Development of functional in vivo imaging of cerebral lenticulostriate artery using novel synchrotron radiation angiography

Xiaojie Lin¹, Peng Miao¹,², Zhihao Mu¹,³, Zhen Jiang¹,³, Yifan Lu¹, Yongjing Guan⁵, Xiaoyan Chen¹, Tiqiao Xiao⁶, Yongting Wang¹ and Guo-Yuan Yang¹,³,⁶

¹ School of Biomedical Engineering, Shanghai Jiao Tong University, Shanghai 200030, People’s Republic of China
² School of Communication and Information Engineering, Shanghai University, Shanghai 200444, People’s Republic of China
³ Department of Neurology, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, Shanghai 200025, People’s Republic of China
⁴ Department of Radiology, Ruijin Hospital, School of Medicine, Shanghai Jiao Tong University, Shanghai 200025, People’s Republic of China
⁵ Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201204, People’s Republic of China

E-mail: gyyang0626@gmail.com

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Abstract

The lenticulostriate artery plays a vital role in the onset and development of cerebral ischemia. However, current imaging techniques cannot assess the in vivo functioning of small arteries such as the lenticulostriate artery in the brain of rats. Here, we report a novel method to achieve a high resolution multi-functional imaging of the cerebrovascular system using synchrotron radiation angiography, which is based on spatio-temporal analysis of contrast density in the arterial cross section. This method provides a unique tool for studying the sub-cortical vascular elasticity after cerebral ischemia in rats. Using this technique, we demonstrated that the vascular elasticity of the lenticulostriate artery decreased from day 1 to day 7 after transient middle cerebral artery occlusion in rats and recovered from day 7 to day 28 compared to the controls (p < 0.001), which paralleled with brain...
edema formation and inversely correlated with blood flow velocity ($p < 0.05$). Our results demonstrated that the change of vascular elasticity was related to the levels of brain edema and the velocity of focal blood flow, suggesting that reducing brain edema is important for the improvement of the function of the lenticulostriate artery in the ischemic brain.

Keywords: angiography, elasticity, lenticulostriate artery, synchrotron radiation

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1. Introduction

Lenticulostriate arteries (LSAs), branching from the middle cerebral artery (MCA) in the human and rodent brain, are major feeding arteries for the corpus striatum in the sub-cortex and extremely important for ensuring regular brain nutrition supply (Marinkovic et al. 2001). The restoration of blood flow in LSAs is highly related to neural survival and functional recovery in corpus striatum after ischemic stroke. During the acute phase of ischemia, blood flow is absent in LSAs and then restored after reperfusion. The endothelial cells of LSAs can be damaged during the ischemic phase, which further affects the reperfusion ability of LSAs. According to our previous study (Lu et al. 2012), functional angiogenesis of micro-vasculature is a main target of ischemic neural repair which firstly requires a sufficient blood supply from major arteries. Therefore, restoration of LSAs is a key point in therapy and rehabilitation of ischemic stroke in the sub-cortex. Development of new therapeutic methods is facilitated by an in vivo imaging technique which can monitor the restoration ability of LSAs with high spatial resolution, especially for pre-clinical small animal studies.

However, current in vivo techniques for assessing cerebral vasculature and arterial functions still suffer from insufficient imaging resolution. Microscopic computed tomography (Micro-CT) provides a good resolution (about $10 \mu m$) for tissue samples but with a much lower resolution (larger than $100 \mu m$) in vivo. Furthermore, Micro-CT imaging cannot provide blood flow or functional information (Holdsworth and Thornton 2002). Digital subtraction angiography (DSA) is another x-ray based imaging method for assessment of vascular abnormalities in both clinical and animal studies, but with limited spatial resolution (larger than $100 \mu m$). Magnetic resonance angiography (MRA) has better resolution (about $50 \mu m$) in imaging and shows the cerebral vasculature and hemodynamics of small animals in vivo (Shih et al. 2012, Liu et al. 2014). Nevertheless, all of these techniques still do not allow direct visualization of small intracranial arteries such as penetrating arteries, LSAs and newly formed small vessels. Doppler micro-ultrasonography is the most useful method to obtain the vascular hemodynamics in clinic and animal studies, but its spatial resolution is reduced with an increased depth of penetration (Greco et al. 2012). Laser speckle contrast imaging (LSCI) and near-infrared fluorescence imaging provide sufficient resolution (about $15 \mu m$) and could provide both vasculature and hemodynamic information in vivo. Unfortunately, the penetrating depth of the optical imaging intrinsically limits their applications in sub-cortex studies (Welsher et al. 2011, Hong et al. 2012, Lin et al. 2013). For imaging vascular functions, radial artery pulse wave analysis of optical imaging data is proposed to examine the arterial elasticity (Cohn et al. 1995, Zheng and Mayhew 2009).

