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Is There a Plateau to the Learning Curve for Acoustic Neuroma Resection?—Experience and Outcomes from a Single Interdisciplinary Team Over Thirty Years

Daniel M. Heiferman[1] Loren N. Riedy[2] Elhaum G. Rezaii[3] Mohammed Nuru[4] Dayna Sloane[4] Cara Joyce[5] Mary E. Moore[5] Rachyl M. Shanker[4] Kurt A. Grahnke[4] Giselle E. K. Malina[6] Caroline C. Szujewski[2] John P. Leonetti[7] Douglas E. Anderson[4]

[1] Department of Neurological Surgery, Edward-Elmhurst Healthcare, Naperville, Illinois, United States
[2] Department of Neurobiology, University of Chicago, Chicago, Illinois, United States
[3] Department of Neurological Surgery, University of Nebraska Medical Center, Omaha, Nebraska, United States
[4] Department of Neurological Surgery, Loyola University Stritch School of Medicine, Maywood, Illinois, United States
[5] Clinic Research Office, Loyola University Stritch School of Medicine, Maywood, Illinois, United States
[6] Department of Emergency Medicine, Harvard Medical School, Boston, Massachusetts, United States
[7] Department of Otolaryngology, Loyola University Stritch School of Medicine, Maywood, Illinois, United States

Address for correspondence Douglas E. Anderson, MD, Department of Neurological Surgery, Cranial Base Surgery Program, Loyola University Stritch School of Medicine, 2160 South First Avenue, Maywood, IL 60153, United States (e-mail: dander1@lumc.edu).

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Abstract

Objective The evolution of acoustic neuroma (AN) care continues to shift focus on balancing optimized tumor resection and control with preservation of neurological function. Prior learning curve analyses of AN resection have demonstrated a plateau between 20 and 100 surgeries. In this study of 860 consecutive AN surgeries, we investigate the presence of an extended learning curve tail for AN resection.

Methods A retrospective cohort study of AN resections by a single interdisciplinary team between 1988 and 2018 was performed. Proportional odds models and restricted cubic splines were used to determine the association between the timing of surgery and odds of improved postoperative outcomes.

Results The likelihood of improved postoperative House-Brackmann (HB) scores increased in the first 400 procedures, with HB 1 at 36% in 1988 compared with 79% in 2004. While the probability of a better HB score increased over time, there was a temporary decrease in slope of the cubic spline between 2005 and 2009. The last 400 cases continued to see improvement in optimal HB outcomes: adjusted odds of HB 1 score were twofold higher in both 2005 to 2009 (adjusted odds ratio [aOR]: 2.11, 95% confidence interval [CI]: 1.38–3.22, $p < 0.001$) and 2010 to 2018 (aOR: 2.18, 95% CI: 1.49–3.19, $p < 0.001$).

Keywords
- acoustic neuroma
- learning curve
- retrosigmoid
- spline
- translabyrinthine

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Conclusion In contrast to prior studies, our study demonstrates the steepest growth for learning, as measured by rates of preservation of facial function outcomes (HB 1), occurs in the first 400 AN resections. Additionally, improvements in patient outcomes continued even 30 years into practice, underlining the importance of lifelong learning.

Introduction

Acoustic neuromas (ANs), also known as vestibular schwannomas, are benign tumors of the cerebellopontine angle. These tumors pose a surgical challenge given the restricted cavity in which to operate, deep extension into the skull base, and adherence to structures such as cranial nerves, cerebral vessels, and the brainstem. The first attempted AN surgery was performed in 1894 by Sir Charles Ballance, and subsequently resulted in a 20% mortality rate for the procedure in the first half of the 20th century.[1] With the advent of the operative microscope, intraoperative cranial nerve monitoring, and evolving surgical techniques, including the introduction of the translabyrinthine (TL) approach by William House in 1960, mortality rates dropped significantly.[2,3] This allowed for further attention toward preserving the continuity of cranial nerves.[4] More recently, national trends have demonstrated an increase in the use of stereotactic radiosurgery and observation, thus shifting the paradigm of patient selection.[5] This evolution of AN care has ushered in an era focused on balancing optimized tumor resection and control with improved patient quality of life measures, including preservation of neurological function.[6,7] Given the complexity of the surgery and the high stakes for success, understanding the learning curve to mastery becomes useful for mentorship strategies and patient counseling. Additionally, learning curve analyses offer insight into what one may expect early in their practice, as compared with the summative outcomes of large series that may not reflect realistic expectations of a young surgeon. Previous studies looking at the learning curve for facial nerve preservation, as measured by House-Brackmann (HB) scores, have demonstrated plateaus in successful outcomes of AN resection following an experience of between 20 and 100 surgeries, specifying a threshold for operative mastery.[8–13] However, a recent study by Younus et al investigated the potential for additional learning during the extended tail of their sample's learning curve of endoscopic endonasal skull base surgery.[14] Significant improvement was identified in particular outcome measures from the first and second halves of their 1,000 patient cohort, suggesting that traditional S-shaped learning curves may need further consideration to best understand the complexities of outcomes over a surgeon's career.[14]

