Original Article
Comparison of SWIM and conventional MRI sequences in 60 cases of cerebral microbleeds with acute and chronic traumatic brain injury

Shu-Ping Peng[1], Yan Qin[1], Shun-Ke Zhou[1], Zhi-Yuan Wang[2], Zi-Shu Zhang[1], Fang-Xu Tao[1], Zhi-Xue Zhang[1], Yi-Ning Li[1], Yu-Dong Xiao[1], Hai-Yan Liao[1], Jun Liu[1]

[1]Department of Radiology, The Second Xiangya Hospital, Central South University, Changsha 410011, Hunan Province, China; [2]Department of Ultrasound, Hunan Cancer Hospital, The Affiliated Cancer Hospital of Xiangya School of Medicine, Central South University, Changsha 410013, Hunan Province, China

Abstract: Objective: To compare the detection ability of the number of micro hemorrhage lesions between the conventional MRI sequences and susceptibility weighted image and mapping (SWIM) as well as the corresponding relationship between lesions and injured vessels in the traumatic cerebral injury. Methods: 60 patients with traumatic brain injuries were collected in this study. All patients received MRI scan in the acute phase (within 72 hours) and chronic phase (1 month later) after injury, named group 1 and 2, respectively. Results: In 60 patients of acute phase (group 1), SWIM sequence was able to detect more lesions than the conventional sequences (*P*<0.05). In the 60 patients of chronic phase (group 2), SWIM sequence was capable of identifying more lesions than the conventional sequences (*P*<0.05). Besides, compared with the conventional MRI sequences, SWIM revealed 57 injured cerebral veins of 44 patients in the acute phase of cerebral injury, which manifested as coarse vascular edges. Among them, the relationship between the hemorrhage lesions and cerebral veins could be revealed directly in 41 veins. Conclusion: For the patients with acute or chronic traumatic cerebral injury, SWIM can display the morphological alteration of cerebral vessels and the relationship with the micro hemorrhage lesions, and is able to reveal clearly the size, morphology and number of intracranial micro hemorrhage lesions. Furthermore, compared with the conventional sequences T1WI, T2WI and FLAIR, it can also identify more micro hemorrhage lesions and is capable to determine the corresponding relationship between the micro hemorrhage lesions and injured vessels.

Keywords: Magnetic resonance imaging (MRI), susceptibility weighted imaging, susceptibility weighted imaging and mapping (SWIM), cerebral microbleeds (CMBs), traumatic brain injury (TBI)

Introduction

Traumatic Brain Injury (TBI), caused by motor vehicle accidents, falls, assaults, or sports injuries affects approximately 7 million people each year [1]. Data in a report, the most extensive to date from a multistate population-based TBI surveillance system, indicate the importance of TBI as a public health problem [2]. TBI has an incidence rate of 1.5 million annually in the United States [3]. TBI is a leading cause of death and disability in young people and people at the most productive time of their lives. An estimated 475,000 TBIs occurred among children aged 0-14 each year [4]. TBI has been referred to as "a silent epidemic [5]". Approximately 5.3 million Americans live with

long-term disability as a result of TBI. The economic impact of TBI on the nation is also enormous, according to the centers for disease control (CDC) in the America, with an estimated total direct and indirect cost of $60 billion per year in 2000 [6]. In China, there is no detailed report about incidence rate of TBI. But with the economic development and social progress, TBI should have a high incidence rate in China.

Cerebral microbleeds (CMBs), are seen as phenomena distinct from larger hemorrhages. CMBs were defined as hyperintense foci that were not compatible with vascular, bone, or artifactual structures on Susceptibility Weighted Imaging (SWI). A round or ovoid hypointense lesion whose diameter was greater than 2 but

smaller than 10 mm and that was clearly not a vessel was considered to be a microbleed [7, 8]. CMBs are small, rounded areas of homogeneous low signal visualized on GRE T2*-weighted images or SWI images because haemosiderin (a paramagnetic product of blood degradation) has high magnetic susceptibility, causing local field inhomogeneities and signal loss.

It is very important to reliably detect and map CMBs including presence, number, distribution, and the size. CMBs have been implicated to play a role in many neurovascular and neurodegenerative diseases. Koennecke HC reviewed literature published through July 2005 from electronic MEDLINE, PubMed, and hand searches and analyzed the prevalence data from more than 5,200 patients. CMBs might indicate a higher risk of future intracerebral hemorrhage and may be a marker of cerebral small-vessel disease and cerebral amyloid angiopathy [9]. CMBs are also found frequently in TBI and traumatic microbleeds (TMBs) can be regarded as a radiological marker of DAI with potential relevance for prognosis [10]. There is a substantial research interest in the predictive value of determining cerebral microbleed severity regarding the incidence or recurrence of primary ICH [11, 12].

Computed tomography (CT) has been useful for the diagnosis and evaluation of the extent and severity of brain involvement in hemorrhage. CT is widely used as the imaging modality for severe head injury because of its short examination time and compatibility with life-supporting instruments. Information obtained on CT is useful and important for cases with hemorrhages. CT can detect large hemorrhages or other lesions that require surgical intervention [13] and has been used to screen patients for large hemorrhages at the acute stage or other lesions that require urgent surgical intervention, but it is insensitive to insensitive to small hemorrhages, whether from early contusion or from DAI (Diffuse axonal injury). A near normal CT scan in a comatose patient after trauma is a common finding in severe DAI. However, for most moderate and even more severe DAIs, the neurological and neurobehavioral symptoms are not readily explained by CT. A near normal CT scan in a comatose patient after trauma is a common finding in severe DAI.

