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Hemodynamic response and safety of vasodilator stress cardiovascular magnetic resonance in patients with permanent pacemakers or implantable cardioverter-defibrillators

Lauren Miller BS[1] | Sergei Airapetov DO[2] | Ajay Pillai MD[2] | Gautham Kalahasty MD[2] | Kenneth A. Ellenbogen MD[2] | W. Gregory Hundley MD[2] | Cory R. Trankle MD[2]

[1]School of Medicine, Virginia Commonwealth University, Richmond, Virginia, USA

[2]Division of Cardiology, VCU Pauley Heart Center, Virginia Commonwealth University, Richmond, Virginia, USA

Correspondence
Cory R. Trankle, VCU Pauley Heart Center, Virginia Commonwealth University, PO Box 980036, Richmond, VA 23298, USA.
Email: cory.trankle@vcuhealth.org

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Abstract

Introduction: Vasodilator stress cardiovascular magnetic resonance (CMR) is a powerful diagnostic modality, but data toward its use in patients with permanent pacemakers (PPMs) or implantable cardioverter-defibrillators (ICDs) is limited.

Methods and Results: Patients with ICDs (>1% pacing) or PPMs who underwent regadenoson single photon emission computed tomography (SPECT) and all patients with ICDs or PPMs who underwent stress CMR were retrospectively identified. SPECT tests were analyzed for hemodynamic responses and new pacing requirements; CMR studies were examined for safety, device characteristics and programming, hemodynamic responses, and image quality. Changes from baseline were evaluated with the Related-Samples Wilcoxon Signed Rank Test. Of 67 patients (median age 65 [IQR 58–72] years, 31 [46%] female, 31 [46%] Black), 47 underwent SPECT and 20 CMR. With regadenoson SPECT, 89% of patients experienced tachycardic responses above resting heart rates (+19 [13–32] beats per minute, $p < .01$). During stress CMR, 10 (50%) devices were asynchronously paced approximately 10 beats per minute above resting rates, and the remaining were temporarily deactivated. Those with asynchronous pacing had no changes in heart rates, whereas patients with deactivated devices had near uniform heart rate accelerations. Image quality was diagnostic in the majority of stress CMR sequences, with nonconditional ICDs contributing 40 of 57 (70%) of nondiagnostic segments.

Conclusion: This data supports the safety of vasodilator stress CMR with promising diagnostic quality images in patients with CMR conditional ICDs and PPMs. Despite a near uniform tachycardic response to regadenoson in the SPECT environment, high rates of asynchronous pacing during vasodilator stress CMR did not result in competitive pacing or adverse arrhythmic events. Further studies are needed to

validate these findings and confirm the diagnostic and prognostic performance of stress CMR in these individuals.

KEYWORDS
artificial cardiac pacemaker, cardioverter defibrillator, implantable, magnetic resonance imaging, single photon emission computed tomography, stress test

1 | INTRODUCTION

Vasodilator stress cardiovascular magnetic resonance (CMR) is useful to detect functionally important epicardial coronary artery and microcirculatory disease (CAD).[1,2] A subset of patients with indications to identify functionally important epicardial coronary artery or microcirculatory disease have permanent pacemakers (PPMs) or implantable cardioverter-defibrillator (ICDs). Vasodilator stress CMR studies in these individuals have the unique requirement of device reprogramming and patient monitoring to ensure a safe test of adequate diagnostic quality. Limited data exist on the use of vasodilator stress CMR in this cohort, with reports of its performance only in CMR conditional devices and only on 1.5 Tesla systems.[3–5] We sought to expand the understanding of the hemodynamic response of patients with PPMs or ICDs by examining the nuclear vasodilator stress testing environment (where device reprogramming is not required), as well as report on our institutional experience in using vasodilator stress CMR in these individuals.

2 | MATERIALS AND METHODS

2.1 | Study population

The study was approved by the local institutional review board. Patients with a PPM and/or ICD who underwent regadenoson single photon emission computed tomography (SPECT) myocardial perfusion imaging at our institution between May 2018 and September 2021 were retrospectively identified and formed the nuclear stress testing cohort. Patients with ICD who did not receive their devices with an expectation of pacing requirements (e.g., those who had implants for primary or secondary prevention of ventricular arrhythmias as opposed to sinus node dysfunction or high-grade atrioventricular block) were only included if they had a pacing burden of >1%.