The two senior authors (D.E.A. and J.P.L.) have been performing AN surgery as a single interdisciplinary team for over 30 years, thus offering a unique insight into the potential for long-term learning over decades of practice, and the opportunity to understand the tail of the learning curve. We present their experience with regard to facial nerve function and tumor control outcomes using an easily interpretable spline model, which illustrates granular insight into the learning curve over a career of AN surgery. To our knowledge, this is the largest and longest AN surgery learning curve study to date. We hypothesized that there is continued learning in AN surgery throughout one's career, as reflected by an increased rate of postoperative HB 1 scores over time.

Methods

Patient Population

With Loyola University Chicago institutional review board (IRB) approval (LU# 210182), patients who underwent AN resection at our institution by the two senior authors (D.E.A. and J.P.L.) between 1988 and 2018 were included in the study and were retrospectively reviewed for demographic, surgical, and outcomes data. Per IRB protocol, the requirement for informed consent was waived due to the retrospective study design.

Patient Characteristics

Demographic information gathered included mean age, sex, and history of prior AN resection or stereotactic radiosurgery. Tumors were characterized by laterality, median size by largest diameter as measured on preoperative magnetic resonance imaging (MRI), presence or absence of any cystic component (as described in surgeon's operative note, pathology report, and seen on diagnostic imaging), and brainstem compression as seen on MRI. Preoperative symptoms were recorded including tinnitus, hearing loss, dizziness, balance difficulty, headache, weakness, numbness, facial pain, facial twitching, aural fullness, and hydrocephalus with or without external ventricular drain or shunt placement.

Surgical Approach and Technique

The surgical approach decision was made collaboratively by the senior authors (J.P.L. and D.E.A.) depending on baseline hearing function and anatomic factors, such as tumor size, extension, and the distance between the superior petrosal sinus and the jugular bulb. The preferred approaches to resection included retrosigmoid (RS), TL, and a combined RS-TL approach. The middle fossa approach was used sparingly given physician practice. Generally, patients with large tumors (> 4 cm) underwent the combined approach, while the TL approach was favored for small tumors (< 1.5 cm) when hearing preservation was not possible. The RS approach was utilized in hearing preservation cases and in those without significant meatal extension. Both senior authors participated in all resections regardless of approach. The neurotologist (J.P.L.) performed the soft tissue

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dissection, bone drilling, and initial tumor dissection at the fundus, and the neurosurgeon (D.E.A.) performed the dural and intradural portions of the resection. Direct facial nerve monitoring was used in all surgeries. Closure included standard autologous fat graft for all TL approaches. For the RS approaches, initially hydroxyapatite was used over a watertight dural closure, then there was a transition to autologous fat graft over the dural closure, and finally, a titanium mesh embedded in polymer cranioplasty was added over the autologous fat.[15]

Extent of Resection

The presence of residual tumor was assessed intraoperatively using a custom 1 cm graduated bayoneted micromeasuring instrument. Extent of tumor resection was divided into three groups: gross total resection (GTR), near total resection (NTR), and subtotal resection (STR). GTR was defined as total removal by the surgeon's operative note with no observable residual tumor identified on postoperative MRI, which was taken either 2 days postoperation or, depending on residual blood products or air in ventricles, 1 to 3 months postoperation. NTR was characterized by the presence of a residual tumor placode that was too small for the surgeon to measure intraoperatively or on postoperative imaging. STR was defined as any measurable amount of residual tumor intraoperatively and/or on postoperative MRI.

