Patient Outcomes after Vestibular Schwannoma Management: A Prospective Comparison of Microsurgical Resection and Stereotactic Radiosurgery

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Received, June 1, 2006
Accepted, June 20, 2006

OBJECTIVE: The best management for patients with small- to medium-sized vestibular schwannomas (versus) is controversial.

METHODS: Prospective cohort study of 82 patients with unilateral, unoperated versus less than 3 cm having surgical resection (n = 36) or radiosurgery (n = 46). Patients having resection were younger (48.2 yr versus 53.9 yr, $P = 0.03$). The groups were similar with regard to hearing loss, associated symptoms, and tumor size. The mean follow-up was 42 months (range, 12 to 62).

RESULTS: Normal facial movement and preservation of serviceable hearing was more frequent in the radiosurgical group at three months ($P < 0.001$), 1-year ($P < 0.001$), and at last follow-up ($P < 0.01$) compared to the surgical resection group. Patients having surgical resection had a significant decline in the following subscales of the Health Status Questionnaire (HSQ) three months after surgery: physical functioning ($P = 0.006$), role-physical ($P < 0.001$), energy/fatigue ($P = 0.02$), and overall physical component ($P = 0.004$). Patients in the surgical resection group continued to have a significant decline in the physical functioning ($P = 0.04$) and bodily pain ($P = 0.04$) subscales at one-year, and in bodily pain ($P = 0.02$) at last follow-up. The radiosurgical group had no decline on any component of the HSQ after the procedure. The radiosurgical group had lower mean Dizziness Handicap Inventory scores (16.5 versus 8.4, $P = 0.02$) at last follow-up. There was no difference in tumor control (100% versus 96%, $P = 0.50$).

CONCLUSION: Early outcomes were better for versus patients having stereotactic radiosurgery compared to surgical resection (Level 2 evidence). Unless long-term follow-up shows frequent tumor progression at currently used radiation doses, radiosurgery should be considered the best management strategy for the majority of versus patients.

KEY WORDS: acoustic neuroma, outcome, radiosurgery, vestibular schwannoma

Neurosurgery 58:000-000, 2006 DOI: 00-0000/00.NEU.0000000000.00000.ac www.neurosurgery-online.com

INTRODUCTION

Vestibular schwannomas (acoustic neuromas) are benign, slow growing tumors that arise from the vestibular-cochlear nerve. Patients diagnosed with vestibular schwannomas (versus) typically present with hearing loss, tinnitus, or dizziness. The incidence of versus diagnosed between 1996 and 2001 has been estimated to be 17.4 per one million people annually (40), and the size of newly diagnosed versus has decreased secondary to the widespread application of magnetic resonance imaging (MRI). Although observation with serial imaging is often recommended for elderly patients with small tumors (11, 34), younger patients in good medical condition are typically recommended to undergo either surgical resection (4, 5, 12, 36), stereotactic radiosurgery (13, 14, 17, 19, 24, 31), or fractionated radiation therapy (1, 6, 7, 44). A review of the English literature published over the past

23 years (111 papers) found no level 1 or 2 evidence to support either surgical resection or radiosurgery as the preferred management for versus patients (30). In this study, we prospectively compared outcomes after versus resection or radiosurgery for adult patients with unilateral, unoperated versus less than 3 cm in average diameter.

MATERIALS AND METHODS

Study Design

The study was a prospective observational comparison of adult patients with unilateral, unoperated versus less than 3 cm having surgical resection or radiosurgery. Patients with Neurofibromatosis Type 2 or patients with recurrent tumors were excluded. No attempt at preoperative randomization was made; patients underwent either surgical resection or radiosurgery based on patient preference after a discussion of the options for treatment. Blinded, independent observers determined tumor size (KNK), facial nerve function (CHJ), and hearing preservation (CDB). Patients provided written, informed consent before enrolling, and the Institutional Review Board of our institution approved all aspects of this study.

