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ORIGINAL ARTICLE

3D Fast Spin-Echo T1 Black-Blood Imaging for the Preoperative Detection of Venous Sinus Invasion by Meningioma

Comparison with Contrast-Enhanced MRV

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Abstract

Objectives To prospectively evaluate the diagnostic value of 3D fast spin-echo (FSE) T1 black-blood magnetic resonance (MR) imaging (3D CUBE T1WI) in comparison with contrast-enhanced MR venography (CE-MRV) in the detection of sinus invasion by meningiomas.

Methods In this study forty consecutive patients with suspected meningiomas adjacent to venous sinus underwent conventional MR imaging, CE-MRV and 3D CUBE T1WI scans. Images obtained by each technique were assessed independently by two neuroradiologists for (1) wall invasion and (2) lumen occlusion of the target venous sinus.

Results The use of 3D CUBE T1W imaging was found to provide an easy way to detect the venous wall invasion by para-sinus lesions. The interobserver agreement was excellent (κ = 0.843; 95% confidence interval CI 0.757–0.929) and the result was highly consistent with the surgical findings (sensitivity 90.48%, specificity 94.12%). In the analysis of the lumen occlusion, the interobserver agreement obtained by 3D CUBE T1WI sequence was excellent (κ = 0.956; 95% CI, 0.913–0.999) with a diagnostic accuracy of 94.74%, which surpassed CE-MRV not only in interobserver agreement (κ = 0.736; 95% CI, 0.639–0.833) but also in diagnostic value (accuracy = 68.42%). Among 38 patients with meningiomas, the existence and extent of peritumoral edema did not correlate with the invasion of adjacent venous sinus.

Conclusion Currently, 3D CUBE T1WI sequence is a reliable technique to provide accurate assessment about the venous sinus invasion by meningioma. Meanwhile, CE-MRV is more suitable in the evaluation of the bypass draining veins around the tumor.

Keywords Black-blood imaging · Meningioma · Invasion of the cranial sinuses · Magnetic Resonance imaging · Contrast-enhanced MR venography

Introduction

Meningiomas are the most common benign intracranial tumors, accounting for approximately 13–26% of all primary tumors of the central nervous system [1, 2]. Most meningiomas typically arise from the non-neural meningothelial progenitor cells, specifically, the arachnoid cap cells along the intradural venous sinuses [3]; therefore, meningiomas are often in close relationship with the major venous sinuses. Those meningiomas which grow into or onto the venous sinuses are called para-sinus meningiomas. With the potential of invading the sinus walls and affecting bridging veins, para-sinus meningiomas pose challenges for surgery [4–8]. Sindou was the first to raise the concept that differ-

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Table 1 Baseline information for all 40 consecutive patients

Clinical characteristics		Total
Number of patients (*N*)		40
Mean age (years)		53.38 ±10.99
Female (*N*, %)		29, 72.5
Mean maximum diameter of tumor (mm)		4.31 ± 1.60
Location (*N*, %):	Superior sagittal sinus	30, 75
	Transverse sinus	7, 17.5
	Torcular	2, 5
	Sigmoid sinus	1, 2.5
Clinical manifestation (*N*, %):	Headache	16, 40
	Hemiparesis	6, 15
	Paresthesia	1, 2.5
	Epilepsy	3, 7.5
	Asymptomatic	11, 27.5
	Others	3, 7.5
Existence of peritumoral edema (*N*, %)		32, 80
Pathological result (*N*, %):	Meningioma (grade I)	31, 77.5
	Meningioma (grade II)	7, 17.5
	Others	2, 5

ent degrees of sinus invasion by meningiomas should be handled in different ways, which has now been widely accepted by neurosurgeons [9]. Improper operation technique, too radical or conservative, was demonstrated to increase the percentage of recurrence and morbidity, and even death by previous studies [4–6, 10]. Hence, the precise judgement of venous invasion by meningiomas is critical to optimize surgical planning and help prevent severe complications for neurosurgeons.

Preoperative evaluation of venous sinus invasion by meningioma should include two key points: (a) whether the sinus wall has been invaded and (b) the extent of venous sinus occlusion. Currently, contrast-enhanced magnetic resonance venography (CE-MRV) is frequently used in the preoperative evaluation of venous meningiomas, which can assess the patency of the involved sinuses, and provide visualization of surrounding anastomotic vessels [11, 12]; however, the judgement of lumen occlusion is indirectly reflected by the path of blood flow in CE-MRV, so that a narrowing or a filling defect of the sinus cannot provide strong evidence of sinus invasion, which hinders surgical planning. Therefore, a MR technique, which can help visualize the wall and opacity of venous sinus is urgently needed in clinical practice.

