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Impact of tumor size and peritumoral edema on outcomes and complications in anterior midline skull base meningiomas

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ABSTRACT

Introduction: Surgical resection is the primary treatment for symptomatic anterior midline skull base meningiomas.
Research question: This study evaluates the impact of tumor size and peritumoral edema on clinical outcome.
Material and methods: A retrospective analysis of 109 patients who underwent resection between 2012 and 2022 was conducted. Tumors were categorized as: size 1 (<30 mm), size 2 (30–50 mm), and size 3 (>50 mm). Peritumoral edema was classified as: type 1 (no edema), type 2 (edema diameter < tumor diameter), and type 3 (edema diameter > tumor diameter). Clinical outcomes were assessed using the Karnofsky Performance Scale (KPS) at discharge, three months postoperatively, and at last follow-up. Additionally, complication rates were analyzed.
Results: Patients with size 3 tumors had significantly worse KPS scores at discharge (50 %) than those with size 2 (70 %) or size 1 tumors (80 %; $p < 0.0001$). At three months, KPS differences remained significant ($p = 0.0209$). For size 3 tumors, KPS at discharge was significantly associated with edema: 90 % for no edema, 70 % for type 2 edema, and 50 % for type 3 edema ($p = 0.0008$). Complication rates were higher in size 2 and 3 tumors (35–37 %) compared to size 1 (14 %; $p = 0.0330$). Tumors with peritumoral edema had increased complication rates (35 %) versus those without (23 %; $p = 0.2051$).
Discussion and conclusions: The combination of large tumor size and extensive peritumoral edema are associated with reduced early postoperative outcomes and higher complication rates. These findings underscore the importance of careful preoperative patient selection and tailored surgical strategies to optimize patient outcomes.

1. Introduction

Surgical treatment of anterior midline skull base meningiomas is characterized by very heterogeneous clinical outcomes (Refaat et al., 2014; Aftahy et al., 2020; Chi et al., 2006; Nakamura et al., 2007; Mukherjee et al., 2015; Bailo et al., 2019). Despite various challenges to microsurgical removal via transcranial approaches due to potential vascular conflicts, close proximity to neuronal structures and peritumoral edema (Gurkanlar et al., 2005; Vignes et al., 2008; Shin et al., 2021), surgical resection remains the first-line treatment for

Abbreviations: ACM, anterior clinoidal meningioma; ICU, intensive care unit; KPS, Karnofsky Performance Scale; MRI, magnetic resonance imaging; OGM, olfactory groove meningioma; PSM, planum sphenoidale meningioma; TSM, tuberculum sellae meningioma; WHO, world health organization.

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space-occupying tumors and symptomatic patients (Mukherjee et al., 2015; Cazac et al., 2018; Rogers et al., 2015). Potential complications range from CSF leakage, seizures, stroke, infection, hemorrhage to hydrocephalus with uncontrollable intracranial pressure increase due to progressive postoperative cerebral edema (Refaat et al., 2014; Nakamura et al., 2007; El Gindi, 2000; Aguiar et al., 2009; Hentschel, 2003). For example, in large olfactory groove meningiomas, the perioperative complication rate can be as high as 39 % with a postoperative mortality rate of 4.9 % (Nakamura et al., 2007; Mukherjee et al., 2015; Aguiar et al., 2009).

Due to these clinical challenges treatment algorithms have been described to guide surgery, focusing on surgical approach and surgical strategy (Aftahy et al., 2020; Fox et al., 2009; Cornelius et al., 2019). However, current treatment algorithms lack identification of tumor-associated risk factors with an impact on clinical outcome. In this regard, tumor size and peritumoral edema have been suggested to influence surgical outcome and postoperative mortality due to decompensation of cerebral edema (Aftahy et al., 2020; Mukherjee et al., 2015; Aguiar et al., 2009). Assuming that removal of a space-occupying frontobasal tumor creates potential open space that may allow the brain to swell, clinical observations point towards potential malignant decompensation of brain edema despite removal of the space occupying pathology. Consequently, decompensation of postoperative cerebral edema has been surgically addressed by performing decompressive craniectomy in a prophylactic approach (Marquardt et al., 2021; Qasem et al., 2025). These surgical observations underscore the clinical significance of tumor size and peritumoral edema in the postoperative course of treatment. However, there remains a lack of evidence-based data comprehensively characterizing the impact of these tumor characteristics on patient outcomes. Therefore, it was the aim of the current study to address the impact of tumor size and peritumoral edema on clinical outcome in patients undergoing surgery for anterior skull base meningiomas.

2. Material and Methods

Study design: All patients who underwent microsurgical resection of an anterior midline skull base meningioma between 2012 and 2022 at the Department of Neurosurgery, University Hospital Frankfurt am Main, Germany, were included in the study. Approval from the local ethics committee was obtained prior to the study. This research was conducted in accordance with the Declaration of Helsinki and all relevant guidelines and regulations. As the study involves retrospective analysis, a waiver of informed consent was granted by the Institutional Review Board (IRB) of Goethe University Frankfurt am Main, Germany, where broad consent includes patient consent for retrospective data analyses. All data were analyzed retrospectively, consequently no additional patient consent was required for the analysis. Routine surgical consent was obtained prior to surgery.

