Intravascular MR-monitored Balloon Angioplasty: An In Vivo Feasibility Study[1]

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Index terms: Angioplasty, experimental • Magnetic resonance (MR), intravascular

JVIR 1998; 9:953–959

Abbreviations: FOV = field of view, RF = radiofrequency, SPGR = spoiled gradient echo, TE = echo time, TR = repetition time, 3D = three-dimensional

PURPOSE: To develop a new method for monitoring balloon angioplasty by using an intravascular magnetic resonance (MR) imaging technique.

MATERIALS AND METHODS: Nine New Zealand White rabbits were used: seven for technique refinement, including surgery, device insertion, stenosis creation, and MR protocol development; and two for the final MR imaging of the balloon angioplasty. The in vivo experimental method involved insertion of a catheter antenna and a balloon catheter, via femoral arteriotomies bilaterally, into the target site of the upper abdominal aorta, where a stenosis was artificially created by binding a plastic cable tie. Then, the entire process of the dilation of the stenosis with balloon inflation was monitored under MR fluoroscopy.

RESULTS: Catheter insertions were successful, and a 5-mm-long stenosis of the aorta was produced in all nine rabbits. Eight complete balloon angioplasty procedures were satisfactorily monitored and recorded, showing clearly the stenosis of the aorta at the beginning of the procedure, the dilation of the stenosis during the balloon inflation, and the complete opening of the stenosis after balloon dilation.

CONCLUSION: Preliminary results of in vivo balloon angioplasty monitored with intravascular MR imaging are presented. MR fluoroscopy, based on the intravascular MR imaging technique, may represent a potential alternative to x-ray fluoroscopy for guiding interventional treatment of cardiovascular diseases.

A new method of using magnetic resonance (MR) imaging to guide therapeutic procedures, called interventional MR imaging, is an exciting technological development. To date, MR-guided therapies have been clinically limited to nonvascular interventions, such as discectomy, laser ablation of breast cancer, laser or radio-frequency (RF) ablation of head and neck tumors, monitoring of prostate cancer therapy, interstitial cryotherapy, interstitial focused ultrasound surgery, and needle biopsies (1–4). Although MR imaging of the cardiovascular system has presented some prominent advantages, such as excellent contrast of soft tissues (including vessel wall), ability to operate in multiple image planes, no contrast agent needed, and no risk of ionizing radiation, MR-guided cardiovascular interventions are still in a developing phase. The reasons for this limitation may include low signal-to-noise ratio, low frame rate, and the lack of an appropriate fast pulse sequence. Since the application of fast gradient echo and echo planar pulse sequences, several investigations of MR-guided vascular interventions have been reported recently (5–9). These in vitro and in

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vivo studies have focused primarily on either the evaluation of the MR compatibility of several vascular interventional devices, such as different guide wires, catheters, balloon catheters, and stents, or the creation of MR tracking techniques for visualization and localization of these devices under MR imaging. To our knowledge, no in vivo studies have been reported in which MR techniques are used to monitor the working process of vascular interventions, such as balloon dilation of a stenotic vessel. This is likely due to the lack of an adequate animal model with vascular stenosis or occlusion, and the lack of a suitable MR imaging technique for directly monitoring and recording the entire process of the interventional procedure.

Recently, a catheter antenna, which can be inserted into a vessel for intravascular MR imaging, has been developed (10). Based on this development, one also can create MR fluoroscopy, which may be an alternative to x-ray fluoroscopy for vascular examinations and interventions (11). The purpose of the present study was, by creating an animal model of aortic stenosis suitable for in vivo investigations of MR-guided vascular interventions, to develop a new technique for monitoring balloon angioplasty under intravascular MR imaging, which is termed intravascular MR-monitored balloon angioplasty.

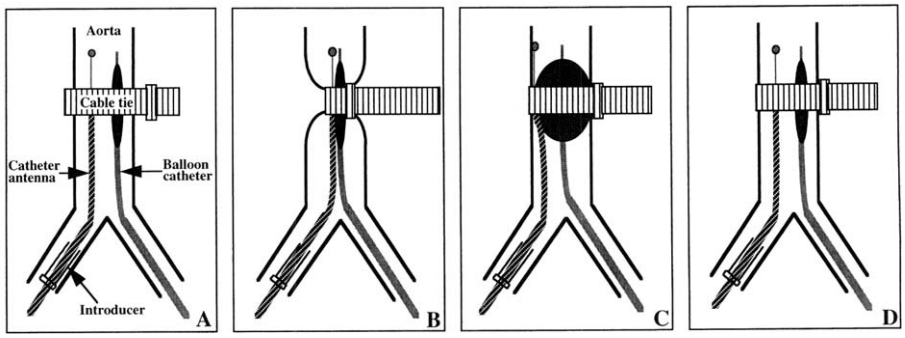


Figure 1. Illustration of the experimental design for intravascular MR-monitored balloon angioplasty on a rabbit.

