Early-Stage Investigations of Ultrasmall Superparamagnetic Iron Oxide-Induced Signal Change After Permanent Middle Cerebral Artery Occlusion in Mice

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Background and Purpose—MR signal changes after intravenous ultrasmall superparamagnetic iron oxide (USPIO) injection are related to inflammatory cells at the subacute stages after focal cerebral injury. However, at the early stages, the interpretation of USPIO-related MR signal alterations remains controversial. Here, we compared MR signal changes after intravenous USPIO injection with the histological iron and macrophage distribution during the first 24 hours in a rodent model of acute stroke.

Methods—Multiparametric MRI at 7T and histological USPIO distribution were confronted from 6 to 24 hours after permanent middle cerebral artery occlusion in mice. Blood–brain barrier disruption was assessed using gadolinium MRI and immunoglobulin staining. Prussian blue staining was performed to depict the USPIO brain distribution. USPIO uptake by phagocytes was assessed by immunochemistry on brain tissue, peripheral blood cells, and monocyte cells derived from bone marrow culture.

Results—After USPIO injection, 4 areas of early signal change were observed on every MRI. In all these areas, iron particles were mostly free whether detected in the vascular and cerebrospinal fluid compartments or in the interstitium. Within the first 24 hours, USPIO-loaded cells were not detected in the blood of injured mice or in cultured monocytic cells incubated with USPIO at plasmatic concentration.

Conclusions—These results suggest that, in this model, early reproducible USPIO-related MR signal changes are mainly caused by passive diffusion of free USPIO after blood–brain barrier leakage and by intravascular trapping rather than by peripheral phagocyte infiltration. (Stroke. 2009;40:1834-1841.)

Key Words: brain ischemia ■ inflammation ■ magnetic resonance imaging ■ ultrasmall superparamagnetic particles of iron oxide

Neuroinflammation is a crucial pathogenic mechanism in ischemic stroke. Postischemic inflammation is dominated by cells of the mononuclear phagocyte system comprising resident microglia and bloodborne macrophages. Noninvasive monitoring of these cells may improve the understanding of the time course of postischemic brain inflammation. Accordingly, there is a real need for novel imaging techniques, specifically detecting inflammatory cells in vivo.

Ultrasmall superparamagnetic nanoparticles of iron oxide (USPIOs) are taken up by mononuclear phagocytic cells after intravenous injection and have been recently introduced as an MRI contrast agent marking macrophages/microglia in inflammatory lesions. In various models of experimental brain ischemia, accumulation of iron oxide particles has been observed in the infarct zone during the subacute stages of lesion development. After 24 hours postischemia, most iron-related signal changes on MRI are indisputably paralleled by phagocyte-associated iron deposition detected on histology. Recent pilot studies have also used USPIO-enhanced MRI to assess neuroinflammation in human ischemic stroke.

However, at the early stages after experimental focal cerebral ischemia, USPIO-related MRI signal alterations are difficult to interpret. The exact route of USPIO uptake and brain distribution remains elusive, hampering the interpretation of USPIO-related signals. Three hypotheses have been proposed to explain the MRI signal changes observed after USPIO injection: (1) intravascular trapping of iron particles; (2) USPIO uptake by phagocytes on the assumption...
that USPIOs are primarily taken up by circulating phagocytes; and (3) interstitial iron particle diffusion into damaged tissue after nonspecific leakage through a disrupted blood–brain barrier.10,11

To assess the acute course of iron particles, MRI signal changes after intravenous USPIO injection were compared with the histological iron and macrophage distribution from 6 to 24 hours after permanent middle cerebral artery occlusion in mice.

Materials and Methods

All animal experiments were performed in accordance with institutional guidelines.

Induction of Focal Cerebral Ischemia

Focal cerebral ischemia was induced under anesthesia with 12 mg/kg xylazine and 90 mg/kg ketamine by permanent middle cerebral artery occlusion (pMCAO) using an operating microscope as described previously.12

Contrast Agents

Ferumoxtran-10 (Sinerem) USPIO contrast agent was provided by Guerbet (Aulnay-sous-Bois, France). A dose of 2 mmol iron/kg body weight (0.15 mL) was injected intravenously into the tail vein 5 hours postinjury.13 Natrium chloride 9% (vehicle alone) was used as a control contrast agent. To assess blood–brain barrier (BBB) integrity, DOTA-gadolinium (Dotarem; Guerbet) was administered intravenously at 0.5 mmol/kg.