TABLE 1. Patient Characteristics

Characteristic	MS (n = 36)	RS (n = 46)	*P* value
Male/female	19/17	27/19	0.76
Mean age (years)	48.2	53.9	0.03
Facial weakness	0 (0%)	0 (0%)	1.00
Facial numbness	2 (6%)	1 (2%)	0.83
Class A or B hearing[a]	22 (61%)	30 (65%)	0.88
Mean HSQ (8 subsets)	61–92	63–88	0.11–0.99
Mean DHI score	11.9	11.0	0.76
Mean Tinnitus score	11.6	9.0	0.12
Mean Headache score	5.7	6.0	0.63
Tumor size			
Intracanalicular	5 (14%)	10 (22%)	0.53
Mean CPA diameter	14.1 mm	12.3 mm	0.25

[a] American Academy of Otolaryngology-Head Neck Surgery Classification system (pure-tone threshold ≤50 dB and speech discrimination score ≥50%) (16).
Abbreviations: CPA, cerebellopontine angle; DHI, dizziness handicap inventory; HSQ, health status questionnaire; MS, microsurgery; RS, radiosurgery.

Patients

Between June 2000 to July 2002, 162 patients with versus were evaluated at our center. Twenty-one patients (14%) were recommended to have observation with serial imaging; nine patients (6%) underwent treatment at other centers. Of the remaining 132 patients, 56 (42%) underwent surgical resection, whereas 76 (58%) had radiosurgery. Forty-three patients (27%) were excluded for the following reasons: age less than 18 yr (n = 3), neurofibromatosis Type 2 (n = 11), tumor larger than 3 cm (n = 11), poor surgical candidate (n = 10), and recurrent tumors (n = 8). Eighty-two of 89 eligible patients (92%) agreed to participate in the study. Thirty-six underwent surgical resection; 46 had radiosurgery. The patient characteristics are outlined in *Table 1*. Patients having resection were younger (48.2 yr versus 53.9 yr, $P = 0.03$). The groups were similar with regard to hearing loss, associated symptoms, tumor size, and all the subscales of the Health Status Questionnaire (HSQ, a modification of the SF-36) (42).

Surgical Technique

The surgical approach was selected after reviewing the preoperative imaging and audiology data, and thoughtful discussion with the patient regarding their priorities and realistic expectations of facial nerve function, hearing preservation and tumor removal. Patients with useful hearing and smaller tumors generally underwent either a retro-sigmoid (n = 25, 69%) or middle fossa (n = 2, 6%) approach. The translabyrinthine approach was chosen when the patients had poor pre-operative hearing (Class D, n = 5). However, patients with tumors greater than 2 cm in mean cerebellopontine angle diameter and useful pre-operative hearing (n = 3), or patients with useful preoperative hearing and tumor extension to the fundus of the internal auditory canal (n = 1) were also deemed better candidates for a translabyrinthine approach to maximize the chance of complete tumor removal and preservation of facial nerve function. Tumor removal was graded as total in 33 patients and near-total (no gross tumor remaining, small fragment left along facial nerve) in 3 patients. The facial nerve was anatomicly intact in all cases at the end of the operation. The mean hospital length of stay was 5.1 days. Stereotactic radiosurgery was performed using a Leksell Gamma Knife® (Elekta Inc., Norcross, GA). MRI was used for dose planning in all cases. The mean number of isocenters used was 8.1; the mean tumor volume was 1.5 cc. The mean tumor margin dose was 12.2 Gy; the mean maximum dose was 26.4 Gy. All cases were performed as outpatient procedures.

Outcome Measures

Data was collected pre-operatively, then at three months, 1-year, and last follow-up. Facial nerve outcomes were based on a blinded review of patient photographs. Five photographs were taken at each interval (at rest, eye closure, eyebrow raising, smiling, frowning). Facial movement was graded as normal (House-Brackmann Grade 1) (18), or not normal. Hearing was graded by the classification of the American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) (9). Postoperative audiograms were performed for all patients within three months of surgery. Patients with retention of hearing were retested at one year, then yearly intervals thereafter. A questionnaire was developed to evaluate subjective symptoms (dizziness, tinnitus, headache). The instrument included the Dizziness Handicap Inventory (DHI) (20), a tinnitus survey (2), and a headache survey (Lawrence H. Pitts, personal communication). The headache survey consisted of five questions assessing this symptom on a Likert scale ranging from zero (no complaint) to five (significant complaint) ranking the frequency, duration, intensity, treatment, and disability associated with headaches. The scale ranged from no headaches (zero points), mild headaches (1–6 points), moderate headaches (7–12 points) and severe headaches (13–20 points). The HSQ was used to measure patients' quality of life (QOL).

