tumor Ears for Patients With > 1 yr of Follow-up (n = 319)											
PTA (db)	Word recognition score (%)										
	100-90	89-80	79-70	69-60	59-50	49-40	39-30	29-20	19-10	9-0	
11-20	14	1	2	0	0	0	0	0	0	0	
21-30	10	8	0	3	1	1	2	0	0	1	
31-40	6	6	3	1	2	0	2	1	0	0	
41-50	6	4	2	5	5	0	2	6	0	4	
51-60	0	1	3	8	4	3	4	1	0	5	
61-70	1	0	1	1	1	2	1	4	4	10	
71-80	1	0	0	2	0	0	2	1	1	11	
81-90	0	1	0	1	0	0	0	2	2	7	
>90	0	0	0	0	0	0	0	1	1	87	
Unknown	6	1	2	4	2	2	1	5	2	14	
C—Hearing Levels in Tumor Ears for Patients > 1 yr of Follow-up (n = 244 Total)											
←Worse PTA (db) improved →	≥50	←Improved		Word recognition score (%)				Worse→			
		40-49	30-39	20-29	10-19	No change	10-19	20-29	30-39	40-49	≥50
≥50	0	0	0	1	0	0	0	0	0	0	0
40-49	0	0	0	0	0	0	0	0	0	0	0
30-39	0	0	0	0	0	1	0	0	0	0	0
20-29	0	0	0	0	0	3	0	0	0	0	0
10-19	0	0	0	0	0	1	0	0	0	0	2
No change	3	1	0	0	3	36	7	7	3	5	7
10-19	0	0	0	2	3	8	11	1	7	5	6
20-29	0	0	0	0	1	4	4	3	4	4	7
30-39	0	0	0	0	0	0	1	2	4	3	5
40-49	0	0	0	1	0	0	1	1	2	1	4
≥50	0	0	0	0	1	1	2	2	1	0	23
Unknown	1	1	1	0	0	8	2	4	3	4	15

The hearing results are displayed according to the American Academy's Hearing Committee's guidelines for minimal standards of reporting.⁷ The cohort contained patients who had pretreatment <10% WRS (n = 75). Table 1c excludes 75 tumor ears with profound hearing loss pretreatment who had <10% WRS = 75, because no change is possible.

Figure 1 shows the Kaplan–Meier curve for patients with maintained or better hearing over time. There is a general decline in hearing with time, especially within the first 3 yr.

The hearing results are also displayed, for historical comparison only, according to the G-R classification in patients with follow-up of ≥ 1 yr (Table A, Supplemental Digital Content 2) and 3 yr (Table B, Supplemental Digital Content 2).⁸ Patients who had hearing pre-SRS at PTA ≤ 50 db or WRS ≥ 50% are represented

in Figure 2. The rates were 77% at 1 yr, 63% at 3 yr, 52% at 5 yr and 35% at 10 yr.

Effect of Tumor Size

Increasing tumor size had a negative effect on the hearing outcome ($P = .040$). For tumors that had a component in the CPA, increasing size resulted in poorer hearing outcomes ($P = .015$).

