DOI:10.55095/CesRadiol2025/021

original article

Pre-operative grading of meningioma using multiparametric magnetic resonance imaging with inclusion of diffusion weighted imaging and susceptibility weighted imaging

Předoperační stanovení gradingu meningeomů s použitím magnetické rezonance včetně difuzně váženého a susceptibilně váženého zobrazení

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Major statement

This study proposes a practical, clinically relevant approach to pre-operative grading of meningioma, using a multiparametric MRI protocol that combines diffusion-weighted imaging (DWI) with susceptibility-weighted imaging (SWI).

Hlavní stanovisko práce

Studie navrhuje praktický, klinicky relevantní přístup k předoperačnímu hodnocení meningiomů pomocí multiparametrického protokolu MR, který kombinuje difuzně vážené zobrazení (DWI) s citlivostně váženým zobrazením (SWI).

SUMMARY

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Aim: Meningiomas, one of the most prevalent primary central nervous system tumors among adults. They were previously studied qualitatively using several morphological characteristics to detect their biological behaviour. However, many of these studies were controversial due to variable sample sizes and subjectivity in their assessment.

Method: study evaluated the benefits of a multi-parametric MRI method comparing morphological data and advanced quantitative diffusion and semi-quantitative SWI parameters in the pre-operative grading of meningiomas. We investigated 36 patients recruited from the neurosurgery out who had extra axial masses with features of meningioma in MRI.

Results: A total of 36 patients were recruited and underwent routine MRI of the brain, followed by DWI and SWI. Morphological features, like tumor size, unclear TBI, lobulated tumor margins, heterogenous contrast enhancement,

SOUHRN

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Cíl: Meningiomy patří mezi nejčastější primární nádory centrálního nervového systému u dospělých. Dosud byly studovány kvalitativně s využitím několika morfologických charakteristik k detekci jejich biologického chování. Mnohé z těchto studií však byly kontroverzní kvůli variabilní velikosti vzorků a subjektivitě při jejich hodnocení.

Metoda: Studie hodnotila výhody multiparametrické metody MR porovnávající morfologické údaje a pokročilé kvantitativní difuzní a semikvantitativní parametry SWI v předoperačním hodnocení meningiomů. Zkoumali jsme 36 pacientů z neurochirurgického oddělení, kteří měli extraaxiální masy s rysy meningiomu v MR.

Výsledky: Celkem bylo zařazeno 36 pacientů, kteří podstoupili rutinní MR mozku, následovanou DWI a SWI. Morfologické znaky, jako velikost nádoru, nejasné TBI, lobulární okraje nádoru, heterogenní kontrastní zvýraznění, byly významně častější u meningiomů

Accepted: 31. 8. 2025

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Conflict of interest: none.

The study was approved by the ethical committee of Faculty of Medicine, Ain-Shams University (FMASU REC) under Fedral wide assurance No. FWA00017585 (FMASU MD 214/2021). The requirement for written consent was waived for this cross-sectional study.

were significantly higher in high grade meningiomas. Low grade meningiomas had significantly higher Mean ADC value and normalized form of ADC (n ADC) in the tumor (ratio between tumor and normal side in ADC). Cut off value of the mean ADC and n ADC in the tumor for the high grade were ≤ 0.7126 and ≤ 0.9469 respectively. ITSSs seen in SWI, showed significant difference between both groups where the most common grade seen in low grade meningiomas was grade 1 and the most common grades seen in high grade meningiomas were grades 2 and 3, seen equally. Sensitivity of the n ADC in the tumor was (85.71%) and specificity was (96.55%) with diagnostic accuracy (86.7%). While sensitivity of SWI to detect high grade tumors was (85.71%), specificity was (68.97%) and accuracy was (72.22%). Therefore, the combination between (SWI & DWI) as diagnostic tools, increased sensitivity to 87.5%, specificity to 100%, and diagnostic accuracy to 97.2%. Combination between DWI and SWI also narrows down cases where SWI helps excluding cases of very low grade and high grade and saves DWI for differentiation of cases in between.

Conclusion: High grade meningiomas in conventional images were strongly associated with large tumor size, unclear TBI, lobulated tumor margins, heterogenous contrast enhancement, midline shift and intratumoral cysts. While in advanced techniques like DWI, high grade meningiomas were strongly associated with lower mean ADC values in the tumor, n ADC in the tumor, and more ITTSSs (grade 2, 3) using SWI. Combination of the quantitative DWI and semi-quantitative assessment of SWI led to the increase of sensitivity, specificity and diagnostic accuracy and less time consumption for preoperative grading of meningiomas.

Key words: Magnetic resonance imaging. Meningioma, Radiological grading, Histopathological grading, DWI, SWI.

vysokého stupně. Nízce maligní meningiomy měly významně vyšší průměrnou hodnotu ADC a normalizovanou formu ADC (n ADC) v nádoru (poměr mezi nádorem a normální stranou v ADC). Mezní hodnota průměrné hodnoty ADC a n ADC v nádoru pro vysoký stupeň malignity byla ≤ 0,7126, respektive ≤ 0,9469. ITSS pozorované v SWI vykazovaly významný rozdíl mezi oběma skupinami, kde nejčastějším stupněm u meningiomů nízkého stupně byl stupeň 1 a nejčastějšími stupni u meningiomů vysokého stupně byly stupně 2 a 3, které se vyskytovaly stejně často. Citlivost n ADC v nádoru byla (85,71 %) a specificita byla (96,55 %) s diagnostickou přesností (86,7 %). Zatímco citlivost SWI k detekci nádorů s vysokým stupněm byla (85,71 %), specificita byla (68,97 %) a přesnost byla (72,22 %). Kombinace diagnostických nástrojů (SWI a DWI) proto zvýšila citlivost na 87,5 %, specificitu na 100 % a diagnostickou přesnost na 97,2 %. Kombinace DWI a SWI také zužuje případy, kdy SWI pomáhá vyloučit případy velmi nízkého a vysokého stupně a šetří DWI pro diferenciální diagnostiku případů mezi nimi.

Závěr: Meningiomy vysokého stupně v konvenčních obrazech byly silně asociovány s velkou velikostí nádoru, nejasným TBI, lobulárními okraji nádoru, heterogenním kontrastním zvýrazněním, posunem středové linie a intratumorálními cystami. Zatímco v pokročilých technikách, jako je DWI, byly meningiomy vysokého stupně silně asociovány s nižšími průměrnými hodnotami ADC v nádoru, n ADC v nádoru a více ITTSS (stupeň 2, 3) pomocí SWI. Kombinace kvantitativního DWI a semikvantitativního hodnocení SWI vedla ke zvýšení citlivosti, specificity a diagnostické přesnosti a ke snížení časové náročnosti předoperačního hodnocení meningiomů.

Klíčová slova: magnetická rezonance, meningiom, radiologické hodnocení, histopatologické hodnocení, DWI, SWI.

INTRODUCTION

Meningiomas originate from arachnoid meningothelial cells. Their frequency rises with age with a mean diagnosis age of 65 and a strong female predisposition (1, 2).