Anterior midline skull base meningiomas were defined as olfactory groove meningiomas (OGM), tuberculum sellae meningiomas (TSM), planum sphenoidale meningiomas (PSM) and anterior clinoidal meningiomas (ACM). Many authors group ACM with sphenoid ridge or suprasellar meningiomas (Zada et al., 2017; Al-Mefty, 1991). Although their clinical and radiologic presentation differs from that of OGM, PSM and TSM, their surgical challenge is more similar to that of anterior midline skull base meningiomas, which is why we have included these skull base meningiomas in our study.

Outcome parameters: The primary outcome measure was clinical outcome using the Karnofsky Performance Scale (KPS) score at three months after surgery. Preoperative KPS, KPS at discharge, KPS at last follow-up, postoperative complications as well as tumor and edema sizes and volumes were analyzed.

Complications were grouped into early complications occurring during the same hospitalization and late complications occurring after discharge. Major complications required either a recurrent surgical intervention or intensive care unit (ICU) admission e.g. due to sepsis or progressive edema. Minor complications required non-surgical intervention, e.g. oral anticoagulation due to pulmonary embolism.

Clinical and radiographic data were collected from our institutional medical record system. T1-weighted axial gadolinium-enhanced MRI sequences were used for tumor dimensions. Tumors were categorized as size 1 (0–30 mm maximum diameter), size 2 (30–50 mm maximum diameter), and size 3 (>50 mm maximum diameter) (Abou-Al-Shaar et al., 2023; Marenco-Hillembrand et al., 2023). Peritumoral edema was assessed using T2-weighted sequences. Maximum diameter in axial sequences categorized edema as type 1 (no edema), type 2 (maximum edema diameter < maximum tumor diameter; moderate edema) and type 3 (maximum edema diameter > maximum tumor diameter; extensive edema) (Baumgarten et al., 2021; Wirsching et al., 2016). All MRI sequences were reviewed by a board certified neuroradiologist.

Surgical technique: Craniotomies included pterional craniotomy (including variations of pterional craniotomy) and bifrontal craniotomies. Surgical approaches included the subfrontal and interhemispheric approach. To ensure homogeneity of surgical techniques, endonasal approaches were not considered in the present analysis. Surgery was performed in either a single-stage or two-stage procedure with initial craniectomy followed by cranioplasty in a two-stage strategy to prevent progressive postoperative cerebral edema (Marquardt et al., 2021; Qasem et al., 2025). Complete resection was measured by the surgeon's personal intraoperative microscopic assessment and radiographically measured with MRI three months postoperatively.

Statistical analysis: Data were analyzed using GraphPad Prism software (version 9.5.1; GraphPad Software, San Diego, CA, USA). Descriptive statistics were calculated for all variables, with continuous data presented as means with standard deviations (SD) or medians with ranges, as appropriate. The normality of data distribution was assessed using the Kolmogorov-Smirnov test. Comparisons between two subgroups were conducted using the Mann-Whitney *U* test for nonparametric data and the unpaired *t*-test for parametric data. For comparisons among three or more subgroups, the Kruskal-Wallis test was applied for nonparametric data, followed by post-hoc analysis with the Mann-Whitney *U* test. For parametric data, one-way analysis of variance (ANOVA) was performed, followed by pairwise comparisons using the unpaired *t*-test. Correlations between tumor size and peritumoral edema were analyzed using Pearson's correlation coefficient. Logistic regression was employed to evaluate the association between complications and tumor size or the presence of peritumoral edema. A p-value <0.05 was considered statistically significant.

3. Results

A total of 109 patients with anterior midline skull base meningiomas were included in the study. Forty-six meningiomas (42 %) arose from the olfactory groove, 33 meningiomas (30 %) from the anterior clinoid process, and 15 meningiomas (14 %) from the tuberculum sellae and planum sphenoidale, respectively.

Baseline patient characteristics: Seventy-eight of 109 patients (72 %) in this study were female. Interestingly, the typical 3:1 female-to-male ratio (Wiemels et al., 2010) among meningioma patients shifted to a 1:1 ratio in size 3 meningiomas. The median age was 57 years (range 33–84). According to the World Health Organization (WHO) grading system, 75 meningiomas (69 %) were CNS WHO grade 1, while 33 meningiomas (30 %) were CNS WHO grade 2, and one meningioma was CNS WHO grade 3 (1 %). The median preoperative KPS was 90 (range 40–100) for all size and edema groups, respectively. The mean follow-up time was 28 (±32) months.

The microscopic complete resection rate was 78 %, the radiographic complete resection rate in the 3-months follow up MRI was 73 %. The overall recurrence rate was 15 %, with the highest rate of 20 % for size 2 and the lowest rate of 9 % for size 1 meningiomas.

Most meningiomas were resected through a pterional (or variations of pterional including frontolateral, frontotemporal or supraorbital) craniotomy (n = 87/109; 80 %), especially in the case of a size 1 meningioma (n = 36/36; 100 %) or size 2 meningiomas (n = 44/46; 96 %). Size 3 meningiomas were mostly operated using bifrontal craniotomy or craniectomy (n = 20/27; 74 %). The remaining seven cases of size 3 meningiomas were resected via pterional (or variations) craniotomy (n = 7; 26 %).

