TOPIC REVIEW

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Stereotactic radiosurgery in the management of petroclival meningiomas: a systematic review and meta-analysis of treatment outcomes of primary and adjuvant radiosurgery

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Abstract

Purpose To summarize the clinical features and outcomes of petroclival meningioma patients treated with stereotactic radiosurgery (SRS) as either a primary or an adjuvant modality.

Methods Relevant articles were retrieved from PubMed, Scopus, Web of Science, and Cochrane. A systematic review and meta-analysis of treatment outcomes comparing primary and adjuvant SRS was conducted.

Results Seven articles comprising 722 cases were included. The mean tumor marginal dose was 13.5 Gy. After SRS, symptoms improved in 28.7%, remained unchanged in 61.3%, and worsened in 10.0% of the cohort. Tumor control was achieved in 94.8% of patients. The mean tumor volume change was -6.4 cm^3. The 5-year and 10-year progression-free survival (PFS) rates were 91–100% and 69.6–89.9%, respectively. Overall, 61.9% of patients underwent primary radiosurgery, and 38.1% had adjuvant radiosurgery. Patients who had primary SRS reported higher rates of tumor control (94.3% vs. 88.2%) and fewer SRS-related complications (3.7% vs. 10.3%) than those who received adjuvant SRS (not accounting for microsurgical complications). The functional status of patients who had primary SRS was more likely to improve or remain unchanged, with an effect size of 1.12 (95% CI 1.1–1.25; $I^2 = 0$). Neither group displayed superiority in worsening functional outcomes or tumor control rate.

Conclusion SRS of petroclival meningiomas was associated with excellent long-term PFS and local tumor control rates. Primary SRS was highly effective for patients with smaller volume lesions without clinically symptomatic mass effect. In patients who warrant initial resection, adjuvant radiosurgery remains an important modality to prevent regrowth while maintaining postresection function.

Keywords Petroclival · Meningioma · Radiosurgery · Gamma knife · Microsurgery · Outcomes · Systematic review · Meta-analysis

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Introduction

Petroclival meningiomas (PCMs) arise from the upper two-thirds of the clivus at the petroclival junction, and medial to the trigeminal nerve [1]. PCMs pose significant surgical challenges because of their proximity to the brainstem and vital neurovascular structures. Thus, achieving gross total resection may be challenging surgically and associated with high morbidity and mortality rates [2].

Until a few decades ago, these tumors were mostly considered untreatable [3, 4]; however, the management paradigm has evolved rapidly and now includes improved microsurgical techniques, earlier detection using imaging, and improved alternative management modalities and strategies

[4]. Stereotactic radiosurgery (SRS) has been widely documented as an important treatment option for newly diagnosed, incompletely resected, or recurrent meningiomas [5]. The primary goal of SRS is to provide long-term tumor control and minimize treatment-related complications, especially in surgically challenging lesions such as PCMs [17].

Despite the recent interest in SRS for the management of skull base meningiomas, controversy still exists regarding its role in managing PCMs [6]. Although primary SRS is recommended for small PCMs and adjuvant SRS for large (defined as tumor diameter of > 3 cm or tumor volume of > 10 cm^3), recurrent, or incompletely resected lesions, few studies have investigated the clinical and radiological outcomes in both patient cohorts (primary or adjuvant SRS) [7–11]. In this systematic review and meta-analysis, we report the clinical and radiological outcomes as well as progression-free survival (PFS) rates after primary or adjuvant SRS for the management of PCMs.

Methods

Literature search

A systematic review and meta-analysis were performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [12]. The PubMed, Scopus, Web of Science, and Cochrane databases were searched from inception to July 26, 2021, operating the combination of the Boolean operators "OR" and "AND" and terms "petroclival" and "meningioma." Articles were uploaded to Mendeley, and duplicates were removed.

Study selection

Predetermined inclusion and exclusion criteria were set. Studies were included if they: (1) involved ≥ 5 patients aged ≥ 18 years with meningiomas located within the petroclival region, as clearly mentioned within the text, and treated with either primary or adjuvant SRS; (2) reported data on clinical features, SRS protocols, and outcomes; and (3) were written in English. Studies were excluded if they: (1) were literature reviews, case reports, technical notes, abstracts, or autopsy reports; (2) did not clearly differentiate data of patients with PCMs from data of patients with different tumors or with meningiomas in different locations; or (3) contained insufficient data on treatments and outcomes. One of the included articles (i.e., Kim et al. [9]) captured patients between 15 and 74 years.