Although MRI requires a longer imaging time and is not compatible with instruments with magnetic parts, its ability to detect small hemorrhages is greater than that of CT [14]. MRI is increasingly being used to identify injury patterns and secondary effects such as edema, infarction, herniation, and hemorrhage. It is well known that CT often fails to detect DAI and that GRE MRI is superior to spin echo imaging for the detection of hemorrhage [15], particularly hemorrhagic shearing injuries [16]. For traumatic contusions, although CT scans can visualize scattered hemorrhages within the brain parenchyma accompanying the surrounding edema, MRI examination with T2WI can detect lesions with higher sensitivity [17].

MR was found to be superior to CT and to be very effective in the detection of traumatic head lesions and some secondary forms of injury. While T2-weighted images were most useful for lesion detection, T1-weighted images proved to be most useful for anatomic localization and classification [18]. However, the MR imaging appearance of hemorrhage is quite variable and depends on multiple intrinsic parameters such as the state of oxygenation of hemoglobin and the integrity of red blood cells, as well as extrinsic parameters such as the field strength of the MR imaging unit, the receiver bandwith, the type of sequence, and the degree of T1 or T2 weighting. Hemosiderin may be observed histologically even without the identifiable hemorrhages [19], and the presence of hemosiderin has been suggested as a biomarker of parenchymal injury [20, 21]. However, hemosiderin deposits associated with microhemorrhages are often too small to be detected on spin echo MR imaging [22], but they are often detectable months after the injury on GRE MRI [23, 24]. One study using conventional MRI suggested that the presence of hemorrhage in DAI is predictive of poor outcome [25]. Similarly, conventional MRI does not reliably correlate with clinical measurements such as the Glasgow Coma Scale(GCS) [26].

SWI is even more sensitive to hemosiderin deposition and is superior to conventional MRI for detecting microbleeds in the brain after trauma. SWI on MRI is a gradient echo technique with post processing that makes sensitive detection of paramagnetic effects using information from the phase image. It specifically designed to be sensitive to small changes in local magnetic susceptibility in the brain tissue [27]. So this sequence is easy to the improved detection of CMBs and other forms of

Table 1. The clinical data of the 60 patients

Total	60 patients
Age	13-72 years, 39.05 on average
Sex	
Male	37 (61.6%)
Female	23 (38.3%)
Injuring reasons	
Traffic accidents	27 (45%)
Fall accident from high place	13 (21.7%)
Tumble	8 (13.3%)
Hitting	12 (20%)
Clinical manifestations	
Headache, dizziness	60 (100%)
Nausea, vomiting	57 (95%)
Drowsiness	13 (21.7%)
Transient coma	27 (45%)
GCS Score	
9-12	39 (65%)
13-15	21 (35%)

ICH. It utilizes the susceptibility difference between tissues to enhance the "native" contrast of different tissue types.

SWI images were subsequently postprocessed using an inverse procedure to generate susceptibility maps of the veins, which called Susceptibility Weighted Imaging and Mapping (SWIM) by E.M. Haacke and his colleagues. SWIM can successfully create venograms of the brain and would make it easier to image venous vessels independent of their size and orientation [28]. The images present a new form of MR venography and can serve as a quantitative means to distinguish potential oxygen saturation abnormalities in SWI data [29, 30]. The measurement of magnetic susceptibility offers an entirely new form of contrast in magnetic resonance imaging and provides a new quantitative measure of extravasated blood [28, 30, 31]. So in this study, we will use SWIM and conventional MRI sequences to compare the detection of CMBs in patients with a cue and chronic TBI.

Subjects and methods

Study population

60 TBI patients treated in the department of emergency or neurosurgery of the Second Xiangya Hospital of Central South University from Nov 2012 to Dec 2013 were collected in this study (**Table 1**). There were 37 males and 23 females, aged 13 to 72 years old, 39.05 on average. Among the 60 patients, 27 were caused by traffic accident, 13 by falling from a high place, 8 by tumble and 12 by hitting. All patients were right-handed. Meanwhile, all patients received MRI scan in the acute phase (within 72 hours) and chronic phase (1 month later) after injuries, named as group 1 and group 2, respectively. The patients and their relatives were informed in detail of the objective and methods of this study, contraindications of MRI scan, matters needing attention for the patients during scan and possible discomforts. After agreement of the patients and their relatives, they signed the informed consent for MRI. In the scan process, the patients were closely monitored by the researchers, and MRI scan must be discontinued once any discomfort or emergency happened in the patients.

Inclusion criteria: Patients with clear trauma history, who were diagnosed by clinical department, and Glasgow coma scale (GCs) score ≥ 8; Patients with complete clinical information, including clinical manifestations, contact information, injuring reasons and injured sites; Patients who and whose relatives agreed with MRI scan, and who were free of severe cardiac and pulmonary diseases and could tolerate MRI scan for about 30 min; Patients who had no contraindications of MRI and claustrophobia.

Exclusion criteria: Previous history of brain traumatic injuries; Clinical diagnosis of mass lesions, vascular malformation, sinus thrombosis and other history of central nervous diseases; History of drug-abuse, alcohol-abuse and psychiatric diseases; Open traumatic craniocerebral injury; Contraindications of MRI scan.