Eighty-seven patients were treated with single-stage surgery (80 %). Twenty-two patients (20 %) were treated with a two-stage surgical procedure with initial craniectomy to prevent progressive postoperative edema and autologous cranioplasty as a second surgical step. Two patients were initially scheduled for single-stage surgery but were converted to a two-stage procedure due to progressive intraoperative edema. All baseline characteristics including surgical approaches are summarized in Table 1.

Size and edema: Thirty-six meningiomas (33 %) had a maximum diameter <30 mm (size 1) at the time of surgery. Forty-six meningiomas (42 %) grew to a size of 30–50 mm (size 2) and 27 meningiomas (25 %) were categorized as size 3 with >50 mm. Fifty-seven of 109 meningiomas (52 %) presented without edema at the time of surgery (type 1). Forty-three meningiomas (40 %) had an extensive edema larger than the maximum tumor diameter (type 3). Nine meningiomas (8 %) had a moderate edema with a maximum diameter smaller than the maximum tumor diameter (type 2). Thirty of 52 meningiomas (58 %) exhibited bihemispheric edema and 20 (42 %) presented with unilateral edema.

The mean maximum tumor diameter on axial MRI sequences was 44 (±22) mm, with 19 (±5.4) mm for size 1; 37 (±5.7) mm for size 2 and 60 (±9.5) mm for size 3 meningiomas. Regarding tumor volume, the mean was 26 (±38) cm^3, with 3.1 (±2.1) cm^3 for size 1, 16 (±9) cm^3 for size 2 and 76 (±49) cm^3 for size 3 tumors. For the mean maximum edema diameter on axial MRI sequences, it was 74 (±37) mm, wherein size 1 meningiomas measured 43 (±37) mm, size 2 measured 60 (±37) mm, and size 3 reached 86 (±37) mm. The mean edema volume was 45 (±111) cm^3, with 1.3 (±3.9) cm^3 for size 1, 57 (±160) cm^3 for size 2 and 83 (±62) cm^3 for size 3 meningiomas.

Size 3 meningiomas were predominantly olfactory groove meningiomas (n = 20/27; 74 %), while size 1 meningiomas were primarily clinoidal meningiomas (n = 17/36; 47 %). Refer to Fig. 1 for classification into size groups based on tumor location. Most size 3 meningiomas presented with type 3 edema (n = 25/27; 93 %), whereas size 1 and size 2 meningiomas were most frequently observed without edema (n = 32/36; 89 % for size 1 and n = 24/46; 67 % for size 2). Pearson correlation analysis indicated a strong correlation between tumor volume and volume of peritumoral edema ($r = 0.52$; $p < 0.0001$, see Fig. 2).

Outcome parameters: The median KPS at three months postoperatively was 90 % independent of size and edema formation. The median KPS at discharge was 75 % and 100 % at the last follow-up.

<u>Outcome depending on tumor size:</u> The median KPS at three months postoperatively and at discharge was significantly different depending on tumor size. The median KPS at three months postoperatively was 90 % in size 1, 85 % in size 2, and 80 % in size 3 tumors ($p = 0.0209$). The median KPS at discharge was 80 % in size 1, 70 % in size 2, and 50 % in size 3 tumors ($p < 0.0001$). KPS at the last follow-up was not statistically different: 100 % in size 1 and 2 meningiomas and 90 % in size 3 meningiomas ($p = 0.1295$). Fig. 3A–C demonstrates outcome data depending on tumor size.

<u>Outcome depending on edema formation:</u> The presence of peritumoral edema showed an influence on KPS at discharge with a significantly improved outcome in tumors without edema (type 1; KPS 80 %) compared to KPS 60 % in type 2 and KPS 70 % in type 3 tumors ($p = 0.0134$). Median KPS at three months and at the last follow-up were not significantly different: KPS at three months postoperatively was 90 % in type 1 tumors, 80 % in type 2 and 3 tumors ($p = 0.2707$); KPS at last follow-up was comparable between different edema types: KPS 90 % in type 1, KPS 100 % in type 2 and 3 ($p = 0.9270$). Fig. 4A–C demonstrates outcome data depending on edema formation.

Table 1
Baseline patient characteristics.