Facial Function

Postoperative facial nerve function was graded utilizing the HB grading scale. HB scores were recorded based on the latest documentation in the medical record prior to any treatment with facial reanimation when this occurred. HB scores were grouped into three categories: scores of 1, 2, and 3 to 6.

Statistical Methods

As a primary outcome, the association between the timing of the AN surgery and the odds of increasing postoperative HB 1 score was investigated using proportional odds models and restricted cubic splines (RCS). RCS is a modeling approach that examines nonlinear relationships between a continuous predictor and an outcome. This model is an improvement over other methods such as dichotomizing (binning), which can lead to a loss of information or impose a linear relationship which may represent a poor model fit. A cubic spline is a smooth piecewise polynomial, and the additional higher order terms beyond the linear coefficient can be tested to determine if the nonlinear model provides more information or a better fit. A univariable proportional odds model regressed HB score (categorized as 1, 2, or 3–6) against the spline effect for procedure date using 5 knots. Predicted probabilities of higher HB scores from this model were plotted to examine trends and determine inflection points in the time period. Patient and tumor characteristics were summarized by time period. Surgical characteristics were compared by time period and assessed for statistical significance using multinomial logistic regression. Adjusted odds ratios (aORs) were presented from a multivariable proportional odds model with predictors that included age, sex, surgical approach, tumor size, and time period. Analyses were performed using SAS version 9.4 (SAS Institute, Cary, North Carolina, united States). Statistical significance was set at an α level of 5% for all statistical tests (i.e., p-value less than 0.05).

Results

Between July 1988 and November 2018, a total of 860 procedures were performed by the same neurotologist (J.P. L.) and neurosurgeon (D.E.A.) team. The mean age was 50 ± 13 years and half of the patients were female ($n = 434$, 50.5%). The median tumor size was 2 cm (interquartile range: 1.5–2.8), which remained statistically stable across time periods, and 10% were cystic ($n = 83$). Median follow-up time was 78 months for 1988 to 2004, 42.9 months for 2005 to 2009, and 24 months for 2010 to 2018 (►**Table 1**).

The likelihood of improved postoperative HB scores increased steadily in the first 15 years of practice (400 procedures), with the predicted probability of HB 1 being 36% in 1988 versus 79% in 2004. A trend toward a slightly lower proportions of HB 1 and 2 occurred between 2005 and 2009 compared with the 5 years prior. Following a local nadir in probability of HB 1 at 73% in 2010, rates of HB 1 again rose steadily through 2018 (►**Fig. 1**).

The TL approach was most common among the earlier procedures (54% from 1988 to 2004), while the RS approach became more prevalent between 2005 and 2009 (59.8%). This change corresponded to an increased focus on hearing preservation in the senior authors' clinical practice at that time. The frequency of the combined TL/RS approach increased over time from 4.8 to 16.8%. There was a statistically significant difference in residual tumor being left intraoperatively over time, as indicated by the differences in frequencies of GTR, NTR, and STR ($p < 0.001$ for all comparisons) (►**Table 2**). ►**Fig. 2** shows a spline curve of the probability of GTR over time. However, after adjusting for tumor size, extent of resection, surgical approach, sex, and age within the adjusted proportional odds model, there was no statistically signification association between extent of resection and the odds of a patient having an HB 1 postoperative facial function outcome ($p = 0.92$) (►**Table 3**).

Compared with early procedures performed between 1988 and 2004, the odds of an optimal HB score were twofold (111 and 118%, respectively) higher in both 2005 to 2009 (aOR: 2.11, 95% confidence interval [CI]: 1.38–3.22, $p < 0.001$) and 2010 to 2018 (aOR: 2.18, 95% CI: 1.49–3.19, $p < 0.001$). Using the adjusted proportional odds model, those who underwent resection via the RS approach had a 70% higher odds of a better HB score compared with the TL approach (aOR: 1.70, 95% CI: 1.19–2.42, $p = 0.004$). The odds of better HB scores were 38% lower for females compared with males over the entire series of patients (aOR: 0.62, 95% CI: 0.45–0.86, $p = 0.004$) (►**Table 3**). With an increase in tumor size, there was a significant downtrend in the rate of HB 1 and HB 1 + 2 (►**Supplementary Fig. S1**, available in the online version only).