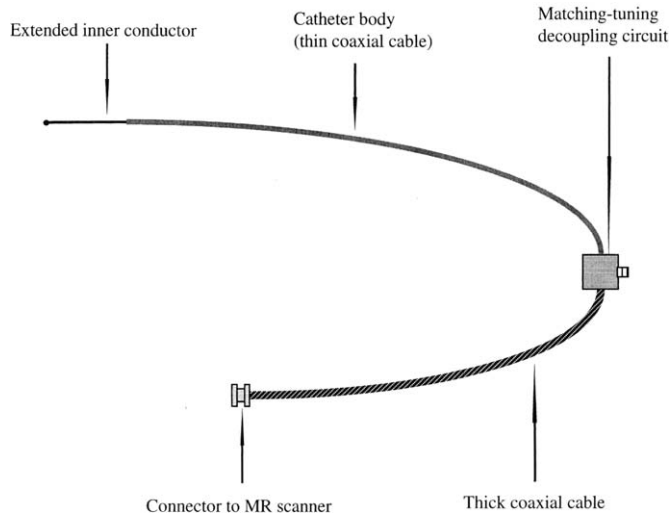


Figure 2. Illustration of a preliminary design for the catheter antenna. The portion from the tip to the electronic circuitry is inserted into blood vessels.

MATERIALS AND METHODS

• Experimental Design

To develop the intravascular MR-monitored balloon angioplasty technique in vivo, live rabbits were used in the present study. The proposed method involved insertion of a catheter antenna and a balloon catheter, via femoral arteriotomies at both sides, into the target site of the upper abdominal aorta, where a stenosis was artificially created. Then, the entire process of dilation of the stenosis with balloon inflation was monitored and recorded under MR fluoroscopy **(Fig 1)**.

• Devices

Catheter antenna—The loopless catheter antenna has been previously described elsewhere (10). Briefly, the catheter antenna system consists of a 5-cm-long conducting wire that was an extended inner conductor from a 35-cm-long coaxial cable (the catheter body). The latter was connected to a matching tuning/decoupling circuit **(Fig 2)**. The conducting wire was 0.5 mm (1.5 F) and the coaxial cable was 1.0 mm (3.0 F) in diameter **(Fig 3)**. The principle of this design is very similar to the dipole antenna used in communications. Since this design has a very simple structure, it is relatively easy to construct in very small diameters. The loopless catheter antenna can be used as a transmit/receive probe for transmitting RF pulses and receiving MR signal, or it can be used as a receive-only probe for MR signal. In the receive-only mode, the RF pulses are transmitted from an external coil such as a body coil.

Balloon catheter—A 4-F, 90-cm-long balloon catheter was used (Medi-tech/Boston Scientific, Watertown, MA). The balloon portion was 4 cm in length and 6 mm in diameter with a burst pressure of 15 atm, and contained two alloy (Tantalum) rings at both proximal and distal ends of the balloon **(Fig 3)**. The insertion of the balloon catheter into

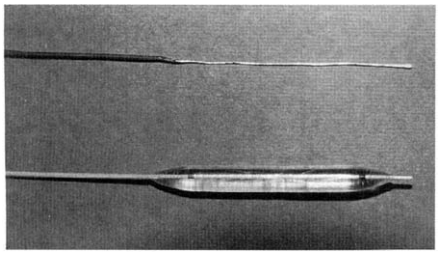


Figure 3. The tip of the catheter antenna (upper) and the tip of the balloon catheter (lower).

the vessel was guided by a 0.018-inch (0.4-mm) guide wire (Meditech/Boston Scientific), which was removed during MR imaging. The balloon catheter was tested with MR imaging and proved to be MR-compatible without producing significant artifacts, despite the two alloy rings on the balloon portion that were designed as markers for positioning the catheter under x-ray fluoroscopy.