Scanning devices and preparatory work

The present study employed the Siemens Magnetom 3.0T magnetic resonance imaging system (Skyra, Germany) and the standard cranial 16-channel phased array coils for conventional MRI sequence and SWI sequence. The scan was started after the patients signed the

informed consent form, removed the metal and other prohibited objects on their body and were familiar with the circumstance and experimental procedure. During scanning, the patients lied on their back on the examination bed, adopting the entering way from the head to feet. Moreover, the patients were enjoined to relax, close their eyes and breathe quietly, not to move head, while they kept their long axis parallel to the long axis of the bed. The patients' heads were placed in the cranial coils, and the sagittal location cursor was on the facial midline. The neck and head of patients was fixed with sponge mat. They all wore ear plugs to reduce noise. The scan was started after asking the patients if any discomfort and ensuring everything looked good.

Scan protocol

Conventional MRI sequence: We employed the Siemens Magnetom 3.0T magnetic resonance imaging system (skyra, Germany), standard cranial 16-channel phased array coils and the software Syngo MR B 15. The scan orientations were imaging results from transverse, coronal and sagittal views, of which the transverse view was the basic view. The scan sequences included T2WI spin-echo sequence, T2FLAIR, T1WI fast spin echo, TSE sequence T2WI (TR 4050 ms, TE105 ms), T2FLAIR (TR 7000 ms, TE 120 ms, IR 2000 ms), T1WI (TR 450 ms, TE 15 ms), FOV 190 mm×230 mm, matrix 240×320, layer thickness 0.5 mm, interlayer spacing 0.5 mm, number of layers 25.

SWI sequence: high resolution 3D fully velocity compensated gradient echo sequence was adopted: TR=30 ms, TE=20 ms, flip angle of 15°, thick of layer 2 mm, interlayer spacing 0 mm, scan field FOV 230 mm×230 mm, matrix 220×350, bandwidth 120 Hz, scan time: 6 min 25 s.

SWIM image post processing and analysis

The original image obtained by SWI sequence scan was saved in the format of DICOM in personal computer, and postprocessing was performed using SPIN software (SignalProcess in NeuroMR, SPIN, Detroit, Michigan), showing maximum intensity projection (MIP), combined phase image and magnitude image. The number, morphology and borderline of intracranial injured vessels and hemorrhage lesions were revealed from multiple angles. Two sub-senior radiologists assessed the hemorrhage lesions

and counted the number of lesions revealed by the sequences after achieving agreement; notably, the hemorrhage lesions with suspicion were excluded. The definition of micro hemorrhage lesions was those with a diameter of 2-10 mm [7, 8]. The high signal on SWIM image was counted as intracranial hemorrhage lesions after excluding the small vessel sections, intracranial foreign-bodies, air and the artifacts of skull base in combination of continued layers of phase images. The number of hemorrhage lesions, distribution features, morphological features and the corresponding relationship with the injured vessels detected by conventional MRI sequences and SWIM sequences were recorded respectively.

Statistical analysis

The number of hemorrhage lesions, distribution features, morphological features and the corresponding relationship with the injured vessels on SWIM, T1WI sequence and T2WI sequence within 3 days and after 1 month of TBI were counted respectively, and a comparative analysis was performed. A statistical analysis of all data was conducted with SPSS 13.0, and all statistical tests were two-sided. The measurement data was expressed as mean value-standard deviation. One-way ANOVA test was used for inter-group comparison and for comparison of the number of lesions revealed by various sequences. $P<0.05$ was considered statistically significant.

Results

Comparison of the number of hemorrhage lesions detected by SWIM and conventional MRI sequences in the acute phase of TBI