TABLE 2. SRS Hearing Results in Patients With More Than 3 yr of Follow-up

A—Pre-SRS Hearing Levels in Tumor Ears Among Patients With > 3 yr of Follow-up (n = 235)											
PTA (db)	Word recognition score (%)										
	100-90	89-80	79-70	69-60	59-50	49-40	39-30	29-20	19-10	9-0	
0-10	13	2	0	2	0	0	0	0	0	0	
11-20	26	3	3	1	0	0	0	1	0	0	
21-30	17	4	2	0	0	0	0	1	0	0	
31-40	13	3	4	5	2	1	1	1	0	1	
41-50	6	2	2	1	2	3	1	0	0	2	
51-60	1	1	0	3	2	1	1	0	0	4	
61-70	0	2	0	0	1	1	1	0	0	2	
71-80	0	0	0	0	0	0	2	3	0	2	
81-90	0	0	0	0	0	0	0	0	0	2	
>90	0	0	0	0	0	0	1	0	0	48	
Unknown	11	7	3	2	4	2	0	0	1	2	
B—Post-SRS Hearing Levels in Tumor Ears for Patients With > 3 yr of Follow-up (n = 235)											
PTA (db)	Word recognition score (%)										
	100-90	89-80	79-70	69-60	59-50	49-40	39-30	29-20	19-10	9-0	
0-10	6	0	0	0	0	0	0	0	0	0	
11-20	9	1	1	0	0	0	0	0	0	0	
21-30	6	4	0	3	0	0	1	0	0	1	
31-40	5	6	3	1	2	0	2	1	0	0	
41-50	4	4	2	3	2	0	1	4	0	4	
51-60	0	0	2	5	3	2	1	1	0	4	
61-70	1	0	0	0	1	1	0	3	3	9	
71-80	1	0	0	2	0	0	1	0	0	7	
81-90	0	0	0	1	0	0	0	1	2	5	
>90	0	0	0	0	0	0	0	1	1	69	
Unknown	6	1	2	1	2	2	1	3	2	12	
C—Posttreatment Change Results > 3 yr of Follow-up (Already < 10% WRS = 60) n = 175											
←Worse PTA (db) improved →	≥50	←Improved		Word recognition score (%)				Worse→			
		40-49	30-39	20-29	10-19	No change	10-19	20-29	30-39	40-49	≥50
≥50	0	0	0	1	0	0	0	0	0	0	0
40-49	0	0	0	0	0	0	0	0	0	0	0
30-39	0	0	0	0	0	1	0	0	0	0	0
20-29	0	0	0	0	0	3	0	0	0	0	0
10-19	0	0	0	0	0	1	0	0	0	0	1
No change	2	1	0	0	2	24	5	5	2	2	3
10-19	0	0	0	1	3	5	6	1	5	3	3
20-29	0	0	0	0	1	2	4	3	2	2	7
30-39	0	0	0	0	0	0	0	2	3	3	3
40-49	0	0	0	0	0	0	0	1	2	1	4
≥50	0	0	0	0	1	1	1	0	1	0	19
Unknown	1	0	1	0	0	7	1	1	3	3	15

The hearing results are displayed according to the American Academy's Hearing Committee's guidelines for minimal standards of reporting.⁷ The cohort contained patients who had pretreatment <10% WRS (n = 60). Table 2C excludes 60 tumor ears with profound hearing loss pretreatment who had <10% WRS = 75, because no change is possible.

Figure 3 shows the hearing results of tumors with undetermined growth behavior prior to SRS. The hearing results worsen with increasing size, with large changes between intracanalicular tumors and tumors 1 cm to 2 cm in the CPA and also from 2 cm to under 3 cm in the CPA.

Effect of Tumor Growth Prior to SRS

Figure 4 shows hearing results for tumors demonstrating growth prior to SRS. Independent of tumor size, tumors that had

undetermined growth behavior prior to SRS show rates of PTA ≤50 db or WRS ≥50% hearing similar (76% at 1 yr, 63% at 3 yr, 54% at 5 yr, and 33% at 10 yr) not significantly different to tumors with demonstrated growth prior to SRS (67% at 1 yr, 53% at 3 yr, 32% at 5 yr and 32% at 10 yr; $P = .67$).

Other Factors

Gender ($P = .09$) and age ($P = .25$) were not predictive of hearing outcomes. There was no association between hearing

TABLE 3. The Outcomes of Tumor Ears With Word Recognition Score $\geq 70\%$ pre-SRS