Cable tie—To create an artificial stenosis, a 12-cm-long and 2.5-mm-wide plastic (polyethylene) cable tie (Baynesville Electronics, Baltimore, MD) was bound around the exposed upper abdominal aorta of the rabbit **(Fig 1)**. The cable tie was tightened in a direction opposite the usual direction so that the cable tie slid open easily as the balloon inflated. The ability to create the stenosis with the cable tie and to release the cable tie tightness with balloon inflation was repeatedly confirmed by testing it on a phantom (6 mm in inner diameter) before the animal experiments. The cable tie also proved to be MR-compatible.

• Surgical Procedure on Rabbits

To adapt this new technique for further use in small arteries on humans, nine female New Zealand White rabbits, 3.5–4.5 kg in weight, were used in the present study: seven for technical refinement, including surgery, the insertion of the catheter antenna and the balloon catheter, the creation of the artificial stenosis and its dilation by balloon inflation, and MR protocol development by testing different pulse sequences; and two for the final MR imaging of the balloon angioplasty procedures based on the previous seven rabbit studies. The animals were treated according to the "Principles of Laboratory Animal Care" of the National Society for Medical Research and the "Guide for the Care and Use of Laboratory Animals" (NIH Publication No. 80-23, revised 1985). The experimental protocol was approved by the Animal Study Committee at our institution.

The rabbit was first anesthetized with a mixture of ketamine (35 mg/kg) and acepromazine (0.75 mg/kg) as well as atropine (0.5 mg/kg) administered intramuscularly. Pentobarbital (25 mg/kg, intravenously) was later administered to bring the animal to a surgical plane of anesthesia. Femoral arteries at both sides were dissected free and cannulated, one with the catheter antenna for intravascular MR imaging and the other with the balloon catheter for intravascular stenotic dilation. To create an artificial stenosis at the upper abdominal aorta of the rabbit, the following surgical steps were performed: (*a*) the upper abdominal wall was anteriorly opened along the midline, allowing exposure of the abdominal cavity; (*b*) the upper abdominal organs were gently shifted from the abdominal cavity onto the right outside the rabbit's body, allowing exposure of the posterior parietal peritoneum; (*c*) a 1.5-cm long section of the upper abdominal aorta, at a level 1.5 cm above the origin of the left renal artery, was carefully exposed; and (*d*) the plastic cable tie was bound around the exposed aortic portion to create the artificial stenosis **(Fig 4)**.

A 4-F introducer sheath (Meditech/Boston Scientific) was inserted via the right femoral artery into the right iliac artery, and then the catheter antenna was sent through the introducer up to the aortic level where the cable tie was placed. The balloon catheter was directly inserted via the left femoral artery into the upper abdominal aorta and positioned side by side along with the catheter antenna. The actual position of the tips of both the catheter antenna and the balloon catheter was determined by measuring the distance between the cable tie site and the puncture point of the femoral artery, and by manually feeling both antenna and balloon through the exposed aortic section. The central point of the balloon and the most sensitive region of the loopless catheter antenna (ie, the point between the extended inner conductor and the catheter body) were centered just at the level of the cable tie site.

Subsequently, the rabbit was transferred to the MR imaging facility, while anesthesia was maintained with serial infusions of pentobarbital (20 mg/kg/h, intravenously) approximately every 30 minutes, or as needed. Non-ferromagnetic electrodes were attached to the rabbit limbs for measurement of the surface electrocardiogram (ECG). The aortic stenosis was imaged using an ECG-gated MR technique. On completion of the experiments, the animals were killed with a dose of 100 mL/kg of pentobarbital.

• Intravascular MR Imaging Technique

All experiments were performed on a Signa 1.5-T imager (GE Medical Systems, Milwaukee, WI). The rabbit was placed in a supine position in the imager and aligned with the main magnetic field. A coronal scout image was first obtained with use of a body coil to determine the anatomic position of the abdominal aorta with the following imaging parameters: fast spoiled gradient-echo (SPGR) pulse sequence, repetition time (TR) msec/echo time (TE) msec = 6.3/1.5, 31.3-kHz bandwidth, 32-cm field of view (FOV), 256 × 160 matrix, and 10-mm slice thickness. Then, axial images of the target aorta were obtained with the loopless catheter antenna in the receive-only mode. The imaging parameters were fast SPGR pulse sequence, TR/TE = 13.3/4.4, 8-cm FOV, 256 × 256 matrix, 20° flip angle, and 3-mm slice thick-