Meningiomas are graded histopathological based on the most recent World Health Organization (WHO) categories, which places 3% of incidence as atypical meningiomas with malignant variations (WHO grade III), 7% as WHO grade II, and 90% of cases as WHO grade I (3).

Low grade (grade I) meningiomas are well circumscribed lesions with benign histopathological characteristics, on the other hand, high grade (grades II and III) meningiomas have more malignant tendency, and recurrence with more death risk due to their invasive growth pattern and the resultant compression of CNS structures (3).

When compared to standard MR imaging, advanced MR imaging techniques have the potential to yield more detailed information on tumor microstructure, blood vessels, and kinetics (4).

Although previous research using apparent diffusion coefficient (ADC) values, were able to identify benign from malignant meningiomas, results were inconsistent since different diffusion weighted imaging (DWI) b values were used, and ADC measurement techniques were uneven (4).

Another revolutionary method is susceptibility-weighted imaging (SWI), which makes use of intra-tumoral susceptibility signals (ITSS) to provide information on blood components, calcified areas, and blood vessels. These metrics might be employed as quantitative or semi-quantitative indicators to differentiate between tumor grades Although SWI was previously employed to differentiate different brain tumor types, it wasn't used in detail to characterize different grades of meningioma (4).

METHODOLOGY

Patient Population

Our cross-sectional study was conducted on 36 adult participants recruited from the neurosurgery out-clinics and directed to the MRI unit.

Inclusion criteria included adult patients of either sex with an intra-cranial extra-axial mass with features befitting those of an intra-cranial meningioma on MRI and/or CT done preoperatively.

Exclusion criteria included claustrophobic patients; patients whose histopathology revealed an alternative diagnosis other than meningioma, those who underwent previous surgery, embolization or received radiotherapy, those with densely calcified lesions, or with significant intralesional haemorrhage or skull base lesions with strong susceptibility artifact.

Each patient provided informed verbal consent prior to the surgery. The study was conducted after the approval of our institution's Ethical and Scientific Committee to ensure data confidentiality and the privacy of our participants.

Patient preparation

Patients were informed to Fast for 6 hours prior to the study. Serum creatinine levels were checked to ensure adequate renal function. Insertion of an intravenous cannula was done for administration of contrast. There was a crash cart available, with supplies and resuscitative drugs in a designated spot outside the scanner room.

Image Acquisition

All examinations were performed on Machine: Philips Achieva 3 T MRI machine. All patients underwent routine MRI of the brain, followed by diffusion weighted imaging (DWI) and susceptibility weighted imaging (SWI).

Conventional MR protocols consisted of the following sequences with mentioned parameters: Axial T2 turbo spin echo (TSE) (TR: 4821.05, TE: 100), Axial and sagittal FLAIR (TR:11000, TE:130), Axial T1 weighted image (TR:141, TE: 1.70), Post contrast T1-weighted axial, coronal, and sagittal images following gadolinium injection done.

For DWI, an EPI sequence consisting of several sections was used, with diffusion sensitivities set to b values of 0 and 1000 s/mm^2 (TR/TE/NEX: 3704/88 ms/I).

Diffusion gradients were applied in three orthogonal orientations (the X, Y, and Z directions) successively. All images employed sections with 5 mm thickness, an interstice gap of 1 mm, a field of view of 163 mm, and a matrix of 128 × 256.

The integrated software generated the ADC maps automatically.

3D flow-compensated gradient-echo sequence was applied to obtain the SWI. From the raw SWI data, phase and magnitude images were rebuilt. After designing phase mask filters based on the corrected phase images, the associated magnitude images were multiplied twice to produce final susceptibility-weighted images from which MinIP images were reformatted. The SWI data were used to form unwrapped and high pass filtered phase images.

Image Analysis

Two radiologists with over ten years of expertise assessed each examination individually.

Conventional images were used to assess the following features

- Tumor size defined as the longest diameter of the mass.
- Tumor location: Skull base, convexity, para-falcine, posterior fossa, others.
- Signal Intensities: comparing the tumor to the grey matter intensity in T1WI and T2WI as hypointense, isointense, hyperintense, or mixed.
- Tumor-brain interface: Clear TBI: appears as hypointense on T1-weighted imaging and hyperintense on T2-weighted imaging or Unclear TBI.
- Tumor margins: either regular or irregular which included lobulated tumors.
- Peritumoral edema: evaluated on axial T2-weighted images representing hyperintense areas of the brain parenchyma as either present or absent.
- Capsular enhancement: the layer of contrast enhancement at the tumor-brain interface whether present or absent.
- Tumor Enhancement: The pattern of contrast enhancement after Gadolinium administration either homogeneous or heterogeneous.
- Necrosis/hemorrhage: present or absent.
- Skull bone invasion: present or absent.
- Intra-tumoral fluid filled cysts: present or absent.
- Midline shift: present or absent.

DIFFUSION WEIGHTED IMAGING

Qualitative evaluation

By visually comparing the ADC signal in the tumor to the normal-appearing white matter (NAMW), choosing a solid, non-necrotic, non-calcified, non-hemorrhagic region of the tumor, it is possible to classify the signal as hyperintense, isointense, hypointense, or focal areas of the lesion or most of the lesion hypointense relative to NAWM.