A—The Outcomes of Tumor Ears With Word Recognition Score $\geq 70\%$ pre-SRS, 1 yr of Follow-up				
Cohort	Pre-SRS $\geq 70\%$ WRS (n)	Post-SRS $\geq 70\%$ WRS (n)	Post-SRS $< 10\%$ WRS (n)	Follow-up (yr) mean (range)
All	168 of 310	83 of 310	136 of 310	5.3 (1.0-18.7)
Intracanalicular tumors	43 of 168 (25.6%)	16 of 43 (37.2%)	11 of 43 (25.6%)	5.3 (1.5-12.6)
In the CPA 1-10 mm	52 of 168 (31.0%)	27 of 52 (51.9%)	11 of 52 (21.2%)	4.6 (1.0-14.3)
In the CPA 11-20 mm	54 of 168 (32.1%)	23 of 54 (42.6%)	11 of 54 (20.4%)	4.8 (1.0-10.6)
In the CPA > 20 mm	19 of 168 (11.3%)	10 of 19 (52.6%)	4 of 19 (21.1%)	5.8 (1.1-10.7)
TOTAL	168 of 168 (100%)	76 of 168 (45.2%)	37 of 168 (22.0%)	5.3 (1.0-18.7)
Demonstrated Prior Growth				
Intracanalicular tumors	9 of 43 (20.9%)	5 of 9 (55.6%)	1 of 9 (11.1%)	5.3 (2.8-11.6)
In the CPA 1-10 mm	8 of 52 (15.4%)	4 of 8 (50.0%)	2 of 8 (25.0%)	3.7 (2.2-6.9)
In the CPA 11-20 mm	11 of 54 (20.4%)	4 of 11 (36.4%)	2 of 11 (18.2%)	4.7 (1.0-9.3)
In the CPA > 20 mm	5 of 19 (26.3%)	3 of 5 (60.0%)	2 of 5 (40.0%)	3.7 (1.3-5.4)
TOTAL	33 of 168 (19.6%)	16 of 33 (48.5%)	7 of 33 (21.2%)	4.5 (1.0-11.6)
Prior Growth Undetermined				
Intracanalicular tumors	34 of 43 (79.1%)	11 of 34 (32.4%)	10 of 34 (29.4%)	5.3 (1.5-12.6)
In the CPA 1-10 mm	44 of 52 (84.6%)	23 of 44 (53.3%)	9 of 44 (20.0%)	4.8 (1.0-14.4)
In the CPA 11-20 mm	43 of 54 (79.6%)	19 of 43 (44.2%)	9 of 43 (20.9%)	4.8 (1.0-10.6)
In the CPA > 20 mm	14 of 19 (26.3%)	7 of 14 (50.0%)	2 of 14 (14.3%)	6.6 (1.1-10.7)
TOTAL	135 of 168 (80.4%)	60 of 135 (44.4%)	30 of 135 (22.2%)	5.1 (1.0-14.4)
B—The Outcomes of Tumor Ears With Word Recognition Score $\geq 70\%$ pre-SRS, 3 yr of Follow-up				
Cohort	Pre-SRS $\geq 70\%$ WRS (n)	Post-SRS $\geq 70\%$ WRS (n)	Post-SRS $< 10\%$ WRS (n)	Follow-up (yr) mean (range)
All	120 of 226	60 of 226	108 of 226	
Intracanalicular tumors	35 of 120 (29.2%)	13 of 35 (37.1%)	10 of 35 (28.6%)	6.0 (3.0-12.6)
In the CPA 1-10 mm	34 of 120 (28.3%)	16 of 34 (47.1%)	8 of 34 (23.5%)	6.1 (3.0-14.3)
In the CPA 11-20 mm	36 of 120 (30.0%)	18 of 36 (50.0%)	9 of 36 (25%)	6.2 (3.0-10.6)
In the CPA > 20 mm	15 of 120 (12.5%)	7 of 15 (46.7%)	4 of 15 (26.7%)	6.9 (3.2-10.7)
TOTAL	120 of 120 (100%)	54 of 120 (45%)	31 of 120 (25.8%)	6.2 (3.0-14.3)
Demonstrated Prior Growth				
Intracanalicular tumors	8 of 35 (22.9%)	5 of 8 (62.5%)	1 of 8 (12.5%)	5.7 (3.2-11.6)
In the CPA 1-10 mm	6 of 34 (17.6%)	3 of 6 (50.0%)	1 of 6 (16.7%)	4.1 (3.0-6.9)
In the CPA 11-20 mm	9 of 36 (25.0%)	4 of 9 (44.4%)	2 of 9 (22.2%)	5.4 (3.0-9.3)
In the CPA > 20 mm	3 of 15 (20.0%)	1 of 3 (33.3%)	2 of 3 (66.7%)	4.6 (4.1-5.4)
TOTAL	26 of 120 (21.7%)	13 of 26 (50%)	6 of 26 (23.1%)	5.1 (3.0-11.6)
Prior Growth Undetermined				
Intracanalicular tumors	27 of 35 (77.1%)	8 of 27 (29.6%)	9 of 27 (33.3%)	6.1 (3.0-12.6)
In the CPA 1-10 mm	28 of 34 (82.4%)	13 of 28 (46.4%)	7 of 28 (25.0%)	6.5 (3.1-14.4)
In the CPA 11-20 mm	27 of 36 (75.0%)	14 of 27 (51.9%)	7 of 27 (25.9%)	6.5 (3.1-10.6)
In the CPA > 20 mm	12 of 15 (80.0%)	6 of 12 (50.0%)	2 of 12 (16.7%)	7.5 (3.2-10.7)
TOTAL	94 of 120 (78.3%)	41 of 94 (43.6%)	25 of 94 (26.6%)	6.5 (3.0-14.4)

