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Review Article

High resolution small animals dedicated magnetic resonance scanners as a tool for laboratory rodents central nervous system imaging

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ABSTRACT

Introduction: Magnetic resonance imaging (MRI) is a noninvasive technique applied in medical diagnosis and for studying animal models of human diseases. MRI offers longitudinal *in vivo* studies without the need to sacrifice animals, thus making data easier to compare. The number of required animals can be limited.

Aim: The aim of this article was to present the role of dedicated small animal MRI scanners in the management of central nervous system visualization and injury in rodents on the basis of the current literature.

Material and methods: Highly specialized animal MRI scanners with a high magnetic field and small bores are used for imaging the nervous system of rodents *in vivo*. Compared to clinical scanners currently operating at magnetic field strengths of up to 3.0 T, dedicated animal MRI scanners operate at higher field strengths between 4.7 T and 14.1 T.

Results and discussion: Small animal imaging results in the reduction of image quality. It is caused by a small signal-to-noise ratio (SNR). The way to increase the SNR is to apply a high magnetic field. Animal MRI scanners operating at higher field strengths between 4.7 T and 14.1 T allow researchers to obtain images with high resolution, and with clearly visible structures of rodent neuroanatomy. Although MRI diagnostics is very useful in neurobiological experiments, the major drawback of dedicated animal MRI scanners is their high cost.

Conclusions: High resolution dedicated small animal scanners of up to 14.1 T are best suited for rodent neuroanatomy imaging as well as for neurobiological experiments and their results.

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1. Introduction

Magnetic resonance imaging (MRI) is the widely used method for imaging whole body structures. The quality of obtained images is enhanced by an increase in magnetic field strength. It provides the possibility of imaging smaller structures.

MRI provides an opportunity to monitor lesions *in vivo* in experimental therapies, with the use of animal models, such as rats and mice, in order to transpose results for the planning of clinical examinations. This method contributes to reducing both costs and the number of animals needed.

Using clinical MRI scanners is connected with the problem of small object volume. It is important to increase the signal-to-noise-ratio (SNR). The way to increase the SNR is to use a high magnetic field. Thus, high resolution dedicated animal scanners have been used for small animal imaging.[17] These scanners are characterized by a high magnetic field strength between 4.7 T and 14.1 T. Dedicated animal scanners allow for an improved SNR, reduce the time of examination, improve resolution, and reflect cortex oxygenation better.[18] The main disadvantage is the high cost of the apparatus, as compared to clinical scanners.

2. Aim

The aim of this paper is to present the role of the dedicated small animal MRI with respect to the management of the central nervous system (CNS) anatomy and injury in rodents on the basis of the current literature.

3. Material and methods

Highly specialized animal MRI scanners with a high magnetic field and small bores are used for imaging the nervous system of rodents *in vivo*. Compared to clinical scanners currently operating at magnetic field strengths of up to 3.0 T, dedicated animal MRI scanners operate at higher field strengths between 4.7 T and 14.1 T.

4. Results

4.1. *Scanners with a magnetic field strength of 4.7 T*

A dedicated animal Varian scanner (Oxford Systems) and transmit/receive coil with an inner diameter of 63 mm was used by Modo et al.[16] The experiments were performed on Sprague-Dawley rats weighing 280–330 g. In part of the group ischemic damage was induced by provoking a middle cerebral artery occlusion (MCAo, rat model of stroke). Then, 3 months following the induction of MCAo, neural stem cells (NSCs) were transplanted into the contralateral hemisphere. NSCs were labeled by gadolinium rhodamine dextran (GRID). Animals were anesthetized with isoflurane in a mixture of 30% O_2 and 70% N_2O. It was discovered that NSCs migrated from the injection site via the corpus callosum into the lesioned area. On T1-weighted images an insignificant number of cells were detected; however, on T2-weighted images cells were easily identified from host cells. Proton density-weighted images also visualized the injected cells, but not as clearly as T2-weighted ones. In the control group (without stroke) cell migration was observed only around the injection area. Histological analysis with a fluorescent microscope confirmed the observations obtained through MRI. Immunohistochemical analysis with fluorescent labeled antibodies for the identification of astrocytes and neurons, allowed for distinguishing of astrocytes and neurons differentiated from the injected stem cells. Imaging parameters are presented in Table 1.