Protocol

Fifty-one male Swiss mice were included (weight, 25 to 30 g; Charles River, L’Arbresle, France). Of these, 31 were examined both by MRI and histology according to the experimental design detailed in Figure 1. Briefly, animals were imaged before and after contrast agent injection and euthanized after the last MR examination, ie, either at Day 0 (6 hours postinjury) or at Day 1 (24 hours postinjury). On analysis, some USPIO-related hypointensities repeatedly observed on MRI did not correlate with Prussian blue positive staining. An additional set of 15 USPIO-injected mice was therefore studied exclusively by histology, including a different brain preparation procedure (n=8 at 6 hours: 6 pMCAO and 2 controls, and n=7 at 24 hours: 5 pMCAO and 2 controls). To investigate intermediate time points, 5 additional pMCAO mice were euthanized between 8 hours and 13 hours postinjury.

Magnetic Resonance Imaging

MRI was performed at 7T (Bruker Biospec) using a birdcage coil for transmission and a surface coil for reception. For all scans, the field of view was 20×20 mm², slice thickness 1.0 mm, number of slices 15, and matrix size 256×256 (except diffusion matrix: 128×128). The MRI protocol, which lasted approximately 45 minutes, comprised the following scans: gradient-echo (GRE) T1-weighted images (WI); TE/TR=3.5/157.5 ms, α=50°; spin-echo T2-WI: TE/TR=75/3000 ms; multi spin-echoes sequence (T2 maps): TE (interecho delay)/TR=11.4/4000 ms, 8 echoes; and diffusion-WI (apparent diffusion coefficient maps): TE/TR=14/2000 ms; b-values: 138, 554, and 1060 s/mm².

Histology and Immunohistochemistry

In a first set of experiments, USPIO was detected in cerebral tissue of paraformaldehyde-fixed brains obtained from experimental or control animals that were intracardially perfused with 4% paraformaldehyde.13 In a second set of experiments, in an attempt to improve detection of USPIO, brains were removed and snap-frozen after brief intracardiac phosphate-buffered saline perfusion. Immunohistochemistry (rat antimouse F4/80 antibody for microglia/macrophage detection [clone MCA497; Serotec, Oxford, UK], rat anti-mouse CD31 antibody for endothelial cell detection [clone MEC13.3; BD Pharmingen, San Jose, Calif] and/or Prussian blue coloration for USPIO detection were performed on cryostat sections as previously described.13 For immunoglobulin deposit detection, brain sections were incubated with biotinylated sheep antimouse secondary antibody and peroxidase activity was visualized using diaminobenzidine supplemented with nickel ammonium sulfate solution. To exclude any background staining due to the presence of endogenous peroxidase, sections were systematically pretreated with 0.3% hydrogen peroxide and methanol for 30 minutes.

Generation and Labeling of Bone Marrow-Derived Macrophages and Monocytic Cells

Total bone marrow (BM) cells flushed out from the tibiae and femur of 12-week-old C57BL/6 mice were cultured as previously described.14 BM-derived macrophages were then obtained by trypsinizing adherent cells 7 days after plating. Alternatively, BM-derived monocyctic cells were obtained by harvesting nonadherent cells 3 days after plating as previously described.14

Flow Cytometry

Flow cytometry, as described previously,14 used the conjugated phycoerythrin-labeled anti-cd11b (clone M1/70) Ab (BD Pharmingen).

In Vitro USPIO Labeling

Cell cultures were incubated for 24 hours in absence (vehicle-treated) or in the presence of USPIO (iron concentration=2 mg/mL) or arionic superparamagnetic nanoparticles anionic (iron concentration=1 mmol/L) as a positive cell labeling control (provided by Nano-H, Lyon, France).15 Immediately after labeling, cells were collected and cytospots were prepared on glass sides with centrifugation.

Analysis of Peripheral Blood Samples

Blood samples were taken from 15 mice. In a first set of experiments, 2 blood samples were taken serially (at 6 hours and 24 hours post-pMCAO) by retro-orbital puncture of 8 mice injected with USPIO. In other experiments, blood samples were taken from 7 pMCAO mice, just before being euthanized. 1 hour after injection of USPIO (n=2) or vehicle alone (n=1) or 19 hours after injection of USPIO (n=2) or vehicle (n=1). Blood samples were then treated by EasyLyse (Dako) to lyse erythrocytes or centrifuged over a Ficoll gradient to eliminate red cells and granulocytes. Cells were then cytospun and assessed for presence of iron particles.