	total	size 1 (>30 mm)	size 2 (30–50 mm)	size 3 (>50 mm)
total n (% of total)	109	36 (33 %)	46 (42 %)	27 (25 %)
newly diagnosed	108	36 (33 %)	45 (42 %)	27 (25 %)
recurrence	1	0	1	0
localization n (% of size group)				
olfactory groove	46 (42 %)	5 (14 %)	21 (46 %)	20 (74 %)
anterior clinoid	33 (30 %)	17 (47 %)	13 (28 %)	3 (11 %)
tuberculum sellae	15 (14 %)	9 (25 %)	6 (13 %)	0
planum sphenoidale	15 (14 %)	5 (14 %)	6 (13 %)	4 (15 %)
age in years median (range)	57 (33–84)	57 (36–73)	57 (33–79)	57 (41–84)
gender n (% of size group)				
female	78 (72 %)	28 (78 %)	36 (78 %)	14 (52 %)
male	31 (28 %)	8 (22 %)	10 (22 %)	13 (48 %)
CNS WHO grade n (% of size group)				
1	75 (69 %)	32 (89 %)	30 (65 %)	13 (48 %)
2	33 (30 %)	4 (11 %)	16 (35 %)	13 (48 %)
3	1 (1 %)	0	0	1 (4 %)
preoperative KPS in % median (range)	90 (40–100)	90 (80–100)	90 (70–100)	90 (40–100)
follow-up (months) mean (standard deviation)	28 (±32)	23 (±27)	33 (±34)	27 (±33)
maximum tumor diameter in mm mean (standard deviation)	44 (±22)	19 (±5.4)	37 (±5.7)	60 (±9.5)
tumor volume in cm^3 mean (standard deviation)	26 (±38)	3.1 (±2.1)	16 (±9)	76 (±49)
maximum edema diameter in mm mean (standard deviation)	35 (±42)	4.9 (±14)	31 (±38)	83 (±31)
edema volume in cm^3 mean (standard deviation)	45 (±111)	1.3 (±3.9)	57 (±160)	83 (±62)
complete microscopic resection n (% of size group)	85 (78 %)	29 (81 %)	33 (72 %)	23 (85 %)
complete radiographic resection n (% of size group)	80 (73 %)	30 (83 %)	31 (67 %)	19 (70 %)
recurrence n (% of size group)	16 (15 %)	3 (9 %)	9 (20 %)	4 (15 %)
surgical approach (craniotomy) n (% of size group)				
pterional (+variations)	87 (80 %)	36 (100 %)	44 (96 %)	7 (26 %)
bifrontal	22 (20 %)	0	2 (4 %)	20 (74 %)
single-stage surgery	87 (80 %)	36 (100 %)	44 (96 %)	7 (26 %)
two-stage surgery	22 (20 %)	0	2 (4 %)	20 (74 %)

Abbreviation: central nervous system (CNS); Karnofsky Performance Scale (KPS); World Health Organization (WHO).

Within the category of size 3 meningiomas, those with extensive edema (type 3) had a decreased KPS (50 %) compared to size 3 meningiomas without peritumoral edema (type 1; KPS 90 %) and to size 3 meningiomas with moderate edema (type 2; KPS 70 %; $p = 0.0008$). Fig. 5 shows outcome data for size 3 meningiomas dependent on edema formation.

<u>Complications:</u> Complications occurred in 31 of 109 patients, resulting in an overall complication rate of 28 %. Among size 1 meningiomas, the complication rate was 14 % (n = 5/36), compared to 35 % for size 2 meningiomas (n = 16/46; $p = 0.0316$) and 37 % for size 3 meningiomas (n = 10/27; $p = 0.0330$). Patients with peritumoral edema

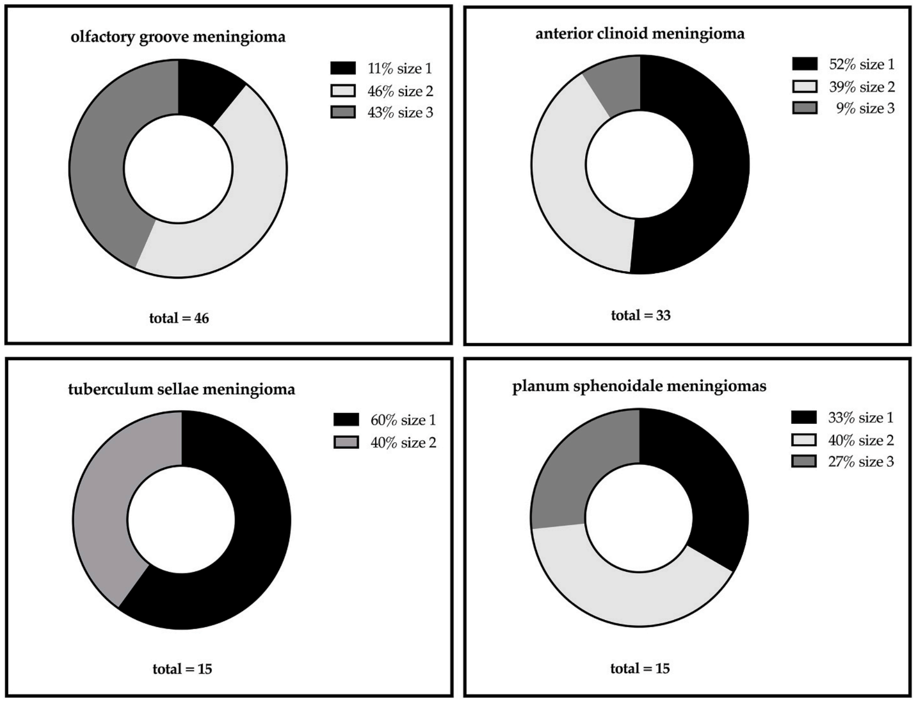

Fig. 1. Classification into size groups based on tumor location
Pie charts showing meningiomas according to their origin, classified into three size groups according to their maximum diameter on axial gadolinium-enhanced T1-weighted MRI: size 1: 0–30 mm; size 2: 30–50 mm; size 3 > 50 mm.