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Table 1 Patient characteristics by time period

	Overall	1988–2004	2005–2009	2010–2018
No. procedures	860	400	204	256
Patient characteristics				
Age, mean ± SD [*n* = 858]	50 ± 13	50 ± 13	48 ± 12	52 ± 14
Female, *n* (%)	434 (50.5)	200 (50.0)	98 (48.0)	136 (53.1)
Prior AN surgery, *n* (%)	22 (2.6)	10 (2.5)	6 (2.9)	6 (2.3)
Prior SRS, *n* (%)	13 (1.5)	(0.0)	11 (5.4)	2 (0.8)
Tumor characteristics				
Right side, *n* (%) [*n* = 840]	388 (46.2)	178 (46.8)	97 (47.5)	113 (44.1)
Cystic, *n* (%) [*n* = 824]	83 (10.0)	1 (0.3)	33 (16.2)	49 (19.1)
Brainstem compression, *n* (%) [*n* = 824]	53 (6.4)	(0.0)	13 (6.4)	40 (15.7)
Size, median (IQR) [*n* = 837]	2 (1.5–2.8)	2 (1.5–2.8)	2 (1.5–2.725)	2.2 (1.7–3)
Preoperative symptoms, *n* (%) [*n* = 826]				
Tinnitus	445 (53.9)	188 (51.4)	111 (54.4)	146 (57.0)
Hearing loss	762 (92.3)	340 (92.9)	189 (92.6)	233 (91.0)
Dizziness	250 (30.3)	110 (30.1)	57 (27.9)	83 (32.4)
Balance issues	168 (20.3)	(0.0)	58 (28.4)	110 (43.0)
Headache	125 (15.1)	41 (11.2)	27 (13.2)	57 (22.3)
Weakness	26 (3.1)	14 (3.8)	4 (2.0)	8 (3.1)
Facial pain	23 (2.8)	(0.0)	9 (4.4)	14 (5.5)
Facial twitch	17 (2.1)	(0.0)	4 (2.0)	13 (5.1)
Numbness	120 (14.5)	43 (11.7)	32 (15.7)	45 (17.6)
Aural fullness	29 (3.5)	(0.0)	8 (3.9)	21 (8.2)
Hydrocephalus	20 (2.4)	5 (1.4)	3 (1.5)	12 (4.7)
External ventricular drain	3 (0.4)	(0.0)	1 (0.5)	2 (0.8)
Shunt	10 (1.2)	4 (1.1)	(0.0)	6 (2.3)

Abbreviations: AN, acoustic neuroma; IQR, interquartile range; SD, standard deviation; SRS, stereotactic radiosurgery.

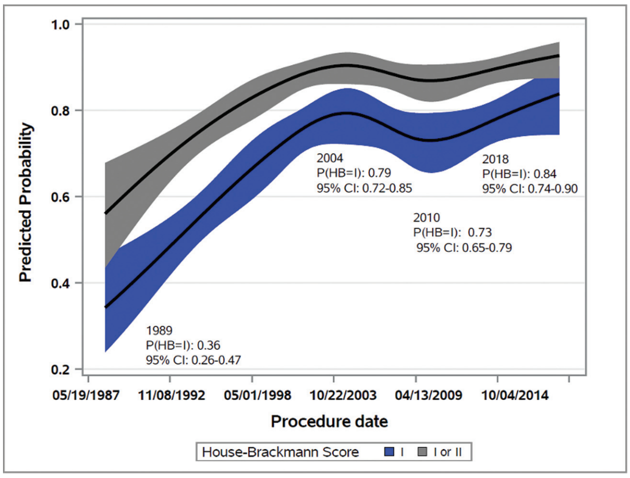

Fig. 1 Probability of House-Brackmann scores by time of procedure.

►**Fig. 3** shows a spline curve illustrating the probability of cerebrospinal fluid (CSF) leaks over 30 years. Total CSF leaks for procedures between 1988 and 2004, 2005 and 2009, and 2010 and 2018 were 25/400, 12/204, and 24/256, respectively. There was no statistically significant difference between the rate of CSF leaks requiring surgical repair (4.5% vs. 2.9% vs. 5.9%) (►**Table 4**).