For the stress CMR cohort, we retrospectively identified all patients with PPM and/or ICD who underwent vasodilator (regadenoson or adenosine) stress CMR at our institution between July 2019 and March 2022.

2.2 | Clinical data

In all patients, the electronic medical record was reviewed for data on patient demographics, medical comorbidities, PPM or ICD information (type of device, indications for implant, lead characteristics, and pacing burden), and hemodynamic response (heart rate, blood pressure, arrhythmic, or heart block events) to the vasodilator agent.

2.3 | Stress testing protocols

In the nuclear stress test cohort, the electronic medical record was reviewed for data on patient demographics, medical comorbidities, PPM or ICD information (type of device, indications for implant, lead characteristics, and pacing burden). Patients received a dose of regadenoson 0.4 mg intravenously, followed by administration of the nuclear tracer. Documented changes in heart rate and blood pressure were recorded, and electrocardiograms were inspected for any new pacing requirements following the vasodilator dose.

Stress CMR exams were performed on 1.5 or 3.0 Tesla systems (MAGNETOM Aera or Vida, Siemens Healthineers). The PPMs and ICDs were identified as conditional (and to what field strength) or nonconditional. Device interrogations were evaluated from before the stress CMR exams as well as after the tests (first available in the medical record following the stress CMR) to record any significant changes that may have been experienced during the test.

Patients with device generators within the left chest wall were asked to raise their left arm above the level of the head throughout the study to minimize the degree of artifact over the cardiac structures. Standard sequences for the stress CMR studies included cinematic series (steady state free precession by default, substituting with gradient echo sequences if there was excessive artifact from the device components on the standard cinematic images), gradient echo-based pulse sequences for first-pass myocardial perfusion sequences during vasodilator stress and rest perfusion (0.15 mmol/kg of gadoteridol at each dose for a total of 0.3 mmol/kg, not to exceed 40 ml of a 279.3 mg/ml solution) with three short-axis slices acquired each RR interval, and delayed gadolinium-enhanced images (standard inversion recovery sequences at 10 min following gadolinium administration with single shot and high-resolution segmented images, with the option for wideband imaging if the initial sequences were nondiagnostic due to excessive artifact). Adenosine infusions (140 mcg/kg/min for 3 min) were the default stress modality in the CMR setting, with changes to regadenoson 0.4 mg intravenously (followed by aminophylline reversal) in patients who had comorbid pulmonary conditions precluding adenosine use or an inability to obtain two peripheral intravenous access points.

For each stress CMR study, the clinical interpretation of the test was recorded, as was any recently preceding or subsequent evaluation

of coronary anatomy (by invasive angiography or computed tomography angiography). In all studies, the cinematic, first pass perfusion, and late gadolinium enhancement images were examined for image quality and graded as "diagnostic" (if the entire segment was visible throughout the imaging series in at least one slice offset) or "nondiagnostic" on the American Heart Association 17-segment model.[6] Patients who received adenosine were visually assessed for the splenic "switch off" sign to help determine adequate hyperemic response.[7] One patient with a nonconditional ICD had the stress test canceled prior administration of the vasodilator agent based on inspection of the perfusion localizer test sequences; image quality was graded from the standard resting images as well as the test perfusion images.

2.4 | Statistical analysis

Data are presented as median (interquartile range) and number (percent). Comparisons between groups were performed using the Mann-Whitney *U*-test and Chi-squared test, and paired hemodynamic data were compared using the Related-Samples Wilcoxon Signed Rank Test. Statistical analysis was performed with SPSS 26.0 (IBM). A $p < .05$ was considered statistically significant.

3 | RESULTS

Forty-seven patients were identified for the stress SPECT cohort and 20 patients in the stress CMR cohort. Patient characteristics are shown in Table 1, predominantly in the 7th decade of life and with a relatively balanced representation of males/female genders and white/black race. Device characteristics, including reasons for implantation, are shown in Table 2.

Patients who underwent regadenoson SPECT displayed a near uniform increase in heart rates in response to the vasodilator stress agent, from a baseline 67 (61–76) to 89 (80–96) bpm (median change +19 [13–32] bpm, $p < .01$; Figure 1). Only five (11%) subjects failed to augment heart rate at least 10 bpm above baseline: two patients with sinus node dysfunction, one patient with high-grade atrioventricular block, one patient with a cardiac resynchronization indication, and one patient with a secondary prevention ICD.