The primary endpoints of this study were retention of normal facial movement (House-Brackmann Grade 1) and the preservation of serviceable hearing (AAO-HNS Class A or B). Assuming the preservation of normal facial movement would be 75% after restion and 99% after radiosurgery, power analysis (power = 0.80, significance = 0.05) showed the study would require 74 patients. Power analysis for preservation of serviceable hearing (assuming hearing preservation of 15% and 60% after restion and radiosurgery, respectively) showed the study would need 42 patients. Secondary endpoints were the effect of treatment on patients' QOL and subjective symptoms.

Follow-up and Statistical Analysis

No patient withdrew from the study. Data available for evaluation included facial photographs (98%), audiograms (94%), and questionnaires (94%). The mean follow-up was 42 months (range, 12 to 62). The groups were compared using Wilcoxon Rank-Sum test, student t-test, and Fisher's exact test. P values less than 0.05 were considered statistically significant.

RESULTS

Facial Movement

Normal facial movement was more frequent in the radiosurgical group at three months (100% versus 61%, $P < 0.001$), 1-year (100% versus 69%, $P < 0.001$), and at last follow-up (96% versus 75%, $P < 0.01$) compared to the surgical resection group. The two patients with facial weakness in the radiosurgical group developed this deficit after surgical removal of the tumor following failed radiosurgery. Normal or near-normal facial movement (House-Brackmann Grade 1 or 2) was more frequent in the radiosurgical group (98% versus 83%, $P = 0.04$) at last follow-up.

Hearing Preservation

Preservation of AAO-HNS Class A or B hearing was greater in the radiosurgical group at 3 months (77% versus 5%, $P < 0.001$), 1-year (63% versus 5%, $P < 0.001$), and at last follow-up (63% versus 5%, $P < 0.001$) compared to the surgical resection group. Preservation of AAO-HNS Class A hearing was greater in the radiosurgical group (n = 18) at 3 months (56% versus 0%, $P = 0.01$), 1-year (50% versus 0%, $P < 0.01$), and at last follow-up (50% versus 0%, $P < 0.01$) compared to the surgical resection group (n = 11). Two of 16 patients (13%) in the radiosurgical group with AAO-HNS Class C or D hearing improved to Class B at last follow-up.