Two authors (O.B.A. and P.P.) independently reviewed the titles and abstracts of all extracted citations and then appraised the full text of articles that met the inclusion criteria. Two authors (A.N.M. and H.A.) settled any

disagreements. Eligible studies were included, and references were screened to retrieve additional relevant studies.

Data extraction

One author (O.B.A.) extracted data from included articles, confirmed by three independent authors (P.P., A.N.M., and H.A.) to ensure accuracy. Missing data were either not reported or could not be differentiated from other data. Data included: author and year of study, patients' ages and sexes, symptoms, cranial nerve involvement, invaded structures, imaging features, lesion size, treatment modality, marginal radiation dose, post-radiosurgery outcomes and tumor volume change, PFS, and follow-up duration. SRS protocols were categorized as (1) primary SRS if patients underwent initial radiosurgery only, or (2) adjuvant if patients underwent SRS after initial microsurgical resection.

Data synthesis and quality assessment

The primary outcomes of interest were clinical characteristics, SRS protocols, PFS, and clinical/radiological outcomes. The level of evidence of each article was evaluated following the 2011 Oxford Centre for Evidence-Based Medicine guidelines. The risk of bias was independently assessed for each article by two authors (P.P. and O.B.A.) using the Joanna Briggs Institute checklists for case series [13].

Statistical analysis

R (Version 4.1.1, 2021.09.0 RStudio, Inc. URL: http://www.R-project.org/; R Foundation for Statistical Computing, Vienna, Austria) was used for all statistical analyses. Continuous variables are summarized as medians or means and ranges, while categorical variables are summarized as frequencies and percentages.

A meta-analysis of pooled data was done according to the types of study obtained. A statistically significant difference was considered as $P < 0.05$ and ratios that are not crossing 1, the value of no effect. Data from all studies were combined to estimate the relative ratio with 95% confidence intervals (CIs) for treatment strategy. The χ^2 test and the Higgins I^2 test were used to assess heterogeneity. Data were pooled in all studies and were conducted using random-effects models.

Results

Study selection

The initial literature search yielded 466 citations from PubMed, 435 from Scopus, 578 from Web of Science, and one article from Cochrane. After going through the study

selection process displayed in Fig. 1, seven articles categorized as level IV evidence were included in this systematic review based on the prespecified criteria. (Table 1; Supplementary Table 1) [8–10, 14–17]. Table 1 describes the SRS clinical outcomes reported by each article, providing an overview comparison across the reported heterogeneous data. Risk of bias assessment resulted in "good" quality (i.e., low risk of bias) for all included studies (Supplementary Table 2).

Demographics and clinical characteristics of the overall cohort

A total of 722 PCMs treated with Gamma Knife SRS were included (Table 2). The mean age of patients was 55.1 years (range, 15–90 years), with female predominance (75.6%). The most common presenting symptoms were ataxia (20.0%), trigeminal neuralgia (17.6%) and headache (16.6%). Trigeminal, facial, and vestibulocochlear nerves were affected in 26.5%, 26.1%, and 19.4% of cases, respectively. The cavernous sinus was the most invaded adjacent structure (37%), followed by brainstem (23.9%) and

Fig. 1 PRISMA flowchart illustrating the search strategy and data selection based on the inclusion and exclusion criteria

Meckel's cave (21.7%). The mean tumor size at presentation was 8.1 cm^3 (range, 0.13–64.9 cm^3).

The WHO grade of 188 meningiomas was reported. One hundred and eighty-three (97.3%) were WHO grade I, three (1.6%) were grade II, and two (1.1%) were grade III. The five cases of grades II and III were reported by Flannery et al. [17], who observed that ultimately patients with atypical (WHO grade II) and anaplastic meningiomas (WHO grade III) clinically deteriorated with evidence of tumor progression at a median interval of 36 months after SRS. The mean radiosurgical isodose prescribed to the tumor margin was 49.3 (range, 30–60), and the mean marginal radiation dose was 13.5 Gy (range, 9–40 Gy).

Management strategies and survival outcomes

At last follow-up, 149 patients (28.7%) showed improved symptoms, 319 (61.3%) had unchanged symptoms, and 52 (10.0%) demonstrated worsened symptoms. Tumor volume decreased or remained stable in 661 (94.8%) patients and increased in 36 (5.2%) patients (Table 2). The mean tumor volume change was −6.4% (range −82% to 225%). The mean clinical follow-up time was 59.6 months (range 6–254 months), while the mean radiological follow-up time was 56.5 months (range 3–204 months). The 5-year PFS rate ranged from 91 to 100%, and the 10-year PFS rate ranged from 69.6 to 89.9%. After SRS, 76 patients with a total of 86 complications were encountered among both treatment strategies (Table 2). CN V deficit was the most common complication (15.1%), followed by hydrocephalus (9.3%), ataxia (8.1%) and dizziness (8.1%).

