The relationship between the apparent diffusion coefficient and the Ki-67 proliferation index in intracranial solitary fibrous tumor/hemangiopericytoma

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Abstract
This study evaluated the value of the apparent diffusion coefficient (ADC) in distinguishing grade II and III intracranial solitary fibrous tumors/hemangiopericytomas and explored the correlation between ADC and Ki-67. The preoperative MRIs of 37 patients treated for solitary fibrous tumor/hemangiopericytoma (grade II, n = 15 and grade III, n = 22) in our hospital from 2011 to October 2020 were retrospectively analyzed. We compared the difference between the minimum, average, maximum, and relative ADCs based on tumor grade and examined the correlation between ADC and Ki-67. Receiver operating characteristic curve analysis was used to analyze the diagnostic efficiency of the ADC. There were significant differences in the average, minimum, and relative ADCs between grade II and III patients. The optimal cutoff value for the relative ADC value to differentiate grade II and III tumors was 0.998, which yielded an area under the curve of 0.879. The Ki-67 proliferation indexes of grade II and III tumors were significantly different, and the average (r = −0.427), minimum (r = −0.356), and relative (r = −0.529) ADCs were significantly negatively correlated with the Ki-67 proliferation index. ADC can be used to differentiate grade II and III intracranial solitary fibrous tumors/hemangiopericytomas. Our results can be used to formulate a personalized surgical treatment plan before surgery.

Keywords Intracranial · Solitary fibrous tumor/hemangiopericytoma · Ki-67 proliferation index · MRI · Apparent diffusion coefficient

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Introduction

The 2016 World Health Organization CNS tumor classification indicates that solitary fibrous tumors (SFTs) and hemangiopericytomas (HPCs) both exhibit the 12q13 chromosome inversion and expression the NAB2-STAT6 fusion product [1]. Given the partial overlap between SFTs and HPCs in pathology, such lesions are currently described as SFT/HPC. In addition, to better interpret the pathological and clinical features of SFT/HPC, SFT/HPC is divided into three grades: grade I SFT/HPC has benign characteristics and a good prognosis, whereas grade II and III SFT/HPC are malignant tumors prone to infiltration of the surrounding tissue structure, postoperative tumor recurrence, and extracranial metastasis [2–5]. However, even though grade II and III SFT/HPC are malignant tumors derived from meningeal interstitial capillary Zimmerman cells, they are associated with different outcomes. Grade III SFT/HPC is more prone to recurrence and metastasis, and the overall survival and disease-free progression intervals are significantly shorter than those of grade II SFT/HPC [2, 4, 6].

Previous studies have shown that radiological features can indirectly reflect the pathological grade of intracranial SFT/HPC. For instance, necrosis, hemorrhage, blurred tumor-brain interface, and obvious brain edema all indicate III grade SFT/HPC [7–9]. However, these radiological features are subjective and cannot quantitatively evaluate molecular information about the tumor. DWI, a non-invasive technique for reflecting the diffusion of water molecules in living tissues, has been widely used in various fields of tumor quantitative analysis. Schob et al. [10] found that the low ADCmin, ADCmean, and ADCmax values reflect a high proliferative activity of primary central nervous system lymphoma. Because grade III SFT/HPC often has higher cell density and mitotic activity, we speculate that the ADC may be able to differentiate grade II and III intracranial SFT/HPC, and there may be a relationship between the ADC and the Ki-67 proliferation index [11]. As far as we know, there is no study that uses only ADC values to differentiate grade II and III intracranial SFT/HPC or evaluates the relationship between ADC and the Ki-67 proliferation index. Therefore, the purposes of this study were to examine the ability of the preoperative ADC to distinguish grade II and III intracranial SFT/HPC and to study the relationship between the ADC and the Ki-67 proliferation index.

Methods

Patients

The study was approved by the ethics committee of our agency. Because this was a retrospective study, the requirement for informed consent was waived. The preoperative MRI and postoperative pathological data of 42 patients with pathologically confirmed grade II and III intracranial SFT/HPC treated in our hospital from January 2011 to October 2020 were analyzed retrospectively. The inclusion criteria were as follows: (1) complete preoperative MRI data (three patients were excluded); (2) complete pathological data after the first operation; and (3) no tumor-related treatment before surgery (two patients were excluded: preoperative vascular interventional embolization). Finally, 37 patients with intracranial SFT/HPC were included, including 15 patients with grade II disease and 22 patients with grade III disease.