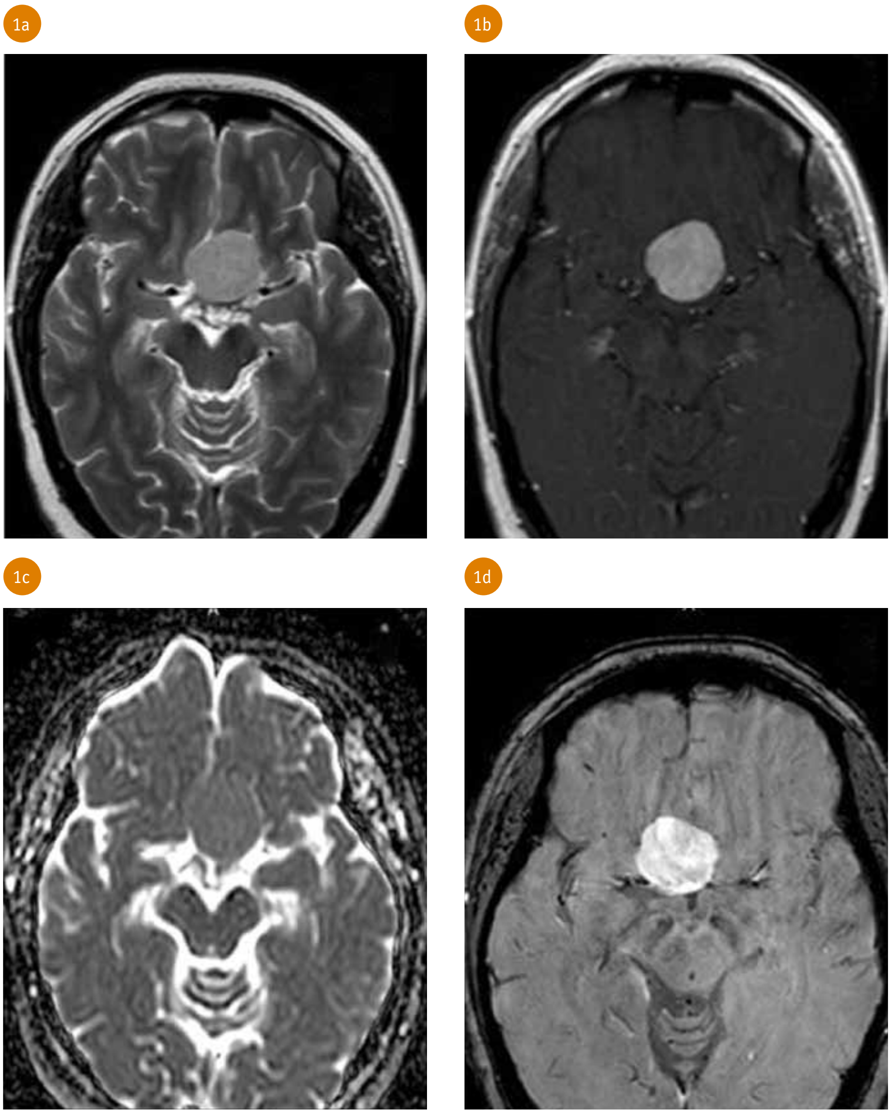
Quantitative evaluation

Several tiny, circular regions of interest (ROI) with an equal diameter of 5 mm were manually identified on each slice of the ADC maps to include the entire solid component of the tumor, excluding hemorrhagic, calcified, or cystic areas. The incorporation of several ROIs allowed for the estimation of the mean ADC values of the tumor. Additionally, On the contralateral normal-appearing white matter, many ROIs were also hand-drawn. The ADC was adjusted and shown as ratios by dividing the mean values of the tumors by the values of the normal white matter, hence normalizing values of ADC.

To measure the ADC values inside the peritumoral edema, a similar process was carried out.

Susceptibility weighted imaging

Source and minimum intensity projection SW images were used to assess intratumoral susceptibility signals (ITSSs) which were described on SWI as



1 **Example of Grade 0 in SWI.** 57-year-old female with nonstop headache. (a) Axial T2 weighted images show a suprasellar meningioma with largest anteroposterior dimension 2cm appears hyperintense, clear TBI and regular margins. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps show relatively increased n ADC ratio in the tumor: (1.171). (d) SWI shows no ITSSs (Grade 0). This case was histopathologically proven to be Grade I.

Příklad stupně 0 v SWI. 57letá žena s nepřetržitými bolestmi hlavy. (a) axiální T2 vážené snímky ukazují supraselární meningiom s největším předozadním rozměrem 2 cm, který se jeví jako hyperintenzivní, s jasným TBI a pravidelnými okraji. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zesílení. (c) odpovídající mapy ADC ukazují relativně zvýšený poměr n ADC v nádoru: (1,171). (d) SWI neukazuje žádné ITSS (stupeň 0), histopatologicky prokázán grade I.

Table 1. **Comparison between low and high meningiomas regarding different tumor characteristics**

Tab. 1. **Srovnání mezi meningiomy nízkého a vysokého stupně ve vztahu k odlišným charakteristikám tumorů**

		Histopathology						T-test	
		Low			High			T	P-value
Tumor Size (Longest dimension) (cm)	Range	2	–	8.5	6.5	–	9	−5.594	< 0.001*
	Mean ± SD	3.831	±	1.499	7.143	±	0.848		
Chi-Square		N		%	N		%	χ^2	P-value
Tumor location	Convexity	11		37.93	4		57.14	0.958	0.812
	Parafalcine	5		17.24	1		14.29		
	Parasagital	5		17.24	1		14.29		
	Skull base	8		27.59	1		14.29		
Convexity location	Frontal	7		63.64	4		100.00	1.983	0.159
	Temporal	3		27.27	1		25.00	0.008	0.930
	Parietal	1		9.09	1		25.00	0.642	0.423
	Occipital	1		9.09	0		0.00	0.390	0.533

P-value > 0.05: non-significant, P-value < 0.05: significant, P-value < 0.01: highly significant
*Chi-square test

hypointense tubular structures or dot-like formations within a tumor, either with or without aggregation. As previously mentioned that Grades (0) had no ITSS, Grade (1) had 1–5 dot-like or linear ITSSs, Grade (2) had 6–10 dot-like or linear ITSSs, and Grade (3) had more than 11 dot-like or linear ITSSs. These grades enabled the degree of ITSS to be used for the semi-quantitative analysis.

NB: Areas or foci of calcification, identified on CT images if available or on the phase images of susceptibility weighted data, were excluded from the assessment detailed above. Areas of frank bleeding visible on conventional sequences were also excluded from the assessment.

2 Example of grade I in SWI. 50-year-old female with dizziness and severe headache. (a) Axial T2WI images show a cerebello-pontine angle meningioma with largest anteroposterior dimension 4cm showing intermediate intensity in T2WI, clear TBI and lobulated margins. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps shows n ADC ratio in the tumor: (1.0.514). (d) SWI showed 1-6 ITSSs (grade 1). This case was histopathologically proven to be Grade I.

Příklad stupně I v SWI. 50letá žena s závratěmi a silnými bolestmi hlavy. (a) axiální T2WI snímky ukazují meningiom v úhlu mozečku a mostu s největším předozadním rozměrem 4 cm, který vykazuje střední intenzitu v T2WI, jasné TBI a lobulární okraje. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zvýraznění. (c) odpovídající mapy ADC ukazují poměr n ADC v nádoru: (1,0,514). (d) SWI ukázalo 1–6 ITSS (stupeň 1), histopatologicky prokázán grade I.

Table 2. **Comparing between both meningioma groups using different tumor characteristics**
Tab. 2. **Srovnání mezi oběma skupinami meningiomů použitím rozdílných charakteristik**

		Histopathology				Chi-Square	
		Low		High			
		N	%	N	%	χ^2	P-value
Tumor brain interface	Clear	28	96.55	3	42.86	13.593	< 0.001*
	Unclear	1	3.45	4	57.14		
Tumor Margins	Regular	22	75.86	0	0.00	13.655	< 0.001*
	Lobulated	7	24.14	7	100.00		
Tumor enhancement	Homogenous	28	96.55	5	71.43	4.659	0.031*
	Heterogeneous	1	3.45	2	28.57		
Peritumoral edema	Absent	20	68.97	3	42.86	1.666	0.197
	Present	9	31.03	4	57.14		
Capsular enhancement	Absent	26	89.66	7	100.00	0.790	0.374
	Present	3	10.34	0	0.00		
Necrosis/hemorrhage	Absent	27	93.10	5	71.43	2.682	0.101
	Present	2	6.90	2	28.57		
Skull bone invasion	Absent	28	96.55	7	100.00	0.248	0.618
	Present	1	3.45	0	0.00		
Intra-tumoral cysts	Absent	29	100.00	5	71.43	8.773	0.003*
	Present	0	0.00	2	28.57		
Midline shift	Absent	27	93.10	4	57.14	6.097	0.014*
	Present	2	6.90	3	42.86		

AP – anteroposterior, TS – transverse, CC – cranio-caudal
P-value > 0.05: non-significant, P-value < 0.05: significant, P-value < 0.01: highly significant
*Chi-square test

Statistical analysis

Statistical Package for Social Science V25 was used to gather, edit, code, and enter the data. Statistical Package for Social Science. For parametric quantitative data, the displayed forms were mean, standard deviation, and range. The qualitative features were expressed using percentages and numbers.