In the CMR cohort, the 18 (90%) of patients had CMR conditional PPMs or ICDs, with 2 (10%) non-CMR conditional ICDs included (Table 3). The CMR scans were predominantly performed on 1.5 Tesla systems, with three studies performed on a 3.0 Tesla system (one with a dual chamber PPM, one with a leadless right ventricular pacemaker, and one with a biventricular ICD, all 3.0 Tesla conditional devices). Half of the patients in the CMR cohort had ICDs, whereas the other had PPMs only. There were 4 (20%), 12 (60%), and 4 (20%) single chamber, dual chamber, and biventricular systems, respectively, with representation of Medtronic (8 [40%]), Boston Scientific (9 [45%]), St. Jude (2 [10%]), and Biotronik (1 [5%]) devices.

For the duration of the CMR studies, 10 (50%) of patients had their devices programmed to asynchronous pacing, which did include one patient with only 0.3% pacing burden. The rest were deactivated (i.e. programmed to OOO, OVO, OAO, or ODO) during the scan, including seven patients with pacing burdens >1%. Prescanning preparations for patients expected to require asynchronous pacing during the CMR study was for 10 bpm above the resting heart rate (native or paced rate based on the presenting rhythm the day of the scan), resulting in asynchronous rates a median of 10 (9–10) bpm

TABLE 1 Baseline characteristics

	Overall cohort ($n = 67$)	SPECT cohort ($n = 47$)	CMR Cohort ($n = 20$)	p-Value
Age, years	65 (58–72)	67 (59–74)	65 (56–70)	.22
Gender, female	31 (46%)	21 (45%)	10 (50%)	.69
Race, white/black	33 (49%)/31 (46%)	20 (43%)/25 (53%)	13 (65%)/6 (30%)	.21
Body mass index, kg/m^2	31.6 (26.4–37.4)	31.0 (25.6–36.4)	34.1 (27.3–40.2)	.14
Medical history				
Hypertension	60 (90%)	43 (91%)	17 (85%)	.43
Hyperlipidemia	55 (82%)	40 (85%)	15 (75%)	.32
Diabetes mellitus	30 (45%)	22 (47%)	8 (40%)	.61
Current or prior tobacco	33 (49%)	24 (51%)	9 (45%)	.65
Known CAD	45 (67%)	31 (66%)	14 (70%)	.75
Prior MI	29 (43%)	21 (45%)	8 (40%)	.72
Prior PCI	29 (43%)	22 (47%)	7 (35%)	.37
Prior CABG	14 (21%)	10 (21%)	4 (20%)	.91

Abbreviations: CABG, coronary artery bypass grafting; CAD, coronary artery disease; MI, myocardial infarction; CMR, cardiovascular magnetic resonance; PCI, percutaneous coronary intervention; SPECT, single photon emission computed tomography.

TABLE 2 Device characteristics

	Overall cohort (*n* = 67)	SPECT cohort (*n* = 47)	CMR cohort (*n* = 20)	*p*-Value
Indication for device				
Primary prevention ICD	12 (18%)	9 (19%)	3 (15%)	.69
Secondary prevention ICD	17 (25%)	11 (23%)	6 (30%)	.58
Sinus node dysfunction	23 (34%)	15 (32%)	8 (40%)	.52
High grade AV nodal block	17 (25%)	10 (21%)	7 (35%)	.24
Cardiac resynchronization	11 (16%)	9 (19%)	2 (10%)	.36
Type of device				
Single chamber PPM	2 (3%)	1 (2%)	1 (5%)	.53
Dual chamber PPM	24 (36%)	15 (32%)	9 (45%)	.31
Biventricular PPM	2 (3%)	2 (4%)	0	.35
Single chamber ICD	3 (4%)	0	3 (15%)	.01
Dual chamber ICD	20 (30%)	17 (36%)	3 (15%)	.08
Biventricular ICD	16 (24%)	12 (26%)	4 (20%)	.63
Device manufacturer				
Medtronic	31 (46%)	23 (49%)	8 (40%)	.50
Boston scientific	28 (42%)	19 (40%)	9 (45%)	.73
St. Jude	7 (10%)	5 (11%)	2 (10%)	.94
Biotronik	1 (1%)	0	1 (5%)	.12
Pacing burden				
Atrial lead	19% (3%–67%)	20% (3%–69%)	15% (4%–40%)	.54
Ventricular lead(s)	9% (1%–98%)	16% (1%–98%)	1% (1%–96%)	.49

