Artifact-Free In-Stent Lumen Visualization by Standard Magnetic Resonance Angiography Using a New Metallic Magnetic Resonance Imaging Stent

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Background—Metallic stents cause susceptibility and radiofrequency artifacts on MR images, which, up to now, have not allowed for complete visualization of the stent lumen by MR angiography. The aim of this study was to investigate the potential of a new dedicated renal MRI stent for artifact-free in-stent lumen visualization in vitro and in a swine model.

Methods and Results—In vitro investigations were performed with prototypes of balloon-expandable Aachen Resonance Renal MRI Stents dilated to diameters of 3 to 6 mm and placed in an aqueous gadolinium solution (1:25). Phase-contrast and contrast-enhanced T1-weighted gradient echo images were acquired. Renal MRI stents (n=12) were deployed in the renal arteries of 6 pigs. Renal arteries were examined with phase-contrast angiography and with flow measurements before and after stent placement in the stented area, respectively. Additionally, a contrast-enhanced, T1-weighted, spoiled-gradient echo sequence after administration of 0.2 mmol gadolinium-DTPA/kg body weight was performed after stent placement. The visibility of artifacts was analyzed on in vitro and in vivo images by two investigators who knew the stent positions. Stent positions were determined visually (in vitro) or by x-ray angiography (animal experiments). No artifacts were detected independent of the applied imaging sequence and the stent orientation to the main magnetic field.

Conclusion—The examined prototypes of fully MR-compatible MRI stents allow artifact-free visualization of the stent lumen with phase-contrast and contrast-enhanced T1-weighted angiography, as well as phase-contrast flow measurements in the stented area. *(Circulation. 2002;105:1772-1775.)*

Key Words: magnetic resonance imaging ■ angiography ■ stents

Magnetic resonance imaging (MRA) is increasingly replacing diagnostic x-ray angiography in virtually all vascular territories. In particular, the advent of contrast-enhanced MRA has led to substantial increases in image quality and diagnostic accuracy. So far, however, MRA has not been able to reliably visualize the lumen of metallic stents,1–3 and consequently, only indirect follow-up of in-stent-restenosis can be made by MR imaging. This is due to susceptibility artifacts and radiofrequency shielding of metallic stents.2 Although nitinol causes smaller artifacts compared with stainless steel, even nitinol stents are not artifact free on MR images.4 We examined fully MR-compatible prototypes of Aachen Resonance Renal MRI Stents to determine their potential for artifact-free in-stent lumen visualization with different MRA techniques.

Methods
Four prototypes of Aachen Resonance Renal MRI Stents (Aachen Resonance, Aachen, Germany) were dilated to diameters of 3 to 6 mm in 1-mm steps. The stents were made of a special MR alloy consisting to >90% of copper, designed to minimize susceptibility artifacts. The stents were placed in a physiological saline solution with gadolinium (Magnevist, Schering) (1:25) and imaged with phase-contrast angiography (sequence parameters as given below, except for simulated ECG signal)5 and T1-weighted gradient echo angiography sequences (sequence parameters as given below) on a 1.5T Intera MR scanner (Philips Medical Systems). Each sequence was performed with the stents oriented 0°, 45°, and 90° to the main magnetic field B0. The MR images were independently examined by two investigators who knew the position of the stents placed in the water-bath phantom, and the images were graded according to the presence of large artifacts (stent lumen totally obscured), small artifact (subtotal narrowing of the stent lumen), or no artifact. Additionally, the signal intensities of the water bath without and with stent were measured.

Approval for the animal experiments was obtained from the Official Committee for Animal Affairs of the German government. Experiments were performed on 6 domestic pigs with an average body weight of 55 kg (range, 48 to 61 kg). A premedication of 0.5 mL atropine/10 kg body weight, 2 mL azaperone/10 kg body weight, and 1 mL ketamine/10 kg body weight was...
applied intramuscularly. Pentobarbital diluted 1:3 with saline solution was injected as needed via a venous access line placed in an ear vein. The animals were intubated and mechanically ventilated.

Before stent placement, a diastolic-triggered 3D phase-contrast angiography was performed (repetition time [TR], 20 ms; echo time [TE], 7 ms; flip angle, 20°; field of view [FOV], 170×120 mm²; matrix, 128×256; slice thickness, 1.5 mm; 50% slice overlap; 40 axial slices; diastolic ECG gating with an acquisition window of 300 ms; and maximum flow velocity, 30 cm/s).³ With the use of the axial images and the calculated maximum intensity projections (MIPs) in the coronal plane, velocity-encoded cine phase-contrast flow measurements (TR, 5.8 ms; TE, 3.6 ms; flip angle, 15°; FOV, 350×175 mm²; matrix 128×256; slice thickness, 5 mm; ECG gating, acquisition of 30 phases of the cardiac cycle; maximum flow velocity, 50 cm/s; 2 signal averages) were performed perpendicular to the course of the renal arteries in the area in which the stent was going to be deployed. Afterward, 12 balloon-mounted Aachen Resonance Renal MRI Stents were placed in the left and right renal arteries of 6 pigs. One stent was placed distally in a first segment branch and dilated to 3 mm. All other stents were placed in the main stem of the renal arteries. One of these stents was dilated with a 6-mm one and one with a 7-mm balloon, whereas all other stents were dilated with a 5-mm balloon. Stent positions were documented on x-ray angiography. Orientation of the stents to the main magnetic field B₀ were determined on these images assuming a parallel course of the aorta and B₀, yielding stent angulations ranging from 36° to 89° (mean 64°).

