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Magnetic Resonance Angiography of Nonferromagnetic Iliac Artery Stents and Stent-Grafts: A Comparative Study in Sheep

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Abstract

Purpose: To compare nonferromagnetic iliac artery prostheses in their suitability for patency monitoring with magnetic resonance angiography (MRA) using conventional angiography as a reference.

Methods: In experiment 1, three Memotherm stents were inserted into the iliac arteries of each of six sheep: two "tandem" stents on one side and a single stent on the other side. In experiment 2, four prostheses (normal and low-porosity Corvita stent-grafts, Memotherm, ZA-stent) were inserted in each of 11 sheep. Patency was monitored before and 1, 3, and 6 months after insertion with 3D phase-contrast and two 2D time-of-flight sequences (TOF-1: TR/TE = 18/6.9, TOF-2: 13/2.5) with and without contrast at 1.5 T. On 206 coronal MIP images (72 pre-, 134 post-stenting), three readers analyzed 824 iliac segments (206 × 4) for patency and artifacts.

Results: There was no difference in the number of artifacts between tandem and single iliac Memotherm stents. The ZA-stent induced significantly fewer artifacts than the other prostheses ($p < 0.00001$). With MRA, patency of the ZA-stent was correctly diagnosed in 88% of cases, which was almost comparable to nonstented iliac segments (95%), patency of the Memotherm stent in 59%, and of the Corvita stent-grafts in 57% and 55%. The TOF-2 sequence with contrast yielded the best images.

Conclusion: MRA compatibility of nonferromagnetic prostheses depends strongly on the design of the device. MRA may be used to monitor the patency of iliac ZA-stents, whereas iliac Memotherm stents and Corvita stent-grafts appear to be less suited for follow-up with MRA.

Key words: Grafts and prostheses—Arteries, iliac—Magnetic resonance angiography—Stent-grafts—Percutaneous angioplasty—Experimental study

Noninvasive magnetic resonance angiography (MRA) is a promising new technique that may replace invasive conventional angiography in various fields in the near future [1–5]. One new application for MRA could be in the follow-up after endovascular prosthesis placement. Monitoring of iliac artery prostheses is of particular interest since iliac prostheses are implanted frequently [6] and direct evaluation of these devices with alternative noninvasive imaging modalities such as color duplex ultrasound may sometimes be difficult in patients with obesity and meteorism [7].

Ferromagnetic endovascular prostheses such as the Palmaz stent are less suitable for MRA since they cause severe artifacts [8]. Prostheses made from nonferromagnetic alloys and metals, such as nitinol, Elgiloy, Phynox, or tantalum, are expected to be more suitable for evaluation with MRA [8]. Up to now there have been very few reports on the use of MRA to monitor metal endovascular prostheses [9–11].

There are two basic techniques for performing MRA: time-of-flight MRA (TOF) and phase-contrast MRA (PCA). Most previous studies have shown a preference for the TOF technique in the evaluation of arterial occlusive disease of the lower extremities, only rarely utilizing the PCA technique [3, 12–17]. An alternative technique evolving only recently is gadolinium-enhanced MRA, which uses fast 3D gradient-echo sequences and requires advanced MR tech-

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niques [2, 18]. It is not yet clear which of these technique is the most useful in the evaluation of a metal iliac artery prosthesis.

The purpose of our experimental study was to determine in an experimental setting in vivo whether there were differences in the MRA compatibility of different types of nonferromagnetic prostheses. Conventional angiography was used as a reference imaging modality.

Materials and Methods

Study Design

After approval by the regional authorities all experiments were performed according to the general guidelines for animal experiments. All interventions were done under general anesthesia using a previously described technique [19]. A total of 17 male sheep with an average weight of 48 ± 9 kg were included. In sheep the aortic bifurcation gives rise to five vessels including a small artery to the tail, two internal iliac arteries, and two long external iliac arteries. There are no common iliac arteries. Prostheses were percutaneously placed via a bilateral femoral artery approach into both external iliac arteries.

The study consisted of two experiments. The first experiment was performed to assess whether there was a difference in the amount of artifact if two prostheses ("tandem" prostheses) were inserted into the same external iliac artery in a distance of about 0.5–1 cm compared with a single stent inserted into the iliac artery on the opposite side. Three Memotherm stents were placed per animal ($n = 6$). Two tandem stents were placed on one side into the cranial and caudal segment of the same artery, and a single stent was placed on the other side opposite to either the cranial or the caudal contralateral stent. The position of the single and tandem stents was systematically varied. In the second experiment, four different prostheses were compared. In each of the animals ($n = 11$) two different types of Corvita stent-grafts (Schneider/Corvita, Brussels, Belgium), a Memotherm stent (Angiomed/Bard, Karlsruhe, Germany), and a ZA-stent (Cook, Bjaeverskov, Denmark) were inserted. The position of the different types of prostheses in the right or left cranial or caudal segment of the external iliac arteries was systematically varied.

Prostheses

All prostheses used were nonferromagnetic. Corvita stent-grafts are composed of a wire mesh made from Elgiloy. Elgiloy is a nonferromagnetic alloy mainly composed of cobalt (40%), chromium (20%), nickel (15%), and molybdenum (7%). The stent-grafts have an inner polymer lining of polycarbonate urethane. The two types of Corvita stent-grafts used differed in the porosity of the polymer. One type, which is already in clinical use [20], has an inner lining of normal porosity with a thickness of about 0.14 mm, and the other, a prototype for investigational purposes only, has a low-porosity lining with a thickness of about 0.28 mm. The wire mesh of the Memotherm stent and the ZA-stent is made from nickel-titanium alloy (nitinol: about 50% nickel and 50% titanium) [8]. Nitinol has been used for years for various endovascular implants, particularly vena caval filters and vascular stents [21–25]. The design of the Memotherm stent, which has been in clinical use for several years, has been described in detail elsewhere [24]. Up to now, the new ZA-stent has been used only in animal experiments [25]. The ZA-stent is knitted from nitinol wire with a circular profile and a diameter of 0.15–0.16 mm. To improve the fluoroscopic visibility of the ZA-stent a radiopaque metal marker is fixed at each end of the stent.

The noncovered stents (Memotherm, ZA-stent) were 3 cm in length and 8 mm in diameter, except in three animals in the first experiment with larger iliac arteries that required 10-mm Memotherm stents. Corvita stent-grafts had to be slightly longer than 3 cm (up to 3.3 cm) to maintain sufficient stability of the prosthesis.

Follow-up

The animals in the first experiment were followed for 1 month ($n = 6$), the animals in the second experiment for either 1 month ($n = 7$) or 6 months ($n = 4$). In the 6-month follow-up group, examinations were performed after 1, 3, and 6 months, and in the 1-month follow-up group only after 1 month. Follow-up included digital subtraction angiography (DSA), 100-mm angiographic spot scans, intravascular ultrasound (IVUS) (Hewlett-Packard, Andover, MA, USA), and MRA. MRA was performed immediately before angiography and IVUS. Angiograms were obtained in anteroposterior and left and right anterior oblique views (40°) via a bilateral femoral approach. A 7 Fr angiographic catheter with graduated radiopaque markers and IVUS were used to determine the degree of stent stenosis.

MRA

Sheep were examined in the supine position with the legs secured by elastic bandages; the hindlegs were extended. They were ventilated with 75% nitrous oxide and 25% oxygen via an extra-long ventilation tube from a standard respirator that was positioned sufficiently far from the scanner to prevent it interfering with the examination. Pentobarbital was additionally administered in regular intervals.

Examinations were performed on a 1.5 Tesla (T) Philips scanner (Gyroscan ACS-NT, Philips, Best, The Netherlands) using the body coil. The gradient strength was 15 mT/m. Three different gradient-echo sequences were used: two two-dimensional (2D) TOF sequences (TOF-1 and TOF-2) and one three-dimensional (3D) PCA sequence. The parameters of the sequences are given in Table 1. With all three sequences images were acquired in the axial plane, and a presaturation slab was placed without a gap caudal to the region to be imaged to reduce signal disturbances from inflowing (venous) blood.

The standard 2D TOF-1 and the 3D PCA sequence were chosen because, in a brief evaluation preceding the study, the 3D PCA sequence was found to provide better image quality than the 2D PCA sequence, whereas the 2D TOF and 3D TOF images were similar, but the time interval required for the 3D TOF was longer. The TOF-2 sequence was specially designed to enhance image quality of stented arteries.

The imaging protocol started with two survey sequences to locate the aortic bifurcation and iliac arteries, following which axial images of the pelvic region were acquired with the above-mentioned MRA sequences and reconstructed in the coronal plane using the targeted maximum intensity projection technique (MIP) [4]. For each sequence 12 MIP images in steps of 15° were reconstructed

Table 1. Parameters of MRA sequences used

Sequence	PCA	TOF-1	TOF-2
Geometry	3D	2D	2D
TR (msec)	18	18	13
TE (msec)	5.6	6.9	2.5
Field of view (mm)	350	350	170
No. of acquisitions	2	2	6
Slice thickness (mm)	6/3[a]	4	3
Slice gap (mm)	—	2	0.4
No. of slices	45	60	40
Image matrix	163 × 256	128 × 256	89 × 128
Threshold (cm/sec)	50		
Flip angle (deg)	20	60	75
Presaturation slab thickness (mm)	50	50	80
Scan time (min:sec)	04:18	03:53	03:36

PCA = phase-contrast MRA; TOF = time-of-flight MRA; TR = repetition time; TE = echo time
[a] Fifty percent overcontiguous 6-mm slices

from the axial images, and a hardcopy of the 12 MIP images was made on a laser printer film in a 3 × 4 format, thus providing an MR angiogram comparable to a conventional multiple-view digital subtraction angiogram. The maximum total MR examination time was about 1 hr. Cardiac and respiratory gating were not used, nor were antiperistaltic drugs administered to reduce bowel movement.

In the first experiment, a PCA and TOF-1 sequence were acquired before and after intravenous contrast administration (Table 2). In the second experiment, a PCA, TOF-1, and TOF-2 sequence were acquired before and after intravenous contrast administration. The first sequence performed after contrast alternated between the PCA and TOF-1 sequence, and a second dose of intravenous contrast was administered immediately before the start of the final TOF-2 sequence in the second experiment. Contrast injections were 0.1 ml/kg of Gd-DTPA.

In 14 of the 17 animals (all 6 in the first and 8 in the second experiment), MRA was also performed before prosthesis implantation using the same protocol as described above for the evaluation after prosthesis insertion. These MR angiograms served as controls.

MRA Analysis

All prostheses evaluated in this study were patent angiographically and with IVUS (<30% diameter stenosis). Only patent prostheses were included to avoid bias due to flow signal changes caused by stenosed or occluded prostheses. The MIP images of each MRA sequence were used for analysis. A total of 206 MRA films were analyzed: 72 before (24 first, 48 second experiment) and 134 (24 first, 110 second experiment) after prosthesis placement.

Each of the 206 MRA films obtained was assigned a computer-generated random number that determined the order in which the films were presented to the readers. The readers were masked to the identity of the animal, the experiment to which the animal belonged, and the fact that all segments were patent angiographically. They were also not given any information about what type of prosthesis had been placed, if any, in each iliac segment. Three independent readers took part in the study who were all experienced in MRA. A dedicated questionnaire was used for analysis. Each reader had to make a judgement separately about the cranial and caudal segments of both external iliac arteries corresponding to the four possible sites for insertion of prostheses. Overall, each reader evaluated 206 × 4 = 824 arterial segments.

In a test phase preceding the main evaluation, the readers could learn from 10 selected representative examinations, comprising both the MRA and the corresponding conventional arterial DSA, what to look for on the MR angiograms after iliac prosthesis insertion, and how to use the questionnaire. These cases were not included in the final study, in which the readers had to do the evaluation from the MR angiograms alone. Each film reading session involved the interpretation of a maximum of 20 MR angiograms.

First the readers had to grade the quality of MRA in each segment as being equal to arterial DSA (grade 1), or slightly (grade 2), modestly (grade 3), or severely (grade 4) reduced in quality compared with DSA, or completely unreadable (grade 5). It was left to each reader to decide which images were defined as unreadable. The readers could indicate which of the following points in their opinion degraded readability of MRA images: metal artifacts, overlying venous signals, motion artifacts, noise, or other. Next, the readers had to state whether they considered each of the four segments of the external iliac arteries (right and left cranial and caudal) patent (<30% diameter stenosis) or not patent (>30% stenosis). Finally, the readers had to decide which of the iliac segments contained a prosthesis, and they had to rank the artifacts that they considered to be induced by the prosthesis into one of four groups compared with all other prosthesis-containing segments. Those segments with minimal artifacts were given a grade of 1, those with greater amount grades of 2 or 3, and those with maximal artifacts a grade of 4. If the artifact was similar in different segments the same grade could be assigned to these segments. In addition to the masked analysis, a subjective qualitative evaluation was performed by a non-masked reader (K.S.) who directly compared the conventional angiograms with the MRA MIP images. The focus of the evaluation was to find out where the artifacts induced by the prosthesis were located in relation to the position of the prosthesis, and whether there was a correlation between the extent of the artifacts and the type of prosthesis and sequence.

Statistical Analysis

For comparative analyses nonparametric tests (Kruskal-Wallis, Mann-Whitney U, and Wilcoxon test) were used. A p value of less than 0.05 was considered statistically significant. Multiple comparisons in pairs were performed with a p value correction according to Shaffer that is based on the Bonferroni procedure [26].

Results

No overlap of stents occurred. The mean diameter (± standard deviation) of the iliac arteries prior to prosthesis insertion was 7.0 ± 0.6 mm in experiment 1 and 7.6 ± 1.1 mm in experiment 2.

Subjective Analysis

In the first experiment the artifacts caused by tandem and single Memotherm stents were similar in degree. Neither did the artifacts of the cranially and caudally placed tandem

Table 2. Experiments performed and prostheses placed

Experiment no.	No. of sheep	MRA before prosthesis	Follow-up (months)	No. of prostheses per sheep	Prostheses placed per sheep	Total no. of prostheses placed	MRA sequences	Before contrast	After contrast
1	6	6 animals	1	3	3 Memotherm stents	18	PCA, TOF-1	×	×
2	11	8 animals	1 (7 sheep), 6 (4 sheep)	4	2 Corvita stent-grafts (1 low and 1 normal porosity), 1 Memotherm stent, 1 ZA-stent	44	PCA, TOF-1, TOF-2	×	×

PCA = phase-contrast MRA; TOF = time-of-flight MRA

stents appear to be different. Artifacts were most pronounced at the ends of the prostheses, where complete signal loss was sometimes seen (Fig. 1). In addition, the flow signal throughout the length of a prosthesis could be artifactually reduced compared with arterial segments where no prosthesis had been placed.

In the second experiment it was found that all prostheses were associated with artifacts regardless of the type of prosthesis or the sequence used. However, the ZA-stent demonstrated markedly less artifact both at the ends and within the stent than any of the other prostheses (Fig. 2). The Memotherm stent appeared to cause slightly more artifacts than both types of Corvita prostheses, the artifacts of which were similar.

Flow signal decrease or loss was observed with all sequences, but it was less pronounced with the TOF-2 sequence. PCA images frequently showed superimposition of venous flow signals, particularly in the proximal cranial right iliac artery segment where the iliac vein and artery cross, but they did not have any difficulty with superimposed signals from neighboring structures such as the ureter or bowel (Fig. 1). In contrast, TOF images were sometimes degraded by superimposed signal from ureter or bowel, whereas venous flow was of no importance.

Contrast administration did not visibly improve image quality when TOF sequences were used. With PCA sequences, the intensity of the flow signal within the stents was increased. However, disturbing venous flow signals overlying the right proximal iliac artery were also enhanced (Fig. 1).

Reader-Based Analysis

Comparison of Single and Tandem Prostheses

In the first experiment comparison of the data did not show a significant difference in the amount of prosthesis-related artifact between single and contralateral tandem Memotherm stents (Wilcoxon test, $p > 0.5$). Neither was there a significant difference in the extent of artifact between cranial and caudal tandem Memotherm stents in the same artery (Wilcoxon test, $p > 0.7$).

Prosthesis-Related Artifacts

In the second experiment the data on the ranking of the prosthesis-related artifacts showed a significant difference only for the ZA-stent. All three readers found that the ZA-stent was associated with fewer artifacts than the other prostheses (Kruskal-Wallis test, Mann-Whitney U-test, $p < 0.00001$) (Fig. 3). There was no significant difference between the Memotherm stent, and the normal- and low-porosity Corvita stentgrafts.

The readers considered 26% (mean of the three readers) of the segments containing a ZA-stent to be free of any stent-related artifact and concluded that these segments did not contain a stent. The corresponding figure for the Memotherm stent was 4%, for the normal-porosity Corvita stent-graft 1%, and for the low-porosity Corvita stent-graft 2%.

True Diagnosis with MRA

The quality of MR angiograms considered appropriate for analysis differed between readers: reader 2 was very critical of image quality, while readers 1 and 3 were less critical. However, the trend in the data of all three readers was similar. Therefore, and in order to ease the comprehensibility of the analysis, the data of the three readers have been summarized in the following description of the results.

Segments Without a Prosthesis

The data include 332 segments before prosthesis placement (first and second experiments) and 24 segments without a prosthesis after prosthesis placement (first experiment) (Table 3). Since the results of the pre- and post-prosthesis placement groups were similar the percentage of true diagnoses was calculated for both groups together. The readers correctly diagnosed patency of the arterial segment in 95% of cases (mean of the three readers).

Segments With a Prosthesis

In the second experiment patency of the ZA-stent (including the data on those segments considered not assessable) was correctly diagnosed in 88% of cases (mean of the three readers) (Fig. 4). This figure is almost equal to the

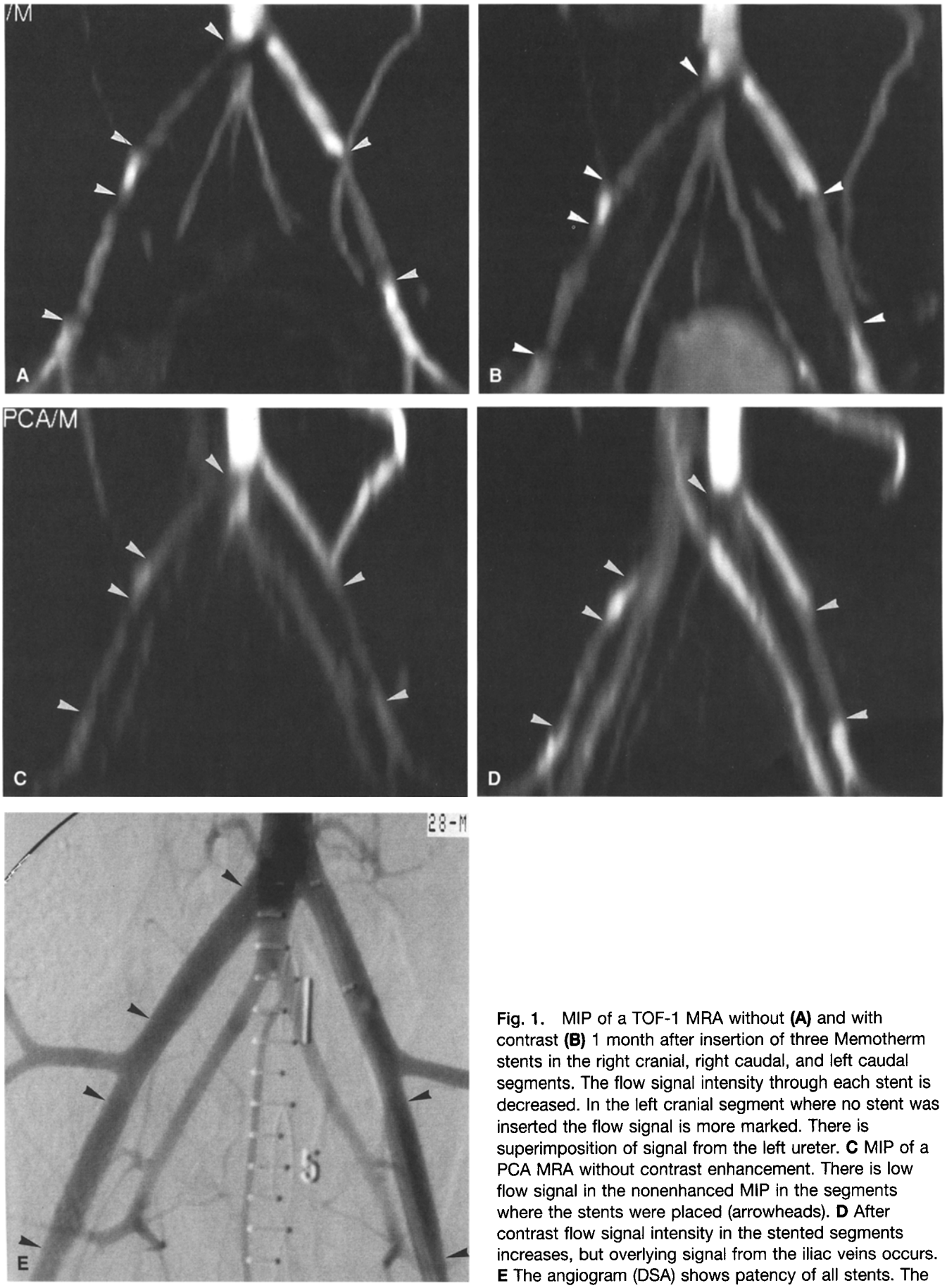

Fig. 1. MIP of a TOF-1 MRA without **(A)** and with contrast **(B)** 1 month after insertion of three Memotherm stents in the right cranial, right caudal, and left caudal segments. The flow signal intensity through each stent is decreased. In the left cranial segment where no stent was inserted the flow signal is more marked. There is superimposition of signal from the left ureter. **C** MIP of a PCA MRA without contrast enhancement. There is low flow signal in the nonenhanced MIP in the segments where the stents were placed (arrowheads). **D** After contrast flow signal intensity in the stented segments increases, but overlying signal from the iliac veins occurs. **E** The angiogram (DSA) shows patency of all stents. The ends of each prosthesis are indicated by arrowheads.

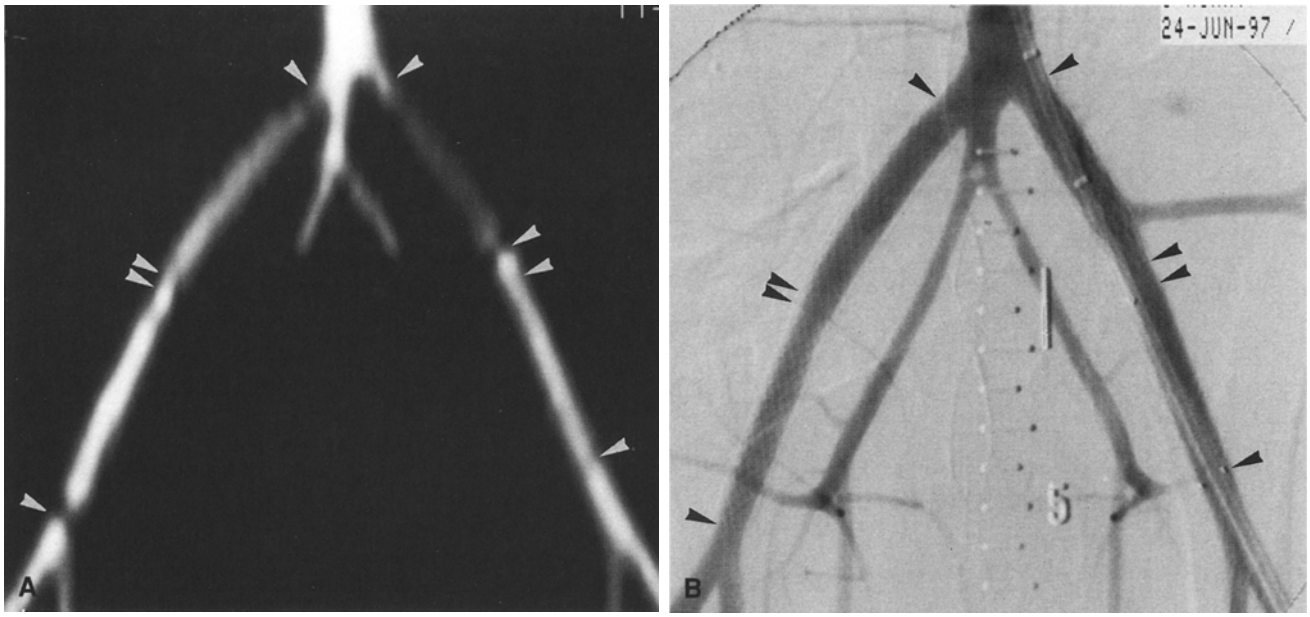

Fig. 2. **A** MIP of a TOF-2 MRA without contrast enhancement 1 month after insertion of a low-porosity Corvita stent-graft in the right cranial segment, a normal-porosity Corvita stent-graft in the right caudal segment, a Memotherm stent in the left cranial segment, and a ZA-stent in the left caudal segment. Artifacts are most marked at the ends of the prostheses. The maximum artifact is caused by the Memotherm stent, less by the Corvita stent-grafts, and least by the ZA-stent, which shows only minimal indentation of the flow signal at the distal end. The ends of each prosthesis are indicated by arrowheads. **B** The corresponding angiogram reveals patency of all prostheses.

result of MRA without a prosthesis. For the Memotherm stent the corresponding value was 59%, for the normal-porosity Corvita graft it was 57% and for the low-porosity Corvita graft, 55%.

On average, the readers found 11% of the iliac segments not assessable if a ZA-stent had been placed, 25% in the case of a Memotherm stent, 27% in the case of a low-porosity Corvita stent-graft, and 29% in the case of a normal-porosity Corvita stent-graft.

Comparison of MRA Sequences

The data of the second experiment were used for a comparison of MRA sequences. All readers found the TOF-2 sequence with intravenous contrast administration superior to the other sequences, and the PCA sequence without contrast administration inferior to all the other sequences. Statistical analysis performed separately for each reader revealed that the only comparisons which demonstrated a significant difference for all three readers were those between TOF-2 with contrast and four other sequences including PCA without contrast (Kruskal-Wallis, Mann-Whitney U-test, $p < 0.000001$), TOF-1 without contrast ($p < 0.0001$), TOF-1 with contrast ($p < 0.0005$), and PCA with contrast ($p < 0.0005$).

Discussion

In comparison with conventional x-ray angiography, MRA has several advantages. It is noninvasive and not burdened by exposure of the patient to radiation. In comparison with color Duplex ultrasound, which is considered the basic noninvasive tool for the follow-up of iliac arterial vascular prostheses, the potential of MRA to depict the stented region directly and completely is greater, and its operator dependency is smaller.

There are an increasing number of reports on the use of MRA in the evaluation of lower extremity arterial occlusive disease [1–3, 5, 12–18, 27], but only a few reports on the evaluation of MRA for monitoring patency of vascular endoprostheses [9–11]. In 1990, Matsumoto and co-workers [10] used gadolinium-enhanced MR imaging to assess the patency of tantalum Strecker stents implanted in the aortas of six dogs. The aortic diameter and the diameter of the stents were not given. The stents were imaged in the coronal and sagittal planes with MR techniques comparable to basic PCA techniques. The authors found that MRA showed flow within the stented vessels with a minimum amount of stent-related artifacts, and concluded that MRA could potentially be used as a noninvasive method for evaluating the patency of MR-compatible endovascular devices such as the Strecker stent. In a later study, the authors found no ferromagnetism and low-level susceptibility artifacts associated with the Strecker tantalum stent in vitro and in vivo [9]. The authors concluded that MR imaging was feasible for evaluating blood vessels after placement of a Strecker stent. In 1995, Laissy and coworkers [11] reported on an in vitro and in vivo clinical study in which they compared contrast-enhanced 2D TOF MRA with digital angiography after placement of Palmaz

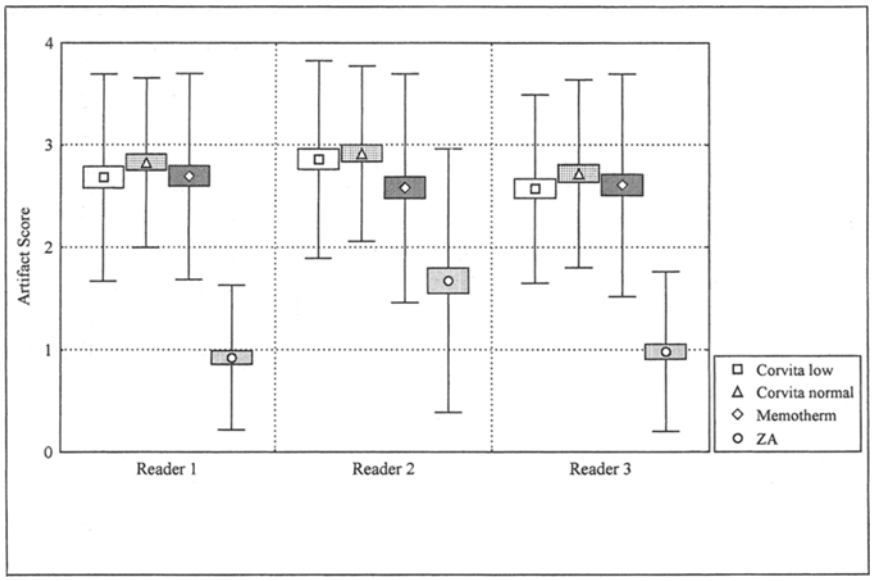

Fig. 3. Mean score (± standard error and deviation) of the artifact caused by the low- and normal-porosity Corvita stent-grafts, Memotherm stents, and ZA-stents plotted separately for each reader. Score 0, no artifact; score 4, maximum artifact.

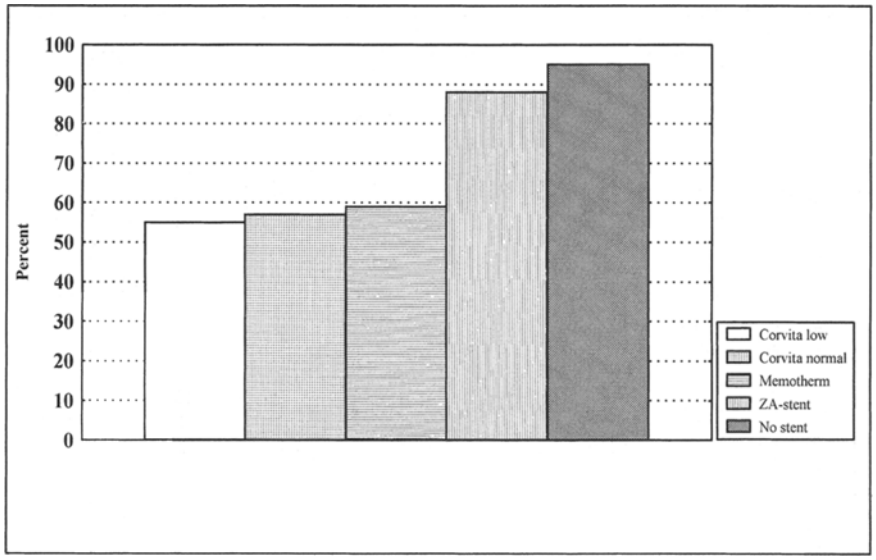

Fig. 4. Percentage value of true MRA diagnoses.

Table 3. True diagnoses with MRA in patent iliac segments without a prosthesis

No. of segments	Reader 1				Reader 2				Reader 3				Readers 1–3 Mean % true diagnosis
	True	False	NA	% true diagnoses[a]	True	False	NA	% true diagnoses[a]	True	False	NA	% true diagnoses[a]	
292[b]	290	2	0	99	263	0	29	90	284	5	3	97	95

NA = not assessable

[a] Percentage of true diagnoses including the segments considered not assessable (NA)

[b] Two hundred and sixty-eight segments before prosthesis placement plus 24 segments after prosthesis placement without a prosthesis (first experiment)

stents, Strecker stents, and Wallstents. Stents were placed in different vessels including the common and external iliac arteries. The authors found that all stents caused a signal reduction or void. The ferromagnetic Palmaz stent was associated with more artifacts than the nonferromagnetic Wallstent and Strecker stent, both of which induced a similar degree of artifact. In contrast to Matsumoto et al. [10], they concluded that MRA did not yet seem well suited for evaluating patency of endovascular prostheses.

There are two major sources of MRA signal reduction within metallic endovascular stents: flow phenomena and susceptibility artifacts due to local inhomogeneities of the

magnetic field caused by ferromagnetic, paramagnetic, or diamagnetic properties of the metal prosthesis [4, 8]. Complex (turbulent) or slow flow can produce signal loss due to phase dispersion within a voxel [4]. While susceptibility artifacts are diagnostically undesirable, an "appropriate" signal reduction or void within the prosthesis due to turbulent and/or reduced flow can be diagnostically useful if it indicates a relevant stenosis or an occlusion of a stent.