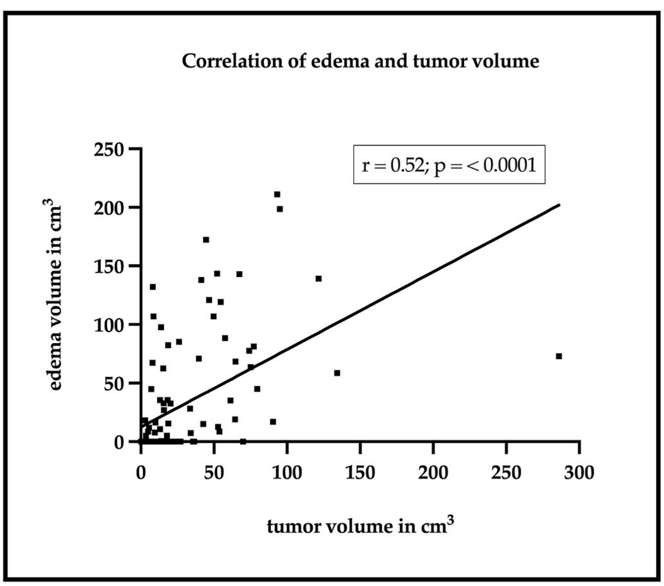

Fig. 2. Correlation of edema and tumor volume
The scatter plot illustrates the correlation between the volume of peritumoral edema and tumor volume. The y-axis represents the volume of edema in cubic centimeters (cm^3), while the x-axis represents tumor volume, also measured in cubic centimeters (cm^3). Each data point represents a tumor, with its position determined by the volume of its associated peritumoral edema. The line shows simple linear regression. Pearson correlation analysis indicates a strong correlation between tumor volume and edema volume ($r = 0.52$; $p < 0.0001$).

had higher complication rates than those without edema (35 % vs. 23 %, $p = 0.2051$). Major complications occurred in 10 of 46 patients (22 %) with size 2 meningiomas and in 5 of 27 patients (19 %) with size 3 meningiomas, compared to only 1 of 36 patients (2 %) with size 1 meningiomas. Hemorrhage was the most common postoperative complication ($n = 8$; 7 %), followed by cerebrospinal fluid (CSF) leakage ($n = 6$; 6 %) and progression of postoperative cerebral edema ($n = 5$; 5 %). The overall re-operation rate across all tumor sizes was 10 % ($n = 11/109$). Detailed information on postoperative complications is presented in Table 2.

In the logistic regression analysis assessing factors associated with complications, neither tumor size, peritumoral edema, age or preoperative KPS showed a statistically significant impact on complication rate. This statistical result is explained by the overall reduced number of complications in the analyzed patient cohort. When analyzing hemorrhagic complications specifically, tumor size demonstrated a significant association. Larger tumors (size 3) were associated with a markedly increased risk of hemorrhagic complications compared to size 1 meningiomas (OR, 22.63; 95 % CI, 1.49 to 343.04).

Pre- and postoperative symptoms: The most common presenting preoperative symptom was visual disturbance, observed in 51 patients (47 %), followed by anosmia in 25 patients (23 %), seizures in 19 patients (17 %) and cognitive dysfunction in 15 patients (14 %). Meningiomas were diagnosed incidentally in 15 patients (14 %), while non-specific symptoms such as headache and dizziness were reported in 9 patients (8 %). Visual disturbances were most prevalent in size 1 meningiomas ($n = 21/36$; 58 %), with clinoidal meningiomas accounting for the majority ($n = 17/36$; 47 %). Size 3 meningiomas were most commonly associated with anosmia ($n = 11/27$; 41 %) and cognitive dysfunction ($n = 10/27$; 37 %).

Postoperatively, symptom improvement was noted in 42 out of 94 symptomatic cases (45 %). Among symptomatic size 1 meningiomas, 18 of 26 cases (69 %) demonstrated improvement, while improvement was observed in 14 of 36 symptomatic size 2 meningiomas (39 %). All size 3 meningiomas were symptomatic (27/27), with postoperative improvement documented in 10 cases (37 %).

Visual disturbances improved in 31 of 51 cases (61 %). Persistent visual disturbances were documented in 14 cases (27 %). Improvement was most notable in size 1 meningiomas ($n = 17/21$; 81 %), followed by size 2 ($n = 10/15$; 67 %) and size 3 ($n = 4/10$; 40 %). Seizure improvement was noted in five of 13 cases (38 %). Cognitive