This table displays the outcomes of ears treated with stereotactic radiosurgery (SRS) of the cohorts with one (Table 3A) and 3 yr of follow-up (Table 3B). Results are only displayed for those case with pre- and post-SRS hearing results and also known dimensions within the cerebellopontine angle (CPA). These included 310 cases with more than 1 yr of follow-up and 226 cases with more than 3 yr of follow-up. The ears are also divided into those of different sizes and those that demonstrated growth prior to SRS and those with undetermined growth behavior prior to SRS. There were 168 cases of WRS $\geq 70\%$ pre-SRS with more than 1 yr of follow-up and 120 cases of WRS $\geq 70\%$ pre-SRS with more than 3 yr of follow-up.

outcome and SRS dosage ($P = .54$), or with maximum tumor dose ($P = .22$). There were too few numbers to determine an association with the number of fractions, and radiation category.

DISCUSSION

Minimal Standards for Reporting of Hearing Outcomes in Vestibular Schwannoma Management

In an effort to facilitate meta-analysis of hearing outcome data minimal reporting standards were proposed by Gardiner

and Robinson in 1998 and the AAO-HNS in 1995. Experts in measuring hearing loss and its life impact recognized serious limitations in these legacy methods.^{8,9} Limitations around previous scales include the creation of arbitrary hearing categories that do not correlate with patient outcomes or satisfaction and the failure of these scales to show changes of hearing of the cohorts within the scale.^{8,9} In 2010, the Hearing Committee of the AAO-HNS undertook as rigorous evidence-based process to establish a more valid tool for describing hearing changes in populations and measuring the impact of therapeutic interventions. This led

FIGURE 1. The Kaplan–Meier curve representing the proportion of patients who had maintained or better hearing levels according to follow-up time are displayed. The numbers at risk for each time point are in parentheses below the time point. A steady decline in the hearing of the cohort occurs as the follow-up time increases with the steepest decline occurring in patients within the first 3 yr of follow-up. Hearing results were grouped into the following categories: Maintained hearing if there was a < 10 db change in pure tone average (PTA) or $< 20\%$ change in word recognition scores (WRS). Better hearing if there was an increase of ≥ 10 db of PTA or $\geq 20\%$ of WRS; Worse hearing if there was a decrease of ≥ 10 db of PTA or $\geq 20\%$ of WRS.

to the adoption, in 2012, of a new set of reporting standards.⁷ This is now widely used and is now a publication requirement of many major journals in otolaryngology and a convenient online

tool is available for authors.¹⁰ The Gardiner–Robinson (GR) scale has long been used in the neurosurgical and radiation oncology literature, and therefore we have included our data in this format (as a supplement) to facilitate comparison with prior publications. We recommend that all authors supply their raw data to enable flexibility in aggregating data during future investigations.

We also recommend emphasis in reporting hearing outcomes based on actual audiometric data and avoid using arbitrary descriptors such as “serviceable” hearing.¹¹ Raw PTA and WRS in quiet data do not reflect the quality of life. The contralateral ear status contributes to impairment degree. Many VS patients with good WRS in quiet, complain of impairment of speech understanding in noise. Many patients rated as “serviceable” hearing under the GR scale have significant hearing difficulty, especially in adverse listening conditions. Most patients with class 2 GR and some even with GR class 1 who have normal hearing in the contralateral ear have a hearing loss that substantially impairs communication. The term “hearing preservation” is often misused in the VS literature. Transition from normal hearing to GR class 2 is far from equivalent to unchanged hearing. The authors argue that it would be preferable to present hearing data in terms of change in PTA (dB) and WRS (%) over time according to tumor size, patient age, pretreatment hearing level, etc. Future studies of VS hearing outcome may use improved audiometric measures, which better relate to actual life impact, such as speech recognition in noise and validated life impact survey.^{12,13}

FIGURE 2. The Kaplan–Meier curve for representing the proportion of patients hearing at levels of PTA ≤ 50 db or WRS $\geq 50\%$ are displayed. The cohort has been also divided into “pre-SRS growth undetermined” and “pre-SRS growth”. Pre-SRS growth is defined as documented imaging evidence of interval enlargement of the tumor preceding SRS. The numbers at risk for each time point are in parentheses below the time point in order (pre-SRS growth undetermined, pre-SRS growth, and total). Those tumors with pre-SRS growth had worse hearing results as follow-up time increases but approached that of tumors with pre-SRS growth undetermined at 10-yr follow-up.