Primary vs. adjuvant radiosurgery

Seven articles encompassed clinical characteristics and outcomes of patients treated with primary (n = 447; 61.9%) and adjuvant SRS (n = 275; 38.1%) (Table 3; Fig. 2A) [8–10, 14–17]. Patients who underwent primary SRS were older (mean age 55.9 vs. 48.6 years for adjuvant SRS), with comparable female patient rates (78.3% vs. 80.6%). At clinical presentation, the mean tumor volume was 7.4 cm^3 in the primary SRS group and 12.1 cm^3 in the adjuvant SRS group. The mean marginal radiosurgery doses were comparable: 15.1 Gy (range 11–16 Gy) in the primary SRS group and 11.2 Gy (range 8–17 Gy) in the adjuvant SRS group. The indications for adjuvant SRS after surgical resection were residual tumor in 203 (73.8%), recurrent tumor in 41 (14.9%), and not specified in 31 (11.2%) patients.

Functional status improvement and stability were evaluated at the end of the follow-up period in 127 patients in the primary SRS group and 114 in the adjuvant SRS group (Table 3). A total of 109 out of 127 (85.8%) in the primary SRS group and 89 out of 114 (78.1%) in the adjuvant SRS
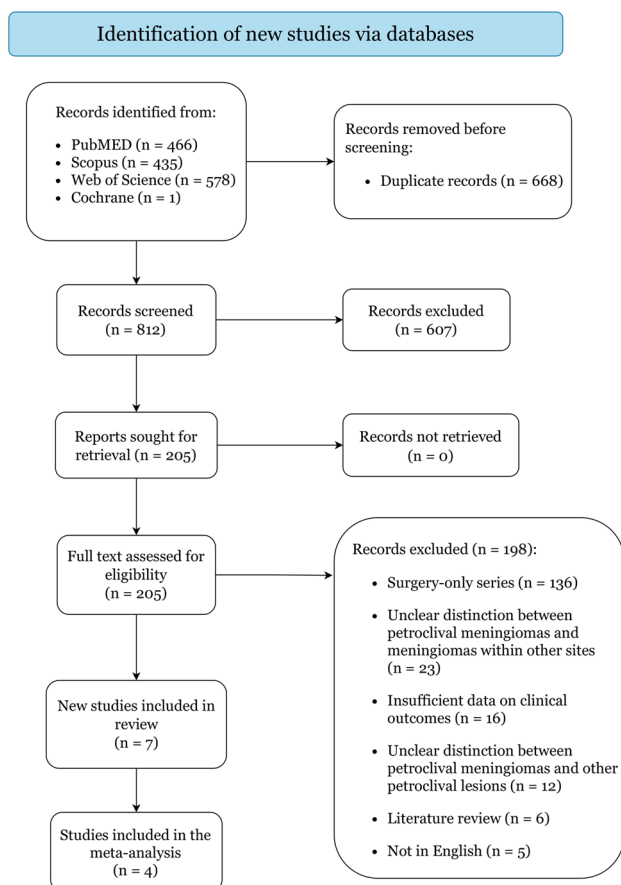
Table 1 Overview of post-SRS outcomes for included studies

Study author (year)	Complications	Functional outcomes at last follow-up, N (%)			Post-SRS tumor volume					Regrowth	PFS rates (%)		Months of follow-up, mean (range)	
		Improved	Stable	Worsened	Decreased N (%)	Stable N (%)	Increased N (%)	Mean change post-SRS	Mean post-SRS tumor volume in cm³ (range)		5 years	10 years	Clinical	Radiological
Ha et al. (2020) [8]	CNs (V, VII), 8 (13); Hemiparesis, hydrocephalus, and cognitive dysfunction = 2 (3)	54 (84)[a]		10 (16)	Pri: 47 (90)[b] Adj: 10 (83)[b]		Pri: 5 (10) Adj: 2 (17)	N/A	N/A	N/A	91.1	69.6	N/A	58.4 (6–164)
Sadik et al. (2018) [10]	Pri: Trigeminal neuralgia, 1 (2) Facial pain, 1 (2) CN VIII, 1 (2)	1 (33%)[c]	1 (33%)[c]	1 (33%)[c]	Pri: 49 (92)	Pri: 3 (6)	Pri: 1 (2)	N/A	N/A	N/A	Pri: 98	N/A	Pri: 64.2 (12–147)[d]	
Kim at al. (2017) [9]	Pri: N/A Adj: Cyst formation, 3 (10)	27 (30)	54 (61)	Pri: 4 (7) Adj: 4 (13)	Pri: 53 (91)[b] Adj: 31 (100)[b]		Pri: 5 (6) Adj: 0	Pri: −14%; Adj: −31%	N/A	Pri: 4 Adj: 1	94.7	88.9	Pri: 66 Adj: 87	Pri: 61 Adj: 81