Histochemical Detection of Intracellular Iron in Blood Mononuclear Cells, BM-Derived Macrophages or BM-Derived Monocytic Cells

The presence of iron particles was detected by using Prussian blue staining on cytospin cells. The presence of iron oxide was assessed qualitatively by optical microscopy.
Results

All animals survived the protocol.

USPIO-MR Signals in Focal Cerebral Ischemia

Permanent middle cerebral artery occlusion resulted in a reproducible focal lesion in the ipsilateral dorsolateral cortex detected as an apparent diffusion coefficient decrease and heterogeneous hyperintense signal on T2-WIs on precontrast MRI at 4 hours post-pMCAO.

In all pMCAO/USPIO mice, 4 areas of consistent signal changes were observed on post-USPIO GRE and T2 imaging at 6 hours and 24 hours. An early marked signal dropout was first detected in the border zone (Area I) of the lesion 1 hour postinjection and persisted 24 hours post-pMCAO (respectively, Figures 2A and 2B).

In the third ventricle and the 2 hippocampus regions (Area II), strongly contrasted hypointense signal lines appeared early after USPIO injection (Figure 3A–B). The hypointensity of the upper dark line (circled on magnification of Figure 3A–B), which anatomically corresponded to the hippocampal lacunar molecular layer, decreased between Hours 6 and 24, unlike the other hypointense lines of this area, which corresponded anatomically to the velum (arrows on magnification of Figure 3A–B).

Along the lateral ventricles (Area III), signal loss was observed at 6 hours (Figure 4B) and 24 hours post-pMCAO (Figure 4C).

Finally, a hyperintense signal was observed in the corpus callosum (Area IV) on GRE T1-weighted imaging (Figure 3B, arrows) with a corresponding signal decrease on T2 maps (Figures 2B, 4C, and Figure 5I, arrows). None of the described MR signal alterations were observed in control pMCAO mice not injected with USPIO. These control mice are presented on T1-WI (Figure 5D) and on T2-WI (Figures 4A and 5F–G). In nonoperated USPIO-
injected control mice, organized signal loss, anatomically corresponding to vessels, was seen on GRE imaging after injection at 6 hours and, to a lesser extent, at 24 hours.

**Histological Distribution of Iron and Phagocytes in Each Area of USPIO-MR Signal Change**

Iron particles were exclusively observed in the areas of reproducible MR signal change after USPIO injection and not in any other part of the brain.

**Area I: Perilesional Zone**

In the perilesional zone, iron staining was visualized exclusively within the blood vessels at 6 hours (Figure 2C) and 24 hours (Figure 2D) in all fixed brains. Vascular localization was furthermore demonstrated by double staining with anti-CD31 for endothelium visualization (Figure 2D). Very few F4/80+ phagocyte cells were present in the perilesional area at these early stages postsclerosis (Figure 2E) in line with a previous study. In the current work, these F4/80+ phagocyte cells were always without iron particles. The unfixed procedure confirmed this vascular localization, but also showed some sparse interstitial Prussian blue staining (extracellular and extravascular; Figure 2F–G).

**Area II: Third Ventricle and Hippocampus Regions**

In this area, at 6 hours and 24 hours, iron staining was present in the vela (Figure 3C–D, arrows), which correspond to prolongations of the pia matter in the brain bathed by cerebrospinal fluid (CSF) and containing vessels. Iron staining was also detected in the vessels of the lacunar molecular layers of the hippocampi (Figure 3C–D). The unfixed brain procedure was clearly better for visualizing free iron particles in this area (in 100% of brains versus 45% in fixed tissue). Using double staining with F4/80 antibody for phagocytes on fixed tissue, few iron-labeled macrophages were detected in the periependymal zone of the third ventricle (Figure 3E–F) or in the vela interposita (perivascular and meningeal phagocytes).

**Area III: Along the Lateral Ventricles**

In this area, iron particles were not observed in the lumen of the ventricle of fixed brains. In contrast, iron staining was detected in the ventricle and the choroid plexus of all unfixed brains (Figure 4E–F) at 6 hours post-pMCAO. In half of these unfixed brains, interstitial iron particles were also detected in the subependymal region (Figure 4E–F).

At 24 hours, iron staining of the choroid plexus remained intense, whereas lumen iron staining disappeared with both fixation procedures. In contrast, the subependymal diffusion increased at 24 hours. As already seen in the border zone of the lesion, very few F4/80+ phagocyte cells were present at these early postsclerosis stages (Figure 4D) and always without iron particles.
Area IV: Corpus Callosum

Surprisingly, no iron staining was observed in the first 24 hours post-pMCAO whether on fixed or unfixed tissue despite a marked and reproducible iron-related MR signal. At 6 hours, there were some F4/80-positive cells in the ipsilateral corpus callosum. F4/80 immunostaining increased at 24 hours with marked phagocyte staining in the whole corpus callosum (data not shown), but without iron particles.

Histological Distribution of USPIO and Phagocytes in Control Mice

In nonoperated USPIO-injected mice, iron staining was observed in vessels and the vascular stroma of the choroid plexus on histology. There was no iron staining in the parenchyma, vessels, or CSF compartments (ventricles, vela) in noninjected mice. In pMCAO mice without USPIO injection, like in pMCAO+USPIO mice, very few F4/80-positive phagocyte cells were present at these early posts ischemia stages in the border zone of the lesion. Likewise, there were only a few F4/80-positive cells in the ipsilateral corpus callosum at 6 hours in pMCAO mice with marked phagocyte staining in the whole corpus callosum at 24 hours.

Assessment of Early BBB Disruption and Diffusion of Immunoglobulins

To test the hypothesis of USPIO leakage through a damaged BBB, the relationships between USPIO-induced signal change on the one hand and presence of a vasogenic edema and BBB integrity on the other were assessed. MRI analysis after DOTA-gadolinium injection showed T1 enhancement of the lesion over time and allowed early BBB breakdown to be demonstrated in the whole lesion at 6 hours (Figure 5D–E) and also at 24 hours. On histology, IgG immunostaining was performed to visualize plasma molecules that had entered the brain through a disrupted BBB. IgG immunostaining in the lesion (Figure 5A) and along the corpus callosum (Figure 5B–C) was colocated with (1) vasogenic edema detected as hyperintensity on T2-weighted images at 6 hours (Figure 5F: lesion and ipsilateral corpus callosum, arrow) and 24 hours (Figure 5G: ipsilateral and contralateral corpus callosum, arrows) in pMCAO mice; and (2) T2 decrease after USPIO injection in pMCAO+USPIO mice (Figure 5H: perilesion and ipsilateral corpus callosum, arrow and Figure 5I: ipsilateral and contralateral corpus callosum, arrows).

USPIO Not Detected in Blood Mononuclear Cells in the First 24 Hours Postinjury

Prussian blue staining of peripheral blood mononuclear cell cytospots did not detect any iron-stained mononuclear cells in blood samples taken in the first 24 hours postinjury in injected mice (data not shown).

Very Weak USPIO Uptake by BM-Derived Monocytic Cells or BM-Derived Macrophages

Analyzing the ability of blood monocytes to ingest USPIO in vitro is difficult; specific culture conditions are required, including adherence to plastic, that alter monocyte functions. Here, USPIO uptake capacity was compared in 2 myeloid cell populations: BM-derived monocytic cells, which can be considered as immediate precursors of blood monocytes, and BM-derived macrophages. BM culture phenotypes were assessed by fluorescence activated cell sorting analysis (Figure 6A–B). After 24 hours with USPIO, no USPIO uptake by monocytic cells was observed and very little if any by BM-derived macrophages (Figure 6C–D, respectively). In contrast, USPIO uptake was detectable after 48 hours of incubation (data not shown) and BM-derived macrophages and monocytic cells efficiently ingested anionic superparamagnetic nanoparticles (Figure 6E–F).
Discussion
The present study observed consistent MRI signal changes after intravenous USPIO injection at 6 hours and 24 hours postinjury. Histological analysis showed that iron staining was mostly associated with the vascular and CSF compartments. Interestingly, at early time points, only brain phagocytes in contact with CSF had already phagocytized USPIO. USPIO-loaded cells were not detected in the blood of injured mice within the first 24 hours. In addition, cultured monocytic cells derived from BM cultures did not display phagocytic activity toward USPIO after 24 hours of incubation at plasmatic concentration. This suggests that, in this specific model of pMCAO, early USPIO enhancement in the brain is mainly caused by nonspecific mechanisms such as BBB leakage and intravascular trapping rather than by peripheral phagocyte infiltration.

It has been claimed that USPIO-enhanced MRI essentially reflects the recruitment of blood-circulating USPIO-loaded monocytes into inflamed tissue, thus demonstrating late-stage inflammation. It cannot be ruled out that, during later stages, monocytes or a subpopulation of activated and/or inflammatory monocytes acquire the ability to phagocytize USPIO. However, our results demonstrate that USPIO-induced MR alterations do not univocally reflect the entry of USPIO-loaded monocytes in the ischemic brain. They further suggest that, at early postischemia time points, USPIOs penetrate in the central nervous system as free particles, BBB disruption being attested by the presence of both gadolinium-enhanced lesions and immunoglobulin deposits. Accordingly, although detection of free USPIOs is probably hampered by standard histological analysis procedures (in vivo perfusion, fixatives, multiple baths), extracellular uptake of USPIO particles within the central nervous system parenchyma of ischemic brains was detectable. Because the interstitial fluid of brain parenchyma is drained into the CSF compartment, our data suggest that USPIOs may circulate as free particles from blood to brain parenchyma and from brain parenchyma to CSF. This hypothesis is further supported by the detection of USPIO in meningeal macrophages (comprising those residing in the velum) and periependymal microglia, 2 populations of brain-resident phagocytes that localize in CSF-bathed areas. The detection of USPIOs in perivascular macrophages is also in accordance with the presence of free USPIOs in the interstitial fluid. Indeed, perivascular macrophages, more than microglia, have been shown to quickly phagocytize antigens and particles circulating in the interstitial fluid of brain parenchyma. Also, providing that free USPIO particles gain access to the CSF, it may be hypothesized that they subsequently penetrate periventricular parenchyma areas and are taken up by activated microglia. It is
noteworthy in this regard that, after the first 48 hours after experimental stroke, USPIOs are detected in the cytoplasm of microglial cells that localize in periventricular parenchymal areas. Finally, free USPIO particles may also enter the CSF compartment through an altered blood/CSF barrier at the level of the choroid plexi.

A hyperintense signal was observed on T1-weighted GRE images in the corpus callosum on Day 1 in pMCAO + USPIO mice exclusively in line with a previous study. However, surprisingly, we did not obtain any iron staining in this location. Failure to detect iron particles in the corpus callosum might be due to the well-documented lack of sensitivity of Prussian blue to interstitial USPIO (as opposed to iron compartmentalized in vessels or in cells). There are indeed a number of indirect indications of the presence of free USPIOs in the corpus callosum: hyperintensity on T1-WI and IgG immunostaining in spatiotemporal agreement with signal change on T2-WI after USPIO injection. Taken together, these data suggest that USPIO have diffused along with edematous fluid, probably after nonspecific leakage secondary to BBB disruption. This result further underlines the fact that free USPIOs cannot be definitely asserted to be absent in tissue simply on the grounds of lack of positive Prussian blue staining. Fluorescent iron oxide nanoparticles and/or electronic microscopy may help validate this hypothesis in the future.

Despite abundant evidence of an inflammatory response after stroke, anti-inflammatory treatment has so far failed in clinical trials. In this context, noninvasive detection of inflammatory cells after brain ischemia could be helpful (1) to select patients who may benefit from anti-inflammatory treatment; and/or (2) to target the potential therapeutic time window. For this purpose, MRI coupled with USPIO, a contrast agent thought to be taken up by macrophages in vivo, appears a promising tool to provide noninvasive information about neuroinflammation. In early clinical studies, no USPIO enhancement was observed 24 hours to 48 hours after USPIO injection or 2 to 4 days after stroke onset in most patients, whereas MR signal changes were consistently observed in studies performed at 5 to 6 days after stroke. The heterogeneous patterns of USPIO enhancement between patients are probably critically dependent on the timing of contrast agent injection relative to stroke onset, but also on the time window of the subsequent MRI scans. Altogether our results demonstrate that further investigation will be necessary to analyze patients’ MRIs with USPIO at early stages after stroke onset. In this perspective, the development of new MR strategies allowing unambiguous discrimination of free USPIOs versus USPIO-labeled cells as well as systematic investigation of potential pitfalls in MR data interpretation are clearly needed to validate the interest of the USPIO-enhanced MRI in larger cohorts.

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Disclosures

None.

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