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Chapter 12

7 Tesla cardiovascular MR imaging: initial clinical experience


Submitted
ABSTRACT

Background
The purposes of this study were to test coronary stent safety at 7T cardiovascular magnetic resonance (CMR) by determining displacement and heating for cobalt alloy stents. Furthermore, to assess initial clinical feasibility of 7T CMR in healthy volunteers and patients with cardiovascular disease in the format of a multiple-case presentation.

Methods
Coronary stents (Cobalt Alloy) ranging from 5-85.8 mm in length were tested for safety by measuring magnetically induced displacement and radiofrequency induced heating according to standardized American Society for Testing and Material test methods. CMR was performed at 7T with various custom-built transmit/receive coils and imaging sequences for evaluation of coronary magnetic resonance angiography, vessel wall imaging, systolic and diastolic heart function and myocardial delayed enhancement.

Results
The 7T magnetic field did not induce a force greater than that of gravity on the stents and the maximum temperature rise was below 1°C. Preliminary results in the format of a multiple-case presentation demonstrated clinical feasibility of 7T CMR in healthy volunteers and patients with cardiovascular disease.

Conclusion
7T CMR is safe to perform in patients with cobalt alloy coronary stents (5-85.8 mm in length) and clinical CMR at 7T is feasible. Technical challenges have to be overcome before routine clinical application becomes possible.
INTRODUCTION

Cardiovascular magnetic resonance (CMR) is considered the gold standard modality for clinical assessment of cardiovascular anatomy, function and myocardial viability (1). CMR might benefit from a higher magnetic field strength, because the increased signal to noise ratio (SNR) allows higher spatial resolution imaging. This is especially important for coronary magnetic resonance angiography (MRA) and vessel wall imaging.

Promising CMR results have been reported in comparative studies using 3T versus 1.5T (2-5) and 7T versus 3T (6). However, the increased field strength produces a series of technical challenges for CMR (2,7). CMR requires robust compensation for heart motion, breathing motion and field inhomogeneity. Another challenge is acquisition of a reliable electrocardiogram (ECG) (8). Snyder et al. showed initial feasibility for CMR at 7T (9), with a subsequent study deriving quantitative assessment of functional parameters in healthy volunteers (10). To our knowledge, there is only limited data available on the feasibility of CMR in patients with cardiovascular disease at 7T. For example, despite recent progress in obtaining human coronary MR images (8) and carotid artery MR images (11) at 7T, specific work on vessel wall imaging at 7T is scarce.

Before clinical CMR at 7T can be performed, coronary stent safety has to be determined. The static magnetic field of the MR system exerts a force during patient positioning on ferromagnetic objects, possibly causing displacement of, for example, coronary artery stents. Furthermore, medical implants can potentially interact with the rapidly changing RF field, thereby inducing unwanted currents and heating of surrounding tissue.

Therefore, the first purpose of the present study was to test coronary stent safety at 7T MR by determining displacement and heating for cobalt alloy stents ranging in length from 5 to 85.8 mm in a worst case scenario. The second purpose was to assess initial clinical feasibility of 7T CMR in healthy volunteers and patients with cardiovascular disease in the format of a multiple-case presentation.

METHODS

All experiments and scans were performed on a 58 cm clear bore Philips 7 Tesla Achieva system (Philips Medical Systems, Best, The Netherlands).

Coronary artery stent safety
Coronary stents (Cobalt Alloy, Medtronic) ranging from 5 to 85.8 mm in length were used in this study. The longest stent (85.8 mm) consisted of four separate stents (1x30,
1x24 and 2x18 mm), which were combined with a small overlap between two adjacent stents. All stents were inflated to obtain an internal diameter of 3 mm.

The magnetically induced displacement force was assessed for each stent size using the deflection angle method, according to the procedure described by the American Society for Testing and Materials (ASTM) (12). The magnetically induced displacement was measured by the angular deflection using a protractor mounted on a stand with the zero degree mark at the 6 o’clock position. A stent was hung on the device by a 0.1 mm nylon thread. The angular deflection from the vertical was measured for all stent lengths with the protractor placed at the position where the magnetic field produces the greatest magnetically-induced deflection. During all these measurements the air circulation in the scanner bore was switched off.

