Current State of MRI-Guided Endovascular Arterial Interventions: A Systematic Review of Preclinical and Clinical Studies

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Background: MRI guidance of arterial endovascular interventions could be beneficial as it does not require radiation exposure, allows intrinsic blood-tissue contrast, and enables three-dimensional and functional imaging, however, clinical applications are still limited.
Purpose: To review the current state of MRI-guided arterial endovascular interventions and to identify the most commonly reported challenges.
Study Type: Systematic review.
Population: Pubmed, Embase, Web of Science, and The Cochrane Library were systematically searched to find relevant articles. The search strategy combined synonyms for vascular pathology, endovascular therapy, and real-time MRI guidance.
Field Strength/Sequence: No field strength or sequence restrictions were applied.
Assessment: Two reviewers independently identified and reviewed the original articles and extracted relevant data.
Statistical Tests: Results of the included original articles are reported.
Results: A total of 24,809 studies were identified for screening. Eighty-eight studies were assessed for eligibility, after which data were extracted from 43 articles (6 phantom, 33 animal, and 4 human studies). Reported technical success rates for animal and human studies ranged between 42% to 100%, and the average complication rate was 5.8% (animal studies) and 8.8% (human studies). Main identified challenges were related to spatial and temporal resolution as well as safety, design, and scarcity of current MRI-compatible endovascular devices.
Data Conclusion: MRI guidance of endovascular arterial interventions seems feasible, however, included articles included mostly small single-center case series. Several hurdles remain to be overcome before larger trials can be undertaken. Main areas of research should focus on adequate imaging protocols with integrated tracking of dedicated endovascular devices.

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To reduce surgical impact, vascular surgery has been mainly replaced by minimally invasive endovascular interventions. Currently, fluoroscopy is the standard imaging modality to guide these endovascular procedures. This technique, however, coincides with radiation exposure, and the administration of contrast agents. Contrary to fluoroscopy, magnetic resonance imaging (MRI) provides high soft-tissue contrast without the use of radiation and contrast agents, since blood itself can be utilized as an intrinsic contrast agent.[1] This might be beneficial for especially young patients and patients with renal impairment. Additional advantages of MRI guidance might improve endovascular procedures. First, three-dimensional (3D) information can be acquired to improve anatomical perception. Second, functional

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information like flow and perfusion parameters can be obtained, which may provide insight into the outcomes of the intervention and may lead to additional adjustments within the same procedure.[2] Finally, MRI guidance can potentially enable minimally invasive bypass surgery, since the 3D imaging and high soft-tissue contrast make the guidewire visible outside the vascular system.

The scope of this review is narrowed down to review MRI-guided endovascular arterial interventions. Although the first experiments of MRI-guided arterial endovascular interventions using tracking devices were already described in 1993,[3] research regarding clinical implementation in human has been scarce. The requirements that must be met before MRI guidance can be safely used, can potentially explain the low level of interest for MRI guidance. An important requirement is the MRI compatibility and visibility of endovascular devices such as guidewires and catheters, which poses a complex problem both from a physics and engineering perspective.[4] Successful methods have been developed for device visualization using active and passive techniques to track endovascular devices, for example, for cardiac interventions (Figure 1).[5] Another requirement for proper MRI guidance is the preservation of high-quality images while maintaining an adequate acquisition frame rate.[5] Furthermore, working within the MRI environment poses additional challenges related to patient access, in-room image feedback and team communication (Figure 2). Nevertheless, recent progress on MRI-guided cardiac catheterization and ablation within the cardiac field showed promising methods which can be translated to arterial interventions.[6,7]

Several articles have been covering the different requirements for MRI-guided endovascular interventions and have been evaluating various device-tracking techniques and MRI sequences to optimize the guidance.[8–10] Furthermore, reviews have been reporting MRI-guided endovascular and cardiac interventions in general,[11–15] describing the different device-tracking techniques, imaging sequences, and possible clinical applications. However, a clear and comprehensive overview of relevant clinical outcomes is not available. Furthermore, an overview of described pitfalls and other challenges as described in current literature might be useful to clarify the stagnant clinical implementation. Hence, the purpose of this work was to review the feasibility of arterial endovascular interventions in phantom, animal, and clinical studies and to identify reported issues that pose the main challenges for clinical implementation.

Materials and Methods

This systematic review was performed in accordance with the PRISMA guidelines and the protocol which was used to guide this review is registered in the PROSPERO database (CRD42019125516). To provide an extensive overview of the field, we extended our search and included phantom and animal studies.

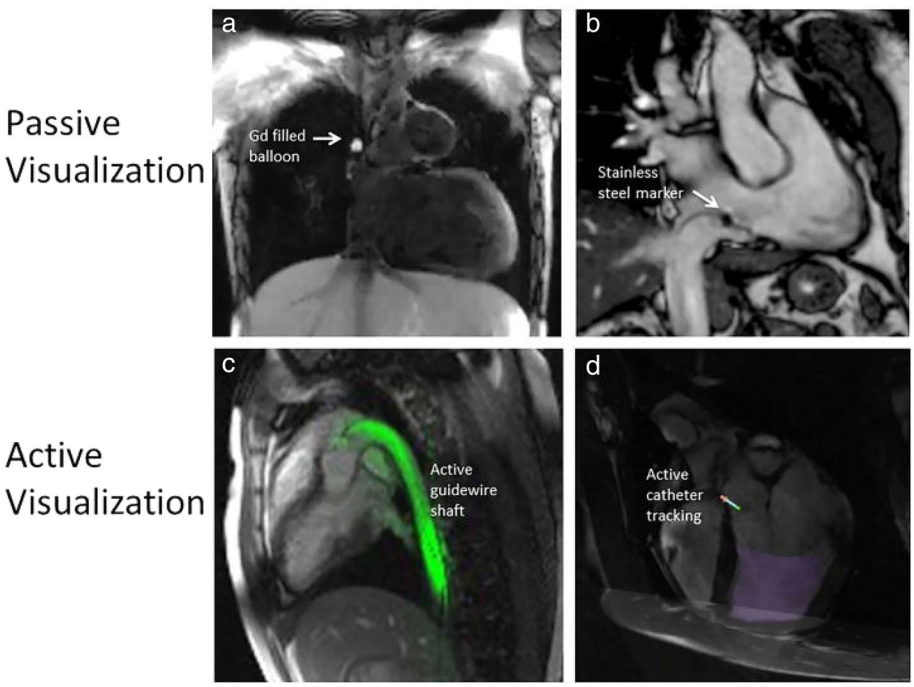

FIGURE 1: Examples of active and passive devices visualization. (a) Gadolinium-filled balloon tip catheter in the superior vena cava. (b) Stainless steel imaging marker on a passive catheter. (c) Color overlay of the active guidewire (loopless antenna) depicting the entire device shaft in-plane. (d) Active tracking coils to overlay catheter tip position and orientation on a preacquired image. The image is required from "real-time MRI guidance of cardiac interventions" by Campbell-Washburn et al.[5] Copyright permission obtained.

FIGURE 2: Example setup for MRI-guided endovascular interventions in a wide-bore 3-T MRI environment within a hybrid procedure room. Patient access is restricted while the patient is positioned at the center of the scanner bore during real-time imaging. The interventionalist should maneuver the endovascular device while observing the image feedback on an in-room display, illustrating challenges of in-bore vascular interventions.

Literature Search

To evaluate the available literature on arterial endovascular interventions, we performed a systematic search. A librarian was consulted for the search strategy. Details of the search strategy are shown in Supporting Information SA. In short, the search consisted of the following three components; vascular pathology, endovascular therapy, and real-time MRI guidance. Pubmed, Embase, Web of Science, and The Cochrane Library were systematically searched. Reference lists of systematic reviews that were identified within the search, were screened for missing but relevant articles.

Data Collection

The articles retrieved from the search were imported in endnote and duplicates were automatically removed.[16] Afterwards, two readers (L.W. and H.N.) independently screened the title and abstract of the remaining articles. Studies were selected for full-text screening if the inclusion criteria for human studies, as shown below, were met according to at least one of the readers. Full-text articles were retrieved and reviewed and disagreements were resolved via consensus or by consulting a third author (J.F.). Screening and selection of the preclinical studies were performed by one reader. Rayyan QCRI, a free web-based tool, was used throughout the screening process.[17]

Study Selection Criteria

Studies describing clinically relevant outcomes after MRI-guided endovascular arterial interventions were included in this review. Articles were excluded if the technical success was not reported. Furthermore, articles were only eligible for inclusion if they reported the number of subjects, subject types and, intervention types. All matching studies until September 2021 were included without restrictions on study type or language. Studies regarding cardiac, valvular, venous, and (chemo)embolization interventions were excluded.

Data Extraction

Data extraction for human studies was conducted by two reviewers (L.W. and H.N.) and disagreements were discussed and solved via consensus or by consulting a third author (J.F.). Using a structured data collection form, the following data were retrieved: the last name of the first author, full title, publication year, intervention type, outcome parameters, results, and sample size. Furthermore, details regarding MRI field strength, real-time MRI sequences, and used devices were extracted. Data extraction for phantom and animal studies was performed similarly by one observer. Study outcomes are presented using descriptive statistics. Due to heterogeneity of the data, the small subject sizes, and the lack of relevant control groups within the studies, risk of bias assessment and meta-analysis were not performed.

Results

Eligible Studies

Using the search strategy, presented in Supporting Information S1, 24,808 articles were identified. After duplicates were removed, 17,796 studies were selected for title and abstract screening. Using the title and abstract screening, 88 full-text articles were assessed for eligibility and 42 articles were included for data extraction. Screening the reference list of the relevant reviews provided one additional eligible article, which was also included in the data extraction process. The PRISMA 2020 flowchart (Figure 3) illustrates the details of the selection process. The interrater agreement was 99.3% for the title and abstract selection process and 95.7% for the full-text selection process. Disagreements were resolved using consensus by both observers.

Study Characteristics

A total of 43 studies were finally included. Six studies described phantom experiments only. Interventions in

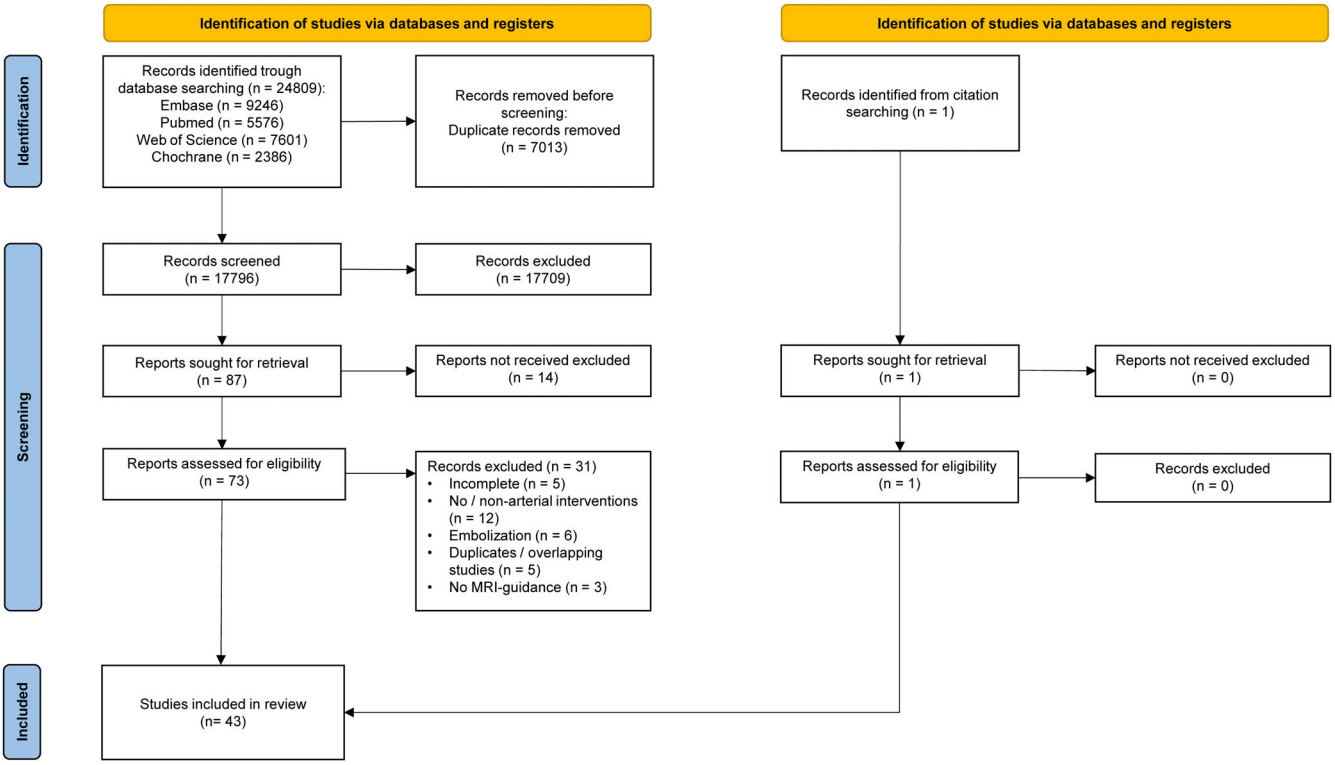

FIGURE 3: PRISMA 2020 flowchart.

animals were performed in 33 of 43 studies with one study also describing phantom experiments.[9] The retrieved data is summarized in Table 1. The interventions in the phantom and animal studies were balloon angioplasty (14/39), stenting (16/39), embolectomy (1/39), aneurysm repair (1/39), or a combination of balloon angioplasty and stenting (7/39).

Four out of the 43 selected studies (9.3%) described MRI-guided endovascular interventions in humans. One study described iliac artery stent placement (13 patients), three studies described balloon angioplasty in peripheral leg arteries (15 patients), aortic coarctations (5 patients), and hemodialysis access grafts (4 patients). The human studies were performed in institutions located in Europe (Germany (3/4), the Netherlands (1/4)). All human studies were published in 2006 or earlier.

The maximum number of living subjects (human or animal) within the selected studies was 15. Four studies compared MRI-guided endovascular interventions with fluoroscopy guidance,[41,42,56,57] two studies compared outcomes for active and passive tracking,[2,10] and one study evaluated the effect of low and high main magnetic field on the outcomes.[38] The definition of technical success, as defined by each article, was reported and differed amongst the varying studies. Examples of reported technical outcomes are artery diameter change, change in functional parameters, and whether or not the stent was correctly placed.

Details regarding MRI field strength, sequence, and devices used for the different studies are summarized in Table 2. The most frequently used field strength was 1.5 T and the sequences used for real-time imaging were mainly gradient echo or steady-state free precession sequences.

Study Outcomes

TECHNICAL SUCCESS AND CLINICAL OUTCOMES. The technical success, as defined by the authors of each study, was 100% in the six phantom studies, however, the sample size in five of six studies was one. Within the 33 animal studies, technical success ranged between 42% and 100%. A total of 11 out of 39 (8%) animal and phantom studies reported outcomes regarding the stenosis degree, arterial diameter, or functional parameters, all of which showed improvement after MRI-guided endovascular interventions.

The technical success within human studies ranged from 50% to 93%. Out of 38 interventions, 31 were successful, resulting in an overall success rate of 82%. The study from Bartels et al only succeeded to perform angioplasty in two of four subjects. The reason for the failed attempts was frequent arm motion in one patient and recoiling of the stenosis in another patient.[18] All reported clinical outcomes, such as the ankle-brachial index, reduction of stenosis, flow, and arterial diameter, showed improvement after MRI-guided procedures.

TABLE 1. Study Characteristics and Outcomes

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Human studies								
Bartels et al[18]	Prospective pilot study	Human	Hemodialysis graft PTA	4	a) Technical success b) Flow increase	a) 2/4 b) 270 mL/min	a) N.A. b) N.A.	-Low spatial and temporal resolution -Manual slice adjustment -Poor device visibility
Paetzel et al[19]	Prospective pilot study	Human	Femoral and popliteal artery PTA	15	a) Technical success b) Stenosis reduction	a) 14/15 b) 57%	a) 31.1 (22–55) minutes b) No complications	-Poor device visibility -Device safety concerns -Lack of real-time imaging -Usability of guidewire
Krueger et al[20]	Prospective pilot study	Human	Aortic coarctation PTA	5	a) Technical success b) Arterial diameter	a) 4/5 b) 7.8 mm before, 13.36 mm after the procedure	a) N.A. b) No complications	-Poor device visibility and device safety -Manual slice adjustment -No automatic device detection
Manke et al[21]	Prospective pilot study	Human	Iliac artery PTA and stenting	14	a) Technical success b) Ankle brachial index	a) 11/14 b) 0.71 before, 0.93 after procedure	a) 73.3 (47–122) minutes b) Subintimal recanalization (1), misplaced stent (1), minor groin hematoma (3), femoral artery pseudoaneurysm (1)	-Long procedure times -Lack of real-time monitoring -Large stent artifacts
Animal studies								
Bücker et al[22]	Pilot study	Pig	External iliac artery stenting	3	Technical success	3/3	a) 15–30 minutes for preparation, 8 minutes for stent deployment b) N.A.	-Long procedure times -Limited patient access
Yang et al[23]	Pilot study	Rabbit	Aortic PTA	2	Technical success	2/2	a) N.A. b) N.A.	-Low frame rate -Low SNR
Quick et al[24]	Pilot study	Sheep	Aortic stenting	2	Technical success	2/2	a) N.A. b) N.A.	-Large stent artifacts -Device safety
Buecker et al[25]	Pilot study	Pig	Iliac artery stenting	7	Technical success	7/7	a) 15 minutes for preparation, 6 minutes (4–7) from insertion to the deployment of the stent b) Incomplete stent deployment (due to accidentally partially removing stent from the catheter before the procedure	-Low temporal and spatial resolution -Latency of MRI acquisition -Limited patient access

TABLE 1. Continued

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Dion et al[26]	Pilot study	Swine	Aortic and iliac artery stenting	5 (3 aorta, 2 iliac arteries)	a) Technical success b) Deviation of planned stent position	a) 5/5 b) 7.8 mm (0–22 mm)	a) 20 minutes for preparation, 13 minutes (12–15) from starting in the distal iliac artery to deployment b) Stent migration of 22 mm	-Learning curve -Low temporal and spatial resolution -Device design/usability -Exclusion criteria for MRI
Godart et al[9]	Pilot study	Pig and phantom	Aortic PTA and stenting	Pig: PTA (5), stenting (1) Phantom: PTA (1)	a) Technical success b) Stent position	a) Phantom: 1/1; pig: 4/5 (PTA), 1/1 (stenting) b) Correct stent placement	a) 45 minutes (without intubation and femoral puncture) b) No complications	-Low framerate -Device visibility
Le Blanche et al[27]	Pilot study	Rabbit	Renal artery PTA	15 (30 arteries)	Technical success	22/30	a) N.A. b) N.A.	-Low temporal resolution
Omary et al[28]	Comparative pilot study (MRI versus fluoroscopy)	Swine	Real artery PTA	4 (3/6 arteries, 1 artery was totally occluded, 1 had no occlusion)	a) Technical success b) Stenosis percentage c) Arterial diameter	MRI: a) 3/3; b) 76.7% before, 41.6% after procedure; c) 1.6 mm before, 2.6 mm after the procedure Fluoroscopy: a) 1/1; b) 90% before, 80% after procedure; c) 0.5 mm before, 1.0 mm after procedure	MRI: a) approximately 90 minutes; b) N.A. Fluoroscopy: a) N.A.; b) N.A.	-Low temporal resolution -Unavailability of devices -Limited patient access -No monitor in the MRI room
Yang et al[29]	Pilot study	Rabbit	Aortic PTA	8	a) Technical success b) Time-to-peak (CE-MRI)	a) 8/8 b) 2 minutes before, 30–40 sec after the procedure	a) N.A. b) N.A.	-Poor guidewire visibility -Device safety
Buecker et al[30]	Pilot study	Pig	Iliac artery PTA	6 (9 arteries)	Technical success	6/9	a) N.A. b) N.A.	-Low robustness of device-tracking -Device visibility -Low framerate
Keuhne et al[31]	Pilot study	Swine	Pulmonary artery stenting	4	Technical success	4/4	a) N.A. b) No complications	-Device safety and design/ usability -Partial visibility of guidewire -Large stent artifacts -Radiofrequency shielding within the stent lumen

TABLE 1. Continued

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Wacker et al[32]	Pilot study	Pig	Renal and iliac artery PTA and stenting	4 (4 renal arteries and 2 iliac arteries)	a) Technical success b) Deviation of planned stent position (range)	a) 6/6 b) 7.3 (2–13) mm	a) Range (54–90 minutes) b) Renal artery rupture (due to using an 8-mm balloon in a 4-mm artery)	-Large stent artifact -Low spatial and temporal resolution -Limited patient access -Device safety
Kuehne et al[33]	Pilot study	Swine	Aortic, carotid, and iliac artery stenting	5	Technical success	7/7	a) N.A. b) No complications	-Difficult to produce the device
Mahnken et al[34]	Pilot study	Swine	Aortic PTA and aortic grafting	4	Technical success	4/4	a) N.A. b) Occlusion of the renal artery (lack of introducer sheath caused dislocation)	-Large artifact size
Feng et al[35]	Pilot study	Swine	Carotid artery stenting	5 (10 arteries)	Technical success	10/10	a) N.A. b) No complications	-Device visibility
Raval et al[2]	Comparative pilot study (active vs. passive tracking)	Swine	Stent placement in aortic coarctation	13	a) Technical success b) Lumen diameter c) Reduction of peak instantaneous gradient pressure d) Reduction of peak-to-peak systolic gradient	Active: a) 8/8 Passive: a) 5/5 Both active and passive: b) 5 ± 1 mm before, 11 ± 1 after surgery (all 13 animals); c) 8 ± 7 mmHg (all 13 animals); d) 4 ± 3 mmHg (all 13 animals)	Active: a) 26 ± 11 minutes Passive: a) 106 ± 42 minutes, b) Coarctation rupture due to oversized balloon (1)	-Device heating
Raman et al[36]	Pilot study	Swine	Abdominal aneurysm repair	11	Technical success	9/11	a) N.A. b) Endoleak (2)	-Unavailability of proper MRI endografts
Terashima[37]	Pilot study	Rabbit	Aortic PTA and stenting	8	Technical success	Angioplasty: 8/8 Stent placement: 2/2	a) N.A b) No complications	-Low temporal and spatial resolution -Requirement of a 3D roadmap
Wacker et al[38]	Comparative pilot study (0.2 vs. 1.5 T MRI)	Pig	Renal artery PTA and stenting	7	a) Technical success b) Deviation of planned stent position (range)	0.2 T a) 4/4, b) 7.3 (2–13) mm 1.5 T a) 3/3, b) 6.8 (2.4–12.7) mm	0.2 T a) range 54–90 minutes, b) N.A. 1.5 T a) range 18–29 minutes, b) N.A.	-Limited patient access (1.5 T) -Low temporal and spatial resolution (0.2 T) -Long procedure times (0.2 T) -Low accuracy of stent position -Device safety and design/ usability

TABLE 1. Continued

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Eggebrecht et al[39]	Pilot study	Swine	Aortic stenting	8	a) Technical success b) Arterial diameter	a) 8/8 b) 0.9 cm (0.825–0.975) before, 2.05 cm (1.925–2.1) after procedure ($P = 0.066$)	a) 2 (2–4) minutes b) Severe arrhythmia with hemodynamic instability	-Device visibility -Device safety
Elgort et al[40]	Pilot study	Swine	Renal artery stenting	6	a) Technical success b) Stenosis percentage c) Deviation of planned stent position	a) 6/6 b) 53.6% before, 14.9% after procedure c) 0.98 ± 0.69	a) 25 minutes (including 15 minutes for 3D imaging) b) No complications	-Device visibility
Omary et al[41]	Comparative pilot study (MRI versus fluoroscopy)	Swine	Renal artery PTA	11	a) Technical success b) Stenosis percentage	MRI: a) 9/11 ($P = 0.5$), b) 63% ± 10 before, 19% ± 16 after procedure Fluoroscopy: 11/11 ($P = 0.5$), b) 71% ± 10 before, 23% ± 16 after procedure	MRI: a) 77 ± 46 minutes, b) arterial dissection (3) Fluoroscopy: a) 31 ± 18 minutes, b) arterial dissection (1)	-Unavailability of proper MRI devices -Long procedure times -Low temporal and spatial resolution
Raval et al[42]	Comparative pilot study (MRI vs. fluoroscopy)	Swine	Carotid artery PTA (chronic total occlusion)	14	Technical success	MRI: 11/14 Fluoroscopy: 1/3	MRI: a) 55 ± 22 minutes, b) extravascular hematoma after wire exiting artery Fluoroscopy: a) 45 minutes, b) contrast extravasation after wire exiting artery, arterial dissection with lethal mediastinal hematoma	-Low temporal and spatial resolution -Device design/usability
Saeed et al[43]	Pilot study	Dog	Stent placement in aortic coarctation	8	a) Technical success b) Flow c) Arterial pressure (lower extremity)	a) 7/8 b) 0.2 L/minute before, 0.8 L/minute after the procedure c) 51 mmHg before, 117 mmHg after the procedure	a) Typically 15–20 minutes b) Death after perforation of a severe coarctation (1)	-Device safety -Low temporal and spatial resolution

TABLE 1. Continued

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Krombach et al[44]	Pilot study	Pig	Iliac artery PTA	5 (10 arteries)	a) Technical success b) Stenosis criteria	a) 9/10 b) Severe before, to mild after the procedure: 5, severe/mild stenosis before, to no stenosis after the procedure: 4	a) N.A. b) Perforation of the iliac artery (1)	-The price of suitable guidewires
Frericks et al[10]	Comparative pilot study (active vs. passive tracking)	Swine	Renal artery stenting	6	a) Technical success b) Deviation of planned stent position	Active: a) 3/3, b) 4 ± 2 mm Passive: a) 3/3, b) 10 ± 3	Active: a) 17 minutes, b) N.A. Passive: a) 23 minutes, b) N.A.	-Manual plane adjustment -Accuracy of stent placement
Kos et al[45]	Pilot study	Swine	Aortic stenting	2 (1 abdominal/1 thoracic)	a) Technical success b) Stent position (autopsy)	a) 2/2 b) Correct position	a) 12 (thoracic) and 10 (abdominal) minutes b) N.A.	-Unavailability of suitable guidewires -No automated marker tracking
Kos et al[8]	Pilot study	Swine	Renal artery PTA and stenting	2 (eight times angioplasty, four stents)	Technical success	12/12	a) 10 ± 2 minutes (angioplasty), 12 ± 3 min. (stenting) b) No complications	-Large artifacts -Marker visibility -Optimization of sequence required
Kos et al[46]	Pilot study	Swine	Iliac and supra-aortic artery PTA and stenting	3 (3 brachiocephalic, 3 subclavian, and 6 iliac arteries)	Technical success	12/12	a) 8 minutes (brachiocephalic), 5 minutes (subclavian), 7 minutes (iliac) b) N.A.	-Manual plane alignment -Passive visibility of both guidewire and catheter -Fixed artifact size
Kramer et al[47]	Pilot study	Pig	Inguinal artery stenting, renal artery PTA	5 (1 inguinal stenting, 10 renal arteries)	Technical success	11/11	a) N.A. b) no complications	-Preplanning of imaging plane -Marker visibility -Device safety -Acoustic noise
Neizel et al[48]	Pilot study	Pig	Iliac artery PTA	6 (12 arteries, of which 4 arteries were stenotic)	a) Technical success b) Stenosis percentage	a) 12/12 b) 70–99% before, to 0% ($n = 3$) and < 50% ($n = 1$) after surgery	a) N.A. b) No complications	N.A.
Massman et al[49]	Pilot study	Swine	Aortoiliac and visceral artery PTA and stenting	9	a) Technical success b) Stent position	a) 9/9 b) Stent positioning within 5 mm of target	a) N.A. b) No complications	-Unavailability of suitable devices

TABLE 1. Continued

Study	Study Design	Subject type	Intervention type	Total sample size	Outcome measures	Outcomes	Procedure times (a) and complications (b)	Reported challenges/ disadvantages
Yang et al[50]	Pilot study	Pig	Embolectomy within the carotid artery	4 (13 carotid arteries)	Technical success	11/13	a) N.A b) N.A.	-Device safety and design/ usability -Long time to manually determine marker location
Phantom studies								
Stroman et al[51]	Feasibility study	Arterial graft	Stenting	1	Technical success	1/1	a) N.A b) N.A.	-Unavailability of suitable devices
Smits et al[52]	Feasibility study	Flow phantom on the arm of a volunteer	PTA	1	a) Technical success b) Flow	a) 1/1 b) 480 mL/minute before, 1080 mL/minute after procedure	a) N.A b) N.A.	-Device safety -Flexibility of imaging
van der Weide et al[53]	Feasibility study	Stenosed tube on arm of a volunteer	PTA	1	Technical success	1/1	a) N.A b) N.A.	-Time-consuming manual MRI plane adjustment
Mekle et al[54]	Feasibility study	Phantom	PTA	1	Technical success	1/1	a) N.A. b) N.A.	-Difficult to distinguish between two passive devices
Attia et al[55]	Feasibility study	Aortic phantom	Stenting	1	Technical success	1/1	a) N.A. b) N.A.	Guidewire design/usability
Rube et al[56]	Comparative pilot study (MRI vs. fluoroscopy)	Phantom	PTA	39	a) Technical success b) Peak velocity	MRI: a) 30/30, b) 20–25 cm/sec before, 10–12 cm/sec after procedure Fluoroscopy: a) 9/9, b) N.A.	MRI: a) 9 minutes (6–111), b) N.A. Fluoroscopy: a) 9 minutes (6–11), b) N.A.	-Device design/usability patient access -Sterility -Manual plane adjustment

CE-MR: contrast-enhanced magnetic resonance imaging; N.A.: not available; PTA: percutaneous transluminal angioplasty; SNR: signal-to-noise ratio.

TABLE 2. MRI Field Strength, Sequence, and Endovascular Device Types Used in the Included Studies

Study	Field strength	Tracking sequence	Endovascular device type
Human studies			
Bartels et al[18]	1.5 T	2D GRE, TR/TE: 14/9.2 msec, FA: 10°, ST: N.A., FR: 0.5 fps	Plastic coated glass fiber guidewire and nonbraided balloon catheters, both enhanced with paramagnetic dysprosium oxide ring-markers (Cordis Europa N.V., Roden, The Netherlands)
Paetzel et al[19]	1.5 T	2D FLASH, TR/TE: 11/5.64 msec, FA: 25°, ST: 6 mm, FR: 2 fps	Guidewire (Terumo; Leuven, Belgium), balloon catheter (Wanda, Boston Scientific; Ratingen, Germany)
Krueger et al[20]	1.5 T	SSFP with radial k-space filling, TR/TE: 3.3/1.6 msec, FA: 45°, ST: 6–8 mm, FR: 9 fps	Custom-made 0.035-inch PEEK guidewire, balloon catheter (Tyshak II, NuMed, Ontario, Canada)
Manke et al[21]	1.5 T	2D FLASH with flow compensation. TR/TE: 14.0/6.1 msec. FA: 30°, ST: 8 mm, FR: 0.53 fps	Nitinol guidewire (Cope; Cook, Bloomington, Ind & Terumo, Tokyo, Japan), angiographic catheter (Cook), self-expanding nitinol stent (Memotherm; Bard-Angiomed, Karlsruhe, Germany), angioplasty balloon catheter (Blue Max; Meditech/Boston Scientific, Watertown, MA)
Animal studies			
Bücker et al[22]	1.5 T	GRE, TR/TE: 8.4/3.6 msec, FA: 10°, ST: 8.5 mm, FR: 0.33 fps	Self-expandable stent (Cook Europe, Bjaeverskov, Denmark) within an MR-compatible catheter
Yang et al[23]	1.5 T	Fast-spoiled GRE, TR/TE: 9.9/2.5 msec, FA: N.A., ST: 5 mm, FR: 4.2 fps	Custom-made loopless catheter antenna, balloon catheter (MediTech/Boston Scientific, Watertown, MA)
Quick et al[24]	1.5 T	FGRE, TR/TE: 7.7/3.6 msec, FA: 10°, ST: N.A., FR: 2 fps	Two active (electrical dipole and coaxial line) custom-made stents created using stainless steel wall stents from Schneider (Bülach, Switzerland)
Buecker et al[25]	1.5 T	GRE with radial k-space filing, TR/TE: 8.4–13.4/3.3–3.6 msec, FA: 8–13°, ST: 8.5–10 mm, FR: 20 fps	Prototype nitinol stent (ZA stent, Cook Europe, Bjaeverskov, Denmark), nitinol guidewire (Cook Europe), fiberglass guidewire with multiple dysprosium markers (Cordis, Roden, The Netherlands), balloon catheter (Cordis) with dysprosium markers
Dion et al[26]	0.5 T	GRE, TR/TE: 13.2/44.9 msec, FA: 30°, ST: N.A, FR: 0.1/0.2 fps	Guidewire (Glidewire; Terumo, Somerset, NJ), iliac stent deployment system (Angiomed; Bard, Karlsruhe, Germany)
Godart et al[9]	0.2 T	FLASH, TR/TE: 120/14 msec, FA: 30–50°, ST: 10 mm, FR: 0.1 fps	Radifocus guidewire (Terumo Europe, Leuven, Belgium) with iron oxide nanoparticles, balloon catheter (Cristal, Balt Extrusion, Montmorency, France), Easy Wallstent (Schneider (Europe), Bülach, Switzerland)
Le Blanche et al[27]	1.5 T		Winch Guidewire (Nycomed Amersham Medical Systems, Paris, France), monorail

TABLE 2. Continued

Study	Field strength	Tracking sequence	Endovascular device type
		T2-weighted turbo SE, TR/TE: 59/4.2 msec, FA: 140°, ST: 6 mm, FR: 0.15 fps	coronary angioplasty balloon catheter (Manfield, Meditech, Boston, MA)
Omary et al[28]	1.5 T	Time-resolved 3D, TR/TE: 5.8/1.4 msec, FA: 30°, ST: 2.6 mm, FR: 0.4 fps Time-resolved 3D, TR/TE: 5.7/1.4 msec, FA: 30°, ST:40 mm, FR: 0.9 fps Single-phase 3D, TR/TE: 6.2/1.6 msec, FA: 45°, ST: 1 mm, Acquisition time: 21.4 s	Nitinol guidewire (Boston Scientific, Watertown, MA), 5F cobra selective visceral catheter, balloon catheter
Yang et al[29]	1.5 T	Fast-spoiled GRE, TR/TE: 5.0/1.4 msec, FA: N.A., ST: N.A., FR: 3 fps	Custom-made loopless catheter antenna, balloon catheter (MediTech/Boston Scientific, Watertown, MA)
Buecker et al[30]	1.5 T	GRE, TR/TE: 12/2.2 msec, FA: 10°, ST: 10 mm, FR: 20 fps	Balloon catheter (Cordis, Roden, The Netherlands) with micro coils
Keuhne et al[31]	1.5 T	bSSFP, TR/TE: 3.4/1.7 msec, FA: 60°, ST: 5–30 mm, FR: 2.2 fps T1-weighted turbo field echo, TR/TE: 3.9/1.3 msec, FA: 60°, ST: 5–30 mm, FR: 2.0 fps	0.035-inch guide wire (Microvena, White Bear Lake, Minn), self-expanding nitinol stent (Memotherm; Angiomed, Karlsruhe, Germany)
Wacker et al[32]	0.2 T	2D spoiled GRE, TR/TE: 5.0/2.0 msec, FA: 25°, ST: 6–8 mm, FR: 1.6 fps	Guidewire (Radifocus; Terumo, Tokyo, Japan), prototype guidewire (Ferro Tip; Somatex), prototype catheter (Somatex, Berlin, Germany), balloon catheter (Ultra Thin; Boston Scientific, Watertown, Mass), balloon-expandable stents (Palmaz; Cordis, Miami, Fla), self-expandable stents (Symphony; Boston Scientific)
Kuehne et al[33]	1.5 T	SSFP, TR/TE: 1.99/1.6 msec, FA: 5° or 45°, ST: 8–10 mm, FR: 8 fps	0.035-inch polyester and nitinol guidewire, custom-made stent delivery system with resonance circuit, nitinol stents (Flexx; Angiomed, Karlsruhe, Germany)
Mahnken et al[34]	1.5 T	2D GRE with spiral k-space filling, TR/TE: 31/4.9 msec, FA: 26°, ST: 10 mm, FR: 10 fps	Amplatz Super-Stiff ST035/180, (Boston Scientific, Natick, MA), excluder stent-graft, (W.L. Gore and Associates, Flagstaff, AZ)
Feng et al[35]	1.5 T	GRE, TR/TE: N.A., FA: 20–35°, ST: 30 mm, FR: 9–15 fps	Guidewire (Terumo; Boston Scientific, Natick, Mass), self-expanding nitinol stents (Smart Stent; Cordis, Miami, Fla), 5-F catheter
Raval et al[2]	1.5 T	SSFP, TR/TE: 3.5/1.7 msec, FA: 60°, ST: 6 mm, FR: 8 fps	Intercept guidewire (Surgi-Vision), nitinol guidewire (Glidewire, Terumo/Boston Scientific), platinum–iridium stents (Cheatham Z stent, NuMed Inc), balloon-in-balloon dilatation catheter (BIB, NuMed), prototype cobalt–nickel–chromium alloy (MP35N) stent (Medtronic)

TABLE 2. Continued

Study	Field strength	Tracking sequence	Endovascular device type
Raman et al[36]	1.5 T	SSFP, TR/TE: 3.8/1.8 msec, FA: 60°, ST: 8 mm, FR: 4–8 fps	Custom-made active guidewire, nitinol endograft (Vanguard, Boston Scientific, Natick, MA), three custom-made active self-expanding endograft designs
Terashima[37]	1.5 T	Self-developed interleaved spiral acquisition, TR/TE: 27.0/4.6 msec, FA: 30^0, ST: 5 mm, FR: 16–20 fps	Stainless steel guidewire (Guidant Corp., Santa Clara, CA, USA), nitinol guidewire (Terumo Corp., Tokyo, Japan), balloon catheter (ACS RX COMET, Guidant Corp.), stent (Pulse Medical Systems, Collegeville, PA, USA)
Wacker et al[38]	0.2 and 1.5 T	0.2 T: 2D spoiled GRE, TR/TE: 5.0/2.0 msec, FA: 25°, ST: 6–8 mm, FR: 1.6 fps 1.5 T: 2D spoiled GRE, TR/TE: 5.0/3.0 msec, FA: 70°, ST: 5–7 mm, FR: 3 fps	Prototype "Ferro Tip" guidewire (Somatex, Teltow, Germany), hydrophilic-coated guidewire (35-inch Radifocus, Terumo, Tokyo, Japan), 5–6 F prototype catheters, (Somatex, Teltow, Germany), commercially available balloon catheters, balloon-expandable stents (Palmaz, Corinthian; Cordis Corporation, Miami Lakes, FL) (Omniflex; Angiodynamics, Queensbury, NY)
Eggebrecht et al[39]	1.5 T	TrueFisp, TR/TE: 3/1.5 msec, FA: 80°, ST: 6 mm, FR: 7 fps	Self-expandable stent-graft device (GoreTAG, W.L. Gore Inc., Flagstaff, AZ)
Elgort et al[40]	1.5 T	TrueFisp, TR/TE: 4.43/2.22 msec, FA: 70°, ST: 5 mm, FR: NA	Guidewire (0.035- inch Radifocus; Terumo, Tokyo, Japan), angiographic catheter (Torcon NB Advantage Angiographic Catheter; Cook, Bloomington, IN), balloon catheter (OmniFlex; Angio Dynamics, Queensbury, NY), stent (Palmaz P204 Balloon-Expandable Intraluminal Stent; Johnson & Johnson, Warren, NJ)
Omary et al[41]	1.5 T	Active: SSFP, TR/TE: 2.9/1.45 msec, FA: 70°, ST: 30 mm, FR: 9 fps Passive: GRE, TR/TE: 2.3/1.45 msec, FA: 20°, ST: 30 mm, FR: 7 fps	Loopless antenna guidewire coil (Intercept; Surgi-Vision, Gaithersburg, Md), 5-F aortic catheter, renal artery catheter, balloon catheter (Cordis Europa, Roden, The Netherlands)
Raval et al[42]	1.5 T	SSFP, TR/TE: 3.5/1.7 msec, FA: 45°, ST: 4 mm, FR: N.A.	Custom-made active gold–silver–gold-plated nitinol wires with MP35N (cobalt–chromium alloy) micro coils and tungsten-braided catheters (Minnesota Medtec) with 1-cm micro coils, adjusted nitinol guidewire (Nitrex, ev3)
Saeed et al[43]	1.5 T	bFFE, TR/TE: 3.7/1.9 msec, FA: 70°, ST: 5–30 mm, FR: 5 fps	Nitinol guidewire (AGA Medical Corp., Golden Valley, MN), self-expanding nitinol stent (Symphony, Boston Scientific Corp., Watertown, MA)
Krombach et al[44]	1.5 T	SSFP, TR/TE: 2.5/1.25 msec, FA: 45°, ST: 8 mm, FR: N.A.	Standard guidewire (Terumo, Tokyo, Japan), standard balloon catheter (Boston Scientific, Glen Falls, NY)
Frericks et al[10]	1.5 T	TrueFISP, TR/TE: 5/2.5 msec, FA: 70°, ST: 5–7 mm, FR: 3 fps	Prototype "Ferro Tip" guidewire (Somatex, Teltow, Germany), steerable hydrophilic-

TABLE 2. Continued

Study	Field strength	Tracking sequence	Endovascular device type
			coated wire (35-inch Radifocus; Terumo, Tokyo, Japan), C-1 catheter (Somatex), balloon catheter (Ultra Thin; Boston Scientific, Watertown, MA), balloon-expandable Palmaz Corinthian stent (Cordis Corporation, Miami Lakes, FL), Omni Flex stent (Angiodynamics, Queensbury, NY)
Kos et al[45]	1.5 T	GRE T1-FLASH, TR/TE: 8.12/5.24 msec, FA: 21°, ST: 5 mm, FR: 2/3 fps	Guidewire (Biotronik Vascular Intervention, Buelach, Switzerland) with iron oxide nanoparticles (MagnaFy; MagnaMedics GmbH, Aachen, Germany), balloon catheter (Pheron, Biotronik), self-expandable stent (Astron, Biotronik), self-expandable stent (Wallstent; Boston Scientific, Maple Grove, MN)
Kos et al[8]	1.5 T	TrueFISP, TR/TE: 5.3/5.2 msec, FA: 80°, ST: 10 mm, FR: 1 fps	Guidewire (Biotronik Vascular Intervention, Buelach, Switzerland) with iron oxide nanoparticles (MagnaFy; MagnaMedics GmbH, Aachen, Germany), vertebral catheter (SOFTouch, Merit Medical, Galway, Ireland), 4-French Cobra 2 catheter (Merit Medical) both enhanced with Magnafy markers
Kos et al[46]	1.5 T	GRE T1-FLASH, TR/TE: 8.12/5.24 msec, FA: 21°, ST: 5 mm, FR: 2/3 fps	Stent (Peiron, Biotronik, Buelach, Switzerland), nonbraided 4 French vertebral catheter (SOFTouch, Merit Medical, Galway, Ireland), self-expandable nitinol stent (Astron, Biotronik), nonbraided Shepherd Flush catheter (Merit Medical), balloon catheter (Pheron, Biotronik), balloon-expandable stent (Peiron, Biotronik)
Kramer et al[47]	1.5 T	bSSFP, TR/TE: 2.6/1.3 msec, FA: 40° or 50°, ST: 8 mm, FR: 3.4 fps	Custom-made fiberglass compound wire, cobra angiography catheter (Supertorque 65 cm, 0.038," Cordis), ACN1 angiography catheter (Cook Inc.), cobra angiography catheter (Glidecath 5F, 65 cm, Terumo, Japan), balloon catheter, microcatheter (Terumo, Japan), self-expanding stent catheter (Jostent SelfX, Abbott Vascular Devices, The Netherlands)
Neizel et al[48]	3 T	SSFP, TR/TE: 3/1.3 msec, FA: 8°, ST: 8 mm, FR: N.A.	Cooke guidewire (Cook Bloomington, IN), cobra catheter (Cook), balloon catheter (Aachen Resonance, Aachen, Germany), drug-eluting balloon "Elutax SV" (Aachen Resonance)
Massman et al[49]	1.5 T	bSSFP, TR/TE: 283/2.18 msec, FA: 60°, ST: 10 mm, FR: 5 fps	Custom-made aramid guidewires with small iron particles, Radiofocus Glidecath Cobra catheter (Terumo Europe, Leuven, Belgium)

TABLE 2. Continued

Study	Field strength	Tracking sequence	Endovascular device type
Yang et al[50]	1.5 T	bSSFP, TR/TE: 3.9/2.0 msec, FA: 10–20°, ST: 8 mm, FR: 1.5 fps	Custom-made PEEK fiber thread catheter with an embedded wireless resonant circuit
Phantom studies			
Stroman et al[51]	1.5 T	FSE, TR/TE: N.A., FA: N.A., ST: 3 mm, FR: 0.25 fps	Custom-made Teflon-coated fiber-optic guidewire with gold-plated tip, Cragg EndoPro system (MinTec, Endotech Ltd., Freeport, Grand Bahama, The Bahamas)
Smits et al[52]	1.5 T	GRE with keyhole technique, TR/TE: 15/8 msec, FA: 10°, ST: 30 mm, FR: 1.5 fps	Fiber-optic guidewire (Cordis, Roden, The Netherlands) with dysprosium oxide rings, nonbraided angioplasty balloon catheter (Cordis) with dysprosium oxide rings
van der Weide et al[53]	1.5 T	GRE, TR/TE: 15/9 msec, FA: 10°, ST: 50 mm, FR: 0.5 fps	Custom-made guidewire with five dysprosium rings, balloon catheter with two dysprosium rings
Mekle et al[54]	1.5 T	bSSFP, TR/TE: 4.31/2.14 msec, FA: 3°, ST: 40 mm, FR: 0.9 fps T1-weighted FLASH, TR/TE: 3.17/1.0 msec, FA: 70°, ST: 40 mm, FR: 1.1 fps	Custom-made PEEK polymer guidewire with iron particle coating (Biotronik vascular intervention, Beulach, Switzerland), standard catheter (Schneider GmbH, Beulach, Switzerland), balloon catheter (FOX PTA catheter, Abbot Laboratories Vascular Enterprises Ltd., Beringen, Switzerland)
Attia et al[55]	1.5 T	2D FLASH, TR/TE: 2.36/0.83 msec, FA: 25°, ST: 20 mm, FR: 2 fps	Fiber-optic guidewire (SEDI, Couronnes, France) with titanium oxide markers (Magpaint Europe, Veldhunten, The Netherlands), angiographic catheter (Terumo, Tokyo, Japan) with titanium oxide markers, Valiant stent-graft (Medtronic Vascular, Santa Rosa, CA)
Rube et al[56]	1.5 T	bSSFP, TR/TE: 4.8/6.9 msec, FA: 70°, ST: 5 mm, FR: N.A. spiral bSSFP, TR/TE: 3.5/20 msec, FA: 70°, ST: 7 mm, FR: N.A. FGRE, TR/TE: 3/7.4 msec, FA: ≤30/60°, ST: 5 mm, FR: N.A.	Prototype guidewire (EPflex GmbH, Dettingen/Erms, Germany) with iron oxide nanoparticles (MagnaFy; MagnaMedics GmbH, Aachen, Germany), Straight catheter (Beacon Tip Royal Flush, Cook Ine., Bloomington, IN), multipurpose catheter (Soft-Vu, AngioDynamics, Latham, NY), PTA Balloon catheter (Workhorse IT, AngioDynamics, Latham, NY). All catheters were enhanced with a resonant circuit

bFFE: balanced fast field echo; (b)SSFP: (balanced) steady-state free precession; FA: flip angle; (f)GRE: (fast) gradient echo; FLASH: fast low angle shot; FR: frame rate; N.A.: not available; (f)SE: (fast) spin echo; ST: slice thickness; TrueFISP: true fast imaging with steady-state precession; TR/TE: repetition time/echo time; 2D: two-dimensional; 3D: three-dimensional.

COMPLICATIONS. The 33 included animal studies performed a total of 277 interventions. Complications were reported during 16 interventions, resulting in a complication rate of 5.8%. The reported complications were: arterial dissection (3), endoleak (2), artery rupture/perforation (2), death after perforation of aortic coarctation (2), extravascular hematoma after wire perforation of the artery (1), contrast extravasation after wire exiting artery (1), arterial dissection with lethal mediastinal hematoma (1), renal artery occlusion (1), severe arrhythmia with hemodynamic instability (1), incorrect

TABLE 3. Challenges Related to MRI-Guided Endovascular Interventions and the Number of Articles Discussing the Challenges

Challenges	Number of articles discussing the challenges (% from total included articles)	Current state/potential solution
Low temporal/spatial resolution	17/43 (39.5%)	Faster MRI techniques continue to evolve and improve. Dedicated imaging protocols are required per application
Device visibility	14/43 (33.3%)	Knowledge of the effects of MRI and marker parameters can be used to optimize device visibility. Devices that are integrated with tracking and/or scanner imaging control could be highly beneficial
Device safety	13/43 (30%)	Several MRI-compatible CE and FDA-approved devices are currently available.[4] However, more different device types are required to catheterize all arteries and enable more intervention types. Furthermore, besides safety, the usability and design should be adequate. If the incentive for MRI-guided endovascular interventions will increase, the industry will likely resolve the issues regarding safety, usability, and availability of devices
Usability/design of guidewire	8/43 (18.6%)	See "Device safety"
Unavailability of devices	8/43 (18.6%)	See "Device safety"
Limited patient access	6/43 (13.9%)	Improvements in low-field MRI can facilitate better patient access and acceptable interventional imaging capabilities[21]
Lengthy procedure times	4/43 (9.3%)	An integrated workflow utilizing automatic device tracking and image plane adjustment could reduce procedure times. In addition, the procedure time is expected to decrease while progressing through the learning curve
Other challenges related to MRI only: *Manual slice alignment* (7) *Tracking issues* (4) *No monitor in MRI room* (1) *Acoustic noise* (1) *Sterility issues* (1) *Requirement of a 3D roadmap* (1) *MRI-related exclusion criteria* (1) *Latency of MRI acquisition* (1)	14/43 (33.3%)	Automatic slice adjustment and tracking can be realized by novel artificial intelligent-based systems. The absence of physical monitors, acoustic noise, and sterility issues currently do not withhold other disciplines from performing interventions using MRI guidance
Other challenges related to MRI and guidewire: *Large stent artifacts* (5)	10/43 (23.3%)	Although specific stents that induce smaller susceptibility artifacts are available, and lumen visualization can be improved by reducing radiofrequency artifacts.[58,59] stent artifacts will

TABLE 3. Continued

Challenges	Number of articles discussing the challenges (% from total included articles)	Current state/potential solution
Low stent placement accuracy (2) *No artifact size adjustment* (2) *Radiofrequency shielding within stent lumen* (1) *Required learning curve* (1)		keep causing visibility issues. It is advised to take these issues into consideration for procedures where stenting is required

stent placement (1) and incomplete stent deployment (1). In 22 studies, the presence or absence of complications has not been reported.

Out of four human studies, only one study reported complications, namely the study of Manke et al.[21] In this study subintimal recanalization (1), misplacement of the stent (1), minor groin hematoma (3), and femoral artery pseudoaneurysm (1) occurred. Complications were absent in two other human studies, whereas one study did not report the presence or absence of complications. Neglecting the groin complications, which are unrelated to the choice of imaging modality, a total of three complications occurred in 34 interventions (8.8%).

PROCEDURE TIMES. The procedure time was reported in one phantom study. The mean procedure time for MRI-guided balloon angioplasty was 9 minutes.[56] Out of the 33 animal studies, 17 reported procedure times, with times ranging from 2 to 123 minutes. It must be noted that the definition of procedure times was different for the various studies and was, in general, not clearly specified. One study compared the procedure times for MRI-guided renal angioplasty in swine with fluoroscopy guidance, with a mean procedure time of 77 ± 46 minutes for MRI guidance and 31 ± 18 minutes for fluoroscopy guidance.[41] Raval et al compared procedure times for angioplasty in chronic total iliac artery occlusion with a mean procedure time of 55 and 45 minutes for MRI and fluoroscopy guidance, respectively.[42]

Two human studies reported the total procedure time, with mean times of 73.3 minutes for both angioplasty and stent placement[21] and 31.1 minutes for angioplasty alone.[19] The procedure times ranged between 22 and 122 minutes. Both studies showed a steep learning curve, with average times of 91 and 38.8 minutes in the first part of the cohort, and 60 and 26.2 minutes in the second part of the cohort.

COMPARATIVE STUDIES. From the selected studies, seven studies (one phantom, six animal) made a comparison of the outcomes between MRI guidance and fluoroscopy guidance,[41,42,56,57] tracking techniques (active versus passive),[2,10] or between low and high main magnetic field MRI.[38] In phantom experiments, Rube et al did not find differences in procedure time and success rate between MRI and fluoroscopy guidance.[56] Inferior results for MRI guidance compared to fluoroscopy in terms of success rate, procedure time, and the number of complications for renal angioplasty in swine were reported by Omary et al.[41] On the other hand, Raval et al reported superior results for MRI guidance to treat chronic total occlusions in swine, showing higher success rates and fewer complications compared to fluoroscopy guidance.[42] Raval et al reported shorter procedure times for active tracking compared to the use of passive marker devices for balloon angioplasty in animals.[2] This is in concordance with results reported by Frericks et al.[10] Furthermore, the results showed a lower stent placement accuracy for passive tracking in renal arteries in swine. The comparison between low and high magnetic field in MRI guidance made by Wacker et al showed reduced procedure times for higher magnetic fields but did not show large differences in technical success rate or stent placement accuracy in pigs.[38]

CURRENT CHALLENGES. Several challenges for MRI-guided endovascular interventions are described within the included articles (Table 3). From the total of 43 included articles, 42 studies reported one or more challenges. MRI-related challenges were most often mentioned, with low spatial and/or temporal resolution being a major hurdle and discussed in 17/43 articles. Furthermore, device visibility, safety, and practical issues (ie, time-consuming manual slice steering, acoustic noise, and limited patient access) were identified as challenging factors.

Discussion

This review objectifies outcomes for MRI-guided arterial endovascular treatments and shows that proper investigation of the clinical value of these procedures is still limited. Overall, only four studies were identified that performed MRI-guided endovascular procedures in humans and none of those compared the outcomes with fluoroscopy, the current gold standard. Phantom, animal, and human studies showed that MRI-guided endovascular interventions are feasible, promising,

and showed improved postprocedural clinical outcomes. However, the selected eligible studies were predominantly preclinical or phase I studies, showing the need for additional research to evaluate the feasibility and clinical relevance of MRI-guided endovascular interventions.

In general, clinical outcomes, such as arterial diameter, ankle-brachial index, and arterial flow, improved after MRI-guided endovascular treatment. The reported outcomes in the included human studies showed a technical success rate of MRI-guided endovascular procedures comparable to the success rate of peripheral arterial disease patients treated by conventional endovascular interventions (76.8%).[60] However, since no comparative human studies are available, it is difficult to directly compare these results. The mean complication rate for MRI-guided arterial endovascular interventions reported in the included studies is in concordance with complication rates of 3% to 33% for fluoroscopy-guided endovascular interventions, as reported in literature.[61] It should be, however, noted that the results reported in this review are extracted from studies with great heterogeneity and varying complexity. Furthermore, the sample size of the studies was rather small, making the outcomes less reliable and certainly prone to underestimation because of the learning curve associated with implementing new techniques.

The procedure times for MRI-guided endovascular procedures are in line with the average times required for fluoroscopy-guided PTA and stenting (30 minutes to 3 hours).[62] The required procedure time, however, depends on the technical difficulty and intervention type. Animal and phantom studies that did directly compare MRI guidance with fluoroscopy guidance showed comparable or prolonged procedure times for MRI-guided procedures. Although longer procedure times are expected for MRI guidance due to several factors, for example, manual slice adjustments, lower temporal resolution, and suboptimal tracking, it must be considered that the MRI-guided procedures in the included studies were novel and the procedure times will likely decrease after users gain more experience. The effect of the learning curve has been demonstrated by three included studies as their results showed a reduction in procedure times after several procedures.[19,21,42]

This review showed that the clinical performance in terms of technical success, complication rates, and clinical outcomes appears promising, but that the use of MRI guidance is still associated with several challenges. A frequently mentioned disadvantage of MRI guidance was related to the spatial and temporal resolution, resulting in low image quality. Suboptimal image quality, in combination with manual and additional steps such as manual slice steering, device visibility, and the use of a 3D roadmap were limiting the use of MRI guidance and likely prolonged procedure times, in particular, in early application stages. Also, device visibility, safety, and usability were reported to be poor. Several studies have already investigated how the different drawbacks of MRI-guided arterial interventions can be overcome. First of all, several techniques for visualizing the device, such as active and passive tracking have been proposed and improved. Visibility in passive tracking can be improved by changing the ferromagnetic properties of the markers or by altering MRI parameters.[63–65] Furthermore, negative and positive contrast can be combined to track different devices simultaneously.[66] MRI sequences with optimized signal-to-noise ratio (SNR) and improved device visibility have been proposed in several articles.[66,67] Active tracking using loop coils or resonant coils enable tracking of multiple devices in real-time with an accuracy of approximately 1 mm.[68] Heating issues related to active tracking should be taken into consideration, but it can be mitigated by using saline coolant[69] or MRI-compatible materials. Although frame rates ~4 frames per second can be sufficient during fluoroscopy guidance,[70] MRI imaging sequences using interleaved spiral acquisition can be used to acquire frame rates of up to 20 frames per second and have been proposed to guide endovascular interventions.[37] These sequences may resolve the issues of low temporal resolution mentioned in the included articles.[71,72] Spatial resolution and SNR are inversely correlated and determine the image quality. The minimum required SNR and resolution, however, will vary for different vessel sizes and marker visibility. In general, the spatial resolution should at least be sufficient to visualize the target vessel, that is, voxel size smaller than the targeted vessel. Reports investigating MR-guided endovascular interventions should include SNR measurements to facilitate better comparison of imaging protocols and come to recommendations on optimized image quality. High-field MRI systems (≥1.0 T) can be used to improve the SNR and further optimize the balance between temporal and spatial resolution, however, high-field MRI is associated with increased susceptibility artifacts and increased safety risks. Contrary to closed bore high-field MRI systems, open low-field MRI (<1.0 T) systems enable improved patient access.[41] An alternative technique, besides MRI or fluoroscopy guidance, is (intravascular) ultrasound guidance.[73,74] This modality can provide additional detailed anatomical and functional information during the endovascular intervention. Ultrasound guidance is, however, limited because it hardly penetrates bone, is reflected at tissue–air interfaces, and is operator-dependent.

Availability of suitable MRI-compatible endovascular devices with CE or FDA approval for use in MRI is crucial, however many studies reported that suitable devices are scarcely available.[75] Besides the good visibility, the physical characteristics of the device, such as torque, steerability, and risk for device kinking should be comparable to, or better than the current devices. At the moment, a limited number of CE-, or FDA-approved MRI-compatible guidewires are commercially available.[4] If more MRI-conditional devices become available, faster clinical implementation of MRI-guided endovascular interventions is possible.[76]

In the included articles, the time-consuming manual adjustment of imaging planes was considered cumbersome. Protocols that allow communication with, and controlling of the MRI system in combination with automatic marker detection can replace this manual task, reducing the procedure time. Several studies have been investigating these techniques with promising results in preclinical studies.[77–80] Finally, automatic detection and plane adjustment can be coupled to a robotic manipulator to control the motion of the endovascular devices. This enables physicians to perform the procedure without being hindered by limited patient access.

Although the abovementioned solutions have been proposed and potentially make the barrier to embrace MRI-guided endovascular procedure lower, the actual clinical implementation of MRI-guided interventions is still limited. A reason for this lack of adoption might be the absence of clinical demand for the advantages of MRI in relation to the accompanying disadvantages and costs. It can, therefore, be anticipated that MRI guidance will not be implemented in standard procedures due to high costs, insufficient quality of real-time imaging, and limited patient access. In these situations, the standard fluoroscopy guidance is a cheap and convenient technology, serving the requirements for appropriate guidance without the MRI-related safety risks. On the other hand, the advantages of MRI guidance in specific cases, for example, in pediatric or renal impaired patients, might be substantial, since the lack of radiation and the functional imaging capabilities could lead to better outcomes. Also, unconventional procedures, such as minimally invasive endovascular bypass surgery, which are impossible using 2D fluoroscopy guidance, can potentially be realized using the advantages of MRI. Furthermore, diagnostic outcomes, such as pulmonary vascular resistance, cardiac output, and hemodynamic measurements, can be accurately determined using MRI-guided catheterization.[81] Contrary to diagnostic procedures, MRI-guided cardiac interventions such as balloon angioplasty, valvuloplasty, or ablation of atrial flutter are sparse, partly due to the lack of procedure-specific MRI-compatible devices.[81,82] Notwithstanding advancements in MRI and image processing techniques, an increased availability of MRI-compatible endovascular devices will be required to enable wider clinical adoption.

Next to solving the reported challenges, additional research comparing the outcomes with fluoroscopy guidance is required before MRI guidance of arterial interventions should be implemented in the clinical setting. Innovations with regards to imaging and device tracking can result in improved outcomes for MRI-guided endovascular interventions. Furthermore, new developments on functional imaging enable evaluation of postprocedural change in flow or perfusion and make treatment adjustment during the actual procedure possible.[83] These innovations will increase the incentive to implement MRI guidance for endovascular interventions, however, it remains important to evaluate the cost-effectiveness and usability.

Conclusion

In conclusion, MRI-guided endovascular interventions in the arterial system seem feasible, however, in vivo studies, especially in humans, are sparse and limited to single-center case series. Although included articles in this review report acceptable complication rates, technical success, and procedure times for MRI-guided endovascular interventions, the scarcity and low quality of data complicate an adequate interpretation of the actual clinical relevance for MRI guidance. Several main challenges have been identified that should be addressed before larger comparative trials can be undertaken. Main areas of research should focus on adequate imaging protocols, improved visibility, safety, and usability of MRI-compatible devices and dedicated algorithms for automatic device tracking and slice steering. Furthermore, it should be investigated which procedures profit from the advantages such as high soft-tissue contrast and 3D imaging in order to accept the challenges related to MRI-guided endovascular arterial interventions.

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