ness. Image intensity was corrected by using the image intensity correction algorithm described elsewhere (10). Before balloon dilation, the mode of operation of the catheter antenna was changed from receive-only to transmit/receive. For recording the entire process of intravascular MR-monitored balloon dilation, we used a fast SPGR pulse sequence with TR/TE = 9.9/2.5, 18 × 1.7-cm FOV, 256 × 24 matrix, and a 5-mm slice thickness. Using this sequence, we recorded the entire process of balloon angioplasty at a rate of 4.2 frames per second. By performing contrast-enhanced three-dimensional (3D) MR aortographies with an intravenous injection of 3 mL of Omniscan (287 mg of gadodiamide per milliliter) (Nycomed, Princeton, NJ), we also compared the aortic changes before and after balloon angioplasty, using the following parameters: 3D fast SPGR pulse sequence, TR/TE = 8.6/1.6, 32-kHz bandwidth, 20-cm FOV, 256 × 128 matrix, 45° flip angle, and 1-mm slice thickness.

• Balloon Angioplasty Procedure

The balloon was inflated by manual injection of 2 mL of contrast medium with a 20-mL plastic syringe. The contrast medium used for balloon inflation was 3% Magnevist (Berlex Laboratories, Wayne, NJ) diluted with saline (14 mg of gadolinium per milliliter). The balloon inflation was started 5–7 seconds after beginning MR imaging, maintained by manual control for 10 seconds, and terminated 5–7 seconds before the completion of MR imaging. The total MR imaging time was 24 seconds for each balloon angioplasty procedure. Five to six procedures of balloon dilation of the cable-tightened aortic stenosis were carried out for each of the seven protocol development rabbits, and four balloon angioplasty procedures were performed in each of the final MR-imaged rabbits.

Figure 4. Surgery on a rabbit. The cable tie is bound around the exposed portion of the upper abdominal aorta.

RESULTS

The techniques of both catheter insertion and stenosis creation were successfully performed in all nine rabbits. An approximately 5-mm-long artificial stenosis of the rabbit aorta was produced by tightening the cable tie. The stenosis was efficiently dilated during the balloon inflation and almost completely opened to its original shape after balloon intervention, which enabled repeat procedures of balloon dilation in each rabbit. The contrast medium injected into the balloon produced high-signal images, which provided an excellent outline of the aortic stenosis and contrasted well to the non-signal aortic wall.

On axial intravascular MR images, the lumen of the abdominal aorta was clearly seen as a bright circle signal, in which both the catheter antenna and the empty balloon were represented as signal voids **(Fig 5)**. The catheter antenna was surrounded by very high signal because of its high sensitivity to the nearby objects. On coronal images, the two alloy rings of the balloon were demonstrated as two small non-signal circles (image artifacts). In our protocol, we used the two alloy markers to precisely adjust the position of the balloon during MR imaging. The artificially induced aortic stenosis was clearly observed at the level between the two alloy markers of the balloon **(Fig 6)**.

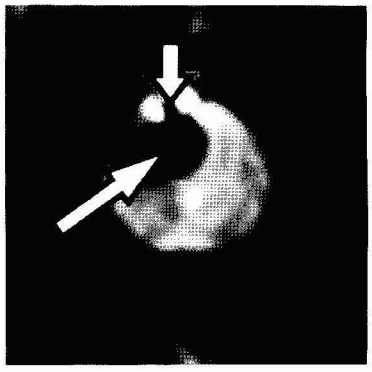


Figure 5. Axial MR image of the rabbit aorta. The aorta presents as a bright signal circle, which includes a catheter antenna (short arrow) and a deflated balloon (long arrow) both without signal. Imaging parameters: fast SPGR, TR/TE = 13.3/4.4, 8-cm FOV, 256 × 256 matrix, 20° flip angle, and 3-mm slice thickness.