Measurements of RF-induced heating were performed according to the ASTM Standard Test method for measurement of radiofrequency-induced heating on or near passive implants (13) with some necessary modifications. A tissue-mimicking phantom (149 mm x 59 mm x 47 mm) was formulated from 1.55 g/L sodium chloride (NaCl) and 31 g/L hydroxyethylcellulose (HEC) in sterile water. To obtain a gel free of air bubbles the phantom was ultrasonicated. The gel was positioned in the 7T scanner room for at least 24 hours prior to testing to obtain a transparent gel that was free of bubbles and temperature-stabilized. A stent was placed in the middle of the phantom, 2.5 cm from the bottom: this is comparable to the depth of a stent in a patient’s body. Two fiber optic temperature probes (Opsens, Quebec, Canada) were used to measure the temperature during MRI-induced heating. The first temperature probe was positioned at the tip of the stent, the site of maximum heating (14), the second was used as a reference and was placed well away from the stent. The temperature was measured every 2.1 seconds and the measurements started 30 seconds before the MRI heating started and ended 30 seconds after the heating stopped.

Besides different lengths of stent, the effect of different relative positions of more than one stent was investigated. Two stents were used, one with a length of 42.4 mm and the other with a length of 19.5 mm. In the first situation, the two stents were placed in a straight line with each other. For the second situation, the two stents were placed at different angles relative to each other. In the last situation, one stent was placed on top of the other stent, forming a T-shape. Temperature measurements were performed in the gap between the two stents. The same custom-built quadrature cardiac coil as used for the clinical imaging experiments (see later) was used for the heating experiments. The phantom was placed with the stent directly below the overlap point of the two loops, which is the position of maximum electric field and therefore maximum heating. The phantom was tested with the stent both parallel and perpendicular to the main
axis of the coil. A multi-slice gradient echo sequence (similar to a cardiac cine-scan) was used. By over-riding in software the manufacturer’s signal absorption rate (SAR) limits, a time-averaged SAR of 5W/kg was produced, well above the regulatory limit of 2 W/kg.

**Clinical imaging protocols**

All studies were conducted according to the principles of the Declaration of Helsinki (current version adopted by the 59th WMA General Assembly, Seoul, October 2008), in accordance with the Medical Research Involving Human Subjects Act (WMO) and according to local guidelines, as specified by the local medical ethical committee.

The MR system was equipped with a vector ECG module. Electrodes were placed at the anterior chest wall: Two electrodes (lead 1 [L1] and L2) at the level of the sternum, one electrode (L3) vertical to L1 and L2, just below the sternum, one electrode (L4) horizontal to L2, on the left thorax along the mid-axillary line (8). ECG triggering was effective in about 80% of patients. All subjects were placed in the bore head first and in a supine position.

**Coronary artery MRA**

Bright blood coronary MRA of the right coronary artery was performed in a twenty-three year old female healthy volunteer. A custom-built quadrature two element surface transceiver (T/R) coil with two overlapping loops of 18 cm diameter was used. Scout images in coronal, transverse and sagittal orientations were used to plan ECG triggered, breath-hold transverse cine scout imaging for both determination of the period of minimal coronary motion and the volume targeting of the 3D stack in parallel with the mid-diastolic right coronary artery (RCA). The RCA was imaged by using a navigator-gated, vector ECG triggered 3D segmented k-space gradient-echo combined with a spectrally selective adiabatic inversion recovery pulse for fat suppression. The in plane field-of-view (FOV) was 420 x 270 mm² with a coverage of 30 mm, TR was 4.06 ms, TE 1.32 ms, FA 15º and voxel size 0.82 x 0.82 x 2.0 mm.

**Vessel wall imaging left carotid artery**

As described previously a flexible 15-cm diameter local surface T/R surface coil was constructed for vessel wall imaging (11). The coil was segmented into six sections by series connected non-magnetic capacitors (American Technical Ceramics) and was positioned at the left side of the neck. A cushion was used to fix the position of the neck.

After acquisition of a three-dimensional (3D) time-of-flight (TOF) sequence to localize the vessel bifurcation, sagittal and coronal 2D scout scans of the left carotid artery were acquired. The multi-contrast carotid vessel wall protocol was planned on these images and consisted of a T1 segmented fast gradient echo (FGE) sequence, a T2 turbo
spin echo (TSE) sequence and a 3D TOF sequence. At 7T BB preparation is performed using local saturation slabs that saturate the inflowing venous and arterial blood. For the $T_2$-weighted TSE protocols no BB prepulse was used.