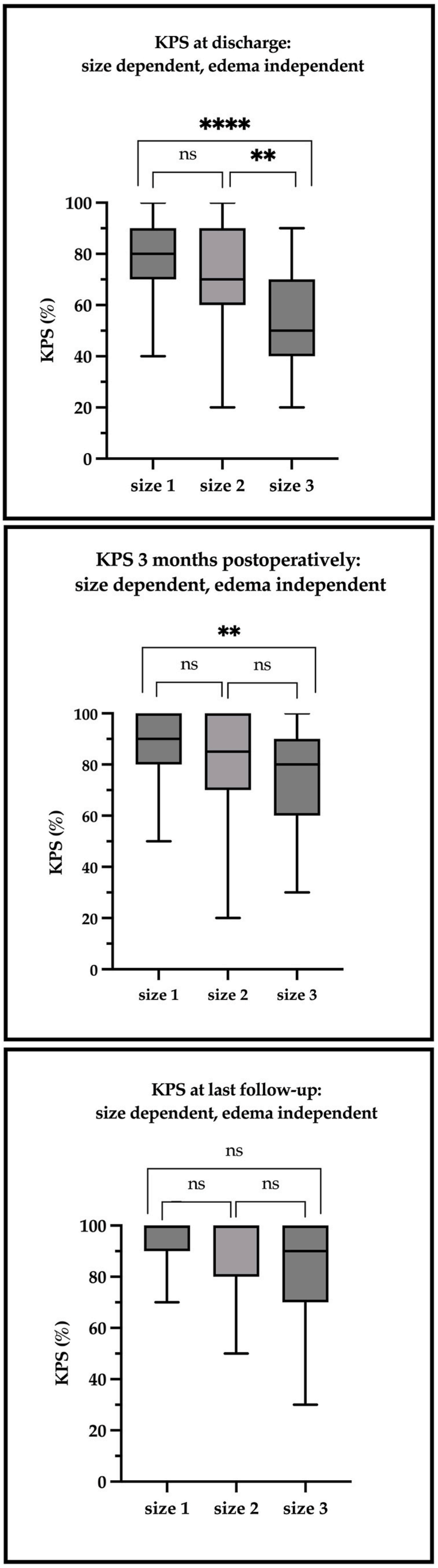

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Fig. 3. Outcome dependent on tumor size
The box plots show the median KPS scores for the three meningioma size groups at three distinct time intervals, irrespective of edema formation: size 1 (<30 mm), size 2 (30–50 mm), size 3 (>50 mm). Panel A illustrates KPS scores at discharge, Panel B portrays KPS scores three months postoperatively, and Panel C delineates KPS scores at the last follow-up. The interquartile ranges are represented by the boxes, the median KPS values are denoted by bold lines, and the whiskers depict the minimum and maximum KPS values.

dysfunction improved in six of 15 documented cases (40 %), persisted in three cases (20 %), and was not consistently assessed in the remaining cases. In all documented cases (n = 25), anosmia persisted post-operatively. While visual disturbances and seizures were well-documented, cognitive dysfunction and anosmia was inconsistently assessed and reported, limiting comprehensive analysis of these outcomes.

4. Discussion

This study identifies a subgroup of patients with anterior midline skull base meningiomas who are at high risk for reduced clinical outcomes and increased complication rates, specifically those presenting with a combination of large tumor size (>50 mm) and peritumoral edema exceeding the tumor dimensions. Both tumor size and peritumoral edema independently influence early perioperative surgical outcomes. However, their individual impact on patient outcomes diminishes in long-term follow-up, indicating a transient effect of each parameter. Neither edema nor tumor size alone are verified as independent risk factors for surgical complications. The combination of large tumor size and extensive edema enables the identification of high-risk patients characterized by an increased complication profile and a persistent reduction in clinical outcome.

Tumor size and edema in anterior midline skull base meningiomas: Studies have consistently shown that larger tumors are more likely to present with pronounced peritumoral edema, which is attributed to increased mass effect and local inflammatory responses (Gurkanlar et al., 2005; Vignes et al., 2008; Shin et al., 2021; Stummer, 2007). This association not only poses challenges for surgical resection by altering anatomical landmarks but also correlates with poorer functional outcomes and a higher incidence of postoperative complications (Aguiar et al., 2009; Haeren et al., 2021). In our patient cohort, especially the combination of large tumor size and extensive peritumoral edema demonstrated reduced clinical outcome. However, neither tumor size nor extensive peritumoral edema are identified as independent risk factors for perioperative complications in our study. This may be due to the limited number of complications in our study, but this may also point out that primarily the combination of both (large size + extensive edema) leads to an increased complication profile and reduced clinical outcome. Consequently, our data clearly show that tumor size and peritumoral edema demonstrate an impact on early surgical outcome. However, this perioperative effect is not verified in long term analysis as shown by non-significant outcome differences at last follow-up for size dependent or edema dependent analysis, respectively. Only in large tumors (size 3), analysis of clinical outcome shows a significant edema dependent negative effect on clinical outcome. Therefore, patients with large tumors (>50 mm) with extensive peritumoral edema can be regarded as high-risk patients, that may benefit from an adapted surgical strategy. Prophylactic decompressive craniectomy has been proposed as a potentially beneficial surgical strategy to reduce perioperative complications and to improve patient safety and surgical outcome in this specific subgroup of patients (Marquardt et al., 2021; Qasem et al., 2025).

