Supplementary Methods

Detailed PubMed Search Strategy

PubMed/MEDLINE was searched from database inception through July 11, 2026. No publication-year restriction was applied. The search was limited to English-language publications for which sufficient information was available to assess eligibility and extract relevant clinical outcomes.

The search strategy combined controlled vocabulary and free-text terms related to meningioma, skull-base anatomical locations, and stereotactic radiation techniques. The complete search strategy was as follows:

```
(
  "Meningioma"[Mesh]
  OR meningioma*[Title/Abstract]
)
AND
(
  "Skull Base"[Mesh]
  OR "skull base"[Title/Abstract]
  OR "skull-base"[Title/Abstract]
  OR "cavernous sinus"[Title/Abstract]
  OR petroclival[Title/Abstract]
```

OR petro-clival[Title/Abstract]

OR clival[Title/Abstract]

OR petrous[Title/Abstract]

OR "cerebellopontine angle"[Title/Abstract]

OR "posterior fossa"[Title/Abstract]

OR tentorial[Title/Abstract]

OR incisural[Title/Abstract]

OR perioptic[Title/Abstract]

OR parasellar[Title/Abstract]

OR "tuberculum sellae"[Title/Abstract]

OR "planum sphenoidale"[Title/Abstract]

OR "anterior clinoid"[Title/Abstract]

OR clinoidal[Title/Abstract]

OR "sphenoid wing"[Title/Abstract]

OR "olfactory groove"[Title/Abstract]

OR "Meckel's cave"[Title/Abstract]

OR "jugular foramen"[Title/Abstract]

OR "foramen magnum"[Title/Abstract]

)

AND

(

"Radiosurgery"[Mesh]

OR "stereotactic radiosurgery"[Title/Abstract]

OR radiosurg*[Title/Abstract]

OR "Gamma Knife"[Title/Abstract]

OR CyberKnife[Title/Abstract]

OR LINAC[Title/Abstract]

OR "linear accelerator"[Title/Abstract]

OR "hypofractionated stereotactic radiotherapy"[Title/Abstract]

OR "fractionated stereotactic radiotherapy"[Title/Abstract]

OR "multisession radiosurgery"[Title/Abstract]

OR "staged radiosurgery"[Title/Abstract]

)

The search yielded 771 records. No duplicate PubMed records were identified within the exported dataset. Before final study selection, the exported PubMed dataset was cross-checked against the final included-publication list using publication titles, author groups, participating institutions, recruitment periods, sample sizes, and PubMed identifiers. This cross-check was

performed to identify potentially missed eligible publications, updated reports, and potentially overlapping patient cohorts.

Reference lists of relevant original studies, systematic reviews, meta-analyses, and practice guidelines were additionally screened to verify the completeness of the location-specific literature. Reference-list screening did not identify an eligible publication outside the PubMed search set; all 28 publications included in the final qualitative synthesis were represented within the PubMed search results.

Screening Process

All 771 records underwent preliminary title and abstract screening with the assistance of an AI-based screening tool. The tool was used to organize the retrieved records and identify publications that were clearly unrelated to location-specific stereotactic treatment of skull-base meningiomas, evaluated an ineligible tumor type or treatment modality, or did not report clinically relevant outcomes. AI-generated screening results were treated as decision-support information rather than as final eligibility determinations.

A total of 496 records were excluded during preliminary title and abstract screening, leaving 275 publications for detailed eligibility assessment. Full-text eligibility assessment considered study design, patient population, tumor histology, anatomical location, treatment modality, cohort size, follow-up duration, availability of location-specific outcomes, potential cohort overlap, and relevance to the objectives of the review. The eligibility of potentially includable publications and the final set of 28 included publications were independently verified by two reviewers (Y.Y. and M.H.L.). Disagreements regarding study eligibility, cohort overlap, or the selection of the principal publication were resolved through discussion and consensus.

During detailed eligibility assessment, 247 publications were excluded, and 28 publications were retained for the final qualitative synthesis. The detailed exclusion categories were as follows:

- Overlapping, superseded, or less complete cohorts, or reports with limited location-specific data: 160
- Mixed skull-base cohorts without separately extractable meningioma outcomes: 38
- Secondary reviews or guidelines not selected for the final synthesis: 18
- Dosimetric, diagnostic, or nonclinical outcome studies: 17
- Case reports, technical notes, or very small reports without adequate outcome data: 12
- Ineligible tumor types or mixed non-meningioma cohorts: 2

The exclusion categories totaled 247 publications. The numbers of records at each stage were used to construct the PRISMA 2020 flow diagram presented in Figure 1.

Detailed Eligibility Criteria

Publications were eligible when they evaluated adult patients with radiologically presumed or histologically confirmed skull-base meningiomas treated using single-fraction stereotactic radiosurgery, hypofractionated or multisession radiosurgery, staged radiosurgery, or stereotactic radiotherapy.