Entire balloon angioplasty procedures were satisfactorily monitored and recorded under MR fluoroscopy, presenting clearly the aortic steno-

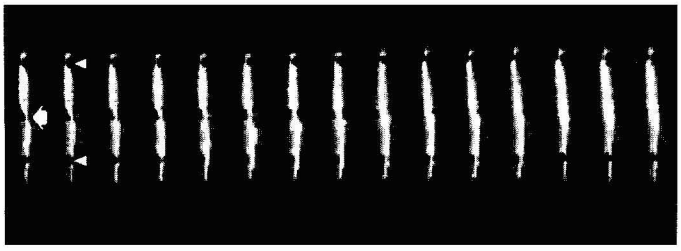
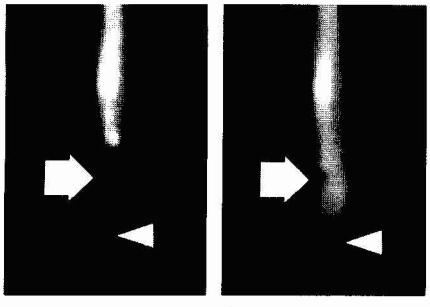


Figure 6. A serial frame from the MR fluoroscopy record of intravascular MR-monitored balloon angioplasty, showing the aortic stenosis (arrow) at the beginning of the procedure and complete opening of the stenosis after total balloon inflation. Arrowheads indicate the circle image artifacts produced by the two alloy rings of the balloon portion. Imaging parameters: fast SPGR, TR/TE = 9.9/2.5, 18 × 1.7-cm FOV, 256 × 24 matrix, 5-mm slice thickness, and 4.2 frames per second.



a. **b.**

Figure 7. Contrast-enhanced 3D MR aortography of the rabbit. Comparison of images obtained before and after balloon dilation of the stenotic aorta. The artificial stenosis (thick arrows) with decreased distal blood flow (arrowhead) is clearly seen before the balloon angioplasty **(a)** and is opened with increased distal blood flow after angioplasty **(b)**. On these two images, the balloon portion is withdrawn from the stenotic aorta. Imaging parameters: 3D fast SPGR pulse sequence, TR/TE = 8.6/1.6, 32-kHz bandwidth, 20-cm FOV, 256 × 128 matrix, 45° flip angle, and 1-mm slice thickness.

sis at the beginning of the procedure, the dilation of the stenosis during balloon inflation, and the complete opening of the stenosis after balloon dilation. **Figure 6** shows images obtained from MR fluoroscopy, recorded during the intravascular MR-monitored balloon angioplasty process. The aortic stenosis with decreased distal blood flow was also clearly observed and was opened with immediately increased distal blood flow after the balloon angioplasty **(Fig 7)**.

DISCUSSION

MR angiography has been shown to be useful in the workup of patients with either peripheral vascular diseases or coronary diseases (12–14). However, MR angiography with a surface coil does not produce enough signal-to-noise ratio for creation of MR fluoroscopy with an acceptable image resolution, and therefore cannot be used for the purpose of interventional therapies. In addition, with MR angiography, one can satisfactorily observe the changes within the vascular lumen, such as a stenosis or occlusion, but not changes in the vessel wall. Intravascular sonography can provide a cross-sectional view of vessels, which is particularly useful in the demonstration of calcified plaque in the vessel wall and percent stenosis of the vessel lumen (15,16). Recently, a few studies have demonstrated the useful applications of intravascular sonography for guiding fenestration in aortic dissection (17) and also for guiding endovascular stent graft placement (18).

To improve the signal-to-noise ratio, some investigators have used intravascular receiver probes to obtain high-resolution MR images of the vessels (19–23). Recently, a new approach to intravascular MR imaging, which is performed by inserting a catheter coil or a loopless catheter antenna into blood vessels, has been developed (10,24). It has been demonstrated experimentally that this new approach will have many applications for vascular examinations, including the following: (*a*) localizing atherosclerotic plaques on the arterial wall, measuring the thickness of the plaques, and analyzing the components of atherosclerotic plaques (25); (*b*) obtaining high-resolution MR images of vessels with a high signal-to-noise ratio that cannot be achieved with standard receiver coils (10); (*c*) observing the cross-sectional images of stenotic arteries, which cannot be seen on standard angiography images (24); and (*d*) creating intravascular MR fluoroscopy, which may function as an alternative to x-ray fluoroscopy for vascular examinations and interventions (11). In the present study, by using the intravascular catheter antenna, we have demonstrated the successful initial results of in vivo intravascular MR-monitored balloon angioplasty. These confirm that the intravascular catheter antenna is useful for the creation of MR fluoroscopy and also provides the ability to perform vascular interventional techniques under MR imaging guidance.