Synchrotron radiation x-ray based angiography (SRA), a state-of-the-art technique, provides a useful in vivo imaging tool for rodent cerebral vasculature (Kidoguchi et al. 2006,
Lu et al. 2012, Lin et al. 2013, Shirai et al. 2013, Yuan et al. 2013). Previous studies demonstrated the SRA was capable of investigating the morphology of LSAs in mice with 30 μm high spatial resolution (Yuan et al. 2013). Here, we reported the application of in vivo functional SRA (fSRA) for measuring the elasticity and blood flow velocity (BFV) of the LSAs in rats based on a transient middle cerebral artery occlusion (tMCAO) model. To explore the potential mechanism, we further analyzed the relationships among the elasticity of LSAs, blood flow velocity (BFV) and brain edema after ischemic injury.

2. Materials and methods

2.1. fSRA

An SRA experiment was conducted at the BL13W beamline of Shanghai Synchrotron Radiation Facility (SSRF). The imaging setup is shown in figure 1(a). After monochromatization of x-ray light sprouting out from a bending magnet, x-ray energy of 33.2 KeV with flux of $2.38 \times 10^{10}$ photons second$^{-1}$ mm$^{-2}$ was obtained for the imaging purpose. To control the ionizing radiation dose, a x-ray shutter was placed before the sample stage. A PCO x-ray charge-coupled device (CCD) camera (pixel size of 9 × 9 μm, FOV of 20 × 4.5 mm, PCO-TECH Inc, Germany) was placed 65 cm away from the sample stage and used to obtain x-ray transmission images continuously with a 4fps frame rate and exposure time of 35 ms.

For animal preparation, an angiographic tube (connecting a PE10 tube to a PE50 tube) was inserted into the external carotid artery (ECA) to the bifurcation of common carotid artery (CCA) for contrast agent injection (figure 1(b)). Before imaging, the rat was placed vertically to the beam path on its left side. During imaging, 150μl of non-ionic iodine contrast agent (Ipamiro, Shanghai, China) with a concentration of 175 mgml$^{-1}$ (350 mgml$^{-1}$, diluted to 50% volume ratio with saline) was injected into the ECA through the angiographic tube at an injecting rate of 133.3 μl s$^{-1}$ which was controlled by a micro-syringe pump (LSP01-1A,
Longerpump, Baoding, China. Two layers of angiographic images were acquired to obtain the entire hemisphere vasculature. In other words, we conducted SRA twice in each animal by moving the animal up and down.

In the imaging procedure, sequential x-ray transmission images $I(x, y, t)$ of the rat brain were recorded (figure 2(a)). Because the injected contrast agent provided sufficient absorption contrast of blood flow and vasculature, Berr–Lambert’s law was used to obtain the absorption maps $I_{abs}(x, y, t)$ which were proportional to the density distributions of contrast agent (equation (1)). In this study, relative blood flow and vascular elasticity were estimated from the absorption maps $I_{abs}(x, y, t)$.

$$I_{abs}(x, y, t) = \ln(I(x, y, 0)) - \ln(I(x, y, t))$$  \hspace{1cm} (1)

where $I(x, y, t)$ was the recorded images (there is no contrast agent injection when $t = 0$).

Before the estimation of relative blood flow and vascular elasticity, image sequences $I_{abs}(x, y, t)$ were firstly calculated. Then based on the absorption map, the blood vessels were manually segmented. The binary images of blood vessels were used to obtain the vessel center line (ridge) and corresponding outlines automatically. The diameter $r_0$ of each vessel was calculated for each ridge point (figure 2(b)). Then, the absorption data of the cross-section line at each ridge point in $I_{abs}(x, y, t)$ was extracted based on the perpendicular relation between ridge and cross-section. Then the spatio-temporal dynamics $I_d(r, t)$ of each cross-section were constructed from the image sequences $I_{abs}(x, y, t)$ (figure 2(c), figure S1(b))(stacks.iop.org/PMB/60/1655).