Table 1 (continued)

Study author (year)	Complications	Functional outcomes at last follow-up, N (%)			Post-SRS tumor volume					Regrowth	PFS rates (%)		Months of follow-up, mean (range)	
		Improved	Stable	Worsened	Decreased N (%)	Stable N (%)	Increased N (%)	Mean change post-SRS	Mean post-SRS tumor volume in cm³ (range)		5 years	10 years	Clinical	Radiological
Starke et al. (2014) [14]	Dizziness, 7 (3) CN III/IV/VI, 6 (2) CN V, 10 (4) CN VII, 3 (1) CN VIII, 1 (0.4) CN IX/X, 3 (1) CN XII, 2 (1) Ataxia, 5 (2) Other cerebellar alterations/deficits, 2 (1) Hydrocephalus, 7 (3) Body weakness, 3 (1) Change body sensation, 1 (0.4)	64 (27)	157 (67)	15 (6)	98 (39)	129 (52)	2 (9)	−1.6 cm³	6.2 (0.4–33)	N/A	97	87	71.1 (6–252)[d]	

Table 1 (continued)

Study author (year)	Complications	Functional outcomes at last follow-up, N (%)			Post-SRS tumor volume					Regrowth	PFS rates (%)		Months of follow-up, mean (range)	
		Improved	Stable	Worsened	Decreased N (%)	Stable N (%)	Increased N (%)	Mean change post-SRS	Mean post-SRS tumor volume in cm³ (range)		5 years	10 years	Clinical	Radiological
Flannery et al. (2010) [17]	CN V, 1 (1) CN IX, 1 (1) CN X, 1 (1) Cerebellar symptoms, 2 (1) Unspecified, 9 (5)	Pri: 26 (27) Adj: 18 (25)	Pri: 59 (88) Adj: 39 (55)	Pri:12 (12) Adj: 14 (20)	Pri: 47 (49) Adj: 31 (44)	Pri: 45 (46) Adj: 29 (41)	Pri: 5 (5) Adj: 11 (15)	N/A	N/A	4	91	86	Median 72 months (24–254)	Median 64 months (3–204)
Roche et al. (2003) [16]	Pri: Ataxia, trigeminal neuralgia, tinnitus = 1 (4) Ataxia and hemiplegia = 1 (4) Adj: Hemiplegia, 1 (13) Group unspecified: Trigeminal neuralgia, 1 (3)	13 (54)	9 (38)	2 (8)	4 (13)	28 (88)	0 (0)	N/A	N/A	N/A	100	N/A	56	53
Subach et al. (1998) [15]	CN VI, 3 (5) CN V, 1 (2) CN VIII, 1 (2)	Pri: 22 (96)[a] Adj: 32 (82)[a]		Pri: 1 (4) Adj: 7 (18)	Pri: 23 (100%)[b] Adj: 34 (87%)[b]		Pri: 0 (0%) Adj: 5 (13%)	N/A	N/A	N/A	N/A	N/A	Pri: 38.8 ± 27.2 Adj: 43.5 ± 23.1	Pri: 34.0 ± 24.5 Adj: 36.0 ± 22.8

Table 1 (continued)

Data are presented as number (%) or mean (range) unless otherwise indicated. Unless stratified data based on treatment group are available, data are reported in combined (primary and adjuvant group combined)

Pri primary, *Adj* adjuvant, *PFS* progression-free survival, *CN* cranial nerve

[a]Value corresponds to improved and stable functional outcomes collectively

[b]Value corresponds to decreased and stable tumor volumes collectively

[c]This study used Barrow Neurological Institute (BNI) pain intensity scoring to evaluate functional outcomes and found that improvement in trigeminal neuralgia was achieved in 61%, 70%, and 33% of the cases at 1, 3, and 7 years of follow-up, respectively

[d]Value corresponds to clinical and radiological follow-ups collectively

group demonstrated functional status improvement or stability at last follow-up. Additionally, our meta-analysis showed an effect size of functional improvement of 1.12 (95% CI 1.01–1.25; $I^2 = 0\%$) in favor of the primary SRS group with statistical significance (P < 0.05; Fig. 2B). The primary SRS patients were also less likely to develop worsening functional status: eighteen out of 127 (14.2%) in the primary SRS group and 25 out of 114 (21.9%) in the adjuvant SRS group. However, our meta-analysis illustrated an effect size of 0.56 (95% CI 0.31–1.01; $I^2 = 0\%$), which failed to reach statistical significance (Fig. 2C).