Complication rates were elevated in larger meningiomas and those with peritumoral edema. Our overall complication rate of 28 % is within the range of 11–39 % reported in the literature (Aftahy et al., 2020; Mukherjee et al., 2015; Aguiar et al., 2009; Pallini et al., 2015). A higher

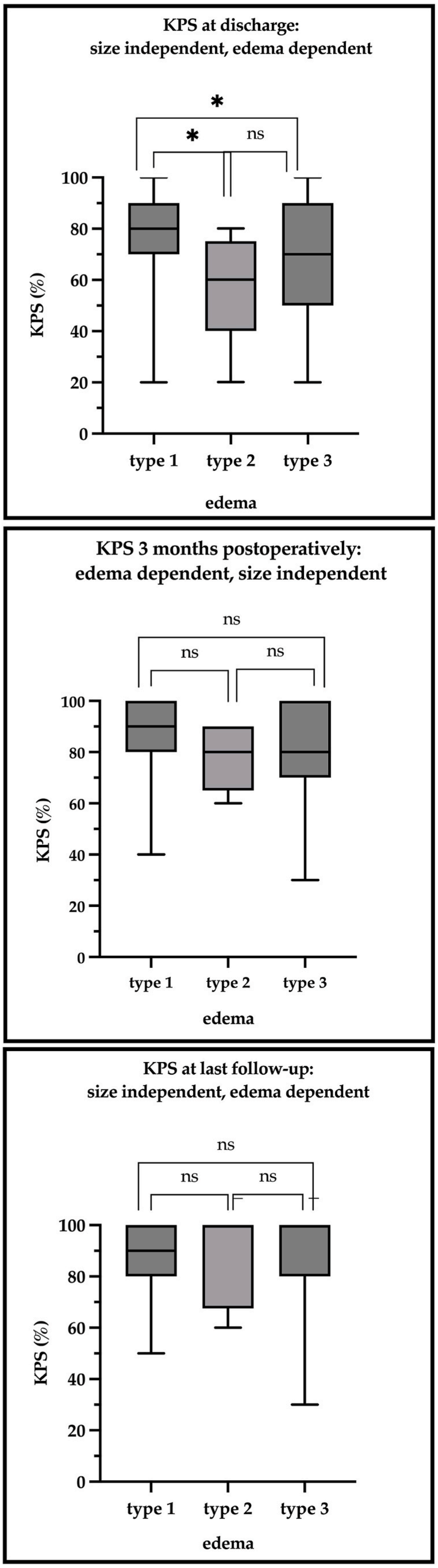

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Fig. 4. Outcome dependent on edema formation
The box plots show the median KPS scores for the three meningioma edema groups at three distinct time intervals, irrespective of tumor size: type 1 (no edema), type 2 (maximum edema diameter < maximum tumor diameter), type 3 (maximum edema diameter > maximum tumor diameter). Panel A illustrates KPS scores at discharge, Panel B portrays KPS scores three months postoperatively, and Panel C delineates KPS scores at the last follow-up. The interquartile ranges are represented by the boxes, the median KPS values are denoted by bold lines, and the whiskers depict the minimum and maximum KPS values.

complication rate of 53 % was observed in OGM larger than 40 mm, compared with 28 % in those <40 mm (Mukherjee et al., 2015). Mukherjee et al. (2015) also reported an increased complication rate in OGM with peritumoral edema (59 %) versus those without edema (19 %), with reduced complications among patients receiving preoperative dexamethasone for 3–5 days. Differences in reported rates may arise from the focus of Mukherjee et al. on OGM, which often reach larger sizes and are associated with more severe edema, leading to the inclusion of larger tumors with extensive peritumoral edema (Mukherjee et al., 2015). Consistently, our data demonstrate higher complication rates in meningiomas larger than 30 mm in diameter (36 %) compared to those smaller than 30 mm (14 %), and in meningiomas with peritumoral edema (35 %) versus without edema (23 %).

Postoperative KPS and long-term outcomes: The KPS score is widely used as a primary outcome measure in clinical practice and oncology trials to assess patients' functional ability and quality of life (San et al., 2023). However, its subjective nature, relying on observer judgment, may introduce variability in assessment and potentially lead to inaccurate results. Despite these limitations, the KPS score remains the most frequently utilized outcome parameter in meningioma studies, which is why we selected it as the primary outcome parameter in the present study. While the KPS represents the clinical standard of care and is therefore consistently documented, additional outcome parameters, such as quality-of-life questionnaires and neuropsychological assessments, are not routinely incorporated into daily clinical practice and thus cannot be systematically analyzed in a retrospective study design. Moreover, previous studies have reported postoperative KPS scores without accounting for tumor size or peritumoral edema in patients with anterior midline skull base meningiomas (Rogers et al., 2015; Abou-Al-Shaar et al., 2023; Baumgarten et al., 2021; Wirsching et al., 2016; San et al., 2023). Our study differs from prior investigations by analyzing patient outcomes based on KPS in relation to tumor size and peritumoral edema, thereby allowing for the identification of a high-risk subgroup among patients with anterior midline skull base meningiomas.