As the first-pass of the contrast agent (time = 0), the $I_d(r, t)$ demonstrated diffusion shape and reached saturation after time $t_0$. During this period, the spatial range and density of contrast agent were spreading and accumulated. In this study, the spatio-temporal dynamics of the contrast agent in $I_d(r, t)$ ($t < t_0$) were fitted to a Gaussian surface (equation (2)). As an absorption imaging technique, the contrast agent at other depths along the light path may introduce noise in the $I_d(r, t)$ of the corresponding cross-section. However, a surface fitting technique can efficiently suppress the noise and provide a robust estimation of fitting parameters.
\[ I_t(r, t) = a \cdot e^{-\frac{(r-r_0)^2}{2\sigma^2} + (t-t_0)^2/\sigma^2} + b \]  

(2)

Based on a recent study (Hong et al 2012) the normalized slope of density versus time is proportional to the blood velocity. Therefore, after the estimation of fitting parameters in equation (2), the relative velocity \( v \) of each cross-section was calculated using equation (3).

\[ v = \int_0^{t_0} \int_{-r_0}^{r_0} \frac{I_t(r, t)}{r_0 \sigma} \, dr \, dt \]  

(3)

The elasticity \( E \) of each cross-section was calculated using equation (4).

\[ E = \frac{v}{r_0} \]  

(4)

2.2. Experimental design

Protocols of animal experiments used in this study were approved by the Institutional Animal Care and Use Committee (IACUC), Shanghai Jiao Tong University, Shanghai, China. Thirty-six adult male Sprague–Dawley rats (Sppir-BK Inc, Shanghai, China) weighing 250–280 grams were used in this study. Animals (5 groups, \( n = 6 \) per group) underwent magnetic resonance imaging (MRI) and SRA 1, 3, 7, 14 and 28 d after tMCAO to detect brain lesions. Animals characterized with MRI and SRA without tMCAO were used as sham (\( n = 6 \)). The mean arterial blood pressure (MABP) was measured before MRI by an automatic sphygmomanometer (BP-98A, Softron, Tokyo, Japan), using the noninvasive tail cuff technique.

2.3. Surgery procedure of transient middle cerebral artery occlusion

The surgical procedure for tMCAO was described previously (Tang et al 2014). Briefly, rats were anesthetized with ketamine (100 mg kg\(^{-1}\)) and xylazine (10 mg kg\(^{-1}\)) intraperitoneally. Rats were then supinely placed on a surgical board and body temperature was maintained at 37 °C by a heating pad (RWD Life Science, Shenzhen, China). After a midline neck incision was made, the ECA, the CCA and the internal carotid artery (ICA) were isolated under an operating microscope (Leica, Wetzlar, Germany). Then, the pterygopalatine artery (PPA) was ligated to improve the model stability and to eliminate interference. A 4-0 suture (20 mm, Dermalon, 1744-31, Covidien, OH) coated with silicone rubber (length = 3 mm, diameter = 0.4 mm, Heraeus Kulzer, Hanau, Germany) was inserted into the ECA stump, reversed into the ICA and finally to the ostium of the MCA (a slight resistance was felt). The success of occlusion was characterized as the reduction of cortical blood flow down to 20% of the baseline, which was measured by a laser Doppler flowmetry (Moor Instruments, Devon, England). After 90 min of occlusion with ligation of the CCA, the suture was removed and the CCA was released for the reperfusion procedure.

2.4. Magnetic resonance imaging examination

A MRI examination was performed before and after the tMCAO using a 3T MR apparatus (Signa3T, GE Healthcare, CT) using an animal head coil with T2-weighted fast spin-echo sequence (TR = 2000 ms, TE = 40 ms, matrix = 160 x 192, FOV = 6.0 x 6.0 cm; slice thickness =1.0 mm; inter slice distance = 0 mm). Rats were anesthetized with ketamine/xylazine intraperitoneally during MRI. After MRI reconstruction, brain edema volume was measured...
using ImageJ and calculated by subtracting the non-edema volume in the ipsilateral hemisphere from the total volume in the contralateral hemisphere and then dividing by the volume of the contralateral hemisphere.

2.5. Statistical analysis

Brain edema volume, MABP and diameter of ICA, posterior cerebral artery (PCA), MCA and anterior cerebral artery (ACA) were presented as mean ± SD. Vascular elasticity, blood flow velocity and diameter of the LSAs were expressed as median ± (25th, 75th centiles). All data were compared using a one-way ANOVA followed by Student’s t-test. A probability value of less than 5% was considered statistically significant.