At last follow-up, primary SRS resulted in decreased or stable tumor volumes in 94.3% of patients with available data compared with 88.2% for adjuvant SRS patients (Table 3). The random effect size was 1.03 (95% CI 0.85–1.25; $I^2 = 85\%$) in favor of the primary strategy; however, substantial heterogeneity was present, and the effect size was not statistically significant (Fig. 2D). An increase in tumor volume was reported in 5.7% after primary SRS and 11.8% after adjuvant SRS. The average clinical follow-up duration was 58.3 and 62.8 months in the primary and adjuvant SRS groups, respectively, and the mean radiological follow-up duration was 57.1 and 55.9 months, respectively (Table 3).

Of studies reporting complications of the primary SRS group, a total of eight complications were reported (Table 3). These complications included trigeminal neuralgia (2 patients), ataxia (2 patients), vestibulocochlear neuropathy (1 patient), facial pain (1 patient), tinnitus (1 patient), and hemiplegia (1 patient). Four patients developed complications after adjuvant SRS (not accounting for microsurgical complications), including three who developed cyst formation and one who developed hemiplegia.

Discussion

PCMs are among the most challenging skull base tumors because of their close anatomical relationship to critical neurovascular structures. Microsurgical resection has been associated with high rates of morbidity ranging from 28% to 76% and mortality ranging from 3.7% to 17% as well as incomplete resection in most patients [18–22]. Large case series and high-quality articles are limited in the literature, especially on the role that SRS may play in managing these lesions. In this systematic review and meta-analysis on PCMs managed with primary or adjuvant SRS, we described the clinical characteristics and management outcomes and presented an outcome comparison between primary and adjuvant SRS. Our meta-analysis showed that primary SRS was correlated with a higher rate of improved/stable functional status compared with adjuvant SRS. In the studies we

Table 2 Summary of clinical characteristics, management strategies, and outcomes of all pooled patients (N = 722)

Variables (N = No. of cases with available data)	Value
Demographics	
Mean age in years (N = 404)[a]	55.1 (15–90)
Female sex (N = 722)	546 (75.6%)
Most reported symptoms (N = 495)	
Ataxia	99 (20.0%)
Trigeminal neuralgia	87 (17.6%)
Headache	82 (16.6%)
Dizziness	71 (14.3%)
Hearing disturbance/tinnitus	47 (9.5%)
Diplopia	47 (9.5%)
Unspecified cerebellar symptoms	20 (4.0%)
Other	42 (8.5%)
Most affected cranial nerves (N = 664)	
CN V	176 (26.5%)
CN VII	173 (26.1%)
CN VIII	129 (19.4%)
CN VI	60 (9.0%)
CN III	44 (6.6%)
CN IV	31 (4.7%)
Other	51 (7.7%)
Abutted/invaded/compressed adjacent structures (N = 46)	
Cavernous sinus	17 (37.0%)
Brainstem	11 (23.9%)
Meckel's cave	10 (21.7%)
Tentorium	5 (10.9%)
Vascular encasement	2 (4.3%)
Cerebellopontine angle	1 (2.2%)
Tumor volume in cm^3 (N = 690)	8.1 (0.13–64.9)
WHO grade (N = 188)	
WHO Grade 1	183 (97.3%)
WHO Grade 2	3 (1.6%)
WHO Grade 3	2 (1.1%)
Dosing details	
Mean (range) isodose line (N = 422)	49.3 (30–60)
Mean (range) marginal dose in Gy (N = 437)	13.5 (9–40)
Post-SRS complications (N = 722)	
Number of reported complications (N = 86)	
CN V deficit	13 (15.1%)
Hydrocephalus	8 (9.3%)
Ataxia	7 (8.1%)
Dizziness	7 (8.1%)
CN VII deficit	5 (5.8%)
CN VI deficit	4 (4.7%)
Cerebellar alterations	4 (4.7%)
Others/not specified	38 (44.2%)
Post-SRS functional outcomes (N = 520)	
Improved	149 (28.7%)
Stable	319 (61.3%)
Worsened	52 (10.0%)
Post-SRS volume change (N = 697)	
Decreased/stable	661 (94.8%)

Table 2 (continued)

Variables (N = No. of cases with available data)	Value
Increased	36 (5.2%)
Mean tumor volume change	−6.4% (−82% to 225%)
Mean follow-up (range)	
Clinical (N = 183)	59.6 (6–254)
Radiological (N = 247)	56.5 (3–204)
PFS	
5-year	91–100%
10-year	69.6–89.9%

Values reported as number (%) or mean/median (range)

CN cranial nerve, *SRS* stereotactic radiosurgery, *WHO* world health organization

[a]Two studies reported the median age and were not included in the total N (Ha et al. [8] median age of 62 years and Starke et al. [14] median age of 57.1 years)

identified, we found no statistical difference in worsening functional status or tumor control rate between primary and adjuvant SRS.