Hearing Outcomes Worsen Over Time

A meta-analysis concluded that approximately 51% of patients undergoing SRS, independent of tumor size, will have their hearing preserved at the same levels around 3 to 4 yr.¹⁴ This is similar to the finding in our study where 50% of patients undergoing SRS have their hearing preserved at the same levels at 3 yr of follow-up. We showed that less than 40% of patients maintain the level of hearing they presented with at 5 yr after SRS and 20% at 10 yr. Transient volume expansion is a phenomenon unique to SRS, compared with other treatments, and has been correlated with hearing deterioration.¹⁵ Because the time following SRS is a factor, studies should not simply report mean follow-up times and should not include tumors with follow-up that is too short (<1 yr). Clinicians should proceed cautiously and not give overly optimistic advice for hearing preservation with treatment vs observation. In one large retrospective cohort, those tumors with initial AAO-HNS hearing Class A, 86% retained “serviceable” hearing.¹⁶ In another retrospective cohort, the majority retained “serviceable” hearing at 5 yr.¹⁷ In another retrospective cohort of 117 patients, actuarial 3-, 5-, and 8-yr results of who maintained GR category I or II were 55%, 43%, and 34% respectively.¹⁸ In a prospective cohort of observation for VS, it was reported that the median time for hearing loss is approximately 10 yr in nongrowing or growing tumors < 2.5 mm/yr.¹⁹ Although microsurgery generally has worse hearing outcomes than SRS, and more potential for immediate detrimental effect, some have argued that it offers better long-term hearing in selected VS

patients, such as those with small intracanalicular tumors.²⁰ There is a lack of long-term prospective comparisons between SRS and observation.

Hearing outcomes in tumors with documented pre-SRS enlargement on serial imaging were not significantly worse than those without documented enlargement up to 5 yr. Because the patients were not randomized to receive SRS, we can only conclude that the hearing results are similar between groups but are unable to comment directly on whether SRS would have had an effect on hearing in those tumors that would have been otherwise selected for observation. A previous study comparing fractionated SRS to the natural history of VS found that the hearing preservation rates were significantly worse in the SRS cohort.²¹ In an observed VS study of 94 patients, only 24% of those had hearing loss from levels PTA ≤ 50 dB and ≥ 50% WRS deteriorating to > 50 dB and < 50% WRS at a median time of 6.3 yr.¹⁷ In one large patient cohort who began with this level of hearing (≤ 50 dB and ≥ 50% WRS), at last follow-up, 68% of observed patients still had hearing at levels of ≤ 50 dB and ≥ 50% WRS at presentation compared to 40% of those who underwent SRS.²² When observing tumors without treatment, if a tumor demonstrates interval growth, hearing declines more in those growing tumors than those that stay stable in size, with no correlation between the amount of change in hearing and in the size of the tumor.¹⁶ The hearing outcomes of patients undergoing SRS deteriorate at the same rate or faster than would be expected through observation.^{23–25} One study reported a

decline of approximately 20 db on the tumor side 3 to 5 yr after SRS compared to hearing on the contralateral ear that remained near unchanged around 10 yr later.¹⁸ We therefore disagree with studies reporting retrospectively on unmatched cohorts, with short follow-up and small cohort numbers advocating “proactive” treatment of nongrowing VS with SRS to preserve hearing.^{26–30} At the least it would be premature to routinely recommend radiation for small tumors with no demonstrated growth to enhance long-term hearing presentation as radiation outcomes may well be less satisfactory than observation alone. As tumor growth prior to SRS did not significantly worsen hearing outcomes, it can be argued that there is no additional harm to hearing by observing smaller tumors and waiting for tumor growth before treatment. Our study did not quantify the amount of enlargement in those tumors that demonstrated growth prior to SRS but it has been suggested that tumors growing faster than 2.5 mm/yr have worse hearing outcomes.^{19,31}

Larger Tumors Have Worse Hearing Outcomes

There is a direct correlation between losing hearing and increasing tumor size prior to SRS. This is independent to whether there was tumor growth demonstrated prior to SRS. Our findings on the effect of tumor size is consistent with that reported in the literature.^{8,24,22,32–35}

Although there is no direct comparison, the hearing outcomes of this study for intracanalicular tumors treated with SRS without

documented enlargement is not better than the natural history of intracanalicular tumors that are observed in a similarly large cohort.³⁶ One study reported that intracanalicular tumors had a median time to hearing loss of over 10 yr.¹⁹ Our data suggested that the majority treated with SRS had hearing reduction between 5 and 10 yr.