MRI protocol

Using the Siemens Verio 3.0 T (Germany) superconducting MR scanner, the plain scan sequence included axial/sagittal SE-T1WI (TR 550 ms, TE 12 ms), axial FSE-T2WI (TR 2200 ms, TE 90 ms), and FLAIR T2WI (TR 9000 ms, TE 110 ms, TI 2371 ms), with an FOV 320 mm × 320 mm, matrix 256 × 256, axial layer thickness 5 mm, layer spacing 1.5 mm, sagittal layer thickness 8 mm, and layer spacing 2 mm. DWI used the SE-EPI sequence plus frequency selective fat suppression technology, TR 4000 ms, TE 100 ms, layer thickness 9 mm, layer spacing 1 mm, FOV 260 mm × 260 mm, and matrix 256 × 192. Diffusion gradients (b value = 0, 1000 s/mm²) were applied in the directions of the x, y, and z axes. The contrast agent was 0.1 mmol/kg Gd-DTPA, the flow rate was 3 mL/s, and the axial-, sagittal- and coronal-enhanced T1WI were obtained. All patients received T1WI, T2WI, T2-FLAIR, DWI, and MRI enhanced scans before treatment.

Image analysis

Two radiologists with more than 10 years of experience in CNS diagnosis analyzed the scans in a single-blind manner (the pathological diagnosis of SFT/HPC was known, but the grade of SFT/HPC was not clear). The measured data included tumor size, tumor volume, maximum ADC, average ADC (MeanADC), MinADC, and relative ADC (rADC). The average of the two observers was taken as the result.

Measurement method

The region of interest (ROI) is located in the solid area of the tumor, with a size of about 20–40 mm², avoiding the tumor areas of necrosis or cystic. The Max ADC value, Mean ADC value, and Min ADC value of the solid tumor area can be obtained from the ROI. At the same time, we select the white matter area at the same level of the tumor and outline an ROI of the same size to obtain the average ADC value of the normal white matter. The rADC value is calculated from the average ADC value.
of the tumor/the ADC value of the white matter of the brain (rADC = MeanADC tumor/MeanADC white matter). The measurement details are shown in Fig. 1.

All tumor specimens were stained with H&E. The immunohistochemical analysis of Ki-67 was performed using a monoclonal mouse anti-human Ki-67 antibody (1:400, Abcam, ab245113, Cambridge, UK). Randomly take small tissue specimens from solid tumor areas for immunohistochemical staining. Cells with a brown nucleus were judged to be Ki-67-positive. The (HPF) count of 1000 tumor cells was randomly read by two pathologists from 10 high-power visual fields, and the Ki-67 proliferation index was calculated as the number of positive cells divided by the total cell count. The average value of the two physicians’ readings was taken as the Ki-67 proliferation index.

**Statistical analysis**

SPSS 25.0 statistical software was used to analyze the results, and Graphpad Prism 8.0 was used to draw graphs. The measurement data of normal distribution are expressed as absolute values ± S, the differences between groups were compared by t-test, the measurement data of skewness distribution are expressed by M (range), and the comparisons between groups were calculated by Mann–Whitney U test. Categorical data are expressed as a percentage, and the Fisher exact probability was used for comparison between groups. Receiver operating characteristic curve analysis was used to evaluate the accuracy of the MRI quantitative data in distinguishing grade II SFT/HPC from grade III SFT/HPC, and the sensitivity and specificity of each parameter were calculated when the Youden index reached the maximum. The correlation of the MeanADC, MinADC, and rADC, with the Ki-67 proliferation index, was analyzed by Pearson correlation analysis. P < 0.05 indicated a statistically significant difference.

**Results**

**Patient characteristics**

In this study, there were 15 patients with grade II intracranial SFT/HPC and 22 with grade III intracranial SFT/HPC. There were 17 men and 20 women, with an average age of 51.32 (±12.06) years. Table 1 shows the clinical data of the patients. There was no significant difference in sex, age, or tumor size between patients with grade II and grade III SFT/HPC.

**Ki-67 proliferation index of grade II and grade III SFT/HPC**

The Ki-67 proliferative index in grade II SFT/HPC tumors was 10.67% (±4.49%), and the Ki-67 proliferative index
in grade III SFT/HPC tumors was 21.36% (±11.07%). The difference was statistically significant ($P < 0.001$) (Table 1, Fig. 2).