**Cardiac function**
Scout images in coronal, transverse and sagittal orientations are used to plan ECG triggered, breath-hold transverse cine scout imaging, performed using TE 1.7 ms, TR 4 ms, FA 15°, and reconstructed pixel size 0.88x0.88 mm. To determine systolic left ventricular (LV) volumes, function and mass, the LV was imaged in a short-axis orientation, as previously described (15). Endocardial and epicardial LV contours were manually drawn in the end-systolic and end-diastolic phases of the short-axis data, using software package MASS® (Medis, Leiden, the Netherlands). LV and right ventricular (RV) ejection fraction (EF), stroke volume (SV), LV and RV end-diastolic volume (LVEDV/RVEDV), LV/RV end-systolic volume (LVESV/RVESV) and LV/RV end-diastolic mass (LVED/RVED mass) were assessed. Transmtral flow was measured for assessment of LV diastolic function, using a velocity sensitivity of 150 cm/s, TE 2.6 ms, TR 4.6 ms, FA 20°, reconstructed pixel size 1.5x1.5 mm. Flow velocities in early diastole (E) and at atrial contraction (A) were measured and their peak flow ratio was calculated (E/A ratio) using the FLOW® software (Medis, Leiden, the Netherlands) (16,17)

**Delayed enhancement**
Delayed enhancement acquisitions were performed approximately 15 minutes after intravenous administration of 0.1 mmol/kg Gadolinium using an inversion-recovery turbo-gradient echo sequence, TE 1.06 ms, TR 3.7 ms, FA 15°, reconstructed pixel size 1.5x1.5 mm. The inversion time was determined with a Look-Locker scan to null the normal myocardial signal.
RESULTS

Coronary artery stent safety
The deflection angle of stents in the length range from 5.0 mm to 85.8 mm varied between 10° and 17°. The average deflection angle was 13° (Figure 1). The results of the RF induced heating are shown in Figure 2. For a stent length between 5.0 and 31.2 mm and between 58.7 and 85.8 mm the change in temperature, and thus the heating, was very low (max 0.1°C). However, for stent lengths between 35.2 and 51.7 mm the heating was higher (max 1.0°C). Overall, an average temperature rise of 0.09 ± 0.28°C (parallel position) and 0.00 ± 0.06°C (perpendicular position) was found. No large temperature change was found for the different relative positions of two stents. The highest temperature change (0.2°C in 6 min) was found for two stents that were placed in a straight line with a small gap in-between.

![Figure 1. Deflection angle of cobalt allow coronary artery stents, measured for length range from 5.0 mm to 85.8 mm.](image1)

![Figure 2. Total change in temperature for different lengths of stents. Blue bars represent total change in temperature at the tip of the stent in parallel orientation with respect to the magnetic field. Purple bars represent total change in temperature at the tip of the stent when placed perpendicular to the magnetic field.](image2)
Cardiovascular MRI – healthy volunteers

(i) Coronary artery MRA
Figure 3 shows a section imaged with a bright blood coronary MRA sequence. Good fat suppression and high vessel sharpness enable a clear delineation of the RCA. Furthermore, anatomic details of the coronary, such as the conus and side branches, are clearly visible.

![Figure 3](image)

**Figure 3.** MRA of the right coronary artery (RCA) in a twenty-three-year old healthy female volunteer obtained with a bright blood coronary MRA sequence. Several structures can be identified in this image: the ostium, conus and a portion of the RCA. Notice the good fat suppression and high vessel sharpness. RVOT = right ventricular outflow tract, Ao = aortic root, LV = left ventricle, Sb = Side branch.

(ii) Vessel wall imaging of the carotid artery
In Figure 4 the left carotid artery of a 32 year old healthy male is depicted. The top row represents T1-weighted images and the bottom row T2-weighted images.
Figure 4. Left carotid artery of a thirty-two year old healthy male. The * is centered in the left carotid artery, the arrow points to the jugular vein. Top row represents T1-weighted images, bottom row T2-weighted images.

(iii) Systolic function

Figure 5 shows cardiac cine images of a healthy twenty-nine year old female. Left ventricular, two-chamber, four-chamber and short axis images are shown in end-diastolic and end-systolic phase. RF penetration depth is sufficient to assess left and right ventricular heart function.

Figure 5. Cine imaging of a twenty-nine year old healthy volunteer. The upper panels are acquired in end-diastole, the lower panels in end-systole. Images A and B depict 2-chamber views, B and E depict 4-chamber views and images C and F represent the short axis view. RF penetration depth is sufficient to assess left ventricular and right ventricular heart function.
Figure 6 shows more recent results acquired in a healthy twenty-five year old female volunteer using a transmit array of eight segmented dipoles (18). Eight custom-built transmit/receive switches were interfaced with the dual transmit system via four Wilkinson lumped element 1:2 splitters. Note the improved homogeneity of RF penetration and increased coverage of the heart in comparison to Figure 5. Improved coverage is also reflected by visualization of anatomic structures outside the heart, such as the spine.

