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

Shu-Ping Peng¹, Yan Qin¹, Shun-Ke Zhou¹, Zhi-Yuan Wang², Zi-Shu Zhang¹, Fang-Xu Tao¹, Zhi-Xue Zhang¹, Yi-Ning Li¹, Yu-Dong Xiao¹, Hai-Yan Liao¹, Jun Liu¹

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

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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 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 DAls, 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 bandwidth, 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
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 craniocebral 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

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**Table 1. The clinical data of the 60 patients**

<table>
<thead>
<tr>
<th>Total</th>
<th>60 patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>13-72 years, 39.05 on average</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>37 (61.6%)</td>
</tr>
<tr>
<td>Female</td>
<td>23 (38.3%)</td>
</tr>
<tr>
<td>Injuring reasons</td>
<td></td>
</tr>
<tr>
<td>Traffic accidents</td>
<td>27 (45%)</td>
</tr>
<tr>
<td>Fall accident from high place</td>
<td>13 (21.7%)</td>
</tr>
<tr>
<td>Tumble</td>
<td>8 (13.3%)</td>
</tr>
<tr>
<td>Hitting</td>
<td>12 (20%)</td>
</tr>
<tr>
<td>Clinical manifestations</td>
<td></td>
</tr>
<tr>
<td>Headache, dizziness</td>
<td>60 (100%)</td>
</tr>
<tr>
<td>Nausea, vomiting</td>
<td>57 (95%)</td>
</tr>
<tr>
<td>Drowsiness</td>
<td>13 (21.7%)</td>
</tr>
<tr>
<td>Transient coma</td>
<td>27 (45%)</td>
</tr>
<tr>
<td>GCS Score</td>
<td></td>
</tr>
<tr>
<td>9-12</td>
<td>39 (65%)</td>
</tr>
<tr>
<td>13-15</td>
<td>21 (35%)</td>
</tr>
</tbody>
</table>
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, TE 105 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 save 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).
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
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 displayed 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-
SWI and conventional MRI sequences in cerebral microbleeds

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

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Acute phase (within 72 hours)</th>
<th>Chronic phase (1 month later)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWI1</td>
<td>18.43±18.46</td>
<td>16.68±15.77</td>
<td>0.578</td>
</tr>
<tr>
<td>FLAIR1</td>
<td>12.98±13.25</td>
<td>12.00±11.50</td>
<td>0.665</td>
</tr>
<tr>
<td>T2WI1</td>
<td>12.82±13.01</td>
<td>10.87±10.65</td>
<td>0.371</td>
</tr>
<tr>
<td>T1WI1</td>
<td>12.35±12.84</td>
<td>10.57±10.41</td>
<td>0.405</td>
</tr>
</tbody>
</table>

SWI sequence is a kind of imaging technique employing magnetic sensitive difference between tissues. Using the Fourier transform the phase image treated across frequency filtering 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 Hospital, Central South University, Changsha 410011, Hunan Province, China. E-mail: liujun_liujundr@163.com

References

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