Discussion

AN surgery is a challenging and nuanced skull base operation. While AN resection had an unfortunately high mortality rate in the infancy of neurosurgery, pioneers of skull base surgery and microsurgery have vastly improved the safety of this procedure. However, preservation of neurological function remains a challenge for resection. Compression of surrounding structures continues to pose a challenge, as any tumor > 3 cm or reactive inflammation around the tumor would likely have elements of brainstem compression. Coupled with the restricted cavity that limits exposure to the tumor and adherence to important structures, microsurgical surgical expertise is required to achieve optimal outcomes.

Our learning curve analysis of facial nerve preservation outcomes in 840 AN resections, by a single interdisciplinary team, over 30 years found two unexpected results. We demonstrated significant improvement in postoperative

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Table 2 Surgical characteristics by time period

Surgical characteristics	Overall	1988–2004 *N* = 400	2005–2009 *N* = 204	2010–2018 *N* = 256	*p*-Value
Approach, *n* (%) [*n* = 860]					< 0.001
TL	380 (44.2)	216 (54.0)	61 (29.9)	103 (40.2)	
RS	377 (43.8)	157 (39.3)	122 (59.8)	98 (38.3)	
Combined TL/RS	80 (9.3)	19 (4.8)	18 (8.8)	43 (16.8)	
MTL	23 (2.7)	8 (2.0)	3 (1.5)	12 (4.7)	
Residual, *n* (%) [*n* = 837]	132	21 (5.6)	23 (11.3)	88 (34.4)	< 0.001
Extent of resection, *n* (%) [*n* = 837]					< 0.001
GTR	700 (83.6)	356 (94.4)	181 (88.7)	163 (63.7)	
NTR	55 (6.6)	20 (5.3)	8 (3.9)	27 (10.5)	
STR	82 (9.8)	1 (0.3)	15 (7.4)	66 (25.8)	
Postoperative HB, *n* (%) [*n* = 810]					< 0.001
I	604 (74.6)	245 (61.3)	163 (79.9)	196 (76.6)	
II	123 (15.2)	68 (17.0)	26 (12.7)	29 (11.3)	
III-VI	83 (10.2)	38 (9.5)	15 (7.4)	30 (11.7)	
Postoperative complications, *n* (%) [*n* = 860]					
Surgical site infection	34(4.0)	12 (3.0)	7(3.4)	15(5.9)	
Intracranial hemorrhage	11(1.3)	3 (0.8)	5(2.5)	3(1.2)	
Venous infarction	2(0.2)	0 (0.0)	0(0.0)	2(0.8)	
Pulmonary embolism	8(0.9)	1 (0.0)	5(2.5)	2(0.8)	
Mortality	0(0.0)	0 (0.0)	0 (0.0)	0 (0.0)	

Abbreviations: GTR, gross total resection; HB, House-Brackmann; MTL, modified translabyrinthine; NTR, near total resection; RS, retrosigmoid; STR, subtotal resection; TL, translabyrinthine.
Note: Residual, combined near total resection and subtotal resection.

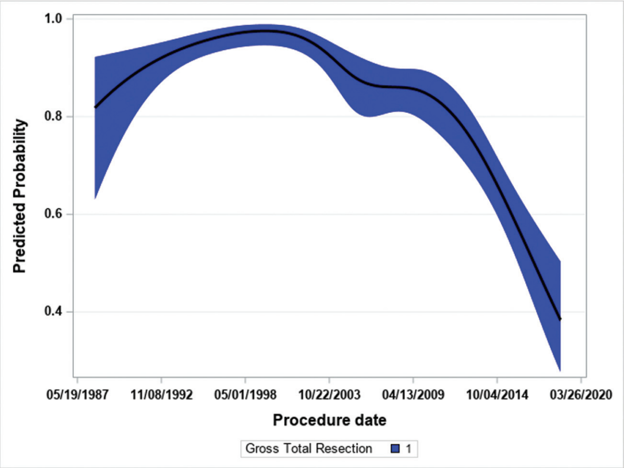

Fig. 2 Probability of gross total resection by time of procedure.