![Figure 6](image)

**Figure 6.** Recent results from our group in a twenty-five year old healthy female volunteer using a transmit array of eight segmented dipoles. The upper panels are scanned in end-diastole, the lower panels in end-systole. Images A and D are 2-chamber views, B and E depict 4-chamber views and images C and F represent the short axis view.

Cardiovascular MRI – clinical cases

(i) **Global systolic dysfunction.**

In Figures 7 (A) and (B) global systolic dysfunction in a 65 year old male is shown. This patient was admitted to the coronary care unit with chest pain and had no previous medical history. His ECG showed complete left bundle branch block, and cardiac enzymes were negative. In order to rule out coronary artery disease, coronary catheterization was performed and no significant coronary artery disease was found. Echocardiography showed a dilated left ventricle with severely diminished left ventricular function, with a left ventricular ejection fraction (LVEF) of 23% and no significant valvular disease. The patient had no clinical signs of infection and detailed history taking revealed no
infectious episode in the recent past. Therefore, recent and acute myocarditis was not suspected. MRI was performed to assess cardiac function and the etiology of the cardiomyopathy. Cardiac MRI showed a substantially dilated, globally hypokinetic left ventricle with an LVEF of 22%, in concordance with the echocardiographic findings. Panels A and B of Figure 7 distinctly show the reduced myocardial contractility. There were no signs of focal wall motion impairments. The most probable diagnosis was idiopathic dilated cardiomyopathy.

(ii) Systolic dysfunction after right coronary artery infarction
Figures 7 (C) and (D) show the short axis view at end diastole and end systole in a 52 year old man with a history of an occluded RCA with collateral filling via the left coronary artery. The patient was seen at the outpatient clinic for a second opinion concerning treatment of coronary artery disease. He complained of atypical chest pain despite appropriate cardiac medication. The echocardiographic window of this patient was very poor and therefore 7T MRI was performed to assess cardiac function. MRI showed basal, midventricular and apical hypokinesia of the inferior wall. The LV was not dilated and function was quantified as follows: end-diastolic volume (EDV) 176ml, end-systolic volume (ESV) 87ml, stroke volume (SV) 88ml and LVEF 50%. For further evaluation stress myocardial perfusion scintigraphy was performed, showing extensive ischemia in the inferior-, septal- and anterior myocardium. Coronary catheterization was performed and revealed significant coronary artery disease in all 3 coronary arteries for which the patient was treated with coronary artery bypass grafting.

(iii) Systolic dysfunction after left anterior descending artery infarction
Figures 7 (E) and (F) show regional systolic dysfunction in a patient after partial occlusion of the left anterior descending (LAD) coronary. The patient is a 60 year old male who was admitted with acute anterior myocardial infarction and no previous medical history. Two hours before admission he experienced chest pain with radiation of pain to his left arm. He was transported to the hospital for an emergency percutaneous coronary intervention (PCI). His coronary angiogram showed an occluded ramus descendens anterior (RDA) after the 2nd diagonal branch. He received balloon angioplasty of the occlusion and a drug eluting stent (Promus 3.5 x 20 mm) was placed in the RDA en coronary blood flow was restored. His circumflex- and right coronary artery showed luminal narrowing of 30-40%, for which no intervention was required. Patient was admitted to the coronary care unit, was put on medication and recovered quickly. He was discharged after 2 days and MRI was performed after 6 days to assess LV function and infarct burden. MRI showed a global moderate systolic function, with profound midventricular hypokinesia/akinesia, mainly in the anteroseptal- and anterior wall, expanding to the apex. The apical
segment showed dyskinesia compatible with aneurysm development. LV volumes were EDV 165ml, ESV 104ml, SV 61ml and LVEF was 37%.

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<th>Global systolic dysfunction</th>
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**Figure 7.** Three different kinds of systolic dysfunction. All images are in short axis orientation. Panel a and b reflect global systolic dysfunction, respectively, at end diastole and at end systole. Note impaired ventricular contraction comparing A and B, representing low ejection fraction. C and D reflect systolic dysfunction after RCA infarction, showing regional akinesia in inferior wall. Panels E and F show focal systolic dysfunction in the anteroseptal myocardial region, compatible with a significant coronary artery stenosis in the LAD.