3. Results

3.1. Elasticity changes of LSAs after tMCAO

We manually segmented the LSAs from the vasculature of each rat and calculated the elasticity of the LSAs using the FSRA method (equation (4)). The elasticity map of the entire vasculature and enlarged view of LSAs are shown in figure 3. Statistical results demonstrated that the elasticity of the LSAs was reduced from day 1 to day 7 after tMCAO (p < 0.001) and then increased from day 7 to day 28. Compared to LSAs, the elasticity of the MCA was not changed after tMCAO (Data not shown).
3.2. Changes of LSAs’ elasticity paralleled with brain edema developments after tMCAO

To assess the developments of brain edema after tMCAO, we calculated the brain edema volume using T2-weighted MRI. We found that the brain edema occurred in MCA area and increased until day 3, following which, edema volume decreased at day 7. Then, tissue hydration appeared at day 14 and continued to increase to day 28 (figure 4). Tissue hydration is presented as the lack of tissue structure with high-intensity signal. The changes of LSAs’ elasticity paralleled with brain edema after tMCAO, which was gradually decreased until day 7 and then recovered after day 7 (figure 4). MABP shows no significant changes after tMCAO (figure 4), indicating that the brain edema and LSAs’ elasticity were not influenced by MABP in this study.

3.3. Changes of LSAs’ elasticity were inversely correlated to BFV after tMCAO

We also calculated the relative BFV in LSAs using fSRA method (equation (3)) to investigate the relations between vascular elasticity and BFV. Interestingly, the changes in BFV were inversely correlated to vascular elasticity. The relative BFV of LSAs was reduced at day 1 and then increased from day 1 to day 7, peaked at day 7, finally decreased and recovered from day 7 to day 28 (figure 5).

3.4. Diameter of LSAs was not changed after tMCAO

Using SRA, we studied the ipsilateral brain vascular morphology after tMCAO. The morphology of the ICA, the PCA, the MCA and their branches such as LSAs and cortical penetrating arteries can be obtained in vivo. There are no statistically significant changes in the diameters of LSAs, ICA, PCA and MCA after tMCAO, even though brain edema changed after tMCAO (figure 6, table 1). This result indicated that the evaluation of LSAs’ elasticity was not due to the morphology changes of LSAs (figure 6).
To increase image contrast, the original data of figure 2(a) was enhanced by an adaptive histogram equalization method. However, for quantitatively comparing the morphologic changes under different conditions, figure 6 just presented the original data. Additionally, figure 2(a) showed the entire brain vasculature while figure 6(a) was only a small region. So the contrast in figure 6(c–h) seems reduced with respect to figure 2(a).

4. Discussion

The functional recovery of LSAs is closely related to rehabilitation after cerebral ischemia. Current imaging methods for arterial functions cannot provide sub-cortical arterial elasticity and BFV both in high resolution. Here, we report fSRA technique as a new tool to simultaneously obtain anatomical, hemodynamic and elastic information in rodent arteries.

In this study, changes in LSAs after tMCAO are investigated using the fSRA method. After tMCAO, the changes in LSAs’ elasticity demonstrate a correlation with the changes in BFV and brain edema. However, the pathogenesis of this phenomenon was still unclear. Brain edema was mainly caused by cytotoxicity in the early stage and angioedema in the later stage after stroke. The cerebral blood volume can be changed after stroke and is promoted by exchange of water between capillaries and surrounding tissues (Krieger et al 2012). In consideration of the self-adjusting capacity of the brain, the arterial functions may be self-regulating to maintain the cerebral water content after stroke. Fluctuations in small arterial elasticity may also be caused by functional or structural alterations that are closely linked to endothelial dysfunction (Grey et al 2003). During brain ischemia, the LSAs lack blood
supply, which seriously impacts the endothelial cells’ survival (Hayashi et al 1998). Many studies have reported that protecting the endothelial cells by VEGF treatment can significantly improve the blood flow after brain reperfusion (Hayashi et al 1998, Ferrara et al 2003). The alteration of vascular functions was also related to the changes in the Nitric oxide-dependent vasodilatation pathway, which may be associated with endothelial dysfunction (Lamireau et al 2002). Therefore, up-regulation of vasoconstrictor receptors (for example, endothelin type B, angiotensin type 1 and 5-hydroxytryptamine type 1B/1D receptors) in cerebral arteries after different types of stroke was revealed in recent studies (Edvinsson and Povlsen 2011). It implied that those therapies may improve the outcome after stroke via improving the vascular functions.