TABLE 2. Results of Health Status Questionnaires

Mean HSQ scores (SD)	Baseline		3-month		1-year		Last follow-up	
(change from baseline, SD)	MS (n = 36)	RS (n = 46)	MS (n = 35)	RS (n = 42)	MS (n = 36)	RS (n = 44)	MS (n = 31)	RS (n = 39)
Health perception	77.9 (15.7)	73.8 (17.2)	76.0 (17.1)	71.5 (16.8)	71.2 (18.2)	72.0 (18.5)	70.9 (20.3)	71.8 (19.4)
			(–1.3, 16.0)	(–3.5, 13.1)	(–6.8, 16.1)	(–2.9, 14.1)	(–7.5, 15.8)	(–4.5, 12.0)
Physical functioning	92.1 (15.0)	88.2 (18.9)	80.9 (15.4)	88.0 (19.5)[b]	87.6 (12.5)	85.7 (20.8)	87.1 (16.8)	83.6 (21.6)
			(–11.0, 19.7)	(–1.2, 8.5)[b]	(–4.5, 14.8)	(–3.7, 15.1)[a]	(–4.4, 16.3)	(–5.4, 20.9)
Role—physical	76.4 (41.8)	84.8 (31.4)	34.3 (40.7)	59.4 (44.3)[b]	69.4 (44.4)	78.4 (34.8)	81.2 (30.4)	80.8 (35.1)
			(–41.4, 57.2)	(–7.7, 28.4)[b]	(–6.9, 60.2)	(–8.0, 36.1)	(2.2, 42.7)	(–8.3, 38.6)
Role—emotional	76.9 (34.6)	84.8 (31.2)	82.9 (32.7)	91.3 (24.5)	92.6 (24.1)	90.7 (24.5)	92.2 (22.6)	93.2 (20.5)
			(6.7, 35.1)	(4.0, 27.8)	(15.7, 35.2)	(3.9, 37.9)	(17.8, 39.9)	(5.1, 26.0)
Social functioning	79.9 (23.6)	85.9 (20.2)	73.2 (21.0)	88.4 (17.1)[b]	79.5 (21.6)	87.2 (19.2)	85.1 (22.2)	89.7 (22.9)
			(–6.1, 26.0)	(0.9, 20.9)	(–0.3, 26.5)	(0.9, 20.4)	(3.2, 26.4)	(2.2, 24.7)
Mental health	74.3 (18.3)	76.1 (18.3)	74.9 (18.0)	80.1 (17.9)	77.1 (14.7)	81.3 (16.0)	76.1 (15.9)	82.9 (12.8)[a]
			(1.1, 17.5)	(2.3, 10.4)	(2.8, 13.3)	(4.5, 11.8)	(–0.4, 13.5)	(3.3, 11.5)
Bodily pain	84.9 (19.4)	84.0 (18.9)	71.3 (24.3)	81.2 (19.5)[a]	73.5 (24.9)	83.1 (20.0)	76.2 (24.1)	81.8 (24.1)
			(–13.1, 29.4)	(–4.2, 14.5)	(–11.3, 28.8)	(–1.4, 17.5)[a]	(–9.8, 25.9)	(–2.4, 16.4)[a]
Energy/fatique	61.0 (19.7)	63.3 (21.7)	52.3 (20.5)	64.8 (18.6)[b]	61.3 (22.3)	64.5 (21.3)	60.8 (19.0)	64.7 (22.7)
			(–7.8, 23.1)	(1.0, 16.9)[a]	(0.3, 25.0)	(0.8, 19.2)	(0.0, 15.8)	(–1.2, 19.8)
PCS	52.8 (7.8)	51.6 (8.4)	43.8 (8.6)	49.5 (9.0)[b]	47.5 (9.0)	49.3 (9.3)	49.2 (8.2)	48.5 (10.7)
			(–8.8, 12.0)	(–2.7, 5.0)[b]	(–5.2, 10.8)	(–2.6, 6.8)	(–3.7, 8.8)	(–3.4, 9.3)
MCS	47.9 (10.7)	50.4 (10.1)	50.3 (9.6)	53.3 (8.9)	52.0 (7.4)	54.2 (7.2)	51.6 (8.1)	54.9 (7.4)[a]
			(2.7, 10.1)	(2.0, 6.0)	(4.0, 9.6)	(2.5, 7.8)	(3.5, 10.4)	(2.7, 7.9)

Abbreviations: HSQ, health status questionnaire; MCS, standardized mental component scale; PCS, standardized physical component scale.
[a] P<0.05
[b] P<0.01

Quality of Life

The results for the HSQ are shown in *Table 2*. Patients having surgical resection had a significant decline in physical functioning ($P = 0.006$), role-physical ($P < 0.001$), energy/fatigue ($P = 0.02$), and overall physical component ($P = 0.004$) three months after surgery. At one year, patients having surgical resection had a significant decline in physical functioning ($P = 0.04$) and bodily pain ($P = 0.04$). At last follow-up, patients having surgical resection had a significant decline in bodily pain ($P = 0.02$). The radiosurgical group had no decline at three months, 1-year, or last follow-up on any component of the HSQ compared to before the procedure.

Associated Symptoms

Patient outcomes with regard to dizziness, tinnitus and headaches are shown in *Tables 3–5.* The only significant difference between the two groups was that at last follow-up the mean DHI was lower in the radiosurgical patients (16.5 versus 8.4, $P = 0.02$).

Complications and Additional Treatment

The most frequent complication after surgical resection was cerebrospinal fluid leakage (resolved with lumbar drain) in 5 patients (14%). Wound infection and deep vein thrombosis occurred in one patient each. Six patients (17%) required either a tarsorrhaphy (5 patients) or gold weight placement (1 patient) for eye protection. No patient underwent further tumor treatment. After radiosurgery, one patient developed trigeminal neuralgia that was controlled with medications. Two patients (4%) had increasing ataxia that improved with placement of a ventriculo-peritoneal shunt. Two patients (4%) underwent later resection 24 and 28 months after radiosurgery because of progressive tumor enlargement. No difference was noted in tumor control (100% versus 96%) over the follow-up interval ($P = 0.50$).