Among 60 TBI patients, MRI scan within 72 hours after TBI showed 741 (0-75, namely, 0 lesion in the patient having the minimum number of lesions and 75 lesions in the patient having the maximum number of lesions) hemorrhage lesions on conventional MRI T1WI sequence, 772 (0-76) on T2WI sequence, 779 (0-77) on FLAIR sequence, whereas 1105 (2-113) on SWIM images. Statistical differences were found by comparing SWIM image with conventional FLAIR sequence ($P=0.042$), T2WI ($P=0.038$) and T1WI ($P=0.024$). Nevertheless, no statistical difference was observed in the number of hemorrhage lesions between T2WI, T1WI and FLAIR ($P>0.05$) (**Figure 1**).
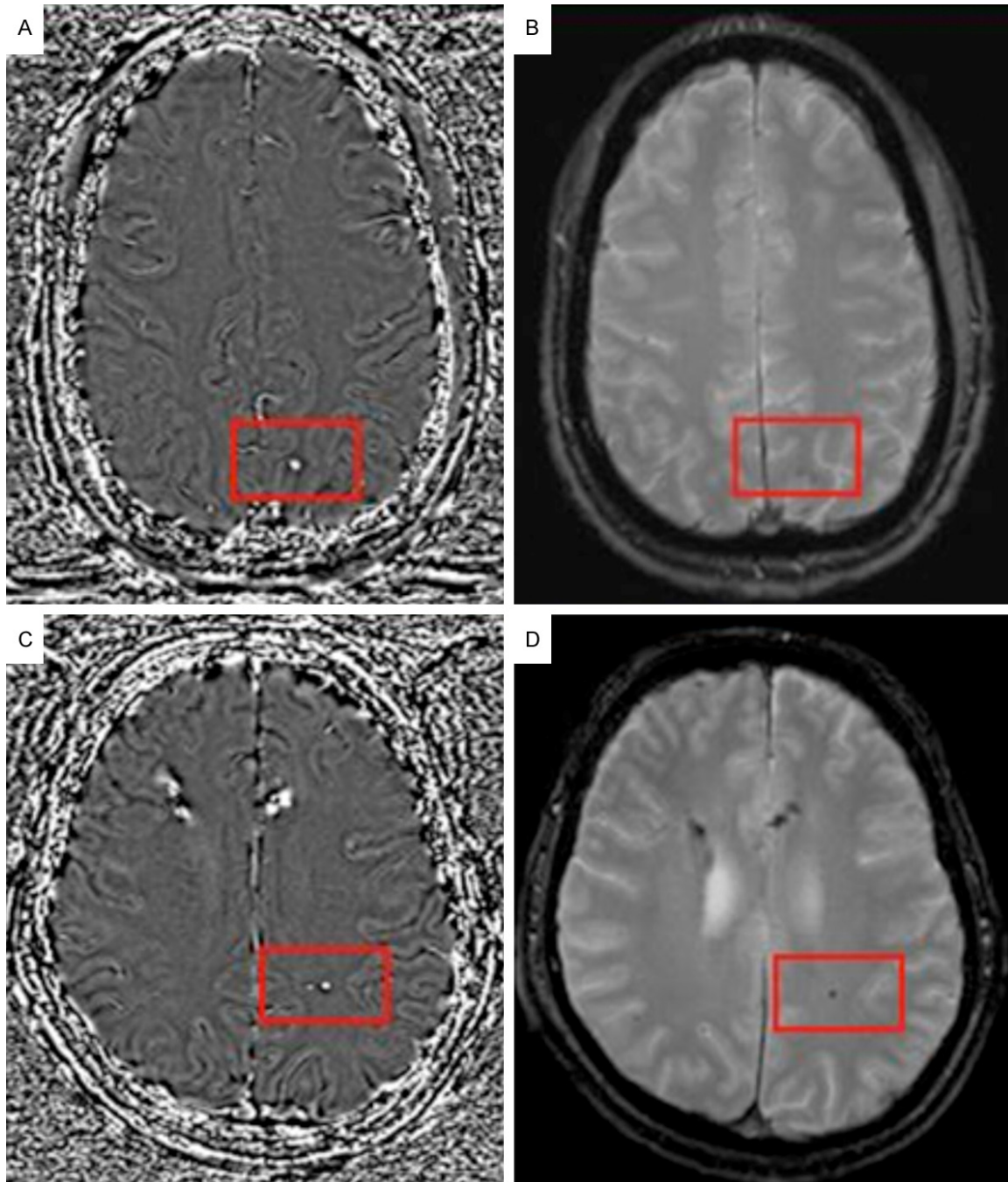
Figure 1. Detection images of hemorrhage lesions in 60 patients within 72 hours after TBI by various MRI sequences (Group 1). A: Male, 24 years, high signal micro hemorrhage lesion at left parietal lobe by SWIM phase; B: The same subject, no signal on the conventional T2WI sequence; C: Female, 35 years, 2 high-signal hemorrhage lesions at left corona radiata by SWIM phase; D: The same subject, only 1 low-signal lesion on the conventional T2WI sequence.

Comparison of the number of hemorrhage lesions detected by SWIM and conventional MRI sequences in the chronic phase of TBI