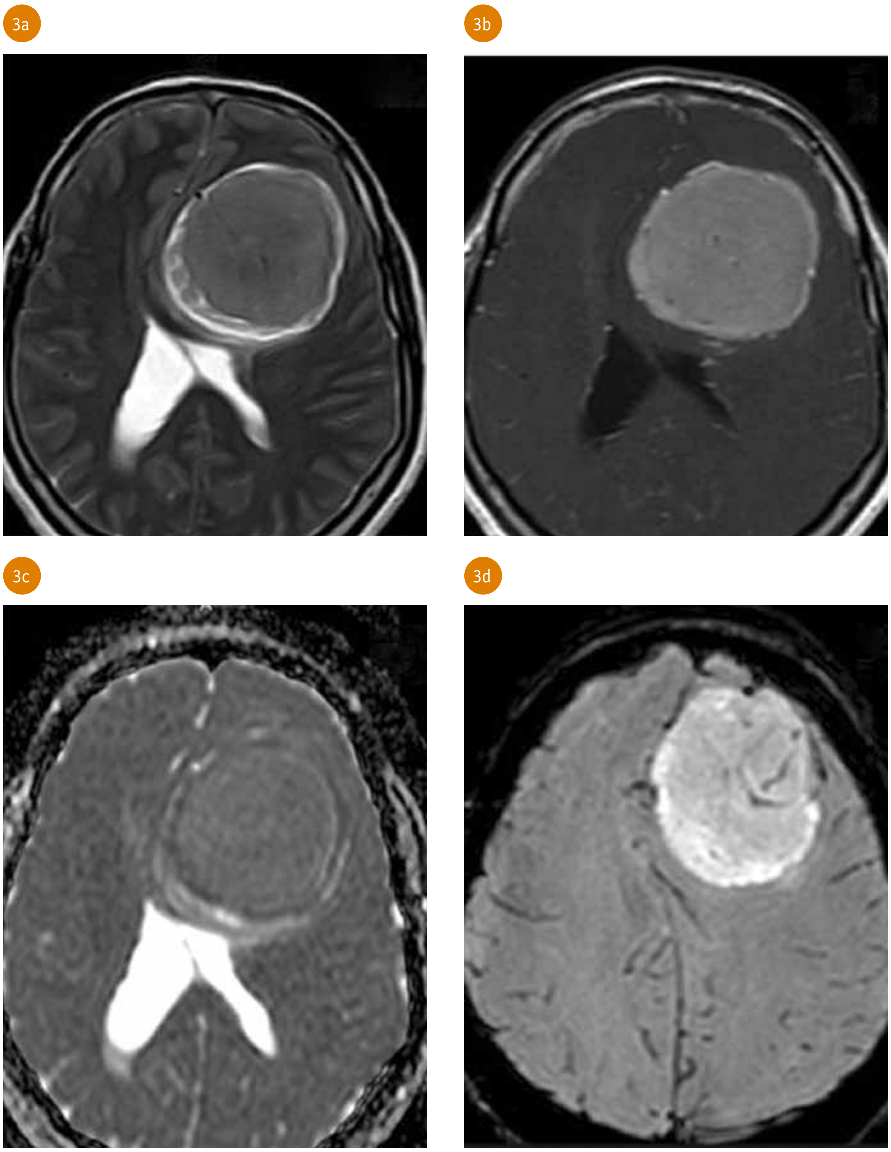
Chi-square test was used to compare the qualitative data between the groups.

Independent t-test was used to compare two groups' quantitative data and parametric distribution.

Unpaired Student T-test was used to compare between two groups in quantitative data.

RESULTS

Out of 36 participants who were part of our study, 29 (80.56%) were histopathological proven to be low-grade meningiomas (grade 1 according to WHO classification) while 7 (19.44%) cases were high grade (grade 2 according to WHO classification). Female sex



3 **Another example of grade I in SWI.** 54-year-old female with personality changes and memory loss. (a) Axial T2 images show a left frontal convexity meningioma with isontensity in T2WI, clear TBI, lobulated margins and midline shift. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps show increased n ADC ratio in the tumor: (1.1617). (d) SWI showed 1-6 ITSSs (grade 1). This case was histopathologically proven to be Grade I.

Další příklad stupně I v SWI. 54letá žena s osobnostními změnami a ztrátou paměti. (a) axiální T2 snímky ukazují meningiom levé frontální konvexity s izontenzitou v T2WI, jasným TBI, lobulárními okraji a posunem středové linie. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zesílení. (c) odpovídající mapy ADC ukazují zvýšený poměr n ADC v nádoru: (1,1617). (d) SWI ukázalo 1–6 ITSS (stupeň 1), histopatologicky prokázán grade I.

Table 3. **Comparison between high and low grade meningiomas regarding mean ADC in the tumor, mean ADC in the surrounding edema, mean ADC in the normal side and the ratio between them**

Tab. 3. **Srovnání mezi meningiomy vysokého a nízkého stupně z hlediska průměrné hodnoty ADC v nádoru, průměrné hodnoty ADC v okolním edému, průměrné hodnoty ADC na normální straně a poměru mezi nimi**

		Histopathology						T-test	
		Low			High			T	P-value
ADC average tumor	Range	0.6646	–	1.082	0.6189	–	0.9785	3.180	0.003*
	Mean ± SD	0.864	±	0.104	0.721	±	0.120		
ADC average normal	Range	0.6114	–	0.8631	0.7322	–	0.8528	−1.063	0.295
	Mean ± SD	0.765	±	0.051	0.787	±	0.039		
ADC ratio tumor/ normal	Range	0.9454	–	1.4181	0.7432	–	1.2516	3.947	<0.001*
	Mean ± SD	1.131	±	0.117	0.919	±	0.165		
ADC average edema	Range	1.62	–	1.811	1.428	–	1.469	7.463	< 0.001*
	Mean ± SD	1.714	±	0.068	1.449	±	0.018		
ADC ratio edema/ normal	Range	1.8885	–	2.4916	1.8068	–	2.0063	3.310	0.007*
	Mean ± SD	2.233	±	0.196	1.888	±	0.088		

ADC – attenuation diffusion coefficient
P-value > 0.05: non-significant, P-value < 0.05: significant, P-value < 0.01: highly significant