DISCUSSION

The best management of patients with small- to moderate sized versus is controversial (22, 33, 39). Current results after

TABLE 4. Results of Tinnitus Survey (Effect on Quality of Life)

Does tinnitus reduce QOL	MS	RS	P value
3-months			
Not at all	38%	26%	
Slightly	38%	50%	
Moderately	21%	19%	
Greatly	3%	2%	
Completely	0%	2%	
Mean tinnitus score	10.4	10.9	0.51
1-year			
Not at all	30%	29%	
Slightly	49%	50%	
Moderately	18%	17%	
Greatly	3%	2%	
Completely	0%	2%	
Mean tinnitus score	10.7	10.3	0.59
Last follow-up			
Not at all	30%	32%	
Slightly	43%	50%	
Moderately	17%	16%	
Greatly	10%	3%	
Completely	0%	0%	
Mean tinnitus score	11.6	10.0	0.29

TABLE 3. Results of Dizziness Handicap Inventory

Dizziness/Imbalance	MS	RS	P value
3-months			
None		29%	39%
Much worse	24%	16%	
Unchanged	9%	41%	
Much better	38%	5%	
Mean DHI score	19.8	11.9	0.06
1-year			
None		46%	37%
Much worse	11%	7%	
Unchanged	20%	34%	
Much better	23%	22%	
Mean DHI score	14.1	11.5	0.69
Last follow-up			
None	35%	61%	
Much worse	20%	3%	
Unchanged	13%	24%	
Much better	32%	13%	
Mean DHI score	16.5	8.4	0.02

TABLE 5. Results of Headache Survey

Headache Severity	MS	RS	P value
3-months			
None	32%	21%	
Mild	12%	35%	
Moderate	53%	42%	
Severe	3%	2%	
Mean headache score	5.6	5.7	0.93
1-year			
None	22%	33%	
Mild	28%	28%	
Moderate	33%	40%	
Severe	17%	0%	
Mean headache score	6.7	5.2	0.18
Last follow-up			
None	26%	36%	
Mild	32%	36%	
Moderate	32%	21%	
Severe	10%	8%	
Mean headache score	6.0	5.0	0.29

surgical resection include high rates of complete tumor removal, low recurrence rates, and preservation of normal or near-normal facial function in approximately 85% of patients with tumors less than three cm in diameter. As a less invasive alternative to surgical resection, stereotactic radiosurgery has been utilized increasingly over the past 20 yr. Five retrospective studies have compared the results of surgical resection and radiosurgery for versus patients (21, 29, 32, 35, 42). Each study found radiosurgery had improved facial nerve outcomes and hearing preservation rates. Patients returned to work faster after radiosurgery, and the costs associated with radiosurgical management were less than open surgery. In large radiosurgical series, the need for later tumor resection has been less than three percent (13, 14, 17, 24, 31, 35). Ideally a randomized clinical trial (RCT) could be performed to compare outcomes for versus patients having surgical resection or stereotactic radiosurgery. However, such a study would be difficult to perform because patients may be reluctant to undergo randomization between open brain surgery or an outpatient based procedure done under local anesthesia. Also, many physicians who regularly manage versus patients are polarized in their thinking on this topic and would be unwilling to participate in a RCT. Recognizing these limitations, we performed a prospective observational study of versus patients managed at our center over a two-yr interval. The pre-operative patient characteristics of the two treatment groups were similar with regard to presenting symptoms, neurological deficits, and tumor size. Patients in the radiosurgical group were slightly older (53.9 yr versus 48.2 yr, $P = 0.03$), but this small difference in age should have little bearing on the results of this study. Blinded, independent observers graded facial nerve outcomes, determined hearing preservation, and measured the tumors. So although this study is not a RCT, it does provide solid level 2 evidence comparing cranial nerve outcomes for versus patients having either surgical resection or radiosurgery.

At every time point examined, patients having radiosurgery more frequently had normal facial movement and retained serviceable hearing compared to the microsurgical group. Despite the importance typically placed on cranial nerve function after versus management, equally important is the effect of treatment on versus patients QOL. Studies have shown that more than half of patients undergoing surgical resection felt their QOL was worse after surgery (10), and only one-third of patients resumed their normal activities of daily living within one month of their operation (8, 32, 42). Betchan et al (3) and Martin et al (28) both found a significant decline in the physical functioning, role-physical, and social functioning components of the HSQ after versus resection when compared to published normal controls. Conversely, the effect of radiosurgery on QOL for versus patients in retrospective studies has been less significant than surgical resection (29, 32, 35, 42). Myrseth et al used the SF-36 to compare the QOL in 140 versus patients having microsurgery or radiosurgery at a mean of 5.9 years after treatment (29). They noted significant deviations from age-adjusted values in the microsurgical group for physical functioning, role-physical, and role-emotional when compared to the radiosurgical patients. Our prospective data also showed the surgical resection group suffered a significant decline in several components of the HSQ at 3-months, 1-year, and at last follow-up compared to their preoperative level of functioning. The radiosurgical group showed no decline in any subset of the HSQ at any point during the follow-up interval.