Table 1. Diameters of ICA, PCA, MCA and ACA after tMCAO. Data were presented as mean ± SD.

| Group  | ICA (μm)     | PCA (μm)     | MCA (μm)     | ACA (μm)     |
|--------|--------------|--------------|--------------|--------------|
| Sham   | 387.6 ± 29.5 | 320.7 ± 20.5 | 313.9 ± 23.7 | 298.8 ± 15.4 |
| Day 1  | 393.8 ± 25.8 | 310.0 ± 28.8 | 324.2 ± 36.6 | 300.2 ± 21.8 |
| Day 3  | 389.1 ± 11.9 | 309.9 ± 21.0 | 302.1 ± 15.3 | 305.9 ± 15.5 |
| Day 7  | 398.1 ± 27.2 | 306.3 ± 18.5 | 308.1 ± 7.0  | 307.2 ± 17.7 |
| Day 14 | 382.7 ± 27.1 | 311.7 ± 12.0 | 310.2 ± 20.1 | 298.2 ± 9.9  |
| Day 28 | 373.7 ± 19.8 | 302.7 ± 38.2 | 301.8 ± 15.6 | 303.4 ± 13.0 |
Lin et al (Lin et al 2002) reported that the cerebral blood flow velocity increased in the ipsilateral cortex from day 1 to day 14 and peaked at day 7 after stroke monitored by MRI, however, our results showed that the BFV of LSAs was only increased from day 1 to day 7, and peaked on day 7. This result suggests that the blood flow alteration may differ between cortex and sub-cortex after stroke. It is also interesting that the cerebral blood flow was decreased to less than 50% of baseline between 1 and 2 d after intracranial hemorrhage (ICH), which is contradictory with ischemic stroke (Yang et al 1994).

Given the many benefits of fSRA over other basic imaging methodologies, this imaging technique could also be utilized in other cerebrovascular and cardiovascular research, such as intracranial aneurysms and atherosclerosis, which is often due to hemodynamic and arterial dysfunction (Cebral et al 2011, Rautou et al 2011). fSRA may also have potential applications for monitoring arterial functions in hypertension, diabetes and atherosclerosis caused by high cholesterol which may cause cerebrovascular and cardiovascular disease (Grey et al 2003). Furthermore, due to the similar principles of SRA and DSA, the theory of fSRA may also be used in clinical diagnoses of hemodynamic and vascular elasticity to analyze arterial functions in patients by post processing the DSA data.

However, ISRA still has some disadvantages that need to be overcome in the future. Firstly, the ionizing radiation effects caused by the synchrotron radiation x-ray still are uncertain, which is a major challenge to transferring it to clinical use, though it has already been used in clinical research (Elleaume et al 2000). Secondly, the limited frames per second of the CCD camera makes it difficult to accurately track the BFV for small arteries (Lin et al 2013). The frame frequency in Spring-8 was 30fps when small animal SRA was conducted, which makes the measurement of the BFV more accurate (Kidoguchi et al 2006, Jenkins et al 2012, Shirai et al 2013).

5. Conclusion

In summary, we reported a reliable in vivo technique, fSRA, to measure the sub-cortical arterial elasticity and BFV based on synchrotron radiation angiography in small animals. Using this novel method, we found that the LSAs’ elasticity fluctuated after ischemic stroke and may be related to BFV and brain edema change.