After stent placement, phase-contrast angiography was repeated. Flow measurements were performed through 10 stents. In two cases, flow measurement was not possible because of a corrupted optical disc. Additionally, a contrast-enhanced T₁-weighted gradient echo sequence (TR, 5.4 ms; TE, 1.44 ms; flip angle, 40°; FOV, 450×315 mm²; matrix, 128×512; slice thickness, 1.5 mm; 50% overlap; 50 coronal slices) was acquired with the use of automatic bolus tracking to start the imaging sequence. A double dose of Omniscan (Nycomed) (0.2 mmol/kg body weight) was applied for the MR angiography, and MIPs were calculated. The calculated MIPs of the phase-contrast and contrast-enhanced angiographies were analyzed by two investigators with regard to the occurrence of artifacts (large or small) or absence of artifacts in the stented area. The regions of stent placement were determined on the digital subtraction angiography images. The Pearson correlation coefficients of the maximum and minimum flow velocities as determined by ECG-triggered phase-contrast MR imaging before and after stent placement were calculated, as well as the slopes of the corresponding regression lines. To investigate possible radiofrequency artifacts, signal intensities in the stents and proximal to them were measured for the gadolinium-enhanced MRA. The values inside and outside the stents were compared by calculating the Pearson correlation coefficient and the slope of the corresponding regression line.

Results

Independent of the diameter and orientation to the main magnetic field, all stents were judged to show artifacts neither on the in vitro nor on in vivo images of the phase-contrast and gradient echo images (Figure 1). The average signal intensity as measured in the area of the stent and without stent during in vitro experiments was 1845 and 1890 for the T₁ gradient echo and 1479 and 1480 for the phase-contrast sequence. The Pearson correlation coefficients of the maximum and minimum flow velocities as measured by phase-encoded MR imaging were \( r = 0.99 \) and \( r = 0.96 \), respectively. The slopes of the corresponding regression lines were 1.1 and 0.98, respectively. Comparison of the signal intensities inside and outside the stents yielded a correlation coefficient of \( r = 0.99 \), with a slope of the corresponding regression line of 0.98.

Discussion

Because of its noninvasive nature and high image quality, MRA rapidly is becoming the standard diagnostic imaging method for almost all vascular territories. One major drawback of the technique is the inability to sufficiently visualize the inner lumen of stents. This is a result of the different susceptibilities of the metals used for stents compared with human tissue, which causes so-called susceptibility artifacts.⁴,⁶ Radiofrequency shielding of the stents reduces the excitation angle inside the stents, causing additional signal loss.⁴,⁶ Despite the fact that nitinol stents show fewer artifacts compared with stainless steel stents, even nitinol stents cause artifacts that are usually too large to allow the evaluation of in-stent restenosis by MRA.⁴ Only with large-diameter nitinol stents in the iliac arteries have sufficiently small artifacts been reported to allow for diagnostic follow-up, either by standard MRA⁷ or by increasing the excitation angle of the MRA sequence.⁸ One further advantage of iliac artery compared with renal artery stents is their orientation almost parallel to the axis of the main magnetic field, which is known to reduce susceptibility artifacts.⁴,⁶ Stainless steel stents, such as those usually used for the rigid stenoses of renal arteries, do not allow direct visualization of the stent lumen.

In the present study, we examined hand-woven prototypes of Aachen Resonance Renal MRI Stents (Figure 2) made of a special metallic alloy with a high copper content to reduce susceptibility and radiofrequency artifacts. In vitro experiments with standard phase-contrast and contrast-enhanced MRA sequences showed no stent artifacts, even for a stent orientation perpendicular to B₀, which in general causes the largest susceptibility artifacts.⁴ These promising in vitro results were further investigated in an animal model by placing the MRI stents in the renal arteries of pigs. No stent artifacts or signal reduction inside the stents were seen on either the phase-contrast or the contrast-enhanced T₁-weighted MRA (Figure 1) independent of the orientation of the stents to B₀, which in general causes the largest susceptibility artifacts.⁴ In our case, the lack of stent artifacts made the direct measurement of flow inside the small MRI stents possible, as proved by the good correlation of maximum and minimum flow measured by 2D cine velocity-encoded phase-contrast imaging. The size of susceptibility artifacts is related to the echo time of the MR sequence. The gradient system of our MR scanner (21 mT/m) allowed an echo time of 1.44 ms, and even the substantially longer echo time of the phase-contrast angiography sequence (7 ms) caused no detectable susceptibility artifacts. Therefore, it can be expected that the MRI stents will remain
artifact free with other imaging sequences, such as vessel wall imaging. The investigated MRI-compatible stents are virtually invisible on MR images, showing neither susceptibility nor radiofrequency artifacts.

Another approach for MR imaging in the presence of stents is to use actively tuned stents as antenna. Further experiments will have to show whether the possible advantage of imaging the arterial wall with a stent used as an antenna close to it will prove more feasible and advantageous compared with the simpler approach of creating stents out of an MR-invisible alloy, which does not require additional capacitors to be tuned, as for the active approach. The handmade prototypes lacked a radial force comparable to standard stainless steel stents, a problem that might be overcome by lasering of the stents.

**Conclusions**

The prototype Aachen Resonance Renal MRI Stent allows artifact-free MR imaging of the renal arteries, enabling direct visualization of the stent lumen by phase-contrast and gadolinium-enhanced MRA as well as flow measurement directly inside the stent.

**References**

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