These 60 TBI patients received MRI scan after 1 month of TBI, and the results showed 627 (0-51) hemorrhage lesions on the conventional MRI T1WI sequence, 652 (0-53) on T2WI sequence, 723 (0-57) on FLAIR sequence, whereas 1001 (2-89) on SWIM image. Statistical differences were found by comparing SWIM image with conventional FLAIR sequence (*P*= 0.040), T2WI (*P*=0.010) and T1WI (*P*=0.007). No statistical difference was observed in the
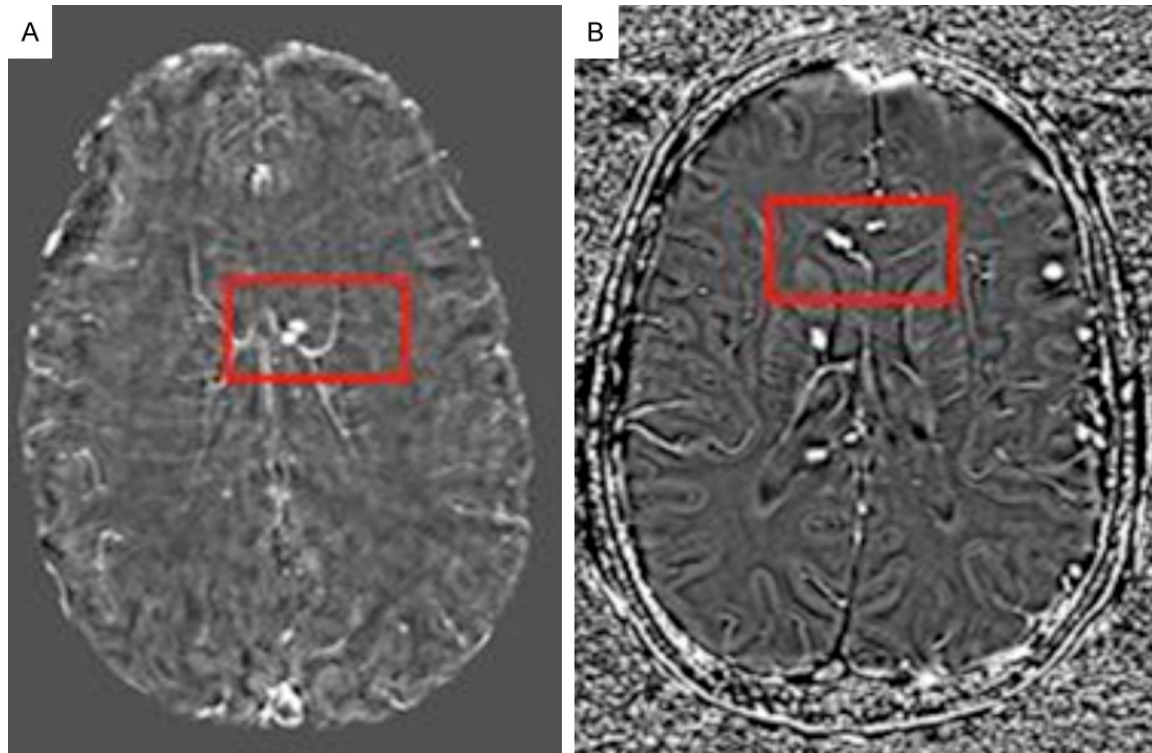
Figure 2. Detection images of hemorrhage lesions of 60 patients 1 month after TBI by various MRI sequences (Group 2). A: Male, 42 years, SWIM image showing venous injury of left thalamus striatum, blurred border of veins, and high signal hemorrhage lesion at the edge of vessel; B: Male, 39 years, SWIM phase image showing injury and hemorrhage of the right septal vein, hemorrhage lesion at the edge of the right septal vein, enlargement in the right septal vein as well as blurred and coarse border.

number of hemorrhage lesions between T2WI, T1WI and FLAIR ($P>0.05$) (**Figure 2**).

Comparison of the relationship between hemorrhage lesions and injured vessels shown by SWIM and conventional MRI sequences in acute phase of TBI

Besides, in revealing the relationship between lesions and intracranial veins, SWIM displayed 57 injured cerebral veins in 44 patients, which manifested as blurred and coarse edges of vessels, and the lesions were located around the injured veins. Among these, the relationship between lesions and veins could be revealed in 41 cerebral veins directly. However, the aforementioned symptoms did not be presented on the conventional MRI sequences (T1WI, T2WI and T2flair).

Presentation of hemorrhage lesions and intracranial veins on SWI and SWIM

On SWI, the hemorrhage lesions and vessels showed low signals. Whereas, on SWIM, the hemorrhage lesions and vein vessels were dis-

played to be high signals, and the vein was manifested as high signals of continued layers, and the superficial veins of the head showed a curving high signal. SWIM images were intuitively presented and had a high distinguishability and recognition performance (**Figure 3**).

Comparison of the number of hemorrhage lesions detected by SWIM and conventional MRI sequences patients in acute phase (within 72 hours) and chronic phase (1 month later) after injuries

As shown in **Table 2**, the results of t-test showed that there were no significant differences of SWI1, FLAIR1, T2WI1 and T1WI1 between patients in acute phase (within 72 hours) and chronic phase (1 month later) after injuries ($P>0.05$).

Discussion

Since Haccke and his colleges overturned SWI into SWIM images in 2010 [28], application of SWIM are reported increasingly. SWIM is able to conduct a quantitative analysis of the cere-
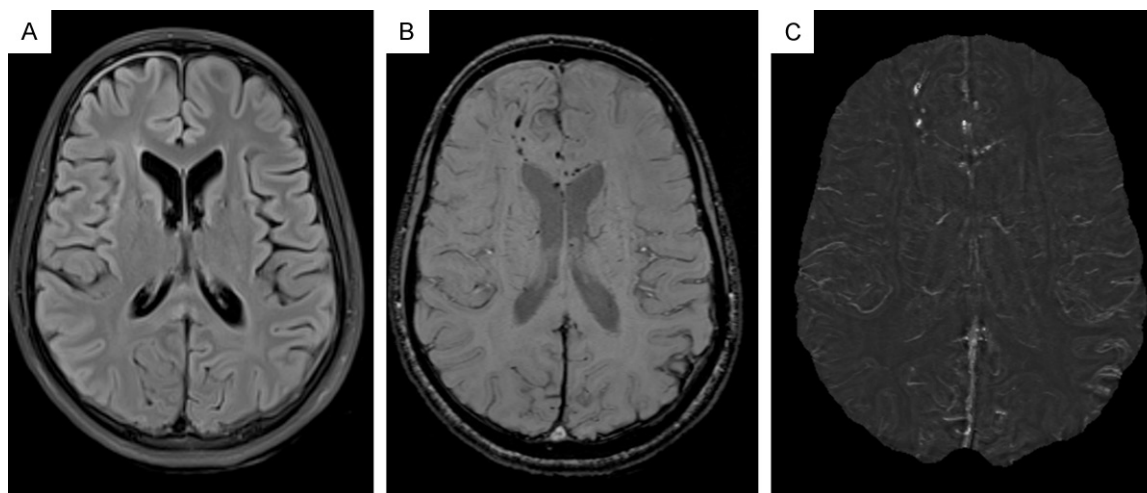
Figure 3. A female patient (38 years old) on 3T (Simens) systems at 1 month after traumatic brain injury (TBI). A: T2 flair imaging shows normal findings; B: SWI sequence shows more low intensity lesions on the same location and corpus callosum; C: SWIM shows high intensity lesions and deep veins.