Other Factors for Hearing Outcomes

Other factors previously suggested to improve hearing outcomes include younger age, better pretreatment hearing, and lower total dose.^{22,32–35} We did not find patient demographic, radiation fractions, or dose factors predicted hearing outcomes. Lower coverage and treatment IDL was associated with poorer hearing outcomes. While the literature reports that NF2 patients have worse hearing outcomes compared to sporadic cases, we had too few NF2 patients in the cohort to detect this statistically.³⁷

We did not specifically analyze the SRS dose to the cochlea and recognize this as a limitation of our study, as a large number of patients received SRS at a time before this was realized as important and recorded, or record transient volume increase, but both have been suggested as adverse predictors, potentially due to long-term effects of cochlear radiation on the cochlea’s vulnerable microvasculature.^{38–41} Part of our cohort with recorded cochlea doses has already been reported with the finding agreeing with others in that cochlear dose correlates with hearing loss.³⁸ In one study, where the mean radiation dose delivered to the cochlear

volume ranged from 1.30 to 10.00 Gy (median 4.15 Gy), the cochlea received significantly higher radiation doses in patients with worsening of hearing after SRS.⁴² A highly significant association between the cochlear and the intracanalicular dose of radiation delivered during SRS was found.⁴² The high rate of tumor control coupled with the prevalence of hearing deterioration suggests that cochlear sensitivity to the long-term effects of radiation may underlie the observed hearing decline. We had too few numbers to analyze patients according to category and modality of SRS or to compare those SRS patients who received doses above the standard prescribed dose at our institution so we cannot comment on these variables.

Some Patients Improve their Hearing Following SRS

We observed a small number of patients that has hearing improvement following SRS.

Sometimes this occurs from 0% word recognition to over 50% word recognition. This number of patients was less when followed for more than 3 yr, compared to more than 1 yr. This uncommon occurrence has been reported in the literature both in sporadic and NF2 patients.⁴³

Study Limitations

This study is limited by its retrospective nature. We were unable to make comparisons between those receiving primary SRS, salvage SRS, and other categories of radiation because of insufficient number of patients. The criteria used for selection of SRS in this cohort was not algorithmically based but rather reflected the differing judgement of individual practitioners, the evolving attitudes in the field over a 2-decade period, and a substantial degree of patient preference. Our results of patients beyond 6 to 7 yr is limited and therefore our results should be interpreted with care beyond 6 yr. There are a multitude of reasons why patients may not have follow-up. They could have been doing well after a long period and therefore chose not to return, they conversely could have growing tumors that are yet to be symptomatic or they may have received treatment at another institution. The small numbers at this time reflects the invention of the Cyberknife (Accuray, Sunnyvale, California) at our institution so there was a population that travelled to receive treatment and then was lost to follow-up. It also reflects the earlier days of SRS when smaller numbers were performed.

CONCLUSION

Following SRS for VS, hearing in the tumor ear gradually deteriorates over time in the majority of patients with the steepest decline in the first 3 yr, especially in larger tumors. Our data does not support a "proactive" strategy of radiating VS at their time of discovery as a means of improving the odds of hearing preservation. While SRS has an overall excellent efficacy in tumor control we recommend reserving SRS for tumors that have demonstrated growth on serial imaging. Future studies of VS hearing outcomes should utilize contemporary minimal reporting

standards and make their full audiometric database available to facilitate future meta-analyses. Use of the legacy GR scales should be discontinued.

Disclosures

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Supplemental digital content is available for this article at www.neurosurgery-online.com.

Supplemental Digital Content 1. Data File. Contains the entire raw collection data for the cohort of patients treated by SRS for VS between 1992 and 2013.

Supplemental Digital Content 2. Table. SRS hearing results. This table displays the cohort's pre- and posttreatment hearing classifications according to the Gardner Robertson classification after **A**, 1 yr and **B**, 3 yr.⁸

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