A dedicated animal Varian scanner (Varian Inc., Paolo Alto, CA, USA) with a magnetic field strength of 4.7 T was used in experiments with stem cells.[14] Adult female C3H mice weighing 25-35 g, and neonatal C3H/SCID mice were used. Adult mice were anesthetized with 5 mg/kg xylazine and 100 mg/kg ketamine, then SPIO-labeled C17.2 NSCs were injected into the cortex and hippocampus. Labeled cells were injected into the right hemisphere, and unlabeled ones into the right hemisphere as a control. Neonatal mice were cryo-anesthetized and labeled cells were injected into the cerebral ventricles. Neonatal mice with unlabeled NSCs or *phosphate-buffered saline* (PBS) injected into the cerebral ventricles were used as the control group for the second group. *In vivo* MR imaging was performed 4 weeks following the injections in adult mice, and 7 weeks following the injections in neonatal mice. Next, *ex vivo* imaging was performed on the 9.4 T vertical bore magnet. In adult mice until the 32nd day after the transplantation, labeled cells were detectable in the hypointense area near the injection site. During the *in vivo* experiment on neonatal rats, labeled cells were not detectable. The presence of labeled cells was found out in *ex vivo* studies as a hypointense area, especially in the olfactory bulb, cortex, hippocampus and the cerebellum. In the control group no hypointense areas were visualized. After MR imaging, histological tests were conducted, and the results were consistent with MRI scans. Imaging parameters are presented in Table 1.

A Bruker Biospec Avance 47/40 scanner (Bruker, Karlsruhe, Germany) with surface coil was used to visualize spinal cord injury in rats.[9] Female Sprague-Dawley rats, weighing 250–300 g, were used in the experiment. The rats' spinal cords were transected at the midthoracic level; rats with unlesioned spinal cords served as control groups. Groups of rats 2–3, 4 and 6 months after the transection and control groups were submitted to MR imaging *in vivo*. Animals were anesthetized with halothane. In the unlesioned spinal cords white and gray matter were easily identified on T1-, T2- and PD-weighted images. However, gray and white matter lesions in spinal cord injury were visible near the cut, up to 10 mm rostrally and caudally. Additionally, co-occurring pathologies were observed, e.g. vertebral dislocation, intramedullary microcysts, and dorsal spinal cord compression. The Omniscan (contrast agent) injection caused a sudden signal intensity, and then filled in the vessels, which testified to the development of scars with a strong vascularization. Histological analysis confirmed the observations obtained through MRI. Imaging parameters are presented in Table 1.

A Bruker Biospec Avance 47/40 scanner with surface coil was also used for *in vivo* imaging of animals implanted with

Table 1 – Account of acquisition parameters depends on main magnetic field strength of the animal dedicated MRI scanners.