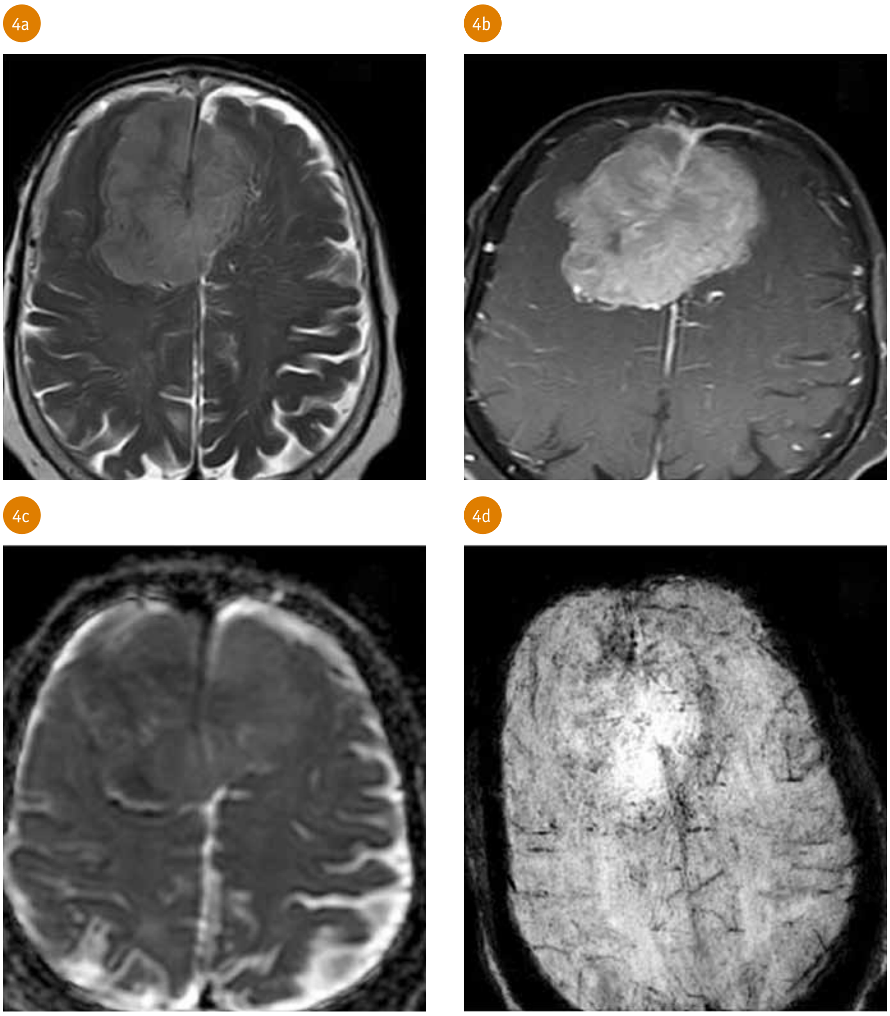
predominated among cases (72.22%) and the most common recorded location was convexity location.

Conventional MRI

In our study, multiple tumor radiological characteristics showed significant differences between both groups as larger tumor size, unclear TBI, lobulated tumor margins, heterogenous enhancement, intratumoral cyst and midline shift were strongly associated with high-grade meningiomas (Table 1, 2).

DWI sequences

Visually inspecting the DWI sequences; (5/7) of high-grade meningiomas showed relative hyperintensity in the tumor when compared to normal appearing white matter (NAWM) in comparison to low-grade meningiomas (11/29), the two groups did not differ significantly from each other.



4 **Example of grade II in SWI.** 73-year-old female with dizziness and sudden loss of consciousness**.** (a) Axial T2 images show a bifrontal parafalcine meningioma measuring 6.8 cm in longest dimension with hyperintensity in T2, clear TBI and lobulated margins. (b) Axial T1 with contrast shows avid slightly heterogenous contrast enhancement. (c) Corresponding ADC maps show lowered n ADC ratio in the tumor: (0.7432). (d) SWI showed 6-11 ITSSs (grade 2). This case was histopathologically proven to be Grade 2.

Příklad stupně II v SWI. 73letá žena s závratěmi a náhlou ztrátou vědomí. (a) axiální T2 snímky ukazují bifrontální parafalcinální meningiom o délce 6,8 cm s hyperintenzitou v T2, jasným TBI a lobulárními okraji. (b) axiální T1 s kontrastem ukazuje mírně heterogenní kontrastní zesílení. (c) odpovídající mapy ADC ukazují snížený poměr n ADC v nádoru: (0,7432). (d) SWI ukázalo 6-11 ITSS (stupeň 2), histopatologicky prokázán grade II.

Table 4. **Diagnostic performance of quantitative ADC values to detect high grade tumors**

Tab. 4. **Diagnostický přínos kvantitativních hodnot ADC při detekci nádorů vysokého stupně**

	ROC curve between High- and Low-Grade Histopathology					
	Cutoff	**Sens.**	**Spec.**	**PPV**	**NPV**	**Accuracy**
ADC average tumor	≤ 0.7126	85.71	93.10	75.0	96.4	84%
ADC ratio tumor/normal	≤ 0.9469	85.71	96.55	85.7	96.6	86.7%

PPV – positive predictive value, NPV – negative predictive value, ADC – attenuation diffusion coefficient

Table 5. **Comparison between low and high grade meningiomas regarding the presence or absence of ITSSs in SWI sequence and their numerical grading**

Tab. 5. **Srovnání mezi meningiomy nízkého a vysokého stupně z hlediska přítomnosti nebo absence ITSS v sekvenci SWI a jejich numerického hodnocení gradingu**

SWI (ITSSs)	Histopathology				Chi-Square	
	Low		High			
	N	%	N	%	χ2	P-value
Grade 0	3	10.34	0	0.00	15.606	0.001*
Grade 1	17	58.62	1	14.29		
Grade 2	9	31.03	3	42.86		
Grade 3	0	0.00	3	42.86		

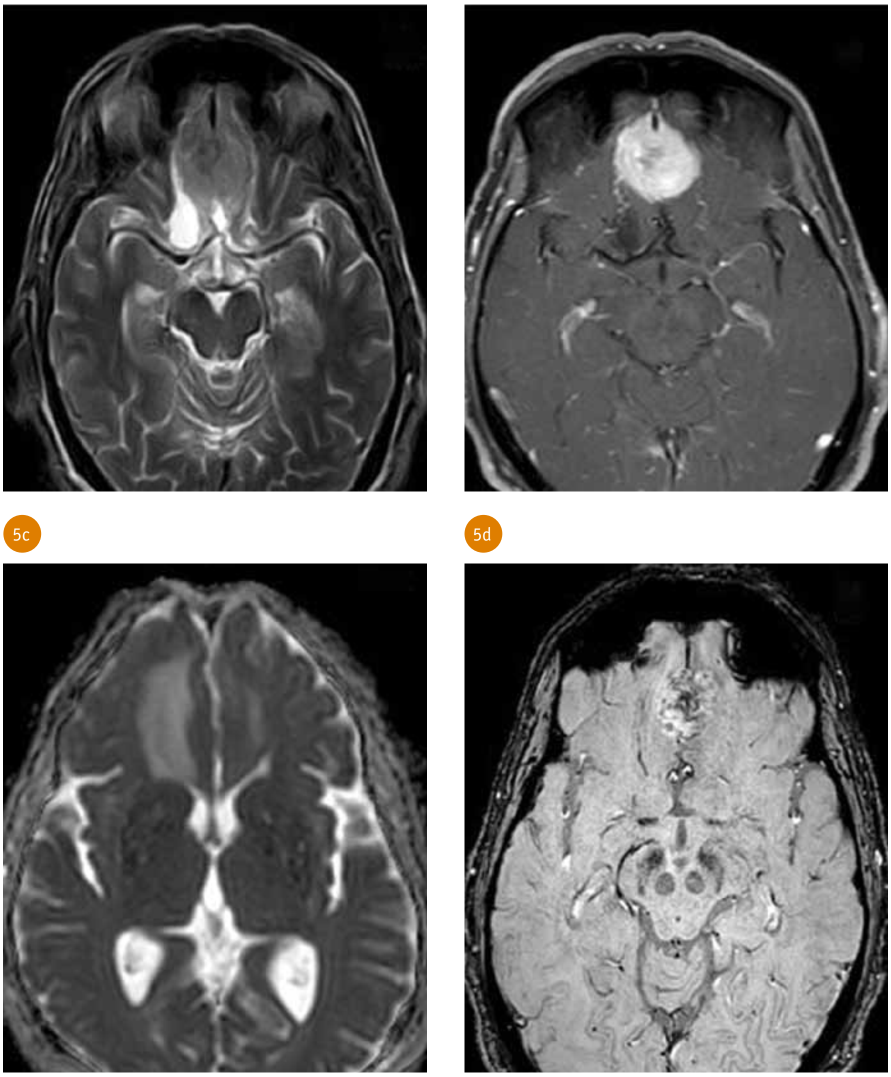
SWI – susceptibility weighted imaging, ITSSs – intratumoral susceptibility signals
P-value > 0.05: non-significant, P-value < 0.05: significant, P-value < 0.01: highly significant
*Chi-square test