The effect of surgical resection and radiosurgery were quite similar for the symptoms associated with versus The only significant difference noted for the associated symptoms was that the radiosurgical group had a lower mean DHI score at last follow-up suggesting fewer problems with imbalance. The effect of surgical resection on imbalance is quite similar to earlier studies. At last follow-up, the mean DHI of our surgical resection patients was 16.5. This compares to a mean DHI score of 17.6 for patients undergoing retrosigmoid removal and 16.8 for patients operated through a translabyrinthine approach (23). No retrospective study to date has used the DHI to measure imbalance after versus radiosurgery.

Our rate of hearing preservation after surgical resection appears low when compared to studies reporting hearing preservations rates from 21 to 88% (4, 5, 36). It is recognized that reported hearing preservation rates vary widely based on patient selection criteria and methods of defining hearing preservation (25, 37). In our series, the rate of hearing preservation included all patients with AAO-HNS Class A or B hearing before surgery, including four patients whose tumors were removed via a translabyrinthine approach, obligating them to deafness postoperatively. In addition to this lack of patient selection, our prospective, blinded assessment of hearing function probably contributed to our low hearing preservation rate. Betchan et al reported the hearing preservation rate in a consecutive series of 142 versus patients with pre-operative AAO-HNS Class A or B hearing (4). Initially, 38 patients (27%) retained AAO-HNS Class A or B hearing. The mean tumor size was 15 mm measured from the pons to the petrous bone. At a mean follow-up of seven years, 30 patients (21%) examined retained AAO-HNS Class A or B hearing. Nonetheless, this rate of hearing preservation would still be significantly less ($P < 0.01$) than we noted after radiosurgery by the same criteria.

Recently, fractionated stereotactic radiation therapy (SRT) has gained increasing prominence as a method to preserve hearing for versus patients (1, 6, 7, 44). It is argued that dose fractionation permits the differential sparing of normal tissues (vestibulocochlear nerve) and potential escalation of total dose when compared to stereotactic radiosurgery. Preliminary studies found hearing preservation rates approaching 80% (7, 44), and a retrospective comparison of stereotactic radiosurgery and SRT determined hearing preservation to be 2.5 times higher in the SRT group (1). Yet, reported hearing preservation rates after SRT have shown wide variation with some centers having less than one-third of patients retaining useful hearing (6). Moreover, at longer follow-up intervals there appears to be lower rates of hearing preservation compared to preliminary studies. A reassessment of the Johns Hopkins experience with SRT found that serviceable hearing was maintained in 59% of patients (40), compared to more than 80% in their earlier report (44). If one considers that radiosurgery provides the same or better hearing preservation rate (63% in this series) and the durability of tumor control after SRT is unknown, it becomes unclear that the theoretical arguments in favor of dose fractionation will become realized in clinical practice.

A number of factors need to be understood so that the findings of this report can be placed into the proper context in the discussion of versus management. One, not every versus patient is appropriate for radiosurgery. Observation with serial imaging can be used to effectively manage many elderly patients with small or minimally symptomatic versuss (11, 34). In addition, patients with large tumors are poor candidates for radiosurgery and should undergo surgical resection. Two, this study was not designed and thus does not provide any meaningful information regarding tumor control rates after surgical resection or radiosurgery of versuss. It is generally accepted that versus recurrence after total excision is approximately three percent, whereas numerous radiosurgical series have been published that similar failure rate after versus radiosurgery. The primary complaint is that earlier studies have reported patients treated with higher radiation doses than commonly used today (24). Hasegawa et al recently reported outcomes for 317 versus patients undergoing radiosurgery between 1991 and 1998 (17). The average tumor margin dose was 13.2 Gy. At a mean follow-up of 7.8 years, the 10-year progression-free survival for patients with tumors less than 15 cc was 97%. Preservation of useful hearing was 68% for patients receiving a tumor margin dose of 13 Gy or less; transient facial weakness occurred in one percent of patients. Nonetheless, more data is needed on the long-term tumor control at the lower doses used in our study to conclude that tumor control rates between the two techniques are similar. Three, if radiosurgery does fail and the tumor continues to enlarge, the published results suggest that tumor removal is more difficult and patient outcomes are poor compared to patients never undergoing radiosurgery (16, 26). In our series, both patients undergoing delayed resection after radiosurgery developed postoperative facial weakness. Last, it is now recognized that patients having radiosurgery are at some risk for developing radiation-induced neoplasms (27). The best estimate of this complication at this time is approximately 0.1 to 0.01%, although this number may increase as more patients are followed for longer intervals after radiosurgery. By comparison, a recent series of 707 patients operated between 1987 and 2001 found the risk of death after versus resection to be 0.1% (38).