Patients and clinical characteristics

We found that PCMs were predominant in females (75.6%), and the mean age of patients at presentation was 55.1 years, both consistent with the reported data on intracranial and skull base meningiomas [23, 24]. The most commonly involved cranial nerves were V, VII, and VIII. PCMs often directly compress the trigeminal nerve or invade adjacent structures, such as Meckel's cave, resulting in Gasserian ganglia compression and trigeminal neuralgia, as reported in 17.6% of cases. These features are in concordance with other petroclival lesions, reflecting the proximity of the petroclival region to cranial nerves and other vital neurovascular structures and indicating the necessity for early intervention to avoid permanent neurological deficits and debilitating long-term outcomes [25, 26].

The mean tumor size at presentation was 8.1 cm^3 (range 0.13–64.9 cm^3), which is comparable with other skull base meningiomas, probably because of their similar threshold sizes above which skull base tumors compress critical structures and become symptomatic [27].

In our systematic review, the mean isodose prescribed to the tumor margin was 49.3% (range 30–60%), similar to the mean 51.5% isodose described in other intracranial meningiomas [28]. Additionally, the mean marginal radiation doses of the cohort in this review was 13.5 Gy, similar to other studies on skull base, parasagittal, and falcine meningiomas (mean doses ranging from 13 to 16 Gy) [7, 29].

Management and tumor outcomes

At last follow-up after radiosurgery, 94.8% of the described cohort experienced decreased or stable tumor volume, which shows a comparable tumor growth control rate with other volumetric studies investigating intracranial meningioma control rates after SRS [30].

Of the whole cohort, the majority (61.3%) had no change in functional status after management (primary and adjuvant SRS), with 28.7% of patients reporting functional improvement and 10% reporting worsening functional status. In contrast, studies describing outcomes of microsurgical resection reported a higher rate of symptomatic relief along with a greater risk of new neurological dysfunction [31, 32]. We ascribe this difference to the distinct therapeutic goals and selection bias of each treatment, as resection aims to achieve initial relief of mass effect with decompression of neurovascular structures, and thus immediate improvement in functional status, whereas SRS aims to offer long-term local tumor control and prevent tumor growth and condition deterioration.

Our 5-year and 10-year PFS rates (91–100% and 69.6–89.9%, respectively) are comparable with those of other skull base meningiomas treated with SRS (88.9–100%, and 77–92%, respectively), likely suggesting that SRS for PCMs achieves comparable tumor control rates with other skull base meningiomas not limited by their anatomical location [33–35].

Primary vs. adjuvant radiosurgery

Resection remains the first option for large symptomatic PCMs in patients suitable for surgery, with adjuvant SRS being reserved for residual and recurrent tumors. These tumors tend to be complex, invading multiple neurovascular structures. Many authors advise that maximal safe resection should be undertaken for eligible patients with symptomatic PCMs followed by adjuvant SRS for residual disease to achieve high tumor control and minimal complication rates [33, 36, 37]. Included articles scarcely reported on adjuvant SRS-related complications and described an overall 4 new

Table 3 Clinical characteristics of patients who underwent primary or adjuvant SRS

Variable	Primary SRS	Adjuvant SRS
Cohort size	447 (61.9%)	275 (38.1%)
Mean age in years	55.9 (25–72) (N=81)	48.6 (15–74) (N=70)
Gender	Female: 87 (78.3%) (N=111)	Female: 25 (80.6%) (N=31)
Mean tumor size in cm^3	7.4 (0.5–17.8) (N=81)	12.1 (0.9–46.3) (N=70)
Mean of marginal dose in Gy	15.1 (11–16) (N=75)	11.2 (8–17) (N=86)
Purpose of adjuvant SRS		(N=275)
Residual tumor		203 (73.8%)
Recurrent tumor		41 (14.9%)
Not specified		31 (11.2%)
Post-SRS functional status	N=127	N=114
Improved/stable	109 (85.8%)	89 (78.1%)
Worsened	18 (14.2%)	25 (21.9%)
Post-SRS volume change	N=283	N=153
Decrease/stable	267 (94.3%)	135 (88.2%)
Increase	16 (5.7%)	18 (11.8%)
Complications	N=135	N=39
Number of patients with complications	5 (3.7%)	4 (10.3%)
Number of reported complications	8 (Trigeminal neuralgia: 2; ataxia: 2; facial pain: 1; CN VIII deficit: 1; tinnitus: 1; hemiplegia: 1)	4 (Cyst formation: 3; hemiplegia: 1)
Mean follow-up in months	N=81	N=70
Clinical	58.3	62.8
Radiological	57.1	55.9

Values are reported as mean (%) unless otherwise indicated.

complications related to adjuvant SRS among 39 patients with available data (not accounting for microsurgical complications). At present, insufficient data exists to endorse aggressive resection compared with maximal safe resection followed by SRS [31, 32].

Almefty et al. [32] reported that 64% of 64 patients with PCMs underwent gross total resection, 65.6% of whom developed immediate postoperative new cranial nerve deficits, often resulting in persistent cranial nerve dysfunction. Similarly, Li et al. [38] found a 66.8% rate of cranial nerve dysfunction along with a 2% rate of surgical mortality in 199 patients with surgically managed PCMs. A consensus seems to suggest that resection of PCMs should be primarily focused on debulking the tumor and decompression of the brainstem and cranial nerves followed by SRS to maximize tumor control and minimize complication rates.

Primary SRS resulted in lower complication rates (3.7% vs. 10.3%), and our meta-analysis indicated better functional outcomes in the primary SRS group compared to the adjuvant SRS group. This might be attributed to the fact that most adjuvant SRS articles did not report specific SRS-related complications and instead grouped them together with microsurgical complications and functional

outcomes, which limited our analysis. Although we found a worsened functional status rate difference between the primary and adjuvant SRS groups (14.2% vs. 21.9%), our meta-analysis failed to show any significant difference. In a study investigating the long-term results of Gamma Knife radiosurgery for parasellar meningiomas, Williams et al. [39] did not find any significant predictive difference between primary SRS and SRS following prior resection. Similarly, in their study investigating Gamma Knife radiosurgery for benign intracranial meningiomas, Ge et al. [40] demonstrated a Hazard ratio of 2.30 in cases with prior resection; however, their multivariate analysis did not reach statistical significance. Thus, it may be challenging to explicitly distinguish the complications of microsurgical resection from SRS in the adjuvant group and to rule out the synergistic effect of resection on the patients' status even after the SRS, especially when most literature does not explicitly report patients' status prior to SRS. Therefore, we believe that the causality between complications and SRS in the adjuvant group remains unclear and necessitates further and more controlled investigation.