The sensitivity of qualitative evaluation was (71.43%), specificity was (62.07%) and Accuracy (63.89%).

Quantitative evaluation using ADC maps

Table 3 demonstrates that both mean ADC in the tumor (p = 0.003) and n ADC (p < 0.001) were significantly higher in low-grade meningiomas than in the high-grade. It also demonstrates the same significant difference in the surrounding peritumoral edema where ADC and n ADC recorded in the edema (p < 0.001). were significantly higher in low-grade meningiomas.

According to the results, the optimal cut-off value for the detection of high-grade meningiomas was (0.7126×10^{-3} mm^2) using the mean ADC in the tumor and the cut-off value for the detection using the n ADC in the tumor was (0.9469×10^{-3} mm^2). Sensitivity using ADC in the tumor for detection of high grade (85.71%) and specificity (93.10%) with diagnostic accuracy (84%), While sensitivity using the n ADC was (85.71%) and specificity was



5 **Another example of grade II in SWI.** 62-year-old male with headache. (a) Axial T2 images show an olfactory groove meningioma measuring 4 cm in longest dimension appears isointense in T2WI, clear TBI and regular margins. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps show n ADC ratio: (1.0611) and nADC ratio in the surrounding edema: (2.2728). (d) SWI showed 6-11 ITSSs (grade 2). This case was histopathologically proven to be Grade 1.

Další příklad stupně II v SWI. 62letý muž s bolestmi hlavy. (a) axiální T2 snímky ukazují meningiom čichové drážky o délce 4 cm, který je v T2WI izointenzivní, s jasným TBI a pravidelnými okraji. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zesílení. (c) odpovídající mapy ADC ukazují poměr n ADC: (1,0611) a poměr nADC v okolním edému: (2,2728). (d) SWI ukázalo 6-11 ITSS (stupeň 2), histopatologicky prokázán grade I.

Table 6. **Diagnostic performance of SWI sequence to detect high grade tumors**

Tab. 6. **Diagnostický přínos sekvence SWI k detekci nádorů vysokého stupně**

SWI (ITSSs)	Histopathology				Chi-Square		ROC curve				
	Low		High								
	N	%	N	%	χ2	P-value	Sens.	Spec.	PPV	NPV	Accuracy
Low	20	68.97	1	14.29	6.937	0.008*	85.71	68.97	40.00	95.24	72.22%
High	9	31.03	6	85.71							

SWI – susceptibility weighted imaging, ITSSs – intratumoral susceptibility signals
P-value > 0.05: non-significant, P-value < 0.05: significant, P-value < 0.01: highly significant
*Chi-square test

Table 7. **Diagnostic performance of combined of DWI and SWI sequence to detect high grade tumors**

Tab. 7. **Diagnostická kombinace sekvencí DWI a SWI k detekci nádorů vysokého stupně**

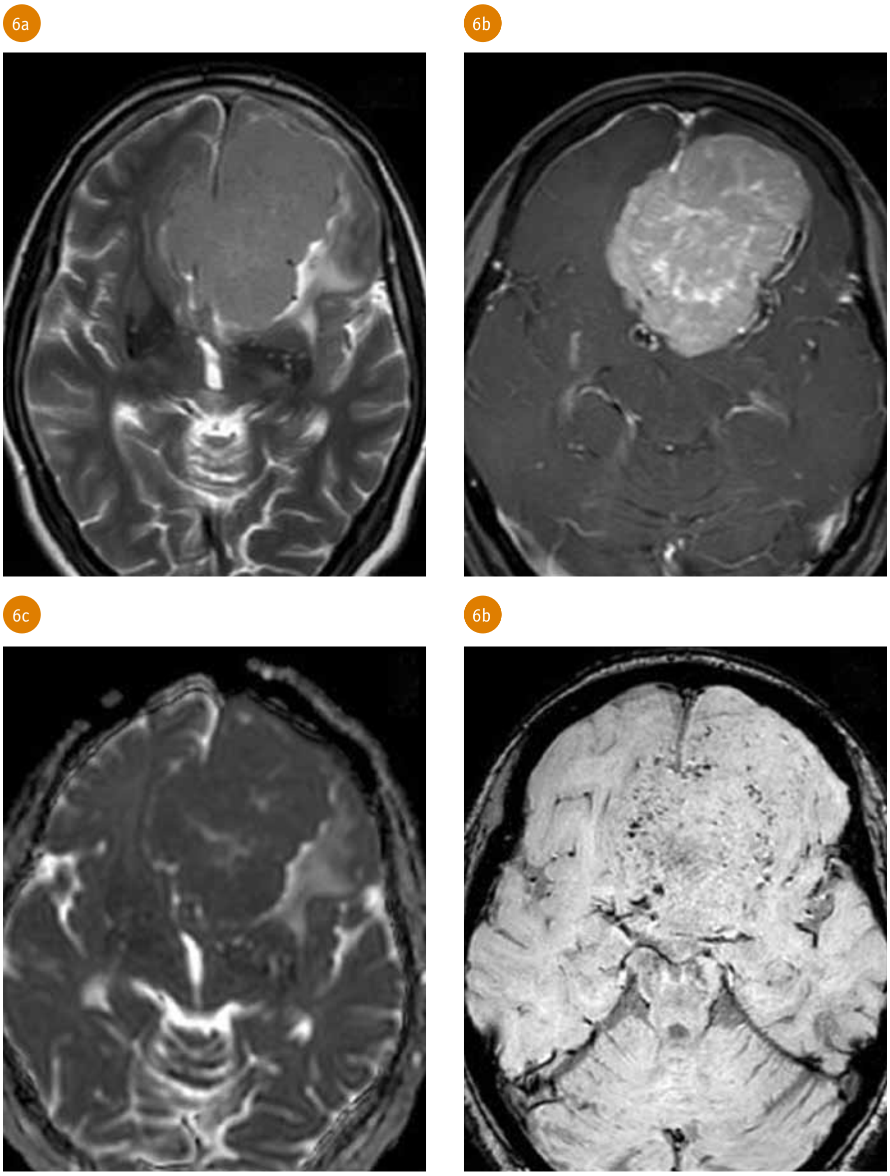
Items	Sen.%	Spe.%	PPV%	NPV%	Accuracy%	P-value
Combination (SWI ITSSs & DWI)	85.7%	100.0%	100.0%	96.7%	97.2%	< 0.001*

SWI – susceptibility weighted imaging, ITSSs – intratumoral susceptibility signals

(96.55%) with diagnostic accuracy (86.7%), as mentioned in Table 4.

SWI sequences

There was a significant variance (p = 0.001) between low and higher grade meningiomas regarding ITSSs: grade 0 (Fig. 1), grade 1 (Fig. 2, 3), grade 2 (Fig. 4, 5), and grade 3 (Fig. 6, 7) detected in SWI. Histopathological proven low grade cases recorded only 3 (10.34%) cases as grade 0, 17 (58.62%) cases (vast majority) as grade 1, 9 (31.03%) cases as grade 2, and no cases were discovered to be grade 3 using ITSSs. While in histopathological proven high-grade meningiomas, we recorded no cases as grade 0, only one case as grade 1 (14.29%), 3 (42.86%) cases as grade 2, and 3 (42.86%) as grade 3 (Table 5).



Example of grade III in SWI. 58-year-old female. (a) Axial T2WI images show a bifrontal meningioma measuring 6.8 cm in longest dimension with intermediate signal, clear TBI and lobulated margins. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps show n ADC ratio: (0.9159) and n ADC ratio in the surrounding edema: (1.9007). (d) SWI showed > 11 ITSSs (grade 3). This case was histopathologically proven to be Grade 2.

Příklad stupně III v SWI. 58letá žena. (a) axiální T2WI snímky ukazují bifrontální meningiom o délce 6,8 cm s intermediárním signálem, jasným TBI a lobulárními okraji. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zesílení. (c) odpovídající mapy ADC ukazují poměr n ADC: (0,9159) a poměr n ADC v okolním edému: (1,9007). (d) SWI ukázalo > 11 ITSS (stupeň 3), histopatologicky prokázán grade II.

Table 6 shows that 20/29 (68.97%) of the histopathological proven low-grade meningiomas were recorded as low-grade using SWI. While 6/7 (85.71%) of the histopathological proven high-grade meningiomas were recorded as high-grade using SWI, with sensitivity of SWI to detect high-grade tumors (85.71%), specificity (68.97%) and diagnostic accuracy (72.22%).

The combination of (SWI & DWI) increased their sensitivity to reach 87.5% and specificity 100%, and diagnostic accuracy to reach 97.2%collectively, with p-value ($p < 0.001$), indicating that the previously mentioned combination adds to the preoperative grading of meningioma (Table 7).

DISCUSSION

Both meningioma groups show altered prognosis and therefore should be dealt with differently, because of the aggressive nature of high-grade meningiomas, the tumor needs to be removed entirely and quickly in order to reduce the likelihood of a high recurrence (5).

Therefore, precise preoperative grading of meningiomas is crucial to enhance surgical decision-making and prognosis of these patients (5).

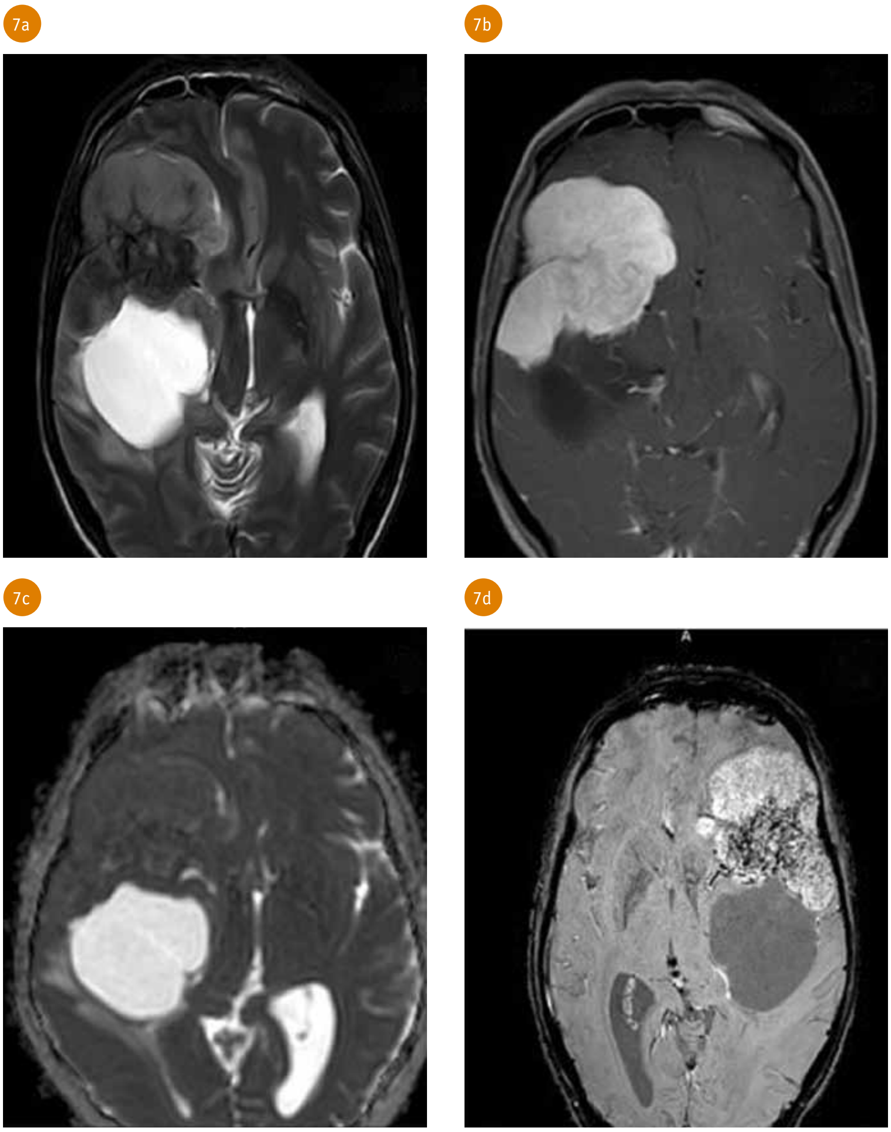
Regarding different tumor characteristics, our study reported that larger tumor size was strongly associated with high-grade meningiomas which was similarly found in several studies (6–8).

Several studies (9–11) agreed with our study and correlated lobulated tumor margins with high-grade meningiomas and explained this by the fact that an uneven margin could arise from an imbalance of intratumoral pressure caused by histological heterogeneity.

Heterogenous tumoral enhancement was found closely correlated to high-grade meningiomas in our study explained by the irregular pathological characteristics brought on by intratumoral necrosis seen in high-grade tumors leading to heterogenicity and was agreed upon by several authors (11, 12).

On the other hand, neither skull bone invasion nor hemorrhage and necrosis were reliably associated with high-grade meningiomas which was consistent with several published studies (11, 13).

Although peritumoral edema could indicate surrounding brain invasion it wasn't correlated with high-grade meningioma in our study, this was explained by Gawlitza et al. (14) who stated that membrane protein



7 **Another example of grade III in SWI.** 46-year-old male with loss of consciousness. (a) Axial T2WI images show a right frontal meningioma measuring 7 cm in longest dimension with intermediate signal intensity, unclear TBI, lobulated margins and a cystic component detected. (b) Axial T1WI with contrast shows avid homogenous contrast enhancement. (c) Corresponding ADC maps showed ADC in the tumor: (0.7332), n ADC ratio: (0.9369) and n ADC ratio in the surrounding edema: (2.003). (d) SWI showed > 11 ITSSs (grade 3). This case was histopathologically proven to be Grade 2.

Další příklad stupně III v SWI. 46letý muž s poruchou vědomí. (a) axiální T2WI snímky ukazují meningiom v pravé čelní oblasti o délce 7 cm s průměrnou intenzitou signálu, nejasným TBI, lobulárními okraji a cystickou složkou. (b) axiální T1WI s kontrastem ukazuje intenzivní homogenní kontrastní zesílení. (c) odpovídající mapy ADC ukázaly ADC v nádoru: (0,7332), poměr n ADC: (0,9369) a poměr n ADC v okolním edému: (2,003). (d) SWI ukázalo > 11 ITSS (stupeň 3), histopatologicky prokázán grade II.

expression and not the tumor grade, might determine the degree of peritumoral edema in individuals with various forms of meningiomas, however, this was inconsistent with other studies (10, 15).

We evaluated whether DWI sequence was able to identify both high- and low-grade groups qualitatively and quantitatively. Our results revealed no significant difference between both groups using conventional DWI sequences qualitatively, with sensitivity to detect high grade from conventional images (71.43%), specificity (62.07%), and accuracy (63.89%). Relatively low percentages might be attributed to the subjectivity of conventional sequences depending mainly the operator judgment.

Quantitatively, our investigation found more accurate results with statistically significant variation in the mean ADC value of the tumor and n ADC in both groups being higher in low-grade meningiomas, this is attributed to densely packed tumor cells and increased fibrosis seen in high-grade meningiomas hence have more reduced water diffusibility in the extracellular compartment, which raises the signal in DWI and lowers the values in ADC maps. This was supported by multiple authors (1, 4, 17).

Detection of high-grade using mean ADC in the tumor showed sensitivity (85.71%), specificity (93.10%), while detection using the n ADC showed sensitivity (85.71%), specificity (96.55%), and raised the diagnostic accuracy from (84%) using mean ADC in the tumor to (86.7%) using the n ADC. This came in disagreement with Chen et al. (4) and Surov et al. (18) who previously mentioned lesser sensitivity and specificity when using the mean ADC in the tumor and n ADC to distinguish between low and high grade meningiomas might be due to using different parameters when analyzing ADC maps.

We also found that mean ADC in the surrounding peritumoral edema and n ADC was significantly higher in low-grade meningiomas which was less studied by different authors.

The ideal cut-off value of the mean ADC in the tumor and the ideal cut-off value of the n ADC to detect high-grade meningiomas were (0.7126 × 10^{-3} mm^2) and (0.9469 × 10^{-3} mm^2), respectively, in comparison to the study done by Chen et al. (4) who reported a cut off value of (1.05 × 10^{-3} mm^2) for the n ADC.

Evaluating ITTSs seen in SWI for detection of high grade meningiomas, we found a significant variance between both groups of meningiomas, where the most common grade seen in low-grade meningiomas was grade 1 (58.62%), and the most common grades seen in high-grade meningiomas were grades 2 and 3 (42.86% both). This was also acknowledged by Chen et al. (4) who explained the significant difference between both groups, by the fact that higher-grade meningiomas should have more hemorrhage and hence should present with more ITSSs on SWI.

In contrast to our results Zhang et al. (10) and Swaika et al. (19) mentioned no statistical variation between both groups using SWI; Zhang et al. (10) explained it by the fact that meningiomas are originally highly vascular tumors regardless of the grade. Swaika et al. (19) didn't exclude calcification among cases which might lead to more signals being detected in lower grade meningiomas, hence lead to controversial results.

We found that 20 out of 29 histopathological proven low-grade meningiomas were recorded as low grade using SWI. While 6 out of 7 histopathological-proven high-grade meningiomas; were recorded as high-grade using SWI, with sensitivity to detect high grade tumors reaching (85.71%), specificity (68.97%) and accuracy of (72.22%). Our results nearly approached Chen et al. (4) who reported a sensitivity of SWI (71.43%), specificity (54.67%) while the diagnostic accuracy was (64.1%).

Using DWI and SWI in combination increased their sensitivity to reach 87.5% and specificity 100%, and diagnostic accuracy to reach 97.2% collectively, with p-value ($p < 0.001$), indicating that the previously mentioned combination adds to the preoperative grading of meningioma.

Furthermore, although SWI alone has much less specificity in detection of different grades in comparison to DWI alone, it's still sensitive in detecting high grade cases eliciting more than 11 ITTSs and low-grade cases with no detected ITTSs thus helps excluding these cases in a less time-consuming way since SWI takes less time in interpretation and reserve DWI necessitating more time in post processing for rest of cases.

One of the limitations of this study that patients were conveniently recruited. Another limitation was that pathology reports lacked the histopathological subtyping of each grade hindering better assessment of each subtype individually. Lastly, although SWI was used in the grading of many brain tumors, relatively few studies were found to compare with regards to meningiomas.

CONCLUSIONS

High grade meningiomas in our study were strongly associated with certain tumor characteristics like large tumor size, unclear TBI, lobulated tumor margins and heterogeneous contrast enhancement.

We observed that quantitative DWI using ADC values was more sensitive, accurate and specific than qualitative assessment of DWI and semi quantitative assessment of SWI, yet more time consuming.

However, using a combination of quantitative DWI and semi quantitative assessment of SWI raised the sensitivity, specificity and diagnostic accuracy of both tests. We also observed that although SWI alone has much less specificity in comparison to DWI alone, it's still sensitive in detecting high grade cases eliciting more than 11 ITTSs and low-grade cases with no detected ITTSs thus helps us excluding these cases in a less time-consuming way using SWI and reserve DWI necessitating more time in post processing for rest of cases.

We recommend further studies done that assess the role of SWI in the grading of brain tumors and specifically meningiomas. We recommend introducing a new grading system for meningiomas using SWI where > 11 ITSSs are to be considered high grade, no ITSSs are to be considered low grade and 0-11 ITSSs to be considered indeterminate grade for further assessment by DWI. ●

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