The introduction of radiosurgery has had a significant impact on versus management at the Mayo Clinic. Early in our experience only elderly patients, those with significant medical co-morbidities, patients with Neurofibromatosis Type 2, or patients with recurrent tumors after prior surgery were considered good candidates for versus radiosurgery (15). Today, patients deemed appropriate for both surgical resection or radiosurgery are informed of the risks and benefits of each technique, and provided with various resources to help with the decision making process. Hopefully, each patient has a clear understanding of their options so they can decide whether observation, surgical resection, or radiosurgery is the best for their particular tumor and life considerations. Over the past fifteen years, the number of patients having versus radiosurgery at our center has steadily increased compared to surgical resection. For example, only 13% of versus patients had radiosurgery in 1993. In 1997, this figure rose to 37%. Since 2000, 58% of versus patients managed at our center have undergone radiosurgery. It remains to be seen whether this study's results will change patients' and physicians' opinions about the relative roles of surgical resection and radiosurgery for newly diagnosed small- to moderate-sized versuss.

Acknowledgements

The authors would like to thank Drs. Michael J. Ebersold, Stephen G. Harner, and Charles W. Beatty for allowing their patients to be included in this study and for their advice and support of this project.

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COMMENTS

For much of its history, neurosurgery has been "limited" by the idea that the adult nervous system does not have the ability to repair itself. This has placed obvious constraints on the scope of therapeutic possibilities for our field. Over the course of the past few years, there has been tremendous interest in a "biological" solution to surmount these limitations, with considerable effort and financial resources devoted to "restorative neurosurgery." These efforts have taken the form of stem cell research and attempts to "engineer" cells at the molecular level. In this review, the authors remind us that perhaps a less "biological" approach may ultimately play a role in restoring function to the damaged nervous system. The field of neuroprosthetics is rapidly expanding, and its capabilities, which are intimately dependent upon computational power, will surely broaden with the increasing influence of new technological paradigms such as nanotechnology. This review is timely and of obvious relevance to neurosurgeons.

Charles Y. Liu
Los Angeles, California

Leuthardt et al. provide a general overview of the idea of neuroprosthetics. This new field involves the use of a brain computer interface (BCI) with which electrical impulses from the brain parenchyma are transformed into usable data to overcome, for example, an acquired or congenital neurological deficit. The idea of a paraplegic patient simply using their thoughts to control a mechanical wheelchair, or better yet, to walk with robotic leg braces, is very appealing. The possibilities for such a technology are seemingly limitless. However, in its current state, there are some issues that must be dealt with. The authors point out many of the hurdles that must be overcome. For example, implanted depth electrodes develop surrounding gliosis, which essentially renders them useless after a period of time. While research into new biomaterials may provide answers to inflammatory reactions of the brain, one must also consider plasticity reactions of the brain. BCI systems must be made to adapt as existing neural connections are used in novel ways. The authors also mention the idea of feedback. This can be accomplished by combining both input and output BCIs. This could be used, for example, to input proprioceptive information to the sensory cortex, while outputting commands to a robotic appendage from the motor cortex. Regardless of the current technological issues, this article gives neurosurgeons an introduction to a field in which we will undoubtedly see a rapid expansion of in the not too distant future.

Lee Tessler
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The idea of the expansion of brain functions and their interaction with the world outside the body is always considered in the human being history. Plato, in *The Republic*, used, for the first time, the word cybernetic to signify the interface between each man and the governance of people. In 1834, André-Marie Ampère included "cybernètique" in his classification of human knowledge.