HB grade during the initial 400 cases. This is in stark contrast to prior studies that demonstrated plateaus occurring between 20 and 100 cases (►**Table 5**).$^{8–13}$ These series ranged from 96 to 300 cases, well within the initial learning curve we found in our series. Just as Younus et al found continued learning after hundreds of cases in endoscopic endonasal skull base surgery, these previous studies on the learning curve in AN surgery may have in fact been too myopic in their scope to determine a true long-term learning curve.[14]

In addition to this, there has been heterogeneity in the definition of “good” facial function outcome in the literature.$^{8–13}$ While traditional teaching has been that the eye closure difference between HB grade 3 and 4 is the most clinically significant, even cases of HB grade 2 can occur with facial weakness due to issues related to facial synkinesis that can significantly impair quality of life. For this reason, the outcome of our primary analysis was the rate of postoperative HB grade 1 facial function. By focusing on a higher outcome threshold of complete preservation of facial function, we have demonstrated a learning curve over many hundreds of cases that has not been shown in the past. Setting such a threshold offers a learning opportunity for continued improvement throughout one’s career. This becomes particularly important as the complexity of a team’s practice matures; as demonstrated for instance in the trend of increasing tumor diameter, frequency of cystic tumors, and presentations with hydrocephalus, shown in ►**Table 1**.

The second unexpected result was the slight, although statistically significant, downtrend in facial function outcome between 2004 and 2010. This finding demonstrates the power of a continuous analysis, such as the spline, in illustrating details in long-term operative learning. While

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Table 3 Adjusted proportional odds models for patient characteristics and postoperative House-Brackmann score

	Odds ratio (95% confidence interval)	*p*-Value
Age (5 y increase)	0.96 (0.90–1.02)	0.14
Sex		0.004
Male	1 (reference)	
Female	0.62 (0.45–0.86)	
Tumor size (1 cm increase)	0.59 (0.50–0.70)	< 0.001
Surgical approach		0.009
TL	1 (reference)	
RS	1.70 (1.19–2.42)	0.004
TL/RS	0.90 (0.51–1.61)	0.73
MTL	0.68 (0.27–1.73)	0.42
Year of procedure		< 0.001
1988–2004	1 (reference)	
2005–2009	2.11 (1.38–3.23)	< 0.001
2010–2018	2.19 (1.45–3.31)	< 0.001
Extent of resection		0.92
GTR	1 (reference)	
NTR	0.88 (0.47–1.64)	0.69
STR	1.01 (0.56–1.82)	0.99

Abbreviations: GTR, gross total resection; MTL, modified translabyrinthine; NTR, near total resection; RS, retrosigmoid; STR, subtotal resection; TL, translabyrinthine.

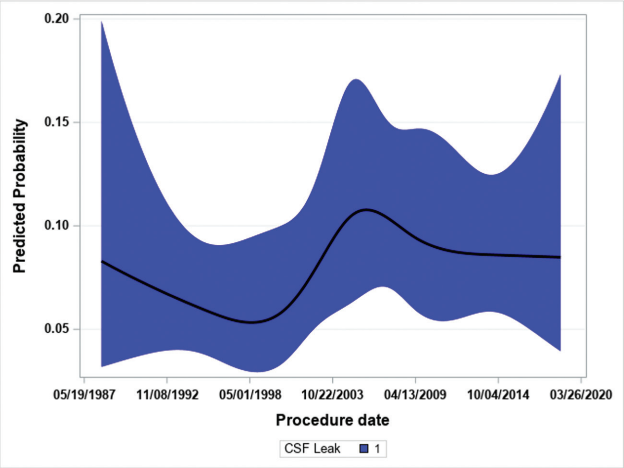

Fig. 3 Probability of cerebrospinal fluid leak by time of procedure.

Younus et al demonstrated long-term learning potential by their massive groupings of 500 endoscopic endonasal cases, slight regressions and relearning curves may have been overlooked.[14] Though retrospective, we postulate this trend (2004–2010) to be related to changes in perspective on operative goals of the senior authors. In 2011, Sughrue et al published a report on their experience with leaving residual tumor for the preservation of facial nerve function and found that there was no difference in tumor recurrence between the GTR and STR groups.[6] With this, the senior authors recall a conscious decision to focus on neurologic preservation over GTR, which is demonstrated in the significant increase in NTR and STR in the final 8 years of data. Since that time, further research has been done on the topic of tumor growth following STR and continues to be an area of debate in the field.[16]