Black-blood MR imaging (BB-MRI) has emerged as a promising technique for direct wall and patency detection since the signal from static tissue is maximized and the transverse magnetization of the flowing blood is made intentionally incoherent, which nullifies the signal from flowing blood [13, 14]. With this advantage, BB-MRI has been applied in the diagnosis of various intracranial vessel diseases, including intracranial atherosclerosis, vasculitis, reversible constriction syndrome, Moyamoya disease, arterial dissection [14–18]; however, to our best knowledge, except for venous sinus thrombosis evaluation, there are still no reports concerning the usage of BB-MRI sequences in the detection of venous sinus invasion by meningiomas [19].

In our study, we introduced a high-resolution 3D fast spin-echo (FSE) T1 BB-MRI technique, called 3D CUBE T1WI, to evaluate its diagnostic value in para-sinus meningiomas and make a comparison with CE-MRV, in order to find whether the 3D CUBE T1WI technique could bring more accurate information and facilitate the surgical planning of para-sinus meningiomas.

Material and Methods

Patients

This study was designed as a prospective, observational, comparative investigation with intra-individual comparison between June 2015 and September 2016. The inclusion criteria were as follows: (a) patients who had suspected meningiomas invading the superior sagittal sinus (SSS), transverse sinus (TS) or sigmoid sinus (SS) with imaging support, (b) who underwent surgery in our hospital and (c) who had a histopathologic diagnosis of meningioma, based on the 2016 World Health Organization (WHO) Classifications of Tumors of the Central Nervous System [20]. The exclusion criteria were the following: (a) MRI data were not available owing to artefacts and (b) patients had other neurological disorders other than suspected meningioma. Of the subjects, 48 underwent conventional MR imaging, CE-MRV and enhanced 3D CUBE T1WI and finally 40 patients received surgery in our hospital several days later. According to 2016 WHO classifications, 38 patients (28 women, 10 men; age range 32–80 years old, mean age 53.55 ± 11.05 years) were diagnosed with meningiomas pathologically, 1 patient was proved to have non-necrotic granulomatous inflammation and 1 was diagnosed with malignant diffuse large B-cell lymphoma pathologically (Table 1).

MR Protocols

Conventional MR Imaging

All MR imaging studies were performed on a 3.0 T scanner (DISCOVERY MR750W 3.0 T with AW Volume Share TM 5; G.E., Milwaukee, MI) equipped with 32 multichannel receiver head coils. We performed T1-weighted imaging, T2-weighted imaging, T2-FLAIR and contrast-enhanced T1-weighted imaging, all based on spin-echo sequence. Contrast-enhanced T1-weighted images were

Table 2 MR parameters of conventional MR Imaging

	T1WI	T2WI	T2-FLAIR	Enhanced T1WI
TR (ms)	2000	4000	4000	2000
TE (ms)	18	94	94	18
Matrix scan	358 × 512	358 × 512	358 × 512	358 × 512
Excitation	1	2	2	1
FOV (mm)	240 × 240	240 × 240	240 × 240	240 × 240
Bandwidth (Hz)	122	122	122	122
Slice thickness (mm)	3	3	3	3
Flip angle (°)	–	–	–	–
Acquisition time (s)	36	43	90	36

TR repetition time, *TE* echo time, *FOV* field of view, *T1WI* T1-weighted imaging, *T2WI* T2-weighted imaging, *FLAIR* Fluid Attenuated Inversion Recovery

obtained after CE-MRV and 3D CUBE T1WI. The parameters of MR sequences are listed in Table 2.

A bolus injection of contrast media Gd-DTPA (Magnevist, Bayer-Schering, Berlin, Germany) was administered with a dose of 0.1 mmol/kg body weight (0.2 ml/kg). We alternated the scanning sequence of CE-MRV and 3D CUBE T1WI after contrast injection each time to avoid possible bias.

CE-MRV

The CE-MRV sequence used was based on the time-of-flight (TOF) technique. The images were orientated axially with following parameters: field of view (FOV): 22.0 × 19.2 cm^2, flip angle: 20°, TR/TE: 25/3.4 ms, number of excitations (NEX): 1.00, slice thickness: 1.4 mm, matrix size of 320 × 192, yielding an in-plane resolution of 0.69 × 1.00 mm^2 without intersection gaps. The receiver band width was 31.25 Hz/pixel. The acquisition time was 3 min 16 s.