The study of the communication and control of regulatory feedback between human and machines was born around the Second World War and the intersection between neurology and electronic network theory became a powerful vogue idea between 1948 and the 1970s. The organic life form interfaced with technological devices strongly stimulates many cultural fields, generates a great debate in the philosophy of mind, telecommunication engineering, and many cult movies performed in the past 20 years (*Terminal Man*, *Blade Runner*, *Minority Report*, *Matrix*) always considered the interface brain-machine under control of the machine.

The development of neuroprosthetics includes deep brain stimulation to improve movement disorders or psychiatric disease, but neuroprosthetics based on the BCI go beyond the imagination of the most writers. Interface with visual cortex could build up visual prosthesis, but the interaction with the retina, hippocampus, and cochlea are just a few examples of possible implants.

There is the awareness that clinical application of BCI has only started, and I am quite sure that improvement of computer technology and knowledge of brain activity will make feasible the clinical application of BCI on severely impaired patients. So far the electroencephalography-based systems represent a promising way to develop an interface to provide a better quality of life. Actually, we don't know which patient affected by acute lateral sclerosis or spinal cord injury will benefit from BCI, and, to select the ideal patient, a first attempt using scalp electroencephalography could be a promising suggestion. Another issue consists of the brain structure to be used for BCI; if the scalp electroencephalogram is one term of the system, it should be stressed that the Ì activity is not constant and rarely recorded (the 8-12 Hz activity is the · rhythm typical of the occipital region). Even when a motor response of a robotic arm is requested, the BCI does not necessarily have to be linked to a pericentral activity. For instance, a Ï activity should be used. The use of the single unit-based system is very attractive, but, unfortunately, is still theoretical and poses heavy limitations. The problems of a long-term function of such a method is real and the single unit approach should be considered after the resolution of the electrode encapsulation phenomenon. From this point of view, the placement on the cortex of strip or grids seems to be the ideal solution. The activity recorded is clear, has fewer artifacts, and its possible application should included on a demanding system to control seizures. Also, the subcutaneous placement of the cable connected to the grid and a subclavicular telemetry device allows safe and easy daily use of the BCI.

Electrocochleography seems to be very attractive, but the corticocortical evoked potential is a challenging alternative. Researchers have to realize that the high definition of the language, visual, and motor areas by this technique allows broad neuronal network detection.

The greatest advantage of the clinical application of BCI justifies accepting the risk faced from more invasive procedures. It must be remembered that, in epilepsy surgery, the preoperative evaluation by the placement of grids on the brain surface has proven to be a very low-risk methodology.

In my opinion, it must be remembered that BCI is not the only solution: the research on restorative neurosurgery focused on stem cells, gene therapy, and neurotrophic factors supporting brain structures, are reporting promising results.

In conclusion, the present report is particularly interesting because of the clinical perspective of the possibility of translating a neural input by an effect independent of any peripheral systems and the prospect to the neurosurgical audience what may be the future of behavioral science. The authors have provided us with a new perspective in the field of neurosurgery, particularly in restorative neurosurgery.

Giovanni Broggi
Milan, Italy

Leuthardt et al. present us with a review of the current state-of-the-art in man-machine interfaces. Focusing on output BCIs intended to restore motor control, they paint an optimistic picture of how these devices may restore function to our patients incapacitated by permanent neurological injuries. Although this technology is still in its infancy, it is certainly likely that useful neuroprosthesis will become available long before neurorestorative strategies, such as stem cell therapies, and neurosurgeons will likely be playing a significant role in the development and implementation of such technology.

Nevertheless, many hurdles remain in this area. The authors are correct in stating that the fidelity and quality of electrical signals would be highest with implantable BCIs, such as cortical or single-unit systems. For these implantable devices, local tissue reactions and scarring can significantly dampen the extraction of electrophysiologic data, and, as the authors point out, the ability to revise such operations needs to be considered. Next-generation devices will have to be composed of truly inert biomaterials or use biological strategies to prevent these phenomena. Other problems relate to the need for BCIs to reliably translate complex electrophysiological data sets into a variety of meaningful signals to reproduce normal human motor function. Ultimately, technological advancements will likely overcome these and other hurdles. The authors have provided a commendable introduction to this exciting and important emerging field.

Michael Y. Wang
Los Angeles, California

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