The rabbit model of artificial aortic stenosis in the present study is a promising model to investigate intravascular MR imaging, intravascular MR-guided balloon angioplasty, and, theoretically, for future investigations of other intravascular MR-guided vascular interventions, such as intravascular MR-guided stent placement. The Magnevist at 3% concentration worked very well for both balloon inflation and observation under MR fluoroscopy. The two alloy rings of the balloon portion served as excellent markers for accurately positioning the balloon under MR fluoroscopy, similar to x-ray fluoroscopy. These markers are very useful for any interventional MR procedure.

The technique presented herein requires further modification, improvement, and practice. Although we currently face some technical construction challenges, a thinner catheter antenna would be better for intravascular MR-guided balloon angioplasty. Similar to a guide wire, the thin catheter antenna can be directly inserted into the central

channel of a balloon catheter, which should also theoretically enable its use in an endovascular stent delivery system. This central positioning of the catheter antenna will also improve image quality because the centrally placed catheter antenna will result in a more equally distributed magnetic signal field within the vessel lumen than an eccentricly positioned one. Meanwhile, a centrally positioned catheter antenna within an interventional catheter will avoid the requirement of a second vascular access site and the need to pass two catheters through a stenosis, which increases the risk of failure and of complications such as dissection of the vessel wall. The current method of side-by-side positioning of the catheter antenna and the balloon catheter may be applied to recanalize a totally occluded artery. For example, the catheter antenna may be positioned in a venous vessel that is parallel to the target artery, providing an image of a vein and an artery side by side. Thus, the recanalization of the arterial occlusion with use of some interventional techniques also can be monitored with MR fluoroscopy if a corresponding MR imaging protocol can be established.

The intravascular MR-guided interventions may be best performed under a short MR imager or an open MR system, which allows the head and lower extremities of the patient to be exposed outside the imager, while clinicians can easily communicate with and conveniently monitor the patient at any time during the interventional procedure. In addition, in the present study we monitored the balloon angioplasty process by using MR fluoroscopy at 4.2 frames per second. It is possible to increase this rate with the optimization of the pulse sequence. We expect that with proper modification of the pulse sequence we will operate MR fluoroscopy at a frame rate higher than 10 frames per second.

Recently, some research groups have reported the results of in vivo studies on the development of MR catheter tracking techniques. In two research groups, investigators tested different MR-compatible catheters, such as the balloon catheter, the embolization catheter, and the angiographic catheter, which were equipped with either a RF coil incorporated into the catheter tip or a copper wire configured around the entire catheter for placement guidance or for visualizing the position of these interventionally used catheters (5,7). In our research group, using the loopless catheter antenna, we developed a narrow catheter-tracking FOV imaging technique, which enabled us to track an intravascular catheter under MR fluoroscopy (11). The combination of MR catheter tracking techniques with the intravascular MR-monitoring technique will certainly refine the concept of MR-guided vascular interventional therapies, and provide the groundwork for use in clinical practice in the near future.

Functional MR before and after therapeutic interventions is a current reality, and the idea of on-line monitoring of the effectiveness of such interventions as a guide to the next therapeutic step is very attractive. Functional cardiac MR techniques, such as MR myocardial tagging (26,27), perfusion (28,29), and blood oxygen level dependent (BOLD) imaging techniques (30,31), have opened up new avenues in the investigation of ischemic heart diseases. Combined with functional cardiac MR techniques, the results of our intravascular MR-guided balloon angioplasty represent the potential for on-line management of ischemic heart disease in the future, although great effort is required to develop MR-guided coronary interventions.

In conclusion, we demonstrate the preliminary result of in vivo intravascular MR-monitored balloon angioplasty. This success confirms that the intravascular catheter antenna has provided the potential for creation of MR fluoroscopy, which may represent an alternative to x-ray fluoroscopy for guiding interventional therapies of cardiovascular diseases.

Acknowledgments: The authors thank Mary McAllister for her help in manuscript preparation, and Walter Rogers, Ogan Ocali, Keven Phelan, and Rick Shunk for providing catheters. Special thanks to Dr. James Earls for his help in 3D contrast-enhanced MR angiography studies.

WEBSITE

The entire record of the intravascular MR-monitored balloon angioplasty procedure can be accessed on our web-page on the internet (http://www.mri.jhu.edu/IVMRI/balloon).

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