Abbreviations: AV, atrioventricular; ICD, implantable cardioverter-defibrillator; CMR, cardiovascular magnetic resonance; PPM, permanent pacemaker; SPECT, single photon emission computed tomography.

above baseline programmed on the day of examination. Heart rate responses to vasodilator stress are shown in Table 3 and Figure 1; patients whose devices were deactivated all demonstrated elevations in heart rates with a median change of +18 (14–21) beats per minute ($p = .01$). Of the 10 patients who were programmed to asynchronous pacing, all demonstrated no change in heart rate with vasodilator stress, and one study was aborted following the perfusion localizers (before vasodilator agent) due to excessive artifact in an CMR nonconditional ICD (Figure 1). Diastolic blood pressure significantly decreased across all cohorts, and there was a significant decrease in systolic blood pressure within the patients undergoing stress CMR whose devices were deactivated (Supporting Information: Figure S1). Of the 12 patients who received adenosine, nine (75%) had a positive splenic switch-off sign, one (12.5%) who was asynchronously paced had no splenic switch-off, and three (37.%) did not have the spleen visible in the first pass perfusion sequences.

Cinematic imaging was changed from steady-state free precession to gradient echo sequences in 10 (50%) patients to help minimize artifact from the device components, and late gadolinium enhancement imaging was performed with wideband sequences in 10 (50%). Overall image quality was graded and is shown in Figure 2. In general image quality was reliably diagnostic in the CMR-conditional devices. The exceptions were one patient with a 3.0 Tesla conditional leadless right ventricular PPM scanned on a 3.0 Tesla system (a single segment was noninterpretable in the apical segment of the septum) and one patient with a 3.0 Tesla conditional ICD scanned on a 1.5 Tesla system (patient was unable to maintain the left arm above the level of the head during the exam; portions of the anterior and anteroseptal walls were noninterpretable).

Patients with CMR-nonconditional ICDs had lower rates of interpretable images, accounting for 40 of the 57 (70%) nondiagnostic segments across cinematic, perfusion, and delayed enhancement sequences. Of the nonconditional ICDs, one subject had noninterpretable cinematic and perfusion images limited to the anterior/anteroseptal walls, and the other patient had the same issues in addition to all perfusion segments being obscured by artifact and more extensive limitations on late gadolinium enhanced imaging. Examples of studies across the range of devices included are shown

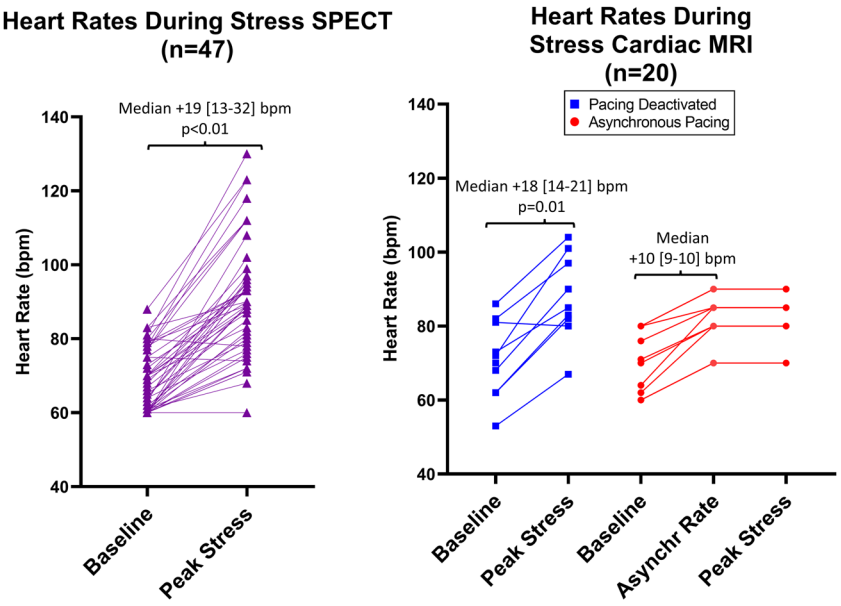

FIGURE 1 Heart rate responses during vasodilator stress testing. Left panel: In the SPECT cohort ($n = 47$), all but five subjects had an elevation of resting heart rates following regadenoson administration, despite a range of indications for ICD or PPM implantation. Right panel: In the CMR cohort ($n = 19$), patients whose devices were temporarily deactivated during the study all had elevations in heart rate. Ten patients were asynchronously paced (typically 10 bpm above baseline rates), and upon vasodilator stress, none experienced a change in heart rate. ICD, implantable cardioverter defibrillator; CMR, cardiovascular magnetic resonance; PPM, permanent pacemaker; SPECT, single photon emission computed tomography.