**Correlation analysis of the intracranial SFT/HPC ADC values and the Ki-67 proliferation index**

The mean Ki-67 proliferation index of the 37 SFT/HPC tumors in this study was 17.03% (±10.24%). Pearson correlation analysis found that the MeanADC ($r = −0.427$, $P = 0.008$), MinADC ($r = −0.356$, $P = 0.03$), and rADC ($r = −0.529$, $P < 0.001$) were negatively correlated with the Ki-67 proliferation index (Table 2, Fig. 2).

**Comparison of ADC values of grade II and grade III intracranial SFT/HPC**

There were significant differences in the MeanADC ($t = 2.702$, $P = 0.011$), MinADC ($t = 2.730$, $P = 0.01$), and rADC ($t = 8.102$, $P < 0.0001$) between grade II and grade III SFT/HPC (Table 3). Representative cases of grade II and III SFT/HPC are shown in Fig. 3 and Fig. 4.

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### Table 1 Baseline characteristics of patients with grade II and III SFT/HPC

| Group            | SFT/HPC                  | $\chi^2$ | $t$   | $P$  |
|------------------|--------------------------|----------|-------|------|
|                  | II grade                 | III grade|       |      |
| Gender           | Male                     | 7 (18.92%)| 10 (27.03%)| —    | 1    |
|                  | Female                   | 8 (21.62%)| 12 (32.43%)| 0.227 | 0.893|
| Location         | Convex surface           | 10 (27.03%)| 13 (35.14%)| 0.227 | 0.893|
|                  | Tentorium                | 4 (10.81%)| 7 (18.92%) |      |      |
|                  | Skull base               | 1 (2.7%)  | 2 (5.4%)  |      |      |
| Ki-67 proliferation index (%) | 10.67 ± 4.49 | 21.36 ± 11.07 | −4.065 | <0.001|
| Age (y)          | 49.40 ± 11.11            | 52.64 ± 13.02 | −0.786 | 0.437|
| Tumor diameter (mm) | 4.93 ± 1.75            | 4.72 ± 1.56 | 0.371  | 0.713|
| Tumor volume (mm$^3$) | 54.79 ± 41.79          | 61.54 ± 24.98 | −0.615 | 0.542|

“.” Fisher exact probability test
Ki-67 proliferation index parameters are still needed to effectively distinguish these HPC before surgery. Therefore, more objective, quantitative to effectively distinguish between grade II and grade III SFT/radiotherapy [11, 18]. However, it is difficult for radiologists resection of the surrounding structure [4], and postoperative including preoperative tumor interventions [16, 17], greater allow surgeons to formulate more detailed treatment plans, dict clinical postoperative tumor progression, which would can be clear before surgery, we can more accurately pre-entities is often rhage, and moderate to high cell density [2]. This means that diagnostic criteria for grade intracranial III SFT/HPC are [12, 13]. The 2016 World Health Organization Intracranial SFT/HPC accounts for about 1% of intracranial tumors [19]. This study analyzed the ADCs of grade II and grade III SFT/HPC tumor entities and found that the MinADC, MeanADC, and rADC were significantly different in grade II and grade III SFT/HPC. The rADC had the highest accuracy in distinguishing grade II and grade III SFT/HPC (area under the curve = 0.897), with a diagnostic sensitivity and specificity of 80% and 95.5%, respectively. Chen et al. [20] found that the standardized ADC is of great significance in distinguishing SFT/HPC from meningioma. When the threshold of the standardized ADC is greater than 1.15, the sensitivity and specificity for distinguishing these two malignancies are 75% and 60.42%, respectively. Although they did not perform subgroup analysis of grade II and III intracranial SFT/HPC, they concluded that the ADC was negatively correlated with tumor malignancy and positively correlated with the extracellular space. Tumor cells in grade III SFT/HPC have increased mitotic activity and an enlarged nucleus and cytoplasm, resulting in the shrinkage of the space around the cells. This restricts the diffusion of water molecules, which decreases the ADC [19, 21]. Therefore, the ADC can reflect changes in the microstructure of tissues. Gihr et al. [22] found that the ADC histogram of tumors can distinguish low-grade from high-grade meningioma and reflects Ki-67 expression of the tumor. In another study [23], ADC histogram parameters differ significantly between glioblastoma and anaplastic astrocytoma and show distinct associations with the proliferative activity in both high-grade-glioma. The results of this study support the conclusions of previous studies showing that the ADC may be able to non-invasively achieve tumor grading and typing, thereby assisting in the development of personalized treatment plans before surgery.