**Transmitral flow in diastolic dysfunction**

(iv) Figure 8 depicts normal and abnormal diastolic heart function, assessed at 7T MRI. The flow curve across the mitral valve is shown. The upper panel illustrates normal diastolic function in a 33 year old healthy male. The lower panel demonstrates impaired diastolic function of a 62 year old male. This patient had diabetes mellitus and was seen at the cardiology outpatient clinic for evaluation of stable angina pectoris due to an occluded right coronary artery with collateral filling by the left coronary artery. An MRI was performed to assess cardiac function. MRI showed a non dilated left ventricle with basalmost ventricular and midventricular mild septal hypertrophy. Mild hypokinesia was seen basal inferior. The E/A ratio was <1 and no regurgitation of the valves was observed.
Figure 8. Diastolic function. Upper panel: an example of a normal flow (E>A) pattern across the mitral valve.
Lower panel: diastolic dysfunction (E<A) in a patient with diabetes mellitus and coronary artery disease.

(v) Delayed enhancement
The same 60 year old male (Figures 7 E and F), with systolic dysfunction after LAD infarction, also had signs of transmural delayed enhancement (Figure 9). Delayed enhancement was located at the sites of wall motion abnormalities, in accordance with scar tissue related to the myocardial infarction. Note that the posterior wall is too dark to reliably assess delayed enhancement in that part of the myocardium, possibly related to inhomogeneous distribution of 180 degree inversion flip angles. This is clearly a case in which the improved image quality afforded by transmit arrays, as shown in Figure 6, will be critical in the future.
Figure 9. Transmural delayed enhancement in the anteroseptal myocardial wall. As can be appreciated from this figure, image quality is still insufficient to adequately assess scar tissue.

(vi) Prominent trabecularization.
The final case is a 33 year old man who was seen at the outpatient clinic for evaluation of palpitations. He experienced short episodes of fast palpitations of sudden onset without syncope. Echocardiography was performed and showed suspicion of non-compaction cardiomyopathy. An MRI was performed to assess cardiac anatomy and function. The MRI showed prominent trabecularization in the apical inferolateral wall, with normal myocardial wall thickness (Figure 10). No criteria for left ventricular non-compaction cardiomyopathy were met. LV function was normal, with an LVEF of 57%. Patient is currently in a good condition and the palpitations were later attributed to AV nodal re-entry tachycardia.

Figure 10. Prominent trabecularization in a 33 year old male. Panel A shows a 4 chamber view, panel B a short axis view at end diastole. The trabeculae are mainly seen in the apical area.
DISCUSSION

Coronary artery stent safety
According to the ASTM test method a deflection angle of less than 45 degrees is considered safe. The force exerted by the magnet is then equal or less than that of gravity. For all tested stent lengths the deflection angle was lower than 45 degrees (max. 13 degrees) and therefore it may be concluded that the 7T MR system did not exert an extra force on the stents. In general, the RF induced heating was higher for the parallel position (0.09 ± 0.28) compared to the perpendicular position (0.00 ± 0.06). This can be explained by the shape of the electric field, which couples more tightly to the test device in this orientation. The highest temperature change was found for a stent length of 42.4 mm (0.93°C in 6 min). Almost no heating was induced in stents longer or shorter than 42.4 mm, indicating that for this particular stent type the critical length lies around the 42.4 mm.

Patients may have multiple stents, depending on the passage or the weak places of the blood vessels. This leads to stents inserted close to each other or placed in a certain relative position. These stents can interact with each other and together they can undergo an interaction with the RF-field of the MR system. To simulate this, several relative positions were tested. Almost no heating was seen. The highest heating (0.20°C in 6 min) was seen for two stents placed in a straight line with a small gap in-between. The heating was probably induced by the largest stent (42.4 mm) because that was found to be the critical length.

A rise of 1°C is generally acceptable in a normal healthy body. The highest increase in temperature for stents was 0.93°C. This temperature rise was only found for one stent length (42.4 mm). For the other stent lengths the maximal temperature rise was far below 1°C (max: 0.35°C).

These results agree well with those of a recent study which also suggested that, if guidelines for local/global SAR are followed, extra RF heating induced by stents may be insignificant (19). In that study two non ferromagnetic coronary stent configurations with lengths of 40 mm and 27 mm were used to assess the safety of scanning of coronary stents at 7T MR. In this study we assessed more stent lengths, ranging from 5 to 85.8 mm. Our results therefore add to the existing data on safety of coronary stent scanning at 7T.