Limitations: It is imperative to acknowledge that our study represents a retrospective analysis focusing on KPS-based clinical data, as these data reflect the standard of clinical care. Outcome parameters such as the modified Rankin Scale (mRS), neuropsychological test batteries, and quality-of-life questionnaires were not included. Retrospective studies are inherently susceptible to surgeon and selection bias, which may influence the study results. Furthermore, our study did not assess the potential impact of different surgical approaches (interhemispheric vs. subfrontal or pterional vs. bifrontal craniotomy (Feng et al., 2020; Morales-Valero et al., 2014; Lévêque et al., 2011)), since the small subgroup sizes based on tumor origin or size and edema may limit the ability to effectively evaluate the influence of surgical approaches on KPS outcomes. Lastly, the retrospective, non-randomized, and single-center design of our study imposes limitations on the generalizability and statistical power of our findings.

5. Conclusion

Our results demonstrate that the combination of large tumor size and extensive peritumoral edema leads to persistently reduced clinical outcomes and an increased complication rate in the surgical treatment of

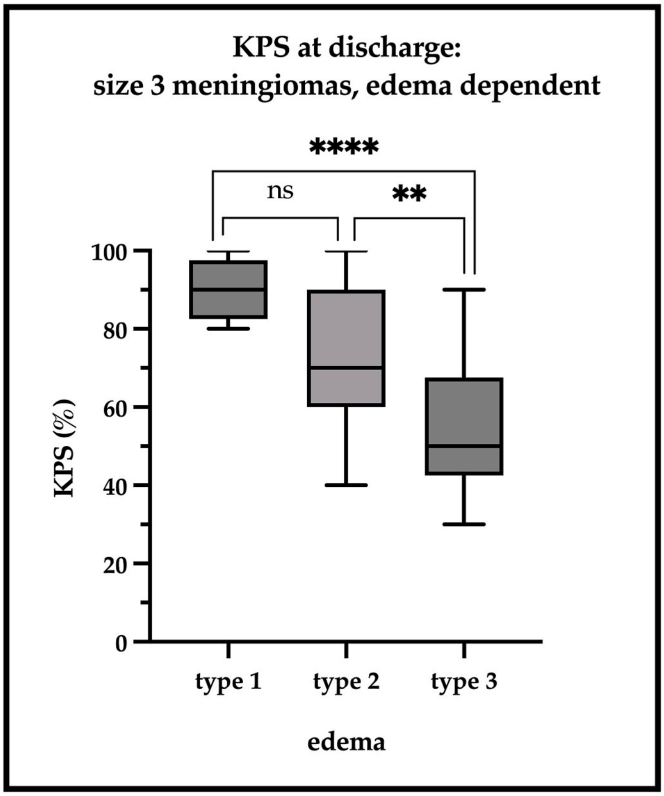

Fig. 5. Outcome for size 3 meningiomas dependent on edema formation
The box plots show the median KPS score at discharge for size 3 meningiomas according to their edema formation: type 1 (no edema), type 2 (maximum edema diameter < maximum tumor diameter), type 3 (maximum edema diameter > maximum tumor diameter). The interquartile ranges are represented by the boxes, the median KPS values are denoted by bold lines, and the whiskers depict the minimum and maximum KPS values.

anterior midline skull base meningioma patients. Patients with a tumor size >50 mm and peritumoral edema exceeding the tumor dimensions exhibit significantly worse outcomes compared to those with smaller tumors and less pronounced edema. While tumor size and peritumoral edema individually influence early perioperative outcomes, this effect diminishes over long-term follow-up. Consequently, neither tumor size nor peritumoral edema alone were identified as statistically significant risk factors for perioperative complications. These findings identify a high-risk subgroup of anterior midline skull base meningioma patients. They underscore the importance of careful patient selection and the adaptation of surgical strategies to optimize outcomes and minimize complications in this challenging patient population.

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Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Table 2
Postoperative complications.

early postoperative complications (same hospitalization):	43 complications in 25 patients (22 %)
major complications:	29 complications in 16 patients (15 %)
hemorrhage	8 (4 EDH requiring surgery; 2 SDH requiring surgery; 2 ICH of which 1 required surgery and 1 required EVD insertion)
CSF leakage	1 (lumbar drain and surgery)
edema	5 (ICU admission; ICP monitoring; hyperosmolar medication)
stroke	1 (due to CVS)
hydrocephalus	1 (due to meningitis and intracerebral hemorrhage)
sepsis	1
others	1 (hemopneumothorax requiring chest tube insertion)
minor complications:	14 complications in 15 patients (13 %)
seizure	7
pneumonia	2
pulmonary emboslism	5
others	2 (hyponatremia requiring replacement)
late postoperative complications (after discharge):	17 complications in 15 patients (16 %)
wound infection	3 (1 including meningitis, 1 including cerebral abscess)
late hydrocephalus	2 (requiring VP-shunt insertion)
late epilepsy	4
CSF leakage	5 (2 requiring surgery, 3 requiring lumbar drain)
others	3 (1 CVS; 1 PTSD; 1 hygroma)

Abbreviations: cerebral vasospasm (CVS); epidural hematoma (EDH); external ventricular drain (EVD); intracerebral hemorrhage (ICH); post-traumatic stress disorder (PTSD); subdural hematoma (SDH); ventricular-peritoneal shunt (VP-shunt).

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