Examined structure	Magnetic field strength	Race of animal	Sequence	TR/TE (ms)	Flip angle, (deg)	Matrix size (pixels)	Pixel size (μm)	Slice thickness/ gap (mm)	Voxel size (mm^3)	Field of view	Number of excitations	Number of slices acquired
Brain	4.70 T Jendelová et al.[12]	Rat – Wistar	T2-weighted TSE	2000/ 42.50	NS	256 × 256	NS	0.50/1.00	NS	3.50 cm	NS	16
	4.70 T Magnitsky et al.[14]	Mouse –C3H, C3H/SCID	2D GRE	330/4	NS	256 × 256	NS	0.20/NS	NS	2.00 cm^2	NS	16
	4.70 T Modo et al.[16]	Rat – Spraque-Dawley	T1-weighted SE T2-weighted SE PD-weighted SE	500/15 4000/45 4000/15	NS	256 × 256	NS	0.50/NS	NS	2.50 × 2.50 cm^2	NS	NS
	7.00 T Hoehn et al.[11]	Rat – Wistar	2D multislice 3D FLASH	200/20	20–25	256 × 256 × 128	78 × 49 × 78	0.50–0.70/ NS	NS	20.00 × 12.00 × 10.00 mm^3	NS	NS
	7.00 T Hadlich et al.[10]	Rat – no race information	T2-weighted TSE	2500/66	NS	768 × 768	NS	0.1/NS	NS	41.00 mm	NS	NS
	7.00 T Cha et al.[6]	Mouse – C57BL6	T1-weighted SE T1-weighted GRE T2-weighted SE $T2^*$-weighted GRE FLASH	500/10 260/6 2000/30 18/10	NS 55 NS 15	256 × 128 256 × 256 256 × 128 64 × 64	NS	0.75/NS 0.75/NS 0.75/NS 0.75/NS	NS	22.00 mm	NS	12 15 12 1
	7.00 T Bock et al.[4]	Mouse – NODSCID	T1-weighted SE T2-weighted multislice SE	300/10 3000/30	NS	NS	NS	NS 0.50/NS	NS	40.00 × 20.00 × 16.00 mm^3 80.00 × 20.00 mm^2	1 6	NS
	9.40 T Badea et al.[1]	Mouse – C57BL/6J	T1-weighted SW T2-weighted CPMG	50/5.10 400/NS	NS	NS 256 × 256 × 512	NS	NS	NS	11.00 × 11.00 × 22.00 mm^3 11.00 × 11.00 × 22.00 mm^3	NS	NS
	9.40 T Boretius et al.[5]	Mouse – C57BL/6J	T2-weighted multislice FSE T1-weighted FLASH GRE	4200/NS 17.00/3.80	NS 25	512 × 512	NS	0.20–0.30/ NS NS	NS	15.40 × 15.40 mm^2 NS	NS	14–20
	9.40 T Magnitsky et al.[14]	Mouse – C3H, C3H/SCID	2D GRE 2D multislice GRE 3D GRE	330/4 330/10 100/10	NS	256 × 256 256 × 256 256 × 128 × 128	NS	0.20/NS	NS	2.00 cm^2 2.00 cm^2 2.00 × 1.00 × 1.00 cm^3	NS	16 64 28
	14.1 T Marques et al.[15]	Rat – Sprague-Dawley	GRE	1100/16	NS	512 × 382	NS	0.40/NS	NS	17.00 × 12.70 mm^2	NS	NS
Spinal cord	4.70 T Fraidakis et al.[9]	Rat – Spraque-Dawley	RARE PD T2 MSME	2500/35 NS/115 2124/8	NS	256 × 256	NS	0.50/NS	NS	4.00 cm	NS	NS
	4.70 T Jendelová et al.[12]	Rat – Wistar	3D GRE	25/5.10	NS	256 × 128 × 96	NS	NS	NS	6.00 × 3.00 × 2.40 cm^3	NS	128

9.40 T Bilgen et al.[3]	Rat – Sprague-Dawley	T1	1000/13	NS	128 × 128	NS	1.00/NS	NS	15.00 mm	2	NS	
9.40 T Bilgen and Al-Hafez[2]	Rat – Sprague-Dawley; Mouse C57BL/6	SE	2000/13	NS	256 × 256	NS	1.00/NS	NS	9.00 × 9.00 mm^2 (axial) 9.00 × 25.00 mm^2 (coronal, sagittal)	2	NS	
		3D-TOF	45/4	45	NS	140 × 140	7.00/NS	NS	18.00 × 18.00 × 9.00 mm^3	NS	NS	
9.40 T Chou et al.[8]	Mouse – C57BL/6	SE	2500/12	NS	256 × 128	100 × 63	0.50/NS	NS	26.00 × 8.00 mm^2	2	NS	
		SE	2500/12		128 × 128	94 × 63	1.00/NS		12.00 × 8.00 mm^2	2		
		DWI	2000/26		128 × 128	94 × 63	1.00/NS		12.00 × 8.00 mm^2	2		
11.10 T Chen et al.[7]	Rat – Sprague-Dawley	T1 SE multislice	330/9.40	NS	NS	200 × 200	1.00/NS	NS	4.00 cm × 2.00 cm^2 (sagittal) 2 × 2 cm^2 (transaxial)	NS	8	10
11.70 T Lepore et al.[13]	Rat – Sprague-Dawley	T2+ 3D GRE	100/6.80	30	256 × 64 × 64	NS	NS	NS	21 × 5 × 5 mm^3	4	NS	

Comments: NS – not specified.