Table 2. Comparisons of MRI scan indicators between patients in acute phase (within 72 hours) and chronic phase (1 month later) after injuries

	Acute phase (within 72 hours)	Chronic phase (1 month later)	P value
SWI1	18.43±18.46	16.68±15.77	0.578
FLAIR1	12.98±13.25	12.00±11.50	0.665
T2WI1	12.82±13.01	10.87±10.65	0.371
T1WI1	12.35±12.84	10.57±10.41	0.405

bral tissue, non-invasive analysis of the cerebral oxygen saturation [29] and a magnetic sensitive value analysis of the intracranial hemorrhage lesions [32]. A study reported that the total susceptibility of a cerebral microbleed measured by using quantitative susceptibility mapping (QSM) is a physical property that is independent of echo time [7]. There are plenty of reports on the comparison of SWI and conventional MRI sequences in presenting intracranial hemorrhage lesions. Nevertheless, reports on SWIM in revealing the intracranial hemorrhage and comparing SWIM with the conventional MRI sequences are fewer. In addition, for micro hemorrhage lesions at acute and chronic phase, comparative studies of SWIM and conventional MRI sequences do not show similar results.

SWI sequence is a kind of imaging technique employing magnetic sensitive difference between tissues. Using the Fourier transform the phase image treated across frequency fil-

tering is transformed into phase mask, and then treated through weighing calculation with magnitude image, thus inhibiting the negative phase signals of paramagnets such as ferritin and veins to the largest degree. At last, the phase-weighted images of continued layers are projected at minimum intensity to obtain the SWI image of vessels. SWI can show the small veins very clearly and reveal trauma-induced hemorrhage lesions and even micro hemorrhagic spots more sensitively than the conventional MRI sequences. Furthermore, it has a wide clinical application in the cerebral vascular malformation, judgment of benign and malignant tumors and classification and neuro degenerative diseases [33]. SWI is much more sensitive than conventional T2*-weighted GRE sequences in detecting hemorrhagic DAI, more accurate and objective assessment of injury can be obtained early after insult, and may provide better prognostic information regarding duration of coma as well as. SWI has been shown not only to detect tiny hemorrhages that may be the only abnormal finding but also to document the presence of brain injury, which may change management of the patient. In addition, lesion number and volume identified by SWI is negatively associated with patients' outcome [34] and neuropsychological functions [35, 36].

All hemorrhage lesions on SWI showed low signal, but the low signal in the cerebral veins, cerebrospinal fluid and sulus posed a difficulty to observation and analysis sometimes.

Whereas, as SWIM image is overturned, the veins and hemorrhage lesions showed high signal and the sulus and cerebrospinal fluid exhibited low signal, which make it easier to comparatively observe. The veins are presented to be high signal of continued layers, facilitating observation and identification.

In a MRI study in 79 patients with mild to severe cerebral injuries, Spitz et al. [33] found that the number of lesions revealed by SWI sequence was much more than that by FLAIR sequence, and about one-third of the conventional FLAIR sequence didn't reveal clear lesions. SWI sequence preceded the FLAIR sequence in revealing the number of cerebral lesions, lesion sites and micro or diffuse lesions, and is very important in the assessment of cerebral injury degree and the prognosis prediction. According to Kou et al. [37], SWI sequence was better than CT scan in presenting the intracranial hemorrhage lesions and subarachnoid hemorrhage traces. Further, they found that the aliasing effect on SWI phase image is beneficial to distinguish of subarachnoid hemorrhage and veins, and can provide supplemental diagnosis information about subarachnoid hemorrhage and helps to diagnose the patients with less volume of hemorrhage, atypical CT performance or without obvious positive results. From this, it has an important potential value. A study by Wycliffe ND et al. [38] compared SWI sequence with the conventional sequences of T1WI, T2WI, FLAIR and CT. They indicated that SWI sequence can reveal the morphology and size of hemorrhage lesions, and is able to present undetectable micro hemorrhagic spots by other sequences; moreover, SWI sequence is also very sensitive to the morphological alteration of cerebral vessels, providing more assistance in precise location and degree analysis of cerebral injury in order to guide the clinical treatment better.

The present study, based on 60 TBI patients, has indicated that MRI SWIM can reveal clearly the morphological change and degree of injury of cerebral vessels. After MRI scan was performed in the acute phase after injury, SWIM presented more hemorrhage lesions (1105) compared with conventional T1WI (741), T2WI (772), and FLAIR (779) sequence, of whom, 9 patients were found to have hemorrhage lesions only on SWIM but to be normal on the conventional MRI sequences. Namely, in the

acute traumatic cerebral injury, SWIM can identify more hemorrhage lesions than the conventional MRI sequences. Meanwhile, during the reexamination in the chronic phase, SWIM also noted more micro hemorrhage lesions (1001) than the conventional T1WI (627), T2WI (652), and FLAIR (723) sequence. This means that after a period of treatment, some micro hemorrhage lesions are absorbed and disappeared, and the detected micro hemorrhage lesions on various sequences are reduced. Compared with the conventional sequences, however, SWIM is still superior to other sequences. Besides, during the acute phase, SWIM identified injured signs of 57 cerebral veins in 44 patients, which manifested as enlarged vessels, coarse borders and uneven signals. Among the 1105 hemorrhage lesions revealed by SWIM, the origin of bleeding vessels can be verified directly in 41 lesions, which is far more superior to other conventional sequences (T1WI, T2WI and T2flair).