The two possible explanations for the increase in artifacts preferably at the ends of the stents involve turbulent flow and enhanced susceptibility artifacts [4, 8]. Even if a prosthesis is completely covered by a layer of neointima, some turbulent flow may occur along the luminal surface of the prosthesis. Flow disturbances may increase at the ends of a prosthesis in the transitional zone to the native artery due to compliance mismatch and more marked irregularities of the luminal vascular surface.

The ZA-stent caused significantly less artifact than the Memotherm stent even though both prostheses are made from nitinol. Minimal differences in the composition of nitinol cannot be excluded; however, it is unlikely that such tiny differences are responsible for such divergent artifacts. It is more likely that the differences are caused by variations in the design of the prosthesis. The shape of the wire mesh of the Memotherm and the ZA-stent is rather different. Depending on its design, a metal stent may more or less shield the spins within the stent lumen from the radiofrequency impulses. This mechanism is probably similar to a mechanism mentioned in a previous report on artifacts in MR imaging by Heindel and co-authors [28]. They argued that MR signal decrease or void associated with nonferromagnetic metal devices resulted from a reduction in radiofrequency amplitude near the prosthesis which is dependent on the shape of the device. In another study, these effects were found to be most pronounced close to the edges and points of the metallic surface [29]. Thus, both flow phenomena and susceptibility artifacts may be responsible for the enhancement of artifacts at the ends of metal stents.

There are several limitations of this study: (1) It is known that the MIP technique may increase the loss of flow signal intensity leading to an appearance simulating a stenosis [3, 30]. Including axial images in the analysis has been recommended to avoid a false positive diagnosis [4]. Presumably, if the axial images had been provided for the readers, the performance of MRA may have been better. Nevertheless, other authors of recent studies have also confined image analysis to MIP images only [18]. Additionally, the one major focus of our study was to find differences in the extent of artifacts induced between various nonferromagnetic endovascular prostheses. This aim could be achieved without analysis of the axial images. Finally, if in the future MRA is to replace angiography as a routine procedure in the follow-up of iliac arterial endoprostheses, the evaluation of MRA images should be as easy as conventional angiography. MIP images provide a view of the vascular tree similar to that of conventional angiography. (2) Meanwhile more advanced MR techniques are available than those used in this study. MR(A) techniques develop rapidly. In a short period what started as a new technique will soon become outdated. The latest MRA scanners have a gradient strength of well above 20 mT/m, which allows for a marked reduction in acquisition time compared with the gradient strength of 15 mT/m we used. It is expected that with high-gradient strength MR scanners and the latest MRA sequence techniques (3D gradient-echo sequences), summarized under the expression "gadolinium-enhanced MRA" in the literature, MRA image quality after metal stent placement in the iliac arteries can be improved [2, 18, 31]. Overlying venous signals as observed with the 3D PCA sequence in our study should be avoidable, and breathhold imaging is possible.

Nevertheless, there are still many scanners in use that are comparable to the one we employed in our study. Moreover, the very good results obtained in nonstented iliac arteries proved that the intrinsic image quality of the less advanced MRA techniques we used was sufficient for analysis. To our knowledge no systematic study of endovascular metal prostheses using the latest MR techniques has been published in the literature. However, from single cases and recent congress reports it becomes obvious that metal stents still pose a severe problem for MRA [31, 32]. Two cases of MRA after stenting were reported as part of two studies that dealt primarily with MRA of nonstented arterial segments. Though advanced MR techniques were used, MRA did not allow correct evaluation of the arterial segment containing the stent (1 renal artery with a stent, the type of which was not mentioned, and 1 iliac artery with a Palmaz stent) [18, 31]. At the 1998 RSNA meeting, Link and coworkers [32] reported on their experience with contrast-enhanced MRA before (28 patients) and after (39 patients) placement of various nonferromagnetic and ferromagnetic stents and stent-grafts. They used state-of-the-art MRA techniques (3D gradient-echo) at 1.5 T. The results before stent placement were very good. MRA also correctly demonstrated patency of the different endoprostheses during follow-up; however, MRA failed to show in-stent restenoses in seven of eight cases due to metal artifacts.

In conclusion, a prerequisite for using MRA on a routine basis for monitoring patency of metal endovascular prostheses is that the prosthesis must induce no or only minimal artifact. Whether or not MRA may be used in the future to monitor patency of metal endoprostheses in the iliac arteries will strongly depend on the design of the device. Iliac ZA-stents may be followed by MRA as they cause only minimal artifact and allow for a true diagnosis of stent patency with an accuracy very similar to the situation without a prosthesis. Our results indicate that it is less advisable to follow iliac Memotherm stents or Corvita stent-grafts by MRA due to the enhanced artifacts they cause. Further systematic studies are necessary to establish whether results may be improved with the latest MRA techniques.

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