mouse embryonic stem cells (ESCs) and rat bone marrow stromal cells (MSCs).[12] These cells were injected into the cortex of rats with a photochemical lesion or with a balloon-induced spinal cord compression lesion. Wistar rats were used in these experiments. Animals were divided into seven groups: (1) rats with a cortical photochemical lesion and with contralaterally grafted ESCs labeled with superparamagnetic iron oxide nanoparticles (SPION) and transfected with enhanced green fluorescent protein (eGFP); (2) rats with a cortical photochemical lesion and with contralaterally grafted rat MSCs labeled with SPION and colabeled with 5-bromo-2-deoxyuridine (BrdU); (3) rats with a cortical lesion and with ESCs labeled with SPION, and transfected with eGFP, administered intravenously; (4) rats with a cortical lesion and with rat MSCs labeled with SPION and colabeled with BrdU, administered intravenously; (5) rats with a cortical photochemical lesion and with the contralaterally injected SPION; (6) rats with a balloon-induced spinal cord compression lesion and with rat MSCs labeled with SPION, administered intravenously; and (7) rats with a cortical lesion or balloon-induced compression lesion injected with PBS into the contralateral hemisphere or intravenously.[12] Animals were anesthetized with 1.5%–2.0% isoflurane. During the first week, the cells migrated to the injured area. Injected cells were observed as hypointense regions at the injection site, corpus callosum and lesioned area. Hypointense signals persisted for more than 50 days. Cells injected intravenously clumped only in the lesion area. The presence of eGFP, BrdU and SPION particles in the areas detected by MRI was confirmed histologically and immunohistochemically. Electron microscopy observations showed a differentiation of injected cells into neurons and astrocytes. Less than 3% of MSCs differentiated only into neurons, without a differentiation into astrocytes; 5% of eGFP ESCs differentiated into neurons, and 70% into astrocytes. Imaging parameters are presented in Table 1.

4.2. *Scanners with a magnetic field strength of 7.0 T*

A Bruker BioSpec scanner (Bruker, Billerica, MA, USA) with transmit/receive coils was used to image implanted ESCs.[11] Male Wistar rats, weighing 260–300 g, were used in the experiment. Animals were anesthetized with 1% halothane in a mixture of volume ratio 30% O_2 and 70% N_2O. Two weeks before the implantation, 11 rats were submitted to a temporary occlusion of the right middle cerebral artery, which resulted in the focal cerebral ischemia. The control group consisted of 3 healthy rats (without ischemic lesions), injected with ESCs only. Transfected ESCs were coincubated with a lipofection reagent FuGENE and SINEREM, containing ultrasmall superparamagnetic iron oxide particles (USPIO) in serum-free medium. Two depots of labeled ESCs were injected into the border between the cortex and the corpus callosum and into the striatum of the left intact hemisphere. MRI was performed immediately after the cells implantation, and carried out for the next 3 weeks. High cell migration ability was observed. During 3 weeks the cells migrated along the corpus callosum to the ventricular walls and accumulated in the lesioned area in the hemisphere opposite to the implantation site. The study involving the control group did not present any differences with respect to the cell

arrangement, because the cells remained at the implantation site. Immunohistochemical analysis confirmed the observations obtained through MRI. Imaging parameters are presented in Table 1.

A Bruker BioSpec scanner was also used by Hadlich et al.[10] to image rat brain and cerebellum. Imaging parameters are presented in Table 1.

A Magnex Scientific scanner (Abingdon, UK) was used to image glioma in C57BL6 mice.[6] Tumor growth was induced by the injection of the GL261 cell line into the mice brain below the cortical surface. Between 1 and 4 weeks after the cells implantation, a group of 7–9 mice were imaged weekly. Animals were anesthetized with an intraperitoneal injection of ketamine (120 mg/kg) and xylazine (20 mg/kg). As the control group 7 mice were used. These animals received 4 μL PBS into the contralateral hemisphere at the same location. Micro-magentic resonance imaging (μMRI) was performed before and after the administration of the contrast agent Magnevist (0.1 mmol/kg) into the internal jugular vein. On T2-weighted images without the contrast agent, and T2-weighted images after contrast enhancement, a tumor was visualized just 1 week after the implantation. In 1–2 weeks, the rim of the tumor was easily identified from the normal brain tissue. However, in late tumors (3–4 weeks) also on T1- and T2-weighted images irregular tumor margins were observed as well as apparent necrosis in the central parts of tumors. A larger tumor size was visible on T2-weighted images than on the T1-weighted ones. This probably resulted from the fact that T2-weighted images showed the tumor and peritumoral edema or infiltration, whereas T1-weighted images showed only the areas of altered blood-brain barrier (BBB). In each case after MR imaging, histological tests of involved structures were performed and compared with MR images. Histological analysis confirmed tumor growth observed through MRI, and showed strong angiogenesis in 3–4 weeks. Imaging parameters are presented in Table 1.