3D CUBE T1WI

The 3D CUBE T1WI was performed before or after the acquisition of CE-MRV. The parameters were as the following: TR/TE 600/16 ms, FOV 20.0 × 20.0 cm^2, flip angle 20°, matrix 288 × 288, yielding an in-plane resolution of 0.69 × 0.69 mm^2, slice thickness 1.0 mm, NEX 0.5, echo train length (ETL) 24, scan plan: oblique, locs per slab (layers per slab): 160. The acquisition time was 4 min 16 s.

Post-processing

Source images from CE-MRV and 3D CUBE T1WI sequences were transferred to a workstation (Advantage Workstation 4.6, General Electric, Milwaukee, WI) for image reconstruction. The images of maximum intensity projection (MIP) reconstruction from CE-MRV were obtained after rotation in 3 orthogonal planes with focus on the invaded sinus. Images obtained by 3D CUBE T1WI sequence were reformatted in sagittal, coronal, and axial planes.

The invasion extent of the venous meningiomas and the CE-MRV images were independently reconstructed and evaluated by two experienced neuroradiologists (both with > 6 years experience) on the basis of conventional MRI and CE-MRV. Another two experienced neuroradiologists (both with > 3 years experience) were responsible for the evaluation of sinus invasion based on the original and reformatted images from 3D CUBE T1WI sequences. The parameters of evaluation included the location of invaded sinus, whether the lumen wall was invaded and patency of the invaded sinus.

The judgement of the invasion of the lumen wall by meningioma depended on the shape of the enhanced lumen wall (e.g. restricted protuberance towards the lumen with/without wavy or serrated wall was regarded as an invasion while linear/smooth wall without protuberance was regarded as no invasion). The patency of venous sinus was subdivided into 3 types: complete occlusion, partial occlusion and no occlusion. Complete occlusion was defined as absolute disappearance of hyperintensity on MRV or hypointensity of lumen on 3D CUBE T1WI, partial occlusion was defined as a restricted narrowing of the sinus diameter (narrowing > 50%) on MRV or a hyperintensity protuberance into venous sinus without complete lumen obstruction on 3D CUBE T1WI and no occlusion was defined as regular, smooth depiction of venous sinus on MRV or coexistence of lumen and clear, smooth margin of lumen wall on 3D CUBE T1WI.

The results from each neuroradiologist were recorded, and then the neuroradiologists responsible for the same sequence were required to discuss their results and to render a final judgement after negotiation. All of the analyses were completed before surgery. All patients were operated on by the same team of neurosurgeons. The neurosurgeon with

Table 3 Agreement for the identification of sinus wall invasion between 3D CUBE T1WI and surgical findings

Judgement by 3DCUBE	Surgical findings		Sum
	Wall invasion	No invasion	
Wall invasion	19	1	20
No invasion	2	16	18
Sum	21	17	38

more than 10 years experience recorded the invasion details during the surgery.

Statistical Analysis

To evaluate the diagnostic performance of CE-MRV and 3D CUBE T1WI in the detection of sinus invasion, we applied Cohen's κ statistics. The levels of interobserver agreement (between readers 1 and 2 for CE-MRV and 3D CUBE T1WI images, respectively) and intermodality agreement (among results of CE-MRV, 3D CUBE T1WI images and surgical findings) with regard to the wall invasion and patency of the sinus lumen were determined by the following criteria: $\kappa < 0.20$, poor; $\kappa = 0.21$–0.40, fair; $\kappa = 0.41$–0.60, moderate; $\kappa = 0.61$–0.80, good; $\kappa = 0.81$–0.90, very good; and $\kappa > 0.90$, excellent agreement. Continuous parameters between different groups of venous meningiomas were compared using Student's two-sided, unpaired t test and one-way ANOVA. Discontinuous variables between different groups of venous meningiomas were tested by Fisher's exact probability test. Statistical analysis was performed with statistical software (SPSS, release 22.0, IBM, Beijing, China). Quantitative data were expressed as the means ± standard deviations, and categorical data were reported as numbers and percentages. A two-tailed p value of less than 0.05 was regarded as significantly different.

Results

Patient Characteristics

Among the 40 cases, the pathological diagnoses were as follows: 5 cases of atypical meningiomas (WHO grade II), 3 cases for meningothelial meningiomas (WHO grade I), 26 cases for fibrous meningiomas (WHO grade I), 1 angiomatous meningioma (WHO grade I), 2 transitional meningiomas, 1 non-necrotic granulomatous inflammation and 1 malignant diffusion large B-cell lymphoma.