Healthy volunteers and clinical cases
Several previous studies showed that ultrahigh field 7T CMR is feasible (9,10,20), despite many technical challenges. Ultrahigh field CMR is very promising (7,21), since the higher SNR inherent to higher magnetic field strengths is advantageous for cine CMR. Additionally, the potential of enhanced spatial resolution may lead to advantages for CMR (7).
MRA has several advantages over coronary computed tomography (CTA) and coronary angiography (CAG): it is non-invasive, non-irradiating and the use of a contrast agent is not required. At 1.5T, a number of studies on the diagnostic accuracy of MRA have proven that proximal coronary artery disease (CAD) can be reliably identified or ruled out (22,23). Higher SNR has been reported in MRA of the RCA at 7T when compared to 3 T (6). The increased SNR can potentially be used to increase spatial resolution with the potential of more accurate detection of significant coronary artery stenosis.

Besides imaging of coronary arteries, we recently showed that ultrahigh field 7T MR imaging also offers potential for imaging of the carotid vessel wall (11). We demonstrated an improved vessel wall SNR and CNR as compared to 3T MR images for both the T1- and T2-weighted images. In the future, this may potentially allow a more detailed assessment of carotid atherosclerosis or plaque morphology in patients.

Previous studies showed that assessment of LV volumes, function and mass at 7T agree well with 1.5T, which is the accepted reference standard in CMR (10,24). A recent study by Suttie et al (25) reported that steady state free precession (SSFP) and fast low angle shot (FLASH) cine imaging at 7T is technically feasible and provides valid assessment of LV volumes and mass compared with CMR imaging at lower, i.e. 1.5T and 3T, field strengths (25).

Another challenge in the field of CMR is imaging of the right ventricle (RV). The non-invasive imaging of function, size and anatomy of the RV is difficult, due to several factors, such as the asymmetric and variable shape of the RV, the mainly longitudinal systolic contraction, thin myocardial wall and location behind the sternum (26). As for LV volumes, function and mass, 1.5T is the golden standard for assessment of the RV. However, the accuracy of quantifying for example RV mass and characterization of myocardial tissue remains uncertain. It is important to improve imaging techniques, since anatomy and function of the RV are known to be predictors of morbidity and mortality in a variety of cardiac diseases, such as arrhythmogenic RV cardiomyopathy (27). The potential improvements in SNR and thereby spatial resolution at 7T MR could add to better imaging quality of RV morphology and function. Recently, the first study on RV imaging at 7T was published, showing that cine imaging of the RV is feasible at ultrahigh field MRI and achieves image quality comparable to the quality at 1.5T (26). There is little literature on assessment of LV diastolic function at ultrahigh field MRI. To our knowledge, only one previous study investigated LV diastolic filling on 7T (10). Trans-mitral flow was assessed with velocity-encoded (VE) MRI, and a strong agreement between trans-mitral stroke volume and E/A ratio at 1.5T and 7T was found. The early and atrial peak filling rates displayed a greater, though not significant, variation at 7T versus 1.5T. These results show that trans-mitral flow assessment with VE MRI is feasible at 7T.
In previous publications it has been shown that functional cardiac scans, coronary magnetic resonance angiography, and vessel wall imaging are all feasible in humans at 7T. In this paper we show that functional and anatomic imaging, even using a simple RF coil setup, are useful within a clinical setting, while also highlighting some of the current inadequacies, mainly associated with limited RF penetration. Many other groups have shown that the use of multi-element transmit arrays can mitigate many of these penetration effects. In parallel, Figure 4 shows improved coverage using a transmit array of eight segmented dipoles (18). Extensive B1 shimming was not performed, with equal phases applied to each segmented dipole, and so image quality may well be improved by optimizing the individual phases. Currently, these types of array require full characterization in terms of safety, SAR monitoring, before they can be used in “routine” clinical practice. The clear improvement in image quality over a single transmit system, combined with our demonstration of clinical potential even with the single transmit system, point to rapid advancements for clinical application.

In conclusion, 7T cardiovascular MRI is safe to perform in patients with cobalt alloy coronary stents ranging from 5 to 85.8 mm. Clinical cardiovascular MRI at 7T is feasible. Technical challenges have to be overcome before routine clinical application becomes possible. Clinical practice has to prove the benefit of ultrahigh field MRI as compared to lower field MRI at 1.5T and 3T.
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