Histopathology can accurately distinguish grade II and III intracranial SFT/HPC based on tumor microstructure and cell morphology. The Ki-67 proliferation index is an important indicator that indirectly reflects the degree of tumor malignancy. Previous studies have shown that a higher Ki-67 proliferation index is correlated with an increased probability of tumor progression [4, 24, 25]. Multiple studies have shown that there is a correlation between the Ki-67 proliferation index of solid tumors and the ADC. Xianwang et al. [26] found a strong negative correlation between the MinADC and the Ki-67 proliferation index in ependymoma. He et al. [27] found that the MinADC and the Ki-67 proliferation index have a slight negative correlation in SFT/HPC, which is consistent with the results of this study. This

**Table 2** Correlation analysis of the intracranial SFT/HPC ADC values and the Ki-67 proliferation index

| Parameters (× 10⁻³mm²/s) | Ki-67 proliferation index (17.03 ± 10.24)% | r | p   |
|---------------------------|------------------------------------------|---|-----|
| MeanADC                    | −0.427                                   | 0.0083 |
| MinADC                     | −0.356                                   | 0.0303 |
| rADC                       | −0.529                                   | 0.0007 |

**Table 3** Comparison of ADC values of grade II and grade III intracranial SFT/HPC

| Parameters (× 10⁻³mm²/s) | SFT/HPC | II grade | III grade | t   | p   |
|---------------------------|---------|----------|-----------|-----|-----|
| MaxADC                    | 0.853 ± 0.098 | 0.789 ± 0.126 | 1.632 | 0.112 |
| MeanADC                   | 0.787 ± 0.078 | 0.693 ± 0.119 | 2.702 | 0.011 |
| MinADC                    | 0.719 ± 0.079 | 0.622 ± 0.121 | 2.730 | 0.009 |
| rADC                      | 1.078 ± 0.126 | 0.912 ± 0.074 | 8.102 | <0.001 |

Discussion

Intracranial SFT/HPC accounts for about 1% of intracranial tumors [12, 13]. The 2016 World Health Organization classification of CNS tumors states that the pathological diagnostic criteria for grade intracranial III SFT/HPC are mitotic activity of at least 5/10 HPF, tumor necrosis, hemorrhage, and moderate to high cell density [2]. This means that the Ki-67 proliferation index of grade III SFT/HPC tumor entities is often ≥10% [9, 14, 15]. If the SFT/HPC grading can be clear before surgery, we can more accurately predict clinical postoperative tumor progression, which would allow surgeons to formulate more detailed treatment plans, including preoperative tumor interventions [16, 17], greater resection of the surrounding structure [4], and postoperative radiotherapy [11, 18]. However, it is difficult for radiologists to effectively distinguish between grade II and grade III SFT/HPC before surgery. Therefore, more objective, quantitative parameters are still needed to effectively distinguish these two tumor grades, so as to effectively guide the implementation of clinical treatment measures.

DWI can non-invasively evaluate the Brownian motion of water molecules in the tissue. The ADC is derived from DWI results and is mainly affected by the combined effect of the volume fractions inside and outside the cell. Therefore, the ADC can be of great significance for tumor grading, preoperative quantitative assessment, and differential diagnosis of brain tumors [19]. This study analyzed the ADCs of grade II and grade III SFT/HPC tumor entities and found that the MinADC, MeanADC, and rADC were significantly different in grade II and grade III SFT/HPC. The rADC had the highest accuracy in distinguishing grade II and grade III SFT/HPC (area under the curve = 0.897), with a diagnostic sensitivity and specificity of 80% and 95.5%, respectively. Chen et al. [20] found that the standardized ADC is of great significance in distinguishing SFT/HPC from meningioma. When the threshold of the standardized ADC is greater than 1.15, the sensitivity and specificity for distinguishing these two malignancies are 75% and 60.42%, respectively. Although they did not perform subgroup analysis of grade II and III intracranial SFT/HPC, they concluded that the ADC was negatively correlated with tumor malignancy and positively correlated with the extracellular space. Tumor cells in grade III SFT/HPC have increased mitotic activity and an enlarged nucleus and cytoplasm, resulting in the shrinkage of the space around the cells. This restricts the diffusion of water molecules, which decreases the ADC [19, 21]. Therefore, the ADC can reflect changes in the microstructure of tissues. Gihr et al. [22] found that the ADC histogram of tumors can distinguish low-grade from high-grade meningioma and reflects Ki-67 expression of the tumor. In another study [23], ADC histogram parameters differ significantly between glioblastoma and anaplastic astrocytoma and show distinct associations with the proliferative activity in both high-grade-glioma. The results of this study support the conclusions of previous studies showing that the ADC may be able to non-invasively achieve tumor grading and typing, thereby assisting in the development of personalized treatment plans before surgery.

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Fig. 3 A 38-year-old woman with grade III SFT/HPC in the frontal region. A–E T1WI and T2WI were relatively uniform before operation, and the frontal bone cancellous signal was abnormal. The DWI and ADC indicated that the tumor was restricted in spreading and the enhancement was uneven. F Re-examination of the head 8 months after surgery revealed that the right frontal area was round-shaped with uneven enhancement. G–H Pathology (H&E×100) showed a large number of heterogeneous cells in the mirror image, and the Ki-67 index was about 30%
negative correlation may be due to differences in cell cycle progression. Smaller cells are in G1 phase and larger cells are in G2/M phase, and as the cell volume increases, the extracellular volume decreases and the ADC decreases. The Ki-67 proliferation index is related to cell proliferation, and high expression of Ki-67 is observed in the G2/M phase. As the mitotic activity of the cell intensifies, the ADC gradually decreases and Ki-67 gradually increases, which leads

Fig. 4 A 54-year-old man with a round grade II HPC in the right temporo-occipital region. A–E Tumor T1WI and T2WI signals were uneven, whereas DWI showed an uneven and slightly high signal. The ADC was uneven and low, the tumor-brain interface was clear, and the enhancement was obvious. F Thirty-six months after the operation, head MRI showed the formation of softening of the brain area, and no tumor recurrence was seen. G–H Pathological map of intracranial HPC (H&E × 200), and the Ki-67 index was 8%
to this negative correlation [28, 29]. This study found that the MeanADC, MinADC, and rADC had a strong negative correlation with the Ki-67 proliferation index in SFT/HPC. Because this tumor microstructure causes macroscopic differences in the ADC, the preoperative ADC predicts the Ki-67 proliferation index of intracranial SFT/HPC tumors. Therefore, the ADC is a preoperative, non-invasive factor that can assist surgeons in developing a detailed surgical plan and follow-up program.

This study had several limitations. First, this study took place in a single center and had a small sample size. Second, because grade III SFT/HPC has more indicative radiological features than grade II SFT/HPC, such as necrosis, obvious cerebral edema, and heterogeneous enhancement, this may cause a certain subjective deviation in the manual measurement of the ADC. Third, only ROI-based ADC measurements are used in this study; So that it is impossible to accurately match the ROI in the image with the pathological immunohistochemical results. Finally, there is a lack of complete follow-up data, and the value of the ADC in the preoperative differentiation of grade II and III intracranial SFT/HPC needs further verification.

**Conclusions**

In summary, this study used the preoperative MeanADC, MinADC, and rADC to effectively distinguish grade II and III SFT/HPC tumor entities. The study also found that there is a strong negative correlation between the ADC and the tumor Ki-67 proliferation index. These conclusions will help clinicians formulate a personalized surgery plan for intracranial SFT/HPC.

**Author contribution** First author: Shenglin Li — theoretical design, article writing, data processing; co-first author: Qing Zhou — theoretical design, article writing, data processing; the second author: Peng Zhang — data collection and patient follow-up; the third author: Shize Ma — theoretical guidance and patient follow-up; the fourth author: Caqiichang Xue — data processing; the fifth author: Juan Deng — data processing; corresponding author: Junlin Zhou, MD, PhD. — theoretical guidance and article revision suggestions.

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**Data availability** Not applicable.

**Code availability** Not applicable.

**Declarations**

**Ethics approval** This study was approved by the Medical Ethics Committee of the Second Hospital of Lanzhou University and informed consent was waived.

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**Consent for publication** Agree to publish.

**Conflict of interest** The authors declare no competing interests.

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