Evaluation of the Sinus Wall Invasion

The sinus invasion could be divided into two parts: wall invasion and lumen occlusion. The 3D CUBE T1W imaging was found to provide a simple way to detect the venous wall invasion by para-sinus lesions. The interobserver agreement was excellent in the evaluation of the invasion of the venous wall ($\kappa = 0.843$; 95% CI, 0.757–0.929). The result was highly consistent with the surgical findings with a sensitivity of 90.48%, a specificity of 94.12%, positive predictive value of 95.00%, negative predictive value of 88.89% and Youden Index of 0.85; however, the sinus wall could not be recognized from the CE-MRV images (Table 3).

Evaluation of Lumen Occlusion

Concerning the detection of lumen occlusion, 3D CUBE T1W imaging surpassed CE-MRV not only in the ease of application but also in the accuracy of diagnosis. In the analysis of the lumen invasion, the interobserver agreement obtained by 3D CUBE T1WI sequence ($\kappa = 0.956$; 95% CI, 0.913–0.999) was better when compared with CE-MRV ($\kappa = 0.736$; 95% CI, 0.639–0.833). Furthermore, in 36 out of 38 cases (94.74%), the evaluation of lumen invasion by 3D CUBE T1W imaging was aligned with the actual status confirmed by surgery ($\kappa = 0.914$; 95% CI, 0.856–0.972). The usage of CE-MRV in the lumen evaluation, on the other hand, was limited. The agreement between CE-MRV and surgical results was moderate ($\kappa = 0.481$; 95% CI, 0.374–0.588) with an accuracy of 68.42%. (Table 4).

Sinus Invasion vs. Clinical Features

The 38 patients with meningiomas were divided into 2 groups depending on the sinus wall invasion (22 with sinus wall invasion confirmed by surgery). No difference was found between the 2 groups in terms of patient age, gender, tumor size or the existence of peritumoral edema. It was notable that the ki-67 index was higher in meningiomas without sinus wall invasion compared with those with wall invasion (3.12 ± 0.63% vs. 2.33 ± 0.30%, $p = 0.019$).

The patients with meningiomas were also divided into 3 groups based on the extent of lumen occlusion (19 cases without lumen occlusion, 8 with partial occlusion and 11 with complete occlusion). There was no difference among the 3 groups concerning patient age, gender, tumor size and ki-67 index. The percentage of existence of peritumoral edema was highest in meningiomas with complete sinus lumen occlusion (90.91%), followed by meningiomas without lumen occlusion (80.00%) but no significant relationship was observed between lumen occlusion and peritumoral edema.

Representative cases of meningiomas with different extent of venous sinus invasion are shown in Fig. 1, 2 and 3.

Table 4 Agreement for the identification of sinus lumen occlusion among 3D CUBE T1WI, CE-MRV and surgical findings

Judgement by 3D CUBE	**Surgical findings**			**Sum**
	Complete occlusion	**Partial occlusion**	**No occlusion**	
Complete occlusion	11	1	0	12
Partial occlusion	0	6	0	6
No occlusion	0	1	19	20
Sum	11	8	19	38
Agreement	Kappa Value = 0.914, 95%-CI: 0.856–0.972			
Judgement by enhanced MRV	**Surgical findings**			**Sum**
	Complete occlusion	**Partial occlusion**	**No occlusion**	
Complete occlusion	8	5	1	14
Partial occlusion	2	1	1	4
No occlusion	1	2	17	20
Sum	11	8	19	38
Agreement	Kappa value = 0.481, 95%-CI: 0.374–0.588			