Although primary SRS offers a minimally invasive modality for the management of small and asymptomatic
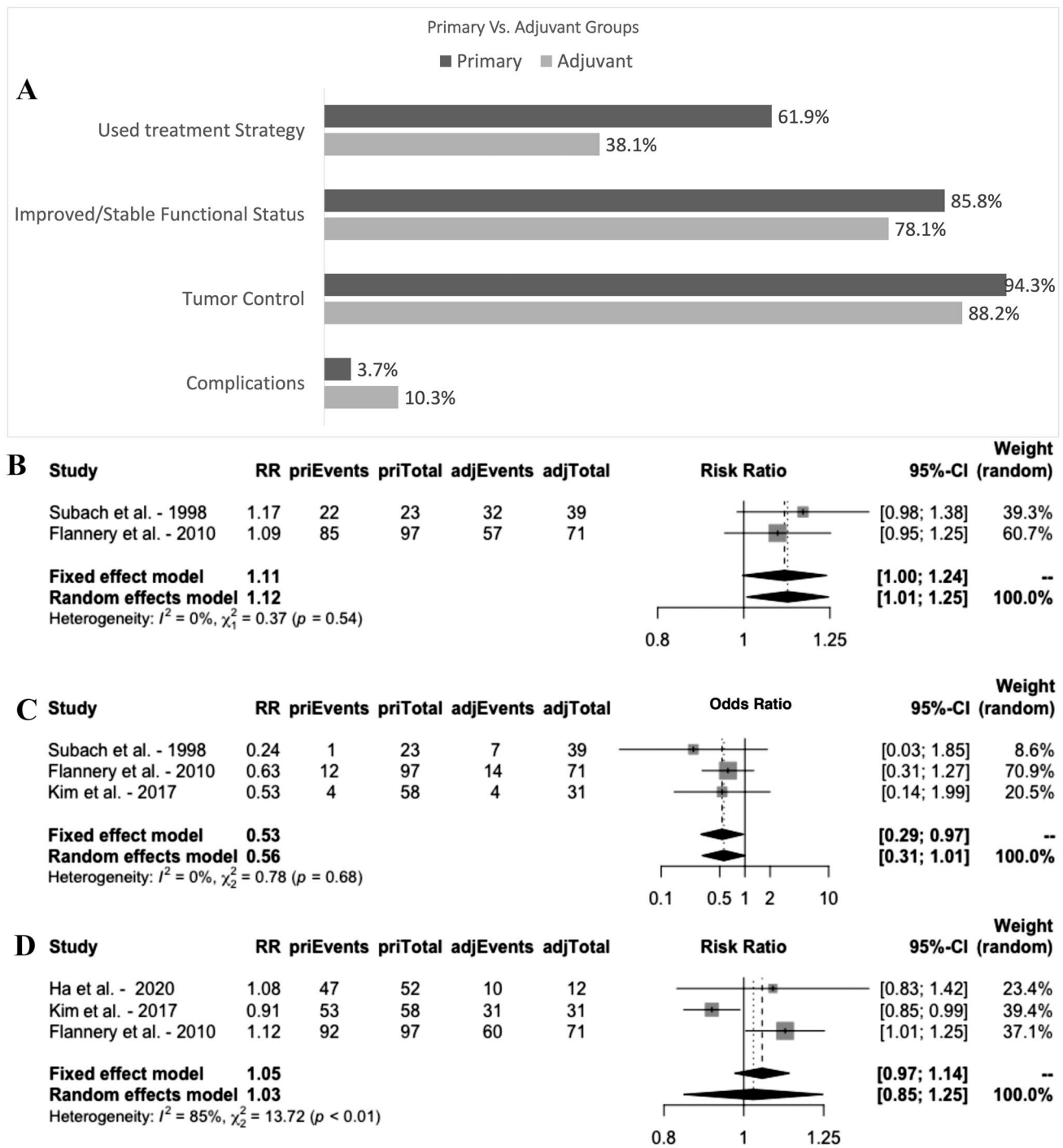
Fig. 2 Bar chart comparing the outcomes of primary vs. adjuvant SRS (**A**). Forest plots for (**B**) improved/stable functional status, (**C**) worsening functional status, and (**D**) tumor control rate between primary and adjuvant SRS. *CI,* confidence interval; *RR,* relative risk; *priEvents,* primary group events; *priTotal,* primary group total subjects; *adjEvents,* adjuvant group events; *adjTotal,* adjuvant group total subjects

PCMs, concerns related to the long-term effect of radiation in the management of meningiomas exist [41, 42]. The publication of the IMPASSE study [43] further indicated that very few meningioma patients who underwent primary SRS developed neurological or radiation-related complications. Similarly, the present meta-analysis indicated that patients who underwent primary SRS were

more likely to achieve improved or stable functional status and had a lower rate of worsening functional status.

The present report found that patients who underwent primary SRS had a higher rate of tumor control and a lower rate of tumor progression compared with patients who underwent adjuvant SRS (94.3% vs. 88.2% and 5.7% vs. 11.8%, respectively). The meta-analysis on tumor control, however, showed no superiority of either strategy. Tumor control and tumor volume change rates were different between the primary and adjuvant SRS groups and the overall cohort. This is primarily related to the inclusion of more articles reporting overall tumor control data indistinctively compared with articles reporting on specific treatment modality (e.g. post-SRS volume change: primary SRS group, n = 283; adjuvant SRS group, n = 153; overall cohort, n = 697). In addition, there is likely a significant selection bias between primary and adjuvant SRS-treated tumors, which may impact the overall results. These data further emphasize the need for large, multicentric controlled studies investigating the functional outcomes and tumor control rates between both treatment modalities.

Limitations

This study was potentially affected by multiple limitations. First is the heterogeneity of reported data, which challenged the consistency of different variables. Different studies adopted different definitions and treatment protocols, including, but not limited to, radiation dose, radiation technique, and indications for treatment. Furthermore, the availability of several variables such as histological grade, invasion of adjacent structures, and mean volume change after treatment was limited.

Conclusion

Radiosurgery, either primary or adjuvant, represents a safe and effective strategy for the management of PCMs. It is associated with improved or stable long-term functional outcomes and high tumor control rates in many patients, along with a low complication profile. Primary SRS may be preferred for patients with small PCMs, whereas adjuvant SRS may be recommended for larger and/or recurrent PCMs to achieve higher tumor control rates while minimizing complications.

Data availability All authors confirm the appropriateness of all dataset and software used for supporting the conclusion. All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Code availability Not applicable.

Declarations

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

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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