Eligible publications were required to report extractable clinical or radiological outcomes for a specific skull-base anatomical location or for a clearly defined skull-base meningioma cohort. Anatomical locations of interest included the cavernous sinus, petroclival and clival regions, petrous region, cerebellopontine angle, posterior fossa, perioptic and parasellar regions,

tuberculum sellae, planum sphenoidale, anterior clinoid, medial sphenoid wing, tentorium and tentorial incisura, olfactory groove, Meckel's cave, foramen magnum, and jugular foramen.

Studies were eligible regardless of whether SRS was used as primary treatment, postoperative adjuvant treatment for residual disease, or salvage treatment for recurrent or progressive disease after surgery. Radiologically presumed meningiomas were eligible because histological confirmation was not routinely available in patients undergoing primary SRS.

Original clinical studies were generally required to include at least 10 relevant patients and to report a mean or median follow-up duration of at least 12 months. Exceptions were permitted for uncommon anatomical subgroups, particularly jugular foramen meningiomas, when larger location-specific studies were unavailable and the publication represented the best available clinical evidence.

Eligible outcomes included radiological tumor regression, stability, or progression; local tumor control; progression-free survival; cranial nerve improvement, stability, or deterioration; visual and hearing outcomes; neurological deterioration; treatment-related adverse events; and the requirement for repeat SRS, additional radiotherapy, or salvage surgery.

Systematic reviews, meta-analyses, and practice guidelines were eligible when they summarized clinically relevant location-specific evidence or provided guidance regarding radiosurgical treatment selection. These secondary publications were used to contextualize findings from original clinical studies and were not treated as independent patient populations when interpreting tumor-control, functional, or adverse-event outcomes.

Publications were excluded when they were isolated case reports, editorials, letters, conference abstracts, technical reports without meaningful clinical outcomes, or small case series without adequate follow-up. Studies were also excluded when skull-base meningioma outcomes could

not be separated from those of non-skull-base tumors or other histological diagnoses.

Additional exclusion criteria included treatment exclusively with conventional external-beam radiotherapy, cohorts predominantly composed of World Health Organization grade 2 or 3 meningiomas without separately extractable benign-tumor outcomes, spinal or extracranial meningiomas, primarily dosimetric or imaging studies without relevant clinical outcomes, and studies without adequate clinical or radiological follow-up.

Management of Overlapping Cohorts

Potentially overlapping cohorts were identified by comparing participating institutions, author groups, recruitment periods, sample sizes, treatment characteristics, follow-up periods, and baseline patient and tumor features.

When a later publication explicitly updated or expanded an earlier patient cohort, the updated report was selected as the principal publication. The earlier report was excluded unless it provided clinically relevant, nonduplicated outcomes that were unavailable in the updated publication.

For other potentially overlapping reports, the publication with the largest cohort, longest follow-up, or most complete location-specific outcome data was selected as the principal report. Secondary publications from an overlapping cohort were retained only when they provided additional nonduplicated information, such as cranial nerve–specific outcomes, visual or hearing outcomes, volumetric response, dose–volume relationships, fractionated-treatment results, or extended follow-up.

A specific overlap was identified among single-institution studies of olfactory groove meningiomas. The updated report by Wei et al. included 79 patients treated between 1987 and 2022 and explicitly included and updated all 41 patients previously reported by Gande et al.

The updated report was therefore retained as the principal publication, whereas the earlier report was excluded as an overlapping and less complete cohort.

When overlapping publications were retained because they provided complementary outcomes, they were not interpreted as independent patient cohorts when summarizing tumor-control rates, functional outcomes, or treatment-related adverse events.

Detailed Data Extraction

Data were extracted using a standardized data-collection framework developed according to the objectives of the review. Extracted publication-level variables included first author, publication year, journal, PubMed identifier, study design, participating institutions, recruitment period, number of patients, number of treated tumors, and follow-up duration.

Patient- and tumor-related variables included age, sex, anatomical location, radiological or histological diagnosis, World Health Organization grade when available, primary versus postoperative treatment setting, previous surgery, previous radiotherapy, tumor volume, maximum tumor diameter, documented tumor growth, and pre-existing neurological deficits.

The treatment setting was classified as follows:

- Primary SRS for a previously untreated tumor
- Postoperative adjuvant SRS for known residual disease
- Salvage SRS for recurrent or progressive disease after previous surgery or other treatment

Anatomical variables included the presence and degree of optic pathway, brainstem, cerebellar, temporal lobe, medullary, or upper cervical spinal cord contact or compression. Optic canal involvement, internal auditory canal extension, cavernous sinus involvement, vascular

encasement, hydrocephalus, and peritumoral edema were recorded when reported.

Treatment-related variables included the radiosurgical platform, single-fraction or multifraction treatment, prescription marginal dose, maximum dose, prescription isodose, number of fractions, cumulative treatment dose, and target coverage. Reported doses to organs at risk were extracted when available, including doses to the optic nerves, optic chiasm, optic tracts, brainstem, cochlea, pituitary gland, medulla, and upper cervical spinal cord.