A Varian scanner (Varian Inc., Palo Alto, CA, USA) with birdcage coil was used to image brain tumor in mice.[4] In this experiment 16 NOD SCID mice were used. Animals were divided into four groups. Tumor growth was induced by the injection of U87 MG human astrocytoma cells into the frontal cortex. The first group of animals was subjected to an injection of tumor cells transfected with angiopoietin 1 (Ang1); the second group – transfected with angiopoietin 2 (Ang2); the third group – tumor cells non-transfected (as control 1); the fourth group (control 2) comprised mice without tumors. MR imaging was performed on four mice simultaneously. T2-weighted imaging began 2 weeks after the implantation and was conducted weekly during 3 consecutive weeks. In the 4th week after the implantation T1-weighted imaging was carried out before and after the injection of the contrast agent Magnevist in a dosage of 0.1 mM/kg into the tail vein. Images were used to define tumor size and edema, and compared to normal mice brain images. Tumor was visible on T2-weighted images 2–3 weeks after the implantation of tumor cells. Furthermore, in the 4th week after the implantation, T1-weighted images with and without the contrast agent were performed to show tumor vascularization and vessel permeability. The outflow of the contrast agent from the vessels was observed, which testified to the existence of disorders in BBB. With the application of the MRI method it was possible to detect other neuropathological anomalies that emerged indirectly or directly as a result of tumor growth. These anomalies were visible on T2-weighted images which clearly showed cerebrospinal fluid and the main structures of the brain. Furthermore, enlarged brain ventricles were observed in mice with injected tumor cells transfected with Ang1. After MR imaging, histological analyses and micro-computed tomography (μCT) were carried out. Both histological tests and μCT confirmed the observations obtained from MR images. Imaging parameters are presented in Table 1.

4.3. *Scanners with a magnetic field strength of 9.4 T*

A Varian scanner (Varian Inc., Palo Alto, CA, USA) and coil implanted subcutaneously at the Th9 level were employed to image the spinal cord in rats.[3] The authors performed their experiment on Sprague-Dawley rats, weighing 300–350 g. As an anesthetic agent 4% isoflurane was used, and then a mixture of 1.5% isoflurane and 30% oxygen and air. The experiment was performed on animals with normal and injured (hemisectioned) spinal cords. Manganese (25 mmol/L aqueous $MnCl_2$ in 10 nL) was used as the contrast agent. In the unlesioned spinal cord Mn was transported in both directions – rostral and caudal from the injection site. The best visualization of contrast agent transport, absorption and accumulation was obtained on T1-weighted images. In the intact spinal cord, Mn dispersion to the surrounding tissue through the axonal transport was observed. The ascertained Mn presence 3 mm caudally from the injection site was detected 30 minutes after the injection of the contrast agent into the normal spinal cord. The lesioned area of the spinal cord was injected with Mn and biotinylated dextran amine (BDA) with lysine. MR imaging was performed. In the lesioned spinal cord, signal enhancement was observed in the part contralateral to the section site. Within the hemisected area only small points were enhanced, which testified to the survival of a small population of neurons. The same results were received in histological BDA labeled specimens. Imaging parameters are presented in Table 1.

A Varian scanner with surface coil was used to image anatomical structures of the spinal cord and its vasculature.[2] The imaging was performed on C57BL mice and Sprague-Dawley rats. High resolution images allowed for the visualization of the anatomical details of the spinal cord and arterial architecture of both mouse and rat spines. The authors observed a similarity in the vascularization of anatomical structures between rat and mouse spines. Imaging parameters are presented in Table 1.