TABLE 3 Device programming and hemodynamic response in the CMR cohort

	CMR cohort ($n = 20$)
CMR safety	
CMR nonconditional ICD	2 (10%)
CMR conditional PPM, 1.5 T/3 T	0 (0%)/10 (50%)
CMR conditional ICD, 1.5 T/3 T	2 (10%)/6 (30%)
Programming during stress CMR	
Pacing deactivated	10 (50%)
Asynchronous pacing	10 (50%)
Vasodilator agent	
Adenosine	12 (63%)
Regadenoson	7 (37%)
Baseline hemodynamics	
Heart rate, bpm	80 (70–85)
Systolic blood pressure, mmHg	132 (122–139)
Diastolic blood pressure, mmHg	69 (62–76)
Peak stress hemodynamics	
Heart rate, bpm	85 (80–90)
Systolic blood pressure, mmHg	125 (106–140)
Diastolic blood pressure, mmHg	56 (51–68)

Abbreviations: ICD, implantable cardioverter-defibrillator; CMR, cardiovascular magnetic resonance.

in Figures 3–5. A summary of the pertinent findings is presented in the Graphical Abstract.

A limited subset of patients ($n = 3$) who underwent stress CMR had correlation with coronary anatomy (either by invasive angiography or computed tomography angiography). The patient-level correlations are shown in Supporting Information: Table S1.

4 | DISCUSSION

In this study of patients with PPMs or ICDs who underwent vasodilator stress testing, our key findings were: (1) in the nuclear stress testing environment (where device reprogramming is not required), 89% of patients experienced an increase in heart rate >10 bpm above baseline with regadenoson administration, (2) there were no adverse events experienced in 19 patients with PPMs and ICDs who underwent vasodilator stress CMR, predominantly with temporary device deactivation or empiric asynchronous device programming 10 bpm above the baseline heart rate, and (3) image quality was diagnostic in all myocardial segments in the majority of cases, with the exception of nonconditional ICDs, including on studies performed on a 3 Tesla system.

Vasodilator stress CMR has been solidified as a noninvasive option for ischemic testing, with its exceptional accuracy across practice centers, cost effectiveness, ability to provide prognostic data, and high correlation with invasive measures of coronary flow limitations.[1,2] Indeed, despite the higher use of stress SPECT compared to CMR in the United States,[8] head-to-head comparisons

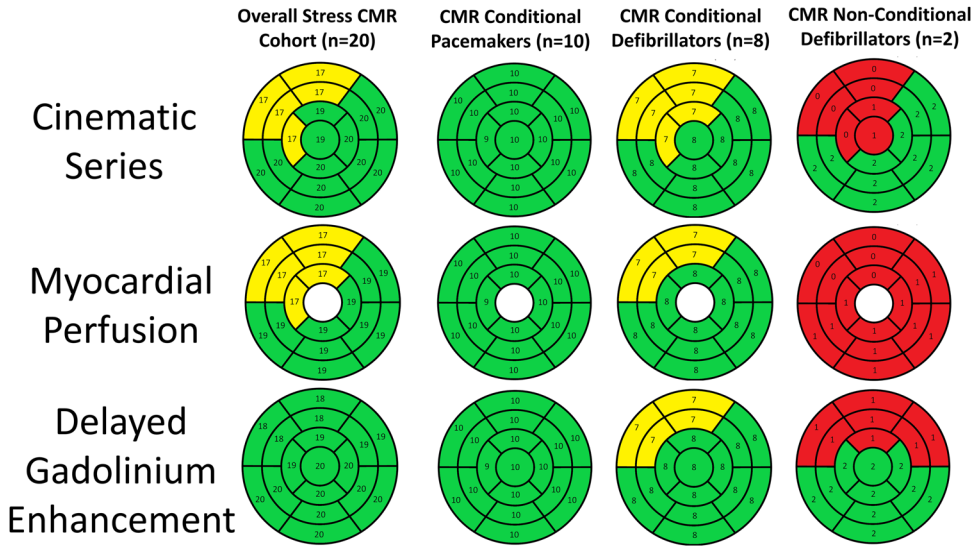

FIGURE 2 Image quality during stress CMR studies. Cinