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Review

Interventional cardiac magnetic resonance imaging: current applications, technology readiness level, and future perspectives

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Abstract

Background: Cardiac magnetic resonance (CMR) provides excellent temporal and spatial resolution, tissue characterization, and flow measurements. This enables major advantages when guiding cardiac invasive procedures compared with X-ray fluoroscopy or ultrasound guidance. However, clinical implementation is limited due to limited availability of technological advancements in magnetic resonance imaging (MRI) compatible equipment. A systematic review of the available literature on past and present applications of interventional MR and its technology readiness level (TRL) was performed, also suggesting future applications.

Methods: A structured literature search was performed using PubMed. Search terms were focused on interventional CMR, cardiac catheterization, and other cardiac invasive procedures. All search results were screened for relevance by language, title, and abstract. TRL was adjusted for use in this article, level 1 being in a hypothetical stage and level 9 being widespread clinical translation. The papers were categorized by the type of procedure and the TRL was estimated.

Results: Of 466 papers, 117 papers met the inclusion criteria. TRL was most frequently estimated at level 5 meaning only applicable to *in vivo* animal studies. Diagnostic right heart catheterization and cavotricuspid isthmus ablation had the highest TRL of 8, meaning proven feasibility and efficacy in a series of humans.

Conclusion: This article shows that interventional CMR has a potential widespread application although clinical translation is at a modest level with TRL usually at 5. Future development should be directed toward availability of MR-compatible equipment and further improvement of the CMR techniques. This could lead to increased TRL of interventional CMR providing better treatment.

Keywords: cardiac catheterization, interventional cardiovascular magnetic resonance, technology readiness level

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Introduction

Use of cardiac magnetic resonance (CMR) has increased dramatically due to its many advantages.[1–7] CMR is the gold standard for quantifying heart chamber dimensions, volumes and ejection fraction due to its excellent temporal and spatial resolution. It provides soft tissue characterisation, perfusion imaging for detecting ischemia, and flow measurements for quantifying shunt volumes or valve regurgitation fractions. CMR can obtain images in any plane and does not use ionizing radiation.

Although X-ray fluoroscopy is the primary modality in cardiac interventions due to its widespread availability and good visualization of versatile

catheters and interventional devices, which are commercially available,[8] use of CMR to guide procedures pre-, intra-, and postprocedurally is increasing because of its many advantages.[1–7] However, clinical translation is hindered by the lack of technological advancements in MR compatible equipment.

The aim of this review is to investigate the clinical implementation of CMR in cardiac interventions by evaluating the technology readiness level (TRL). The TRL methodology was developed by National Aeronautics and Space Administration (NASA) to define several levels of 'readiness' for emerging technologies, and is still used by several organizations such as the US Department of Defense and the European Space Agency. In medical literature, it has been used for assessment of robotic gastro-intestinal endoscopy[9,10] and of several devices designed to improve healthcare for elderly.[11–13]

Methods

An extensive literature search was performed using the PubMed database. The search included the following PubMed search and Mesh terms:

1. 'Magnetic Resonance Imaging, Interventional'[Mesh] OR 'interventional magnetic resonance imaging'[tiab]
2. 'Cardiac Catheterization'[Mesh] OR 'Cardiac Catheterization'[tiab] OR 'Coronary Angiography'[Mesh] OR 'Coronary Angiography'[tiab] OR 'Percutaneous Coronary Intervention'[Mesh] OR 'Percutaneous Coronary Intervention'[tiab]
3. 'Cardiac Catheterization'[Mesh] OR 'Cardiac Catheterization'[tiab] AND 'Biopsy'[Mesh] OR 'Image-Guided Biopsy'[Mesh] OR 'Myocardial biopsy'[tiab] OR 'Endomyocardial biopsy'[tiab]
4. 'Cardiac Electrophysiology'[Mesh] OR 'Cardiac Electrophysiology'[tiab] OR 'Pulmonary Vein Isolation'[tiab] OR 'Catheter Ablation'[tiab] OR 'Catheter Ablation'[Mesh]
5. 'Atrial Fibrillation'[Mesh] OR 'Atrial Fibrillation'[tiab] OR 'Arrhythmias, Cardiac'[Mesh] OR 'cardiac arrhythmias'[tiab]

Inclusion criteria for the selected papers were: the paper had to be peer-reviewed, written in English language, published before June 2021 and concern interventional CMR rather than diagnostic CMR. The results of the initial search were screened by title and abstract for eligibility. After screening, the full text was read for eligibility. Finally, references were crosschecked for additional papers.

The following subcategories were made: technical aspects, electrophysiology (EP) procedures, right-sided cardiac catheterization and congenital procedures, coronary procedures, valvular procedures, and other procedures. The advancement toward clinical translation was assessed by evaluating the TRL. For this review, the nine TRL levels used by the US Government Accountability Office (GAO)[14] were modified as shown in Table 1. The subcategory technical aspects comprise papers describing technical developments without clinical applications and were therefore not assigned a TRL.

Results

The literature search returned 466 papers. After screening by language, title, and abstract 359 papers were excluded. These were mostly papers regarding extra-cardiac procedures. After reading the full text of the remaining papers for eligibility, a further 21 papers were excluded, mostly because the topic was diagnostic CMR rather than interventional. After crosschecking the references of these papers, 31 subsequent papers were included leading to a total of 117 papers. Figure 1 shows the PRISMA figure of the literature search. Figure 2 shows the division in subcategories, which are described in the subsections below. Table 2 lists the TRL levels of the various subcategories.

Technical aspects

Most papers in this category focused on development of MR compatible equipment and disposables such as catheters, which is usually the limiting factor for procedures not achieving a higher TRL.

Catheters can be visualized in the MR image either by active or passive tracking. Some papers focused on passive tracking, a technique were instruments can be discerned due to their material characteristics. Most contain some form of para- or ferromagnetic materials. With optimized imaging protocols, these devices can be discerned from the surrounding anatomical structures.[54–58] Other papers focus

Table 1. TRL levels based on the US Government Accountability Office (GAO).[14]

TRL level based on US-GAO	Description based on US-GAO	Modified TRL level description as applied in this review
TRL 1 Basic principles observed and reported	Published research identifying problem/possible technology	Proposed hypothesis of using interventional CMR
TRL 2 Technology concept and/or application formulated	Papers of analytic studies. Supporting analyses providing scientific information and data to develop research proposals	Preprocedural CMR used to guide interventions
TRL 3 Analytical and experimental critical function and/or characteristic proof of concept	Proof of concept in laboratory, publication of results	*Ex vivo* phantom studies
TRL 4 Component and/or breadboard validation in lab	Proof of concept and safety demonstrated in *ex vivo* animal bowel	*Ex vivo* animal studies
TRL 5 Component and/or breadboard validation in relevant environment	Evidence of device being equivalent to predicate device (FDA 510(k)) ready for clinical trials	*In vivo* animal studies
TRL 6 (Sub)System model or prototype demonstration in relevant environment	Clinical trials conducted in small number of humans	Proven feasibility in single human case
TRL 7 System prototype demonstration in operational environment	Clinical safety and effectiveness trials in operational environment. Determination of short-term adverse events and risks associated with the device. Final design validated	Proven efficacy in single human case
TRL 8 System completed and qualified through test and demonstration	FDA 510(k) or equivalent approved	Proven feasibility and efficacy in series of humans
TRL 9 System proven through successful mission operations	The device is being marketed. Postmarketing studies	Widespread clinical translation

CMR, cardiac magnetic resonance; GAO, Government Accountability Office; TRL, technology readiness level; FDA, Food and Drug Administration.

on balloon angiographic catheters that can enhance visualization by inflating them with carbon dioxide or a gadolinium contrast-doped solution.[58–60]

Passive tracking has some limitations. The imaging plane must be frequently manipulated to keep the device within the field of view and in plane.[59] Furthermore, the narrow imaging planes often allow only one device to be projected at a time, where many cardiac interventional procedures require more than one catheter or device at once.[56,59,61]

More recent papers report on active tracking, a technique which is based on coils or other detectors incorporated into the catheter. These are electronically connected to the scanner and by using standard MR read-out techniques, the exact three-dimensional position of the coils can be determined. The catheter position can then be overlaid on the MR images. This method provides better visualization and easier localization of the instruments compared with passive tracking, but requires the tracked device to be modified.[16,58,62–65] In contrast to most passive tracking

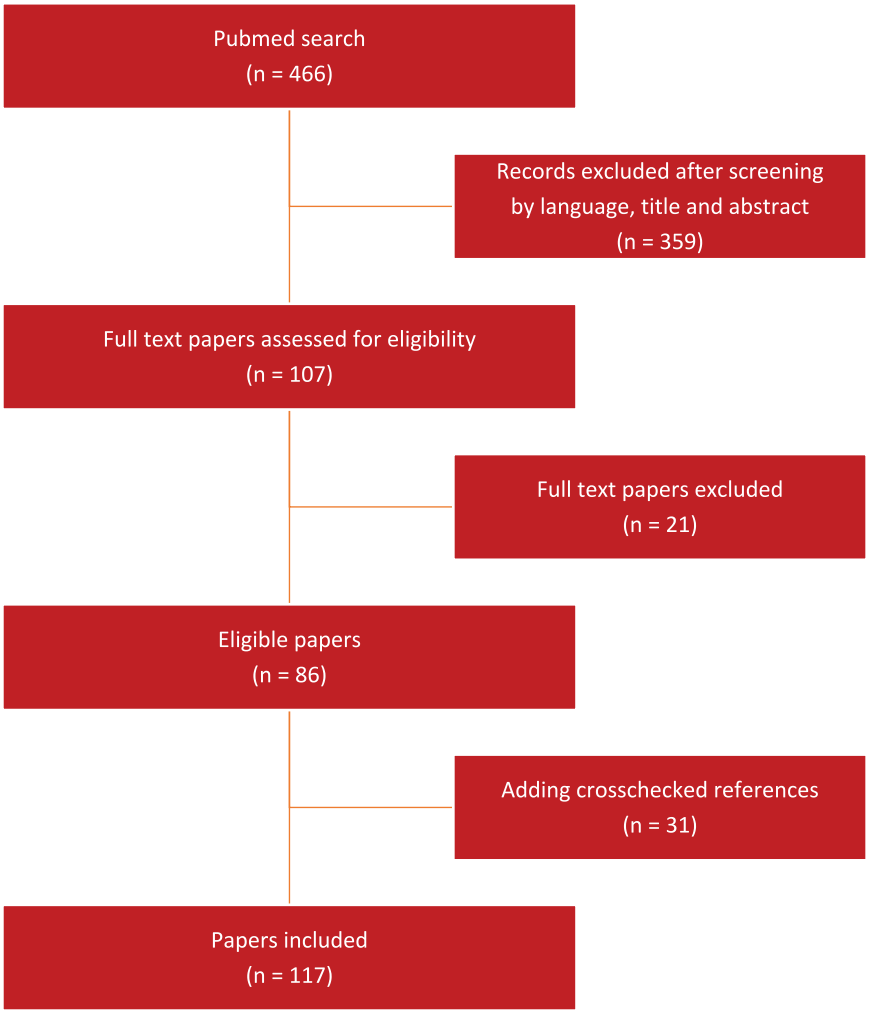

Figure 1. Flowchart depicting the selection of papers.

algorithms, in active tracking, the imaging plane can be automatically adjusted to the catheter. A major limitation is that the connection to external circuits via a long wire in a strong magnetic field makes it prone to induction of an electrical current or heating.[56,57,61,66,67]

Nazarian *et al.*[55] found that active tracking requires fewer imaging planes compared with passive tracking. Also, the robustness of active tracking of micro coils may be further enhanced by using dephasing magnetic field gradient pulses applied orthogonal to the frequency encoding gradient pulse used in conventional MR tracking.[62]

Furthermore, several papers reported about the important safety issues involved with using instruments and devices under real-time MR guidance. One of the most important issues is heating of conductive objects.[67,68] Inductive loops, formed by equipment leads, for example, can potentially cause unwanted tissue burns. Long structures such as guidewires or actively tracked catheters that use long conductive wires may also be inadvertently heated.[66,69] Temperatures up to 74°C have been observed in nitinol guidewires.[59]

However, several methods exist to minimize these issues, most importantly adjusting instrument design by decoupling possible resonant circuits, using alternative nonconductive components, for example, Kevlar or interrupting the metallic segments to reduce radiofrequency (RF)-induced heating.[68,69] Because not all effects can be fully

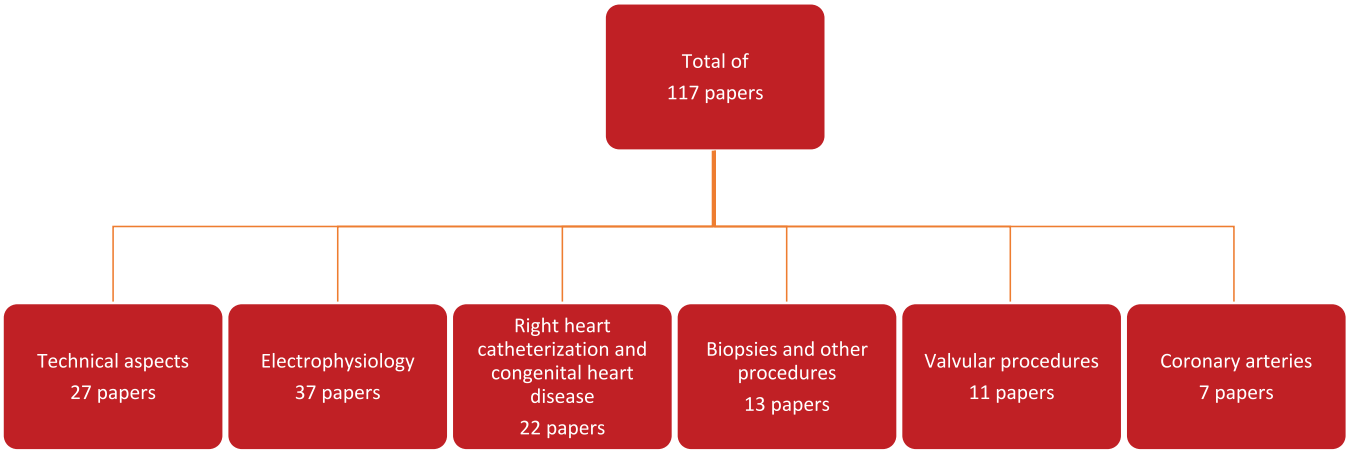

Figure 2. Flowchart depicting the various subcategories.

eliminated, the MR sequence can be optimized to cause less RF dissipation, for example, by using lower flip angles and more RF-efficient gradient echo spiral imaging.[23,69–72]

Electrophysiology

EP was one of the most advanced fields regarding implementation of interventional CMR, specifically the cavotricuspid isthmus ablation, which has a TRL of 8. Most other EP procedures have a TRL of 5. Of the 116 selected papers, 37 described studies on MR-guided catheter ablations, which is the most of all subcategories.[15–22,55,64,73–99]

Catheter ablation uses RF or cryothermal energy to disable the heart tissue, which is believed to cause arrhythmias. The disadvantage of current X-ray fluoroscopy-guided catheter ablation is the disappointing clinical success rate on the long-term, due to either technical failure (e.g. failure to form durable transmural lesions) or pathophysiological causes (e.g. incorrect selection of ablation targets). Especially information on pre-existing scar and peri-procedural lesion visualization are potential advantages of MR.

Real-time MR-guided catheter ablation in animals has been described as early as 2000.[19] Several groups describe MR-guided RF catheter ablation in the left ventricle,[20–22] right ventricle,[18,19] left atrium,[17] and right atrium.[81] Cryoablation was described as well.[83,86] In addition, Grothoff *et al.*[16] described active catheter tracking and left atrial access via transseptal puncture under MR guidance, which Raval *et al.*[100] had also described in a non-EP procedure. Aside from RF ablation in the left atrium, pacing and activation mapping were also performed in the coronary sinus. These are all crucial elements for future real-time MR guidance of atrial fibrillation (AF) ablation, during which pacing and activation mapping are frequently used. Authors describe that preprocedural anatomic imaging might be needed in the case of active tracking for adequate visualization of surrounding structures.[16] Furthermore, left atrial electrograms did not allow recording of very low amplitude signals. These were filtered out by the signal filtering that was used to prevent artifacts from the surrounding environment. This was a limitation for His-electrograms, which must be able to detect very low amplitude signals and distinguish them from artifacts.[16] Nevertheless, the prospect of real-time MR-guided left atrial ablation is promising.

Several human clinical studies have been performed, showing the feasibility of MR-guided catheter ablations for strictly anatomically defined ablations. Due to the benefits of interventional CMR for tissue characterization and lesion visualization, a future benefit is foreseen for substrate-guided ablations. Nazarian *et al.*,[55] in 2008, described the first MR-guided placement of catheters and recording of intracardiac electrograms in the right atrium, right ventricle, and bundle of His in humans ($N=2$) using prototype passively tracked catheters. In 2013, Sommer *et al.*[99] described a series of five patients who underwent atrial flutter ablation, AV-nodal re-entry tachycardia ablation, or an electrophysiological study under X-ray fluoroscopy guidance. Afterwards,

Table 2. Cardiac procedures divided into subcategories with their respective TRLs.

Procedure	TRL level	References
Electrophysiology		
Right atrial flutter ablation	TRL 8	Grotthoff *et al.*[15]
Left atrium ablation	TRL 5	Grotthoff *et al.*,[16] Schmidt *et al.*[17]
Right ventricle ablation	TRL 5	Dukkipati *et al.*,[18] Lardo *et al.*[19]
Left ventricle ablation	TRL 5	Toupin *et al.*,[20] Mukherjee *et al.*,[21] Krahn *et al.*[22]
AV-node ablation	TRL 5	Schmidt *et al.*[17]
Congenital procedures		
Diagnostic right and left heart catheterization	TRL 8	Veeram Reddy *et al.*,[23] Ratnayaka *et al.*,[24] Pushparajah *et al.*,[25] Knight *et al.*,[26] Velasco Forte *et al.*,[27] Meierhofer *et al.*[28]
Ventricular septal defect closure, treatment of pulmonary artery stenosis and aortic coarctation	TRL 6	Grant *et al.*[4]
Atrial septal defect closure	TRL 5	Ratnayaka *et al.*,[29] Rickers *et al.*[30]
Cavopulmonary shunt	TRL 5	Ratnayaka *et al.*[31]
Valvular procedures		
Transcatheter aortic valve replacement	TRL 5	Kuehne *et al.*,[32] Horvath *et al.*,[33] McVeigh *et al.*,[34] Miller *et al.*,[35] Miller *et al.*,[36] Horvath *et al.*,[37] Horvath *et al.*[38]
Pulmonary valve stenosis balloon dilatation	TRL 6	Tzifa *et al.*[39]
Coronary procedures		
Diagnostic catheterization	TRL 5	Green *et al.*,[40] Zhang *et al.*,[41] Qiu *et al.*,[42] Spuentrup *et al.*,[43] Serfaty *et al.*,[44] Heidt *et al.*[45]
Percutaneous coronary intervention	TRL 5	Spuentrup *et al.*[43]
Other procedures		
Endomyocardial biopsy	TRL 5	Behm *et al.*,[46] Rogers *et al.*,[47] Unterberg-Buchwald *et al.*[48]
Intramyocardial injections	TRL 5	Carlsson and Saeed,[49] Krombach *et al.*,[50] Tomkowiak *et al.*,[51] van Es *et al.*[52]
Pericardiocentesis	TRL 5	Halabi *et al.*[53]

TRL, technology readiness level.

patients underwent a real-time MR-guided procedure where catheters were placed in the right atrium and the right ventricle using passive catheter tracking. Intracardiac electrograms were successfully recorded and simple programmed stimulation maneuvers were performed. In this case, commercially available MR-compatible catheters were used (Vision™, Imricor Medical

Systems, Burnsville, MN, USA). Grothoff *et al.*[15] described the first real-time MR-guided cavotricuspid isthmus ablations in a series of patients ($N = 10$). Complete conduction block was achieved in one patient. This was partly due to the study protocol limiting the procedure time in the MR-room to 90 min. Nevertheless, in the other nine patients, only limited additional ablation pulses were required under X-ray fluoroscopy guidance to gain complete isthmus block. In 2016, the same group described the first cavotricuspid isthmus ablations in humans using active catheter tracking in combination with passive tracking, which enhanced catheter navigation.[64] Complete bidirectional block was achieved in 50% of cases (three out of six patients). In a follow-up study[94] of 30 patients, MR-guided cavotricuspid isthmus ablation was achieved in 93% compared with 100% in the control group. One recurrence of AF (3%) occurred in the control group. This validation proving feasibility, safety, and efficacy of cavotricuspid isthmus ablation in humans warrants a TRL of 8, which is among the highest score of all categories that are mentioned in this review.

Right heart catheterization and congenital cardiology

Along with cavotricuspid isthmus ablation, diagnostic right heart catheterization too is well advanced regarding implementation of interventional CMR, also achieving a TRL of 8. Most other congenital procedures had a TRL of 5.

In children with congenital heart disease, cardiac catheterization is often required for diagnosis, treatment, and follow-up. Therefore, MR-guided catheterization is beneficial.[24,101–103] Its excellent resolution enables the sometimes complex congenital anatomy to be well visualized, while also enabling measurements of pulmonary artery pressure and left atrial or wedge pressure. MR phase-contrast enables calculation of the pulmonary vascular resistance, although arrhythmias and turbulent flow are major constraints.[104,105]

Several research groups assessed the feasibility of MR-guided right heart catheterization in phantoms, animals, and patients.[23–26,60,102,104–108] In 2003, Razavi *et al.*[102] was among the first to describe diagnostic right heart catheterization under real-time MR guidance. Pulmonary artery pressure, wedge pressure, pulmonary artery and aortic or left atrial oxygen saturations were measured. Pulmonary vascular resistance was calculated using the Fick method and using MR flow measurements. Catheters were visualized by passive tracking and enhanced by attaching a CO_2-filled balloon to the tip. In 2015, the group of Pushparajah *et al.*[25] described a cohort of 149 patients with congenital heart disease who underwent 167 catheterizations for pulmonary vascular resistance assessment (including the procedures from the 2003 publication)[102] using either only MR guidance or a combination of MR and X-ray fluoroscopy guidance, firmly establishing its feasibility. While this group used conventional guidewires under X-ray fluoroscopy when necessary, Veeram Reddy *et al.*[23] demonstrated the use of an MR-conditional guidewire for right and left heart catheterization successfully in 24 out of 25 cases. Meierhofer *et al.*[28] also describe successful use of MR-conditional guidewires for right and left heart catheterization and pressure measurement in great vessels in 23 out of 25 cases of patients with congenital heart disease.

Feasibility of MR-guided transcatheter closure of atrial and ventricular septal defects (ASD/VSD) was described in several animal studies, achieving a TRL of 5.[29,30,104,107,109,110]

Rickers *et al.*[30] showed the first feasibility of MR-guided closure of ASD in seven swines. The shunt was visualized using MR angiography after administration of gadolinium-gadopentetate dimeglumine using T1-weighted gradient echo sequences, and the size of the defect was measured using orthogonal short- and long-axis images. An Amplatzer Septal Occluder device to close the ASD was then attached to a custom-designed nitinol delivery cable and loaded into the delivery sheath to facilitate deployment. Postmortem examination showed good correlation of the ASD size when an antenna guide wire crossing the ASD had been used, allowing for a smaller field-of-view without aliasing artifacts. MR-guided VSD-closure was described in animals by Ratnayaka *et al.*[29] Furthermore, Raval *et al.*[100] described transseptal puncture under real-time MR guidance using a custom-made actively tracked needle. The feasibility of transseptal puncture can be useful in a wide variety of procedures.

Finally, Ratnayaka *et al.*[31] described one of the most complicated MR-guided interventions. In

15 swines, a transcatheter cavopulmonary anastomosis and a shunt were created using novel, purpose-built devices after commercially available endografts were tested but provided suboptimal distal anastomosis. While the advantages of performing this procedure via a transcatheter route are further enhanced when done under MR guidance, they have not yet translated to human studies or clinical practice (TRL 5).

Valvular procedures

Feasibility of MR-guided valvular procedures has been tested in animal studies mostly since 2004,[111] especially in the aortic valve position, and thereby achieving a TRL of 5.

Real-time MR guidance of transcatheter aortic valve implantation has several possible advantages over X-ray fluoroscopy guidance and angiography. It allows precise positioning, and immediate assessment of the function of the prosthesis using flow measurements.[112,113] After the initial proof of concept in 2004, several other *in vivo* animal studies have been performed.[32–38] It has been shown that the commercially available Medtronic CoreValve® prosthesis can be used under real-time MR guidance, with small modifications made to the delivery device, of which the metal braiding had to be removed due to severe susceptibility artifacts.[35,112,113]

However, clinical implementation has been limited by several aspects, being the costs and time required to implement an interventional CMR catheterization suite, and safety aspects such as MR-incompatible implants in patients. The only valvular procedures performed under real-time MR guidance in humans and thereby achieving a TRL of 6, were described by Tzifa *et al.*[39] After first performing 20 balloon dilatations in five swines using a nonmetallic guidewire and passive catheter tracking, balloon dilatation of pulmonary valve stenosis was performed in two humans. Although both procedures took approximately 3 h, both patients had significant reduction of the gradient over the pulmonary valve and no complications were reported.

Coronary artery catheterization and interventions

Coronary artery catheterization and intervention under real-time MR guidance has been performed in a limited number of animal studies,[40–45] achieving a TRL of 5. Spuentrup *et al.*[43] described successful engagement of both coronary artery ostia in seven pigs using passive tracking. Stent placement was successful in 10 of 11 coronary arteries. Limitations of this study included the incorporation of nondiseased coronary arteries and, with a passive tracking approach, the guidewire tips could not be visualized in distal parts of coronary arteries.

A comparison between X-ray fluoroscopy and real-time MR guidance was made by Green *et al.*[40] A stenosis was surgically created in the proximal left circumflex coronary artery in nine swines. Conventional X-ray fluoroscopy-guided coronary catheterization was performed 3 weeks after surgery to objectify the stenosis. On the MR-scanner, the same femoral arterial sheath was used for left coronary artery catheterization, using an actively tracked guidewire and the same angiographic catheter, which led to successful intubation of the left coronary artery in eight out of nine cases. This showed an excellent correlation with an intra-class correlation coefficient of 0.955.

MR-guided coronary interventions have hardly made any progress since 2008 due to the small size of the coronary arteries and the lack of MR-compatible materials with sufficient stiffness, guiding stability, and MR visibility. In the most recent animal study performed by Heidt *et al.*,[45] the authors still had to rely on custom-designed catheters.

Other procedures

Several other cardiac catheterization procedures requiring intracardiac or pericardial access were described, predominantly in animal studies and therefore achieving a TRL of 5.

Few groups[46–48] investigated the use of MR guidance for endomyocardial biopsies, as the diagnostic yield of these biopsies is often dependent on the distribution of disease. The largest study investigating the use of real-time MR guidance for endomyocardial biopsies was performed by Rogers *et al.*[47] In five swines, late gadolinium enhancement MRI was performed 3 weeks after inducing myocardial infarction by obstructing an obtuse marginal branch. X-ray fluoroscopy and real-time MR-guided biopsies were taken, and the diagnostic yield of the MR-guided biopsies

(63 of 77 biopsies, 82%) was significantly better than that of the X-ray fluoroscopy-guided biopsies (49 of 87 biopsies, 56%). This suggests MR guidance of endomyocardial biopsies can improve the diagnostic yield compared with X-ray fluoroscopy guidance.

In animal studies, intramuscular injection of bone marrow stem cells into myocardial infarct border zones has shown functional myocardial recovery, but convincing feasibility has not been shown in humans. Hatt *et al.*[114] suggested this might partly be due to the delivery method and target location. Intramyocardial injections have been performed successfully under real-time MR guidance in animals by several authors.[50–52] However, the limited clinical application of stem cell therapy in ischemic heart disease limits the requirement of interventional CMR for this purpose.

Halabi *et al.*[53] described real-time MR-guided pericardiocentesis in 12 swines with either no effusion, small (50 ml), moderate (100 ml) or large effusion (150 ml) using commercially available passive access titanium needles (CMR Puncture Needle, 18G × 15 cm, Philips Invivo, Schwerin, Germany) via a subxiphoid access route. It was successful in all cases.

Feasibility of pericardiocentesis in an MR-environment is essential, since cardiac tamponade is a known complication of various cardiac procedures. Damaging delays may be prevented when pericardiocentesis can be performed in the same environment.

Discussion

A detailed systematic review of the available literature on interventional CMR for cardiac procedures was performed and TRL of these procedures was assessed. Although several limitations still need to be overcome to further advance and improve clinical translation, interventional cardiac MRI is a highly promising technique. Particularly in diagnostic right heart catheterization and cavotricuspid isthmus ablation, the technique has advanced toward clinical translation over the past 10 years, reaching a TRL of 8. Other procedures have mostly been done in animal studies, achieving a TRL of 5.

To date, technical aspects like catheter tracking and heating of instruments are still major limitations. Passive tracking often only shows part of the device, is time-consuming and is problematic when multiple devices need to be visualized at the same time. Active tracking provides more convenient visualization, but requires substantial device modification and is prone to heating. The lack of an MR-compatible defibrillator and the need to acquire new technical expertise are other factors preventing widespread clinical translation of MR-guided procedures. Nevertheless, the possibility of adding the strong diagnostic features of CMR (e.g. high spatial and temporal resolution, excellent anatomic visualization, tissue characterization, and flow measurements) to interventional procedures is very valuable, with the advantage of not exposing patient and staff to ionizing radiation. Furthermore, Campbell-Washburn *et al.*[115] have described how low-field-strength MRI (0.55 T) reduces heating, which allowed conventional metallic guidewires to be used in right heart catheterization in seven cases, while efficient spiral image acquisitions enabled good image quality. Diagnostic right heart catheterization is especially beneficial in children with congenital heart disease, who often have to undergo multiple assessments of pulmonary artery pressures and pulmonary vascular resistance and benefit most from avoiding ionizing radiation. This is a particular area that might benefit from low-field-strength interventional CMR.

In EP, clinical translation of interventional CMR has been achieved in right-sided procedures. Real-time MR-guided cavotricuspid isthmus ablation in atrial flutter has been described in a series of 30 patients[94] and was shown to be equally effective as X-ray fluoroscopy guidance. Left-sided ablation is still limited by the lack of an MR-compatible needle available for transseptal puncture. Lesion visualization in the left atrium is also impeded by the difficulty of imaging the thin atrial wall with the currently available resolution, although this also applies to the right atrium where substantial progress had been made. Nevertheless, this area would particularly benefit from tissue characterization, as it could give immediate feedback on the efficacy of the procedure because of the ability to ensure ablation lesions are interconnected and transmural, leading to a higher success rate of AF ablation and less re-do procedures. Conventional T1 and T2 mapping, especially when using contrast enhancement for T1-weighted imaging, are also useful to determine reversibility of RF-lesions.[22]

Another area that could benefit from interventional CMR is endomyocardial biopsy, since diagnostic yield is affected by disease distribution. Small animal studies have already shown a superior diagnostic yield for MR-guided interventions compared with X-ray fluoroscopy-guided interventions.[47,48] However, to date, MR-compatibility of bioptomes is a limiting factor.

Valvular and coronary procedures have mostly been performed in animal studies, and clinical translation in these areas appears not imminent for a longer period.

Conclusion

Our results show that diagnostic right heart catheterization and cavotricuspid isthmus ablation have the highest TRL in interventional CMR, achieving a TRL of 8. These procedures are clinically feasible and have several advantages over conventional X-ray fluoroscopy guidance. Other procedures, like left-sided RF-ablation and endomyocardial biopsy might benefit greatly from the features of interventional CMR (e.g. tissue characterization and lesion visualization), but have so far been performed almost exclusively in animal studies, therefore achieving a TRL of 5. Further clinical translation of such procedures is dependent on the development of MR-compatible instruments, but we believe that once this is achieved, interventional CMR will greatly contribute to improving success rates of left-sided ablation and diagnostic yield of endomyocardial biopsies.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Author contributions

Sophie C. Rier: Conceptualization; Investigation; Methodology; Project administration; Visualization; Writing – original draft; Writing – review & editing.

Suzan Vreemann: Conceptualization; Methodology; Writing – review & editing.

Wouter H. Nijhof: Conceptualization; Methodology; Writing – review & editing.

Vincent J.H.M. van Driel: Conceptualization; Methodology; Writing – review & editing.

Ivo A.C. van der Bilt: Conceptualization; Methodology; Project administration; Supervision; Writing – review & editing.

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