Also Chou et al.[8] used a Varian scanner and surface coil to image spinal cord injury in C57BL/6 mice. Animals were anesthetized with a mixture of 1.5% isoflurane, 40% oxygen and 58% air. Each mouse was scanned on the 1st and 3rd day after the spine damage induction. High resolution of the images was acquired in sagittal and axial planes using spin-echo sequences. The damaged area visualized by MRI was confirmed histologically. Imaging parameters are presented in Table 1.

A Bruker BioSpin scanner (Ettlingen, Germany) with birdcage resonator and surface coil was used by Boretius et al.[5] Imaging was performed on C57BL/6J mice anesthetized with 5% isoflurane in oxygen. Imaging was carried out with T2-weighted images in a fast spin-echo sequence, and T2-weighted images after the administration of the contrast agent $MnCl_2$ (40 mg/kg) in a 3D Flash sequence. Structures such as cerebral cortex, olfactory bulb, hippocampus and cerebellum were identified, and the distinguished layer-like structures were compared with histological specimens. These layers that were observed on MR images did not necessarily correlate with histology results, but they were similar. Imaging parameters are presented in Table 1.

An Excite scanner (GE Healthcare, Milwaukee, WI, USA) with solenoid coil was used to perform mouse neuroanatomy.[1] In the experiment C57BL/6J mice were used. Animals were anesthetized with pentobarbital (100 mg/kg) injected intraperitoneally. Mice brains were scanned and this allowed for identification of 33 neuroanatomical structures. A high resolution of T1- and T2-weighted images helped to prepare a neuroanatomical atlas of mouse brain. Imaging parameters are presented in Table 1.

4.4. *Scanners with a magnetic field strength of 11.1 T*

A Bruker Avance scanner (Bruker NMR Instruments, Billeria, MA, USA) with a magnetic field strength of 11.1 T was used to image the peripheral nerve in rats.[7] In the experiment Sprague-Dawley rats weighing 250 g were used. Animals were anesthetized with isoflurane (2 L/min oxygen, 4% isoflurane). The spinal cord and the peripheral nerve root were identified in MRI. Signal enhancement was detected after the administration of the contrast agent Omniscan (10 mg/mL). Imaging parameters are presented in Table 1.

A Bruker Avance scanner with a magnetic field strength of 11.7 T was employed to show the migration of neuronal-restricted precursor (NRP) cells and glial-restricted precursor (GRP) cells in injured spinal cords.[13] In these experiments Sprague-Dawley rats weighing 250 g were used. Animals were anesthetized with an intraperitoneal injection of an anesthetic mixture, containing acepromazine maleate (0.7 mg/kg), ketamine (95 mg/kg) and xylazine (10 mg/kg). Rats with normal and lesioned spines, implanted with SPIO labeled NRP and GRP cells, were derived from the embryos of transgenic Fisher 344 rats. These cells expressed the marker gene – human placental alkaline phosphatase (AP). With an MRI method, a migration of labeled cells through the white and gray matter 5 mm from the injection site was observed. After MR imaging, histological tests and immunohistochemical analyses were performed. Histological analyses confirmed MRI results, showed the localization and migration of implanted cells by AP localization. The injected cells were also morphologically differentiated into neurons, astrocytes and oligodendrocytes. Imaging parameters are presented in Table 1.

4.5. *Scanners with a magnetic field strength of 14.1 T*

A Varian/Magnex Scientific scanner with a magnetic field strength of 14.1 T with surface coil was used to visualize rat brain and its vasculature.[15] The experiment was performed on Sprague-Dawley rats. Animals were anesthetized with 2% isoflurane. Very clear images of the entire brain and its vasculature were obtained through MRI. High resolution imaging allowed for the visualization of small capillary vessels. Imaging parameters are presented in Table 1.

5. Discussion

Small animal research provides highly important information concerning pathogenesis and tumor growth, and may define how to cure CNS diseases in humans. For that purpose in some experiments clinical scanners are used, but the quality of the obtained images is limited by the SNR. The usage of dedicated small animal MRI scanners with an increased SNR allows scientists to obtain high resolution images and clearly visible structures of interest to researchers. Such images are easier to interpret and the analysis of the obtained results is also easier to arrive at.[1–18]

6. Conclusions

High resolution dedicated small animal scanners of up to 14.1 T are best suited for rodent neuroanatomy imaging and for analyzing the results of neurobiological experiments.

Conflict of interest

None declared.