While the most significant learning occurred during the first 400 cases, as previously noted corresponding to the steepest slope of the spline plot, continued statistically significant variances in the slope of the spline curve throughout the senior authors' careers is suggestive of lifelong learning, as we hypothesized. The senior authors' decision to continue gradual resection was dependent primarily on both the ability to identify the dissection plane and the nerve responses to electrical stimulation, with no further resection if additional manipulation became detrimental to the facial nerve outcome. The relationship between the size of the residual tumor and the likelihood of recurrence remains an unanswered issue. Also, a shift toward more use of the RS

Table 4 CSF Leak rate by year of procedure

	Overall ($N = 860$)	1988–2004 ($N = 400$)	2005–2009 ($N = 204$)	2010–2018 ($N = 256$)	*p*-Value
CSF leaks					
Requiring surgical repair, *n* (%)	39 (4.5)	18 (4.5)	6 (2.9)	15 (5.9)	**‘88–04 vs. ‘05–09:** $p = 0.35$ **‘88–04 vs ‘10–18:** $p = 0.44$ **’05–09 vs. ’10–18:** $p = 0.14$
Lumbar drain only, *n* (%)	14 (1.6)	6 (1.5)	2 (1.0)	6 (2.3)	**‘88–04 vs. ‘05–09:** $p = 0.60$ **‘88–04 vs. ‘10–18:** $p = 0.43$ **’05–09 vs. ’10–18:** $p = 0.27$
Aspiration or pressure dressing only, *n* (%)	8 (0.9)	1 (0.3)	4 (2.0)	3 (1.2)	**‘88–04 vs. ‘05–09:** $p = 0.03$ **‘88–04 vs. ‘10–18:** $p = 0.14$ **’05–09 vs. ’10–18:** $p = 0.49$

Abbreviation: CSF, cerebrospinal fluid.

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Table 5 Prior studies demonstrating learning curve plateaus

Author	Number of surgeries	Number of years	Successful HB scores	Learning curve analysis	Case threshold	Single team
Buchman et al[8] (1996)	96	7	1, 2	Chronological grouping	60	Yes
Moffat et al[9] (1996)	300	15	1, 2, 3	Chronological grouping	50–100	Not reported
Welling et al[10] (1999)	160	9	1	Chronological grouping	20	No
Elsmore and Mendoza[11] (2002)	127	24	1, 2	Chronological grouping	40–100	No
Foroughi et al[12] (2010)	102	15	1, 2, 3	Cumulative sum	27	No
Wang et al[13] (2013)	153	12	1, 2, 3	Cumulative sum	56	Yes
Present series (2021)	860	30	1	Spline	400 with continued learning	Yes

Abbreviation: HB, House-Brackmann.

approach mid-career may have a role in these trends, corresponding to a focus on preservation of serviceable hearing.

Though this is the largest and longest AN surgery learning curve study to date, limitations include those intrinsic to any retrospective study design, including the potential for the introduction of error during data collection. We also did not report on hearing preservation rates in this series for sake of clearer comparison, as a large portion of the AN cases were nonhearing preservation surgeries (i.e., TL surgeries). Technological advances over the course of the senior authors' careers, including improvements in surgical microscopes and imaging modalities, are important to recognize as possible confounders to improvement in facial nerve outcomes, which we are unable to control for, given the study design. Furthermore, changes to the senior authors' practice, including increased use of the RS approach with an increased focus on hearing preservation, as well as an increase in the rate of STR in the latter years of this series, are unable to be controlled for regarding the success of facial function preservation, as previously discussed. However, modulation of goals and techniques are an important component to a career long learning curve. The data represents the institutional experience of a single interdisciplinary team at a high-volume surgical center for AN, thus limiting the generalizability of this study. Nonetheless, we provide a rare insight into the threshold of learning and improved outcomes given our large sample and decades of expertise by the senior authors.

Conclusion

The learning curve for complete preservation of facial function for AN surgery may take hundreds of cases, as our study has demonstrated the steepest growth in the first 400 cases for the senior authors. Furthermore, variance in personal practice may occur as collective care changes over time. Continued efforts to improve facial nerve, and most recently cochlear nerve, outcomes appear to be ongoing, even after the 30 years of experience. Importantly, throughout one's career, we must be vigilant to adapt with paradigm shifts and technological advances, accept mid-career learning curves, and regroup as a team to optimize patient outcomes.

Conflict of Interest
None declared.

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