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

Han Nijsink, MSc, Christiaan G. Overduin, PhD, Loes H. Willems, MD, Michiel C. Warlé, MD, PhD, and Jurgen J. Fütterer, MD, PhD

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...
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. 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, 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. Successful methods have been developed for device visualization using active and passive techniques to track endovascular devices, for example, for cardiac interventions (Figure 1). Another requirement for proper MRI guidance is the preservation of high-quality images while maintaining an adequate acquisition frame rate. 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.

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. Furthermore, reviews have been reporting MRI-guided endovascular and cardiac interventions in general 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. Copyright permission obtained.](image)
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
animals were performed in 33 of 43 studies with one study also describing phantom experiments. 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, two studies compared outcomes for active and passive tracking, and one study evaluated the effect of low and high main magnetic field on the outcomes. 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. All reported clinical outcomes, such as the ankle-brachial index, reduction of stenosis, flow, and arterial diameter, showed improvement after MRI-guided procedures.
| 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\[16\]   | Prospective pilot study | Human | Hemodialysis graft PTA | 4                 | a) Technical success      | a) 2/4                            | b) Flow increase                  | b) 270 mL/min                          | -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      | a) 14/15                          | b) Stenosis reduction              | 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      | a) 4/5                            | b) Arterial diameter               | b) 7.8 mm before, 13.36 mm after the procedure | -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      | a) 11/14                          | b) Ankle brachial index            | b) 0.71 before, 0.93 after procedure | -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 |
| Study                  | Study Design         | Subject type | Intervention type       | Total sample size | Outcome measures                                           | Outcomes          | Procedure times (a) and complications (b)                                                                 |
|------------------------|----------------------|--------------|-------------------------|-------------------|-----------------------------------------------------------|-------------------|--------------------------------------------------------------------------------------------------------------------------------|
| Dion et al\(^{26}\)   | Pilot study          | Swine        | Aortic iliac artery stenting | 5 (3 aorta, 2 iliac arteries) | a) Technical success  
b) Deviation of planned stent position | a) 5/5            | a) 20 minutes for preparation, 13 minutes (12–15) from starting in the distal iliac artery to deployment  
b) Stent migration of 22 mm |
| Godart et al\(^{27}\) | 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 |
| Le Blanche et al\(^{27}\) | Pilot study          | Rabbit       | Renal artery PTA        | 15 (30 arteries)    | Technical success | 22/30            | a) N.A.  
b) N.A.                                                                                                                                          |
| 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.                                                                 |
| Yang et al\(^{29}\)   | Pilot study          | Rabbit       | Aortic PTA              | 8                 | a) Technical success  
b) Time-to-peak (CE-MRI) | a) 8/8            | a) N.A.  
b) N.A.                                                                                                                                          |
| Buecker et al\(^{30}\) | Pilot study          | Pig          | Iliac artery PTA        | 6 (9 arteries)     | Technical success | 6/9              | a) N.A.  
b) N.A.                                                                                                                                          |
| Keuhne et al\(^{31}\) | Pilot study          | Swine        | Pulmonary artery stenting | 4                 | Technical success | 4/4              | a) N.A.  
b) No complications                                                                                                                                      |
| 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     | 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 stent artifact 
 -Low spatial and temporal resolution 
 -Limited patient access 
 -Device safety |
| Kuehne et al     | Pilot study             | Swine        | Aortic, carotid, and iliac artery stenting            | 5                 | Technical success                                                                 | 7/7                        | a) N.A. 
 b) No complications | -Difficulty to produce the device |
| Mahnken et al    | 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       | Pilot study             | Swine        | Carotid artery stenting                              | 5 (10 arteries)   | Technical success                                                                 | 10/10                     | a) N.A. 
 b) No complications | -Device visibility |
| Raval et al      | 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      | Pilot study             | Swine        | Abdominal aneurysm repair                            | 11                | Technical success                                                                 | 9/11                      | a) N.A. 
 b) Endoleak (2) | -Unavailability of proper MRI endografts |
| Terashima        | 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     | 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 |
| 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<sup>19</sup> | Pilot study           | Swine        | Aortic stenting                 | 8                 | a) Technical success                                 | a) 8/8                                                                     | a) 2 (2–4) minutes                   | -Device visibility                |
|               |                       |              |                                 |                   | b) Arterial diameter                                 | b) 0.9 cm (0.825–0.975) before, 2.05 cm (1.925–2.1) after procedure     | -Device safety                      |                                  |
|               |                       |              |                                 |                   |                                                       | (P = 0.066)                                                               |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | a) 8/8                                                                     | a) 2 (2–4) minutes                   |                                  |
|               |                       |              |                                 |                   |                                                       | b) Arterial diameter                                 | b) 0.9 cm (0.825–0.975) before, 2.05 cm (1.925–2.1) after procedure     | -Device visibility                |
|               |                       |              |                                 |                   |                                                       | (P = 0.066)                                                               |                                           |                                  |
| Elgort et al<sup>20</sup> | Pilot study           | Swine        | Renal artery stenting           | 6                 | a) Technical success                                 | a) 6/6                                                                     | a) 25 minutes (including 15 minutes for 3D imaging) | -Device visibility                |
|               |                       |              |                                 |                   | b) Stenosis percentage                               | b) 53.6% before, 14.9% after procedure                                  |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | c) Deviation of planned stent position                              |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | a) 0.98 ± 0.69                                                          |                                           |                                  |
| Omary et al<sup>21</sup> | Comparative pilot study (MRI versus fluoroscopy) | Swine        | Renal artery PTA                | 11                | a) Technical success                                 | MRI: a) 9/11 (P = 0.5), b) 63% ± 10 before, 19% ± 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 |
|               |                       |              |                                 |                   |                                                       | Fluoroscopy: 11/11 (P = 0.5), b) 71% ± 10 before, 23% ± 16 after procedure |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | a) 0.98 ± 0.69                                                          |                                           |                                  |
| Raval et al<sup>22</sup> | Comparative pilot study (MRI vs. fluoroscopy) | Swine        | Carotid artery PTA              | 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 |
|               |                       |              | (chronic total occlusion)       |                   |                                                       | a) 0.98 ± 0.69                                                          |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | 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                      |                                           |                                  |
| Saeed et al<sup>23</sup>  | Pilot study           | Dog          | Stent placement in aortic coarctation | 8                 | a) Technical success                                 | a) 7/8                                                                     | a) Typically 15–20 minutes             | -Device safety                   |
|               |                       |              |                                 |                   |                                                       | b) Flow                                                                   |                                           |                                  |
|               |                       |              |                                 |                   |                                                       | c) Arterial pressure (lower extremity)                                 |                                           | -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\(^4\) | 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\(^15\) | 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\(^4\) | 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\(^16\) | 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\(^17\) | 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\(^18\) | 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\(^19\) | 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<sup>50</sup> | Pilot study | Pig | Embolectomy within the carotid artery | 4 (13 carotid arteries) | Technical success | 11/13 | a) N.A | -Device safety and design/usability -Long time to manually determine marker location |
| Phantom studies | | | | | | | | |
| Stroman et al<sup>51</sup> | Feasibility study | Arterial graft | Stenting | 1 | Technical success | 1/1 | a) N.A | -Unavailability of suitable devices |
| Smits et al<sup>52</sup> | 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<sup>53</sup> | 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<sup>54</sup> | 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<sup>55</sup> | Feasibility study | Aortic phantom | Stenting | 1 | Technical success | 1/1 | a) N.A b) N.A | Guidewire design/usability |
| Rube et al<sup>56</sup> | 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 | MRE: 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.
| 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\(^ {27}\) | 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 |
| Study | Field strength | Tracking sequence | Endovascular device type |
|-------|----------------|-------------------|--------------------------|
| Omary et al<sup>28</sup> | 1.5 T | Time-resolved 3D, TR/TE: 5.8/1.4 msec, FA: 30°, ST: 2.6 mm, FR: 0.4 fps | Nitinol guidewire (Boston Scientific, Watertown, MA), 5F cobra selective visceral catheter, balloon catheter |
| Yang et al<sup>29</sup> | 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<sup>30</sup> | 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<sup>31</sup> | 1.5 T | bSSFP, TR/TE: 3.4/1.7 msec, FA: 60°, ST: 5–30 mm, FR: 2.2 fps | 0.035-inch guide wire (Microvena, White Bear Lake, Minn), self-expanding nitinol stent (Memotherm; Angiomed, Karlsruhe, Germany) |
| Wacker et al<sup>32</sup> | 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<sup>33</sup> | 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<sup>34</sup> | 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<sup>35</sup> | 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<sup>2</sup> | 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) |
| Study          | Field strength | Tracking sequence | Endovascular device type                                                                                                                                 |
|---------------|----------------|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Raman et al   | 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     | 1.5 T          | Self-developed interleaved spiral acquisition, TR/TE: 27.0/4.6 msec, FA: 30°, 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  | 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, Corinithian; Cordis Corporation, Miami Lakes, FL) (OmniFlex; Angiodynamics, Queensbury, NY) |
| Eggebrecht et al | 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  | 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   | 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   | 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   | 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 | 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| 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- |
| Study          | Field strength | Tracking sequence                                      | Endovascular device type                                                                                                                                 |
|---------------|---------------|--------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Kos et al     | 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     | 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     | 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  | 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  | 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 | 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) |
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
| 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. 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.                                                                                                         |
| 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 | 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. |
| Tracking issues                                |                                                                               |                                                                                                                                                                                                                                |
| No monitor in MRI room                         |                                                                               |                                                                                                                                                                                                                                |
| Acoustic noise                                 |                                                                               |                                                                                                                                                                                                                                |
| Sterility issues                               |                                                                               |                                                                                                                                                                                                                                |
| Requirement of a 3D roadmap                    |                                                                               |                                                                                                                                                                                                                                |
| MRI-related exclusion criteria                 |                                                                               |                                                                                                                                                                                                                                |
| Latency of MRI acquisition                     |                                                                               |                                                                                                                                                                                                                                |
| Other challenges related to MRI and guidewire: Large stent artifacts | 10/43 (23.3%)                                                               | Although specific stents that induce smaller susceptibility artifacts are available, and lumen visualization can be improved by reducing radiofrequency artifacts. stent artifacts will                                                                                                                                 |
|                                               |                                                                               |                                                                                                                                                                                                                                |
sosten 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. 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. 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. 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.

Two human studies reported the total procedure time, with mean times of 73.3 minutes for both angioplasty and stent placement and 31.1 minutes for angioplasty alone. 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, tracking techniques (active versus passive), or between low and high main magnetic field MRI. In phantom experiments, Rube et al did not find differences in procedure time and success rate between MRI and fluoroscopy guidance. 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. 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. Raval et al reported shorter procedure times for active tracking compared to the use of passive marker devices for balloon angioplasty in animals. This is in concordance with results reported by Freericks et al. 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.

**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%). 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. 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). 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.

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. Furthermore, negative and positive contrast can be combined to track different devices simultaneously. MRI sequences with optimized signal-to-noise ratio (SNR) and improved device visibility have been proposed in several articles. Active tracking using loop coils or resonant coils enable tracking of multiple devices in real-time with an accuracy of approximately 1 mm. Heating issues related to active tracking should be taken into consideration, but it can be mitigated by using saline coolant or MRI-compatible materials. Although frame rates ~4 frames per second can be sufficient during fluoroscopy guidance, 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. These sequences may resolve the issues of low temporal resolution mentioned in the included articles. 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. An alternative technique, besides MRI or fluoroscopy guidance, is (intravascular) ultrasound guidance. 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. 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. If more MRI-conditional devices become available, faster clinical implementation of MRI-guided endovascular interventions is possible.
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. 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. 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. 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. 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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