As shown in above, the micro hemorrhage lesions revealed by SWIM on MRI at acute and chronic phase in 60 TBI patients are significantly different from those revealed by conventional T1WI, T2WI and T2flair sequence on MRI. It indicates that SWIM is superior to the conventional sequences in revealing follow-up observations of cerebral trauma-induced micro hemorrhage lesions.

There are several limitations to this study. First, none of the cases were subject to autopsy, and there was no histological confirmation of the hemorrhages in the brain. Thus, we can only speculate the hemorrhages in these injuries. Second, the number of the cases of the current study is rather small and the statistical analyses we made are simple ones. We recognize that more detailed statistical analyses with a larger number of cases are still needed. Third, the population studied was heterogenous and included cases from complicated mild TBI to severe brain injury. And, fourth, the size and volume of the lesions were not analyzed in each sequence, and the focus was not related to clinical symptoms and prognosis. We will carry out further research in the following work.

Conclusion

The application of MRI SWIM in traumatic brain injury has very unique advantages. Briefly, it is much superior to the conventional sequences

in detecting acute or chronic micro hemorrhage lesions after brain injury and determining the corresponding relationship between the lesions and injured vessels. Undoubtedly, SWIM is playing an increasingly important role in the comprehensive assessment and prognosis prediction of traumatic brain injury.

Disclosure of conflict of interest

None.

Address correspondence to: Jun Liu, Department of Radiology, The Second Xiangya Hosipital, Central South University, Changsha 410011, Hunan Province, China. E-mail: liujun_liujundr@163.com

References

[1] McNair ND. Traumatic brain injury. Nurs Clin North Am 1999; 34: 637-659.

[2] Langlois JA, Kegler SR, Butler JA, Gotsch KE, Johnson RL, Reichard AA, Webb KW, Coronado VG, Selassie AW and Thurman DJ. Traumatic brain injury-related hospital discharges. Results from a 14-state surveillance system, 1997. MMWR Surveill Summ 2003; 52: 1-20.

[3] Sosin DM, Sniezek JE and Thurman DJ. Incidence of mild and moderate brain injury in the United States, 1991. Brain Inj 1996; 10: 47-54.

[4] Langlois JA, Rutland-Brown W and Thomas KE. The incidence of traumatic brain injury among children in the United States: differences by race. J Head Trauma Rehabil 2005; 20: 229-238.

[5] Goldstein M. Traumatic brain injury: A silent epidemic. Ann Neurol 1990; 27: 327.

[6] Finkelstein E CP and Miller T. The Incidence and Economic Burden of Injuries in the United States. New York: Oxford University Press; 2006.

[7] Liu T, Surapaneni K, Lou M, Cheng L, Spincemaille P and Wang Y. Cerebral microbleeds: burden assessment by using quantitative susceptibility mapping. Radiology 2012; 262: 269-278.

[8] Cordonnier C, Al-Shahi Salman R and Wardlaw J. Spontaneous brain microbleeds: systematic review, subgroup analyses and standards for study design and reporting. Brain 2007; 130: 1988-2003.

[9] Koennecke HC. Cerebral microbleeds on MRI: prevalence, associations, and potential clinical implications. Neurology 2006; 66: 165-171.

[10] Scheid R, Ott DV, Roth H, Schroeter ML and von Cramon DY. Comparative magnetic resonance imaging at 1.5 and 3 Tesla for the evaluation of traumatic microbleeds. J Neurotrauma 2007; 24: 1811-1816.

[11] Lee SH, Kim BJ and Roh JK. Silent microbleeds are associated with volume of primary intracerebral hemorrhage. Neurology 2006; 66: 430-432.

[12] Greenberg SM, Eng JA, Ning M, Smith EE and Rosand J. Hemorrhage burden predicts recurrent intracerebral hemorrhage after lobar hemorrhage. Stroke 2004; 35: 1415-1420.

[13] Stiell IG, Wells GA, Vandemheen K, Clement C, Lesiuk H, Laupacis A, McKnight RD, Verbeek R, Brison R, Cass D, Eisenhauer ME, Greenberg G and Worthington J. The Canadian CT Head Rule for patients with minor head injury. Lancet 2001; 357: 1391-1396.

[14] Bradley WG Jr. MR appearance of hemorrhage in the brain. Radiology 1993; 189: 15-26.

[15] Atlas SW, Mark AS, Grossman RI and Gomori JM. Intracranial hemorrhage: gradient-echo MR imaging at 1.5 T. Comparison with spin-echo imaging and clinical applications. Radiology 1988; 168: 803-807.

[16] Kuzma BB and Goodman JM. Improved identification of axonal shear injuries with gradient echo MR technique. Surg Neurol 2000; 53: 400-402.