REFERENCES

[1] Badea A, Ali-Sharief AA, Johnson GA. Morphometric analysis of the C57BL/6J mouse brain. *NeuroImage*. 2007;37(3):683–693.
[2] Bilgen M, Al-Hafez B. Comparison of spinal vasculature in mouse and rat: investigations using MR angiography. *Neuroanatomy*. 2008;5:12–18.
[3] Bilgen M, Dancause N, Al-Hafez B, He Y-Y, Malone TM. Manganese-enhanced MRI of rat spinal cord injury. *Magn Reson Imaging*. 2005;23(7):829–832.
[4] Bock N, Zadeh G, Davidson LM, Qian B, Sled JG, Guha A, et al. High-resolution longitudinal screening with magnetic resonance imaging in a murine brain cancer model. *Neoplasia*. 2003;5(6):546–554.
[5] Boretius S, Kasper L, Tammer R, Michaelis T, Frahm J. MRI of cellular layers in mouse brain *in vivo*. *NeuroImage*. 2009;47(4):1252–1260.
[6] Cha S, Johnson G, Wadghiri YZ, Jin O, Babb J, Zagzag D, et al. Dynamic, contrast-enhanced perfusion MRI in mouse gliomas: correlation with histopathology. *Magn Reson Med*. 2003;49:848–855.
[7] Chen X, Astary GW, Mareci TH, Sarntinoranont M. *In vivo* contrast-enhanced MR imaging for direct infusion into rat peripheral nerve. *Ann Biomed Eng*. 2011;39(11):2823–2834.
[8] Chou PC, Tatar I, Bilgen M. Multimodal MRI evaluation of acute mild-contusive injury in mouse spinal cord. *Neuroanatomy*. 2008;7(1):83–92.
[9] Fraidakis M, Klason T, Cheng H, Olson L, Spenger C. High-resolution MRI of intact and transected rat spinal cord. *Exp Neurol*. 1998;153(2):299–312.

[10] Hadlich S, Kühn J-P, Puls D. 7-Tesla small animal MR imaging. *Radiol Technol*. 2009;80(6):585–588.
[11] Hoehn M, Küstermann E, Blunk J, Wiedermann D, Trapp T, Wecker S, et al. Monitoring of implanted stem cell migration *in vivo*: a highly resolved *in vivo* magnetic resonance imaging investigation of experimental stroke in rat. *Neuroscience*. 2002;99(25):16267–16272.
[12] Jendelová P, Herynek V, Urdzíková L, Glogarová K, Kroupová J, Andersson B, et al. Magnetic resonance tracking of transplanted bone marrow and embryonic stem cells labeled by iron oxide nanoparticles in rat brain and spinal cord.
J Neurosci Res. 2004;76(2):232–243.
[13] Lepore AC, Walczak P, Rao MS, Fischer I, Bulte JWM. MR-imaging of lineage-restricted neural precursors following transplantation into the adult spinal cord. *Exp Neurol*. 2006;201(1):49–59.
[14] Magnitsky S, Watson DJ, Walton RM, Pickup S, Bulte JWM, Wolfe JH, et al. *In vivo* and *ex vivo* MRI detection of localized and disseminated neural stem cell grafts in the mouse brain. *NeuroImage*. 2005;26(3):744–754.
[15] Marques JP, Maddage R, Mlynarik V, Gruetter R. On the origin of the MR image chase contrast: an *in vivo* MR microscopy study of the rat brain at 14.1 T. *NeuroImage*. 2009;46(2):345–352.
[16] Modo M, Mellodew K, Cash D, Fraser SE, Meade TJ, Price J, et al. Mapping transplanted stem cell migration after a stroke: a serial, *in vivo* magnetic resonance imaging study. *NeuroImage*. 2004;21(1):311–317.
[17] Mystkowska D, Tutas A, Jezierska-Woźniak K, Mikołajczyk A, Bobek-Billewicz B, Jurkowski MK. Usefulness of clinical magnetic resonance scanners for imaging experimental changes in laboratory rodents' central nervous system. *Pol Ann Med*. 2012;19(1):43–49.
[18] Pruszyński B. Postępy diagnostyki obrazowej w roku 2003. Progress in image diagnostics in 2003. *Med Prakt*. 2004;1:49–54.