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References

Cebral J R, Mut F, Weir J and Putman C 2011 Quantitative characterization of the hemodynamic environment in ruptured and unruptured brain aneurysms AJNR. Am. J. Neuroradiol. 32 145–51
Cohn J N, Finkelstein S, McVeigh G, Morgan D, LeMay L, Robinson J and Mock J 1995 Noninvasive pulse wave analysis for the early detection of vascular disease Hypertension 26 503–8
Edvinsson L I and Povlsen G K 2011 Vascular plasticity in cerebrovascular disorders J. Cereb. Blood Flow Metab. 31 1554–71
Elleaume H et al 2000 First human transvenous coronary angiography at the European Synchrotron Radiation Facility Phys. Med. Biol. 45 139–43
Ferrara N, Gerber H P and LeCouter J 2003 The biology of VEGF and its receptors Nat. Med. 9 669–76
Greco A, Mancini M, Gargiulo S, Gramanizini M, Claudio P P, Brunetti A and Salvatore M 2012 Ultrasound biomicroscopy in small animal research: applications in molecular and preclinical imaging J. Biomed. Biotechnol. 2012 519238
Grey E, Bratteli C, Glasser S P, Alinder C, Finkelstein S M, Lindgren B R and Cohn J N 2003 Reduced small artery but not large artery elasticity is an independent risk marker for cardiovascular events Am. J. Hypertens. 16 265–9
Hayashi T, Abe K and Itoyama Y 1998 Reduction of ischemic damage by application of vascular endothelial growth factor in rat brain after transient ischemia J. Cereb. Blood Flow Metab. 18 887–95
Holdsworth D W and Thornton M M 2002 Micro-CT in small animal and specimen imaging Trends Biotechnol. 20 534–9
Hong G, Lee J C, Robinson J T, Raaz U, Xie L, Huang N F, Cooke J P and Dai H 2012 Multifunctional in vivo vascular imaging using near-infrared II fluorescence Nat. Med. 18 1841–6
Jenkins M J, Edgley A J, Sonobe T, Umetsu K, Schwenke D O, Fujii Y, Brown R D, Kelly D J, Shirai M and Pearson J T 2012 Dynamic synchrotron imaging of diabetic rat coronary microcirculation in vivo Arterioscler. Thromb. Vasc. Biol. 32 370–7
Kidoguchi K, Tamaki M, Mizobe T, Koyama J, Kondoh T, Kohmura E, Sakurai T, Yokono K and Umetani K 2006 In vivo x-ray angiography in the mouse brain using synchrotron radiation Stroke 37 1856–61
Krieger S N, Streicher M N, Trampel R and Turner R 2012 Cerebral blood volume changes during brain activation J. Cereb. Blood Flow Metab. 32 1618–31
Lamireau D, Nuyt A M, Hou X, Bernier S, Beauchamp M, Gobeil F Jr, Lahia I, Varma D R and Chemtob S 2002 Altered vascular function in fetal programming of hypertension Stroke 33 2992–8
Lin X, Miao P, Wang J, Yuan F, Guan Y, Tang Y, He X, Wang Y and Yang G Y 2013 Surgery-related thrombosis critically affects the brain infarct volume in mice following transient middle cerebral artery occlusion PLoS One 8 e75561
Lin T N, Sun S W, Cheung W M, Li F and Chang C 2002 Dynamic changes in cerebral blood flow and angiogenesis after transient focal cerebral ischemia in rats. Evaluation with serial magnetic resonance imaging Stroke 33 2985–91
Liu J, Wang Y, Akamatsu Y, Lee C C, Stetler R A, Lawton M T and Yang G Y 2014 Vascular remodeling after ischemic stroke: mechanisms and therapeutic potentials Prog. Neurobiol. 115C 138–56
Lu H et al 2012 Netrin-1 hyperexpression in mouse brain promotes angiogenesis and long-term neurological recovery after transient focal ischemia Stroke 43 838–43
Marinkovic S, Gibo H, Milisavljevic M and Cetkovic M 2001 Anatomic and clinical correlations of the lenticulostriate arteries Clin. Anat. 14 190–5
Rautou PE, Vion AC, Amabile N, Chironi G, Simon A, Tedgui A and Boulanger C M 2011 Microparticles, vascular function and atherothrombosis Circ. Res. 109 593–606
Shih Y Y, Muir E R, Li G, De La Garza B H and Duong T Q 2012 High-resolution 3D MR microangiography of the rat ocular circulation Radiology 264 234–41
Shirai M, Schwenke D O, Tsuchimochi H, Umetsu K, Yagi N and Pearson J T 2013 Synchrotron radiation imaging for advancing our understanding of cardiovascular function Circ. Res. 112 209–21
Tang Y, Cai B, Yuan F, He X, Lin X, Wang J, Wang Y and Yang G Y 2014 Melatonin pretreatment improves the survival and function of transplanted mesenchymal stem cells after focal cerebral ischemia Cell Transplant. 23 1279–91
Welsher K, Sherlock S P and Dai H 2011 Deep-tissue anatomical imaging of mice using carbon nanotube fluorophores in the second near-infrared window Proc. Natl Acad. Sci. USA 108 8943–8
Yang G Y, Betz A L, Chenevert T L, Brunberg J A and Hoff J T 1994 Experimental intracerebral hemorrhage: relationship between brain edema, blood flow and blood-brain barrier permeability in rats J. Neurosurg. 81 93–102
Yuan F, Wang Y, Guan Y, Ren Y, Lu H, Xiao T, Xie H, Vesler P S, Chen J and Yang G Y 2013 Real-time imaging of mouse lenticulostriate artery following brain ischemia Front. Biosci. (Elite Ed) 5 517–24
Zheng Y and Mayhew J 2009 A time-invariant visco-elastic windkessel model relating blood flow and blood volume Neuroimage 47 1371–80