[17] Scheid R, Preul C, Gruber O, Wiggins C and von Cramon DY. Diffuse axonal injury associated with chronic traumatic brain injury: evidence from T2*-weighted gradient-echo imaging at 3 T. AJNR Am J Neuroradiol 2003; 24: 1049-1056.

[18] Gentry LR, Godersky JC and Thompson B. MR imaging of head trauma: review of the distribution and radiopathologic features of traumatic lesions. AJR Am J Roentgenol 1988; 150: 663-672.

[19] Adelson PD, Jenkins LW, Hamilton RL, Robichaud P, Tran MP and Kochanek PM. Histopathologic response of the immature rat to diffuse traumatic brain injury. J Neurotrauma 2001; 18: 967-976.

[20] Oehmichen M, Walter T, Meissner C and Friedrich HJ. Time course of cortical hemorrhages after closed traumatic brain injury: statistical analysis of posttraumatic histomorphological alterations. J Neurotrauma 2003; 20: 87-103.

[21] Raghupathi R and Margulies SS. Traumatic axonal injury after closed head injury in the neonatal pig. J Neurotrauma 2002; 19: 843-853.

[22] Wardlaw JM and Statham PF. How often is haemosiderin not visible on routine MRI following traumatic intracerebral haemorrhage? Neuroradiology 2000; 42: 81-84.

[23] Johnston KC and Marx WF Jr. Microhemorrhages on gradient echo MRI. Neurology 2003; 60: 518.

[24] Ripoll MA, Siosteen B, Hartman M and Raininko R. MR detectability and appearance of small experimental intracranial hematomas at 1.5 T and 0.5 T. A 6-7-month follow-up study. Acta Radiol 2003; 44: 199-205.

[25] Paterakis K, Karantanas AH, Komnos A and Volikas Z. Outcome of patients with diffuse axonal injury: the significance and prognostic value of MRI in the acute phase. J Trauma 2000; 49: 1071-1075.

[26] Scheid R, Walther K, Guthke T, Preul C and von Cramon DY. Cognitive sequelae of diffuse axonal injury. Arch Neurol 2006; 63: 418-424.

[27] Haacke EM, Xu Y, Cheng YC and Reichenbach JR. Susceptibility weighted imaging (SWI). Magn Reson Med 2004; 52: 612-618.

[28] Haacke EM, Tang J, Neelavalli J and Cheng YC. Susceptibility mapping as a means to visualize veins and quantify oxygen saturation. J Magn Reson Imaging 2010; 32: 663-676.

[29] Li M, Hu J, Miao Y, Shen H, Tao D, Yang Z, Li Q, Xuan SY, Raza W, Alzubaidi S and Haacke EM. In vivo measurement of oxygenation changes after stroke using susceptibility weighted imaging filtered phase data. PLoS One 2013; 8: e63013.

[30] Liu S, Neelavalli J, Cheng YC, Tang J and Mark Haacke E. Quantitative susceptibility mapping of small objects using volume constraints. Magn Reson Med 2013; 69: 716-723.

[31] Schweser F, Deistung A, Lehr BW and Reichenbach JR. Quantitative imaging of intrinsic magnetic tissue properties using MRI signal phase: An approach to in vivo brain iron metabolism? Neuroimage 2011; 54: 2789-2807.

[32] Liu J, Xia S, Hanks RA, Wiseman NM, Peng C, Zhou S, Haacke EM and Kou Z. Susceptibility Weighted Imaging and Mapping of Microhemorrhages and Major Deep Veins after Traumatic Brain Injury. J Neurotrauma 2016; 33: 10-21.

[33] Spitz G, Maller JJ, Ng A, O'Sullivan R, Ferris NJ and Ponsford JL. Detecting lesions after traumatic brain injury using susceptibility weighted imaging: a comparison with fluid-attenuated inversion recovery and correlation with clinical outcome. J Neurotrauma 2013; 30: 2038-2050.

[34] Tong KA, Ashwal S, Holshouser BA, Nickerson JP, Wall CJ, Shutter LA, Osterdock RJ, Haacke EM and Kido D. Diffuse axonal injury in children: clinical correlation with hemorrhagic lesions. Ann Neurol 2004; 56: 36-50.

[35] Babikian T, Freier MC, Tong KA, Nickerson JP, Wall CJ, Holshouser BA, Burley T, Riggs ML and Ashwal S. Susceptibility weighted imaging: neuropsychologic outcome and pediatric head injury. Pediatr Neurol 2005; 33: 184-194.

[36] Babikian T, Tong KA, Galloway NR, Freier-Randall MC, Obenaus A and Ashwal S. Diffusion-weighted imaging predicts cognition in pediatric brain injury. Pediatr Neurol 2009; 41: 406-412.

[37] Kou Z, Wu Z, Tong KA, Holshouser B, Benson RR, Hu J and Haacke EM. The role of advanced MR imaging findings as biomarkers of traumatic brain injury. J Head Trauma Rehabil 2010; 25: 267-282.

[38] Wycliffe ND, Choe J, Holshouser B, Oyoyo UE, Haacke EM and Kido DK. Reliability in detection of hemorrhage in acute stroke by a new three-dimensional gradient recalled echo susceptibility-weighted imaging technique compared to computed tomography: A retrospective study. J Magn Reson Imaging 2004; 20: 372-377.