Outcome variables included radiological tumor regression, stability, or progression; local tumor control; progression-free survival; and outcomes according to primary, postoperative adjuvant, or salvage treatment when separately reported. Functional outcomes included improvement, stability, or deterioration of visual function, ocular motor function, trigeminal nerve function, facial nerve function, hearing, vestibular symptoms, swallowing, lower cranial nerve function, and long-tract neurological function.

Treatment-related adverse events included new or worsened cranial neuropathy, visual deterioration, hearing deterioration, peritumoral edema, adverse radiation effects, radiation necrosis, hypopituitarism, vascular complications, and other neurological deterioration considered related to stereotactic treatment.

The requirement for additional treatment was recorded, including repeat SRS, fractionated radiotherapy, salvage microsurgery, cerebrospinal fluid diversion, or other subsequent interventions.

When both tumor-level and patient-level outcomes were available, tumor-level data were used for radiological outcomes, whereas patient-level data were used for neurological outcomes and treatment-related adverse events whenever possible. When outcomes were reported only as actuarial estimates, the reported progression-free survival or local-control estimates were

extracted at the stated follow-up intervals.

Anatomical Classification

The included publications were classified according to the principal dural attachment or predominant anatomical compartment of the treated tumor. The principal anatomical categories were as follows:

- Cavernous sinus
- Petroclival and clival
- Cerebellopontine angle and posterior petrous
- Posterior fossa
- Perioptic
- Tuberculum sellae and planum sphenoidale
- Anterior clinoid and medial sphenoid wing
- Tentorial and tentorial incisural
- Olfactory groove
- Foramen magnum
- Jugular foramen

When a publication included tumors involving more than one skull-base compartment, it was assigned according to the location used by the original authors or the predominant anatomical component. Publications reporting mixed skull-base cohorts were retained only when relevant location-specific outcomes were separately extractable.

Studies evaluating large or extensive skull-base meningiomas treated using hypofractionated, fractionated, multisession, or staged stereotactic techniques were analyzed separately because these treatment strategies were not limited to a single anatomical location.

Detailed Methodological Quality Assessment

Methodological quality was evaluated using appraisal tools appropriate to the design of each publication.

Original single-arm observational studies and case series were evaluated using the Joanna Briggs Institute Critical Appraisal Checklist for Case Series. The appraisal considered whether the inclusion criteria were clearly defined; whether the condition was measured in a standardized and reliable manner; whether valid methods were used to identify the condition; whether participants were consecutively and completely included; whether demographic and clinical characteristics were adequately reported; whether outcomes and follow-up were sufficiently described; and whether the statistical analyses were appropriate.

Comparative observational studies were assessed using the Newcastle–Ottawa Scale when applicable. The assessment considered cohort selection, comparability of treatment groups, ascertainment of treatment exposure and outcomes, adequacy of follow-up, and completeness of outcome reporting.

Systematic reviews and meta-analyses were evaluated using AMSTAR 2. The assessment considered protocol development, comprehensiveness of the literature search, justification of study selection, assessment of methodological quality, handling of heterogeneity, interpretation of risk of bias, and evaluation of publication bias when applicable.

Practice guidelines were used primarily as contextual evidence regarding clinical indications and treatment selection. They were not evaluated together with original clinical studies using

the Joanna Briggs Institute case-series checklist and were not regarded as independent patient cohorts.

No numerical methodological-quality threshold was used as an automatic exclusion criterion. This approach was selected because high-quality location-specific evidence was limited for several uncommon skull-base meningioma subgroups. Instead, methodological limitations were considered when determining the relative interpretive weight, reliability, generalizability, and clinical applicability of each publication.

Detailed Evidence Synthesis

The included publications were synthesized narratively according to anatomical location. For each location, the synthesis evaluated the clinical circumstances in which primary, postoperative adjuvant, or salvage SRS was used; tumor volumes and anatomical characteristics represented in the literature; commonly used marginal doses and fractionation strategies; radiological tumor-control and progression-free survival outcomes; neurological and cranial nerve outcomes; treatment-related adverse events; and the requirement for additional treatment.

Particular attention was given to location-specific organs at risk and to the circumstances in which surgical decompression, hypofractionated treatment, or conventionally fractionated stereotactic radiotherapy was favored over single-fraction SRS.

Formal quantitative pooling was not performed because of substantial heterogeneity in study design, anatomical classification, previous treatment, tumor volume, radiosurgical platform, prescription dose, fractionation, follow-up duration, and outcome definitions. Differences in reporting radiological progression, functional outcomes, and adverse radiation effects further limited the appropriateness of pooled analysis.

Greater interpretive weight was assigned to multicenter studies, larger institutional cohorts, studies with longer follow-up, updated reports of previously published cohorts, and studies reporting location-specific neurological or cranial nerve outcomes. Systematic reviews, meta-analyses, and practice guidelines were used to contextualize the original clinical evidence but were not treated as additional independent patient cohorts.