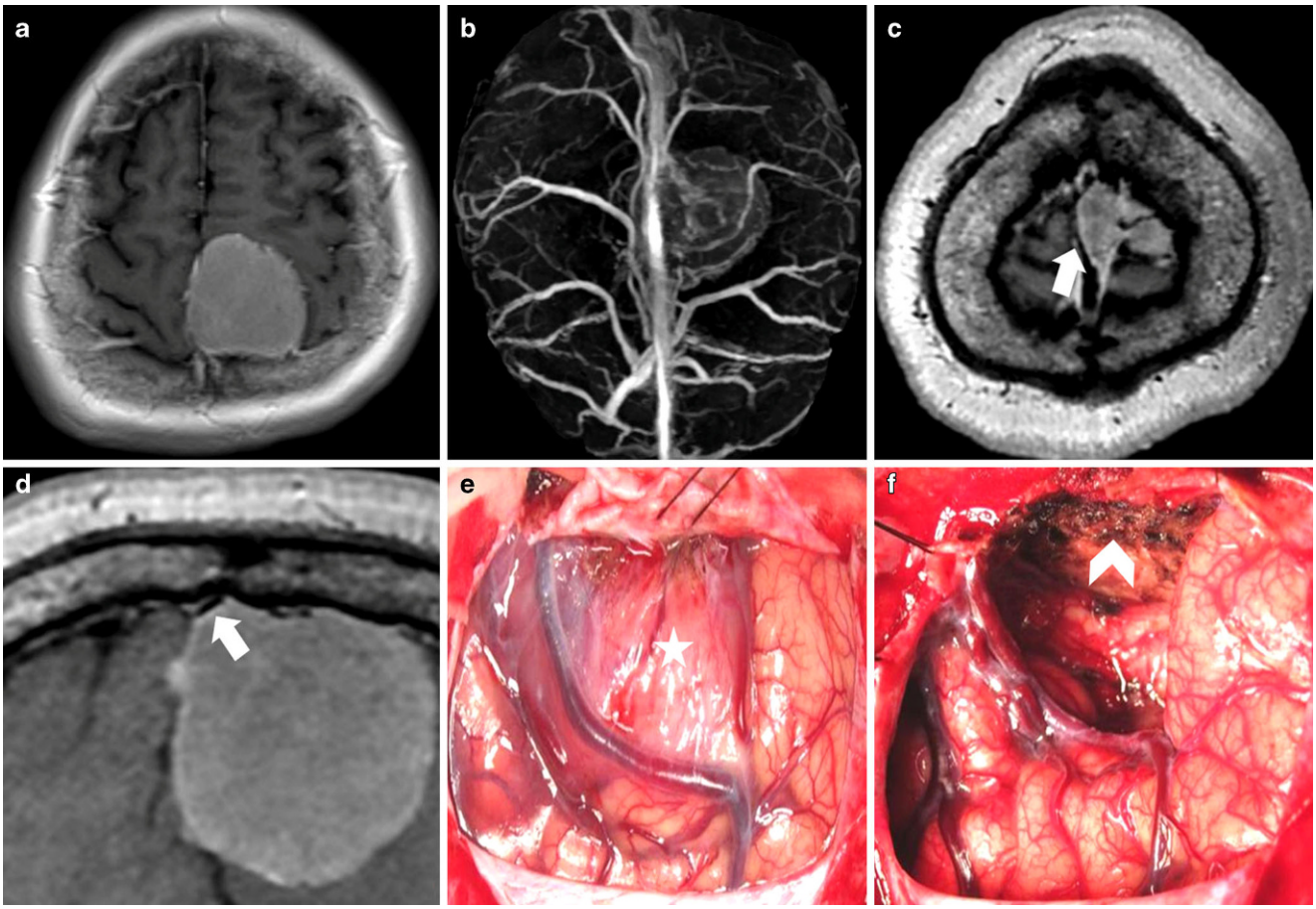

Fig. 1 A 34-year-old woman suffered from paresthesia for 2 months. **a** Axial contrast-enhanced T1W imaging showed a homogeneously enhanced mass in the left parietal region. **b** The middle part of the SSS was narrowed and bypass veins appeared in the reconstructed image from CE-MRV sequence. **c,d** Axial and coronal 3D CUBE T1WI showed clear relationship between meningioma and SSS. Clear and smooth margin of meningioma and narrowed but patent SSS (*arrow*) could be observed. **e** Intraoperative photograph showed huge tumor (*star*) along SSS and bypass veins around the tumor. **f** The tumor is then completely removed and SSS was coagulated (*arrowhead*)

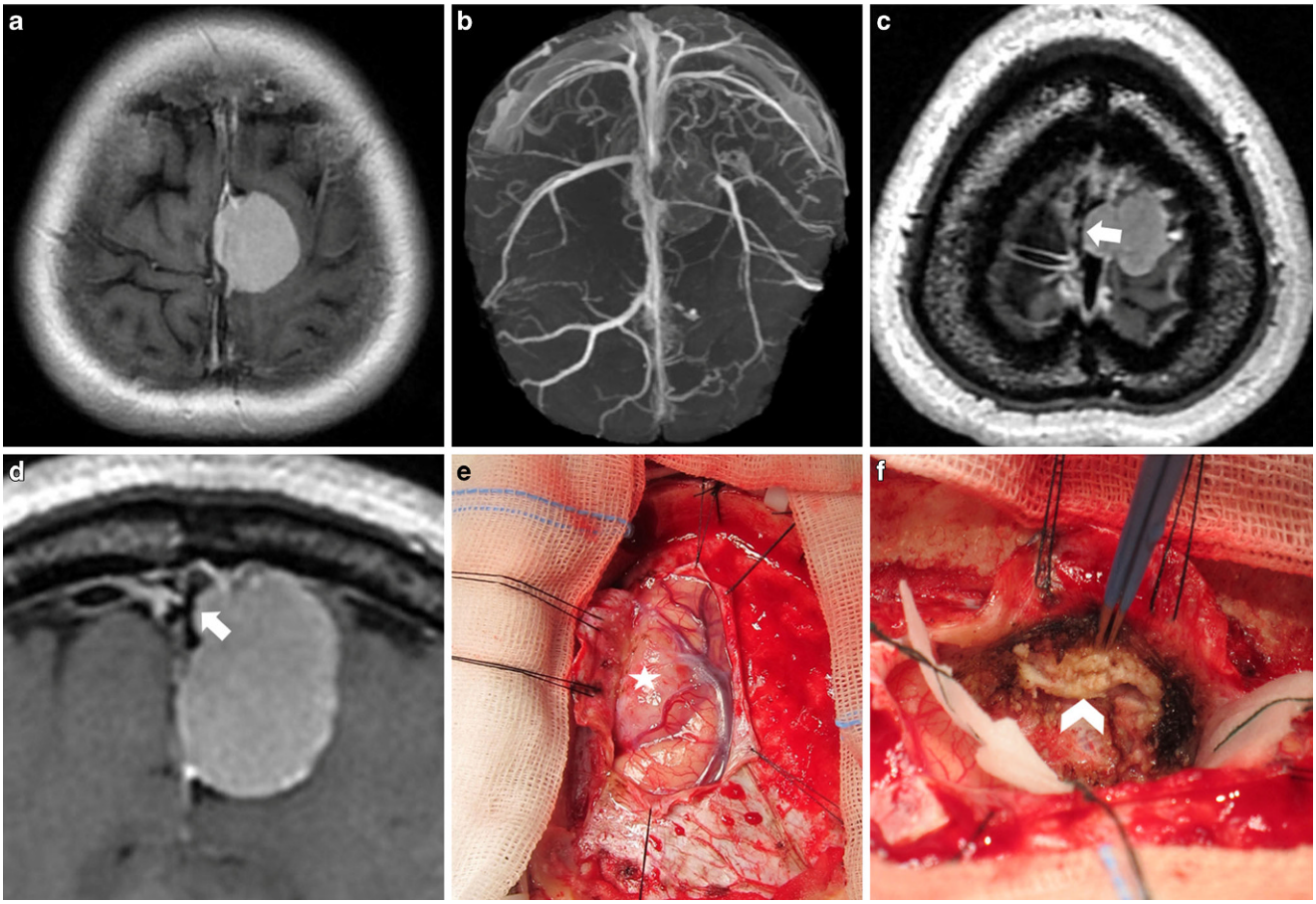

Fig. 2 A 54-year-old woman was incidentally suspected to have meningioma. **a** Axial contrast-enhanced T1W imaging showed a homogeneously enhanced mass in the left frontal region. **b** The middle part of the SSS was narrowed and ipsilateral bypass veins were compressed in the reconstructed image from CE-MRV sequence. **c,d** In the axial and coronal 3D CUBE T1WI images the wall of SSS was irregular (*arrow*) with partial lumen occlusion. **e** Intraoperative photograph showed tumor (*star*) along SSS. **f** After complete resection of the tumor, the SSS was exposed. The SSS was invaded by meningioma and lost its normal appearance (*arrowhead*)

Discussion

A meningioma located against the dura which makes up the sinus wall is also called a para-sinus meningioma. Some para-sinus meningiomas with high ki-67 grow rapidly [8, 21]. When their growth encounters the restriction of the brain tissue or skull, such masses may easily invade the nearby sinuses.

The treatment of a para-sinus meningioma can be problematic. Sindou developed a classification and divided para-sinus meningiomas into 6 types according to the extent of their invasion to venous sinuses. Type I meningioma attached to the outer surface of the sinus wall, type II lateral recess invaded, type III ipsilateral wall invaded, type IV ipsilateral wall and roof of the sinus both invaded, type V sinus totally occluded but the contralateral wall free of invasion and type VI sinus totally invaded with no walls free of invasion [9, 21].

Different types of para-sinus meningiomas should be surgically treated by different techniques [8–10, 21, 22]. If the meningioma is attached to the outer surface of the sinus wall or totally outside the sinus wall (type I), only simple resection of the outer dural layer and coagulation of the inner layer are needed at the site of attachment. For para-sinus meningiomas with partially occluded sinus (types II–IV), resection of the intraluminal fragment and the invaded sinus wall is necessary since subtotal resection is associated with a high rate of tumor recurrence. For para-sinus meningiomas with complete lumen occlusion, total removal with sinus reconstruction by using a patch is recommended by several previous studies [10]. Thus, preoperative assessment of sinus invasion is important for essential presurgical preparation; however, the techniques used today for the judgement of venous sinuses do not meet the needs of neurosurgeons. Main imaging techniques can be divided into 2 groups, one is intraluminal imaging, e.g. digital subtraction angiography (DSA), computed tomography venography (CTV) and MRV. The type of imaging could reflect the patency of venous sinuses and give a whole picture of the intracranial systems including bridging veins

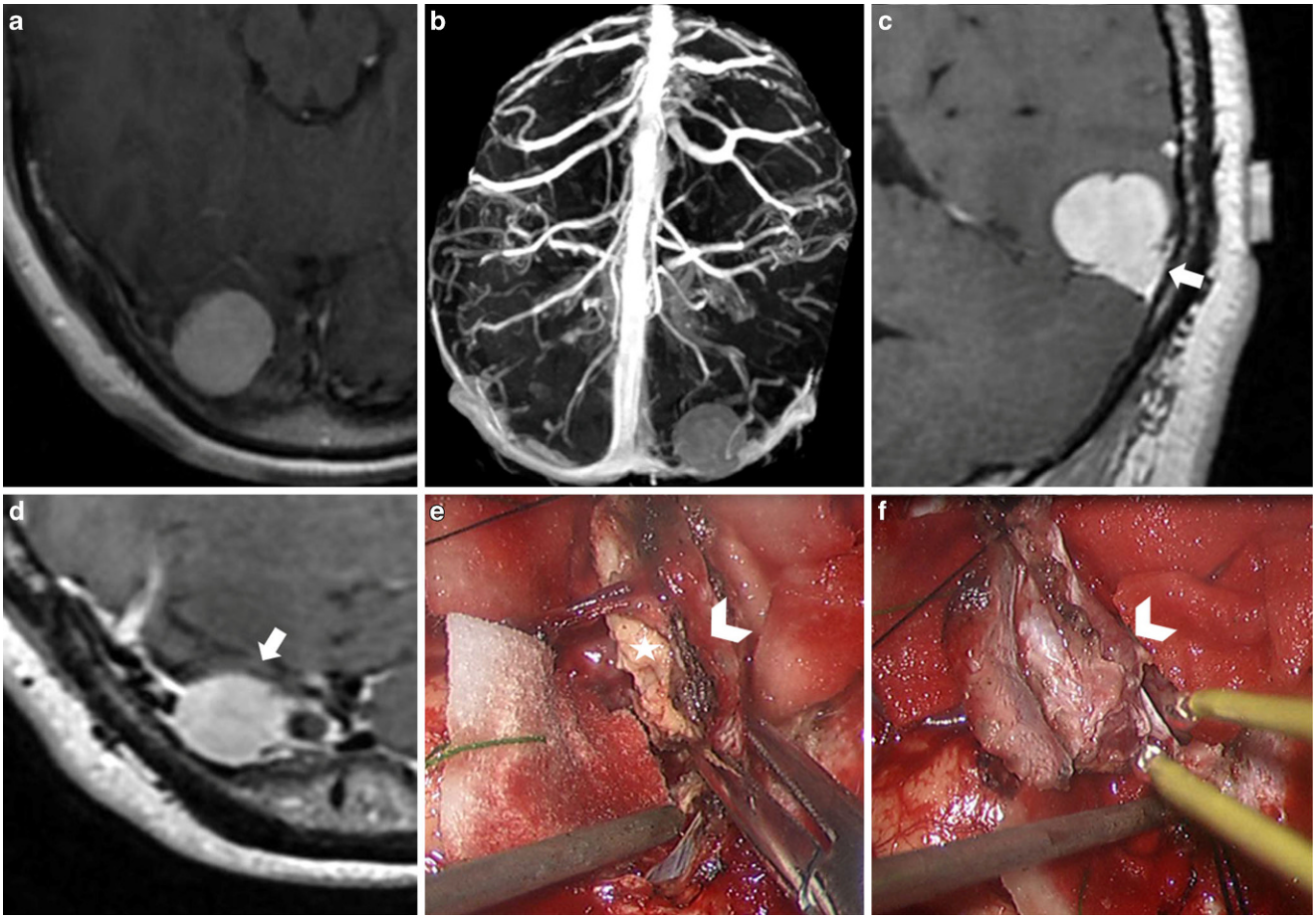

Fig. 3 A 53-year-old woman suffered from headache for several years. **a** Axial contrast-enhanced T1W imaging showed a homogeneously enhanced mass in the right occipital region. **b** The middle part of the transverse sinus was narrowed in the reconstructed image from CE-MRV sequence. **c,d** In the axial and coronal 3D CUBE T1WI images, the transverse sinus was invaded by meningioma with complete occlusion (*arrow*). **e** Intraoperative photograph showed tumor (*star*) hidden behind the transverse sinus (*arrowhead*). **f** Then the tumor and the transverse sinus (*arrowhead*) were both removed

but without a description of venous wall, which is not ideal for detection of tumor invasion [12]. In our research, CE-MRV, as one of the bright blood sequences, demonstrated the blood flow inside the sinus and it was difficult to separate compression from occlusion. In addition, the speed of flow inside the sinus affects the signal intensity, hence the abnormal shape of venous sinus exaggerates the manifestation of lumen invasion and makes it appear to be occluded even though the sinus is still patent. Another type is the normal structural imaging, e.g. T1WI, T2WI and enhanced T1WI. These sequences could provide the information of meningiomas and venous wall, but the resolution and contrast ratio between lumen and blood flow are very low. The 3D CUBE T1WI-based 3D FSE technique facilitates the visualization of the wall of venous sinus by depression of the blood signal inside the veins [18].

In our study, 3D CUBE T1WI exhibited great potential in illustration of the invasion of the sinus wall and lumen by meningiomas. The structure of the venous sinus could be depicted in detail, making it much easier for radiologists to achieve precise diagnosis with high interobserver agreement concerning the wall invasion and lumen occlusion by para-sinus lesions, which actually made up the pitfalls of CE-MRV.

Although 3D CUBE T1WI seemed to be promising when used in the diagnosis of venous sinus invasion, it is essential to choose the most suitable plane for observation. Since the cross-section of most venous sinuses is irregular, mostly triangular, only the images acquired in the plane perpendicular to the sinus can reflect the invasion status. According to our findings, 3D CUBE T1WI images in the coronal plane are suitable to detect the invasion of the anterior two thirds of the SSS, while for posterior one third of the SSS the axial plane is the most suitable.

The percentage of peritumoral edema was reported to be around 60%, and was partially related to tumor location [22–25]. In our research, we hypothesized that peritumoral edema could be induced by the occlusion of draining veins

in previous studies; however, according to the results the existence and the extent of peritumoral edema did not correlate with neither the wall invasion nor the lumen occlusion. The percentage of peritumoral edema in meningiomas with complete sinus invasion (90.91%) was higher (not significantly) than the percentage in tumors with partial occlusion (62.50%) or without occlusion (80.00%). This finding might be due to the dynamic process of peritumoral edema, which would develop with compression and occlusion of the draining veins and would recede with the generation of bypass veins.

To our knowledge, this is the first study to use BB-MRI in the evaluation of tumor-related sinus invasion, which was important for clinical practice. There are still some limitations. First, the number of subjects in this study is limited and the lesions were basically meningiomas. Further studies with a larger sample will help to confirm the results obtained in this study. Second, we did not compare 3D CUBE T1WI with other techniques, such as DSA, which is the gold standard for the patency of the lumen. Third, this was not a long-term study and regular postoperative evaluation should be added to track the surgical effect and patient prognosis. More efforts should be devoted in further studies.

Conclusion

Our results suggested that the 3D CUBE T1WI sequence was a more reliable method in the detection of sinus invasion in para-sinus lesions compared with CE-MRV based on surgical findings. A combination of 3D CUBE T1WI sequence and CE-MRV can provide comprehensive information about sinus invasion and surrounding bridging vessels simultaneously, which is critical for operative planning in patients with para-sinus lesions involving the venous sinuses.

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Compliance with ethical guidelines

Conflict of interest D. Wang, Y. Lu, B. Yin, M. Chen, D. Geng, L. Liu, J. Wen, P. Zhong and Y. Li declare that they have no competing interests.

Ethical standards The present study was approved by the local ethics committee at Fudan University. Informed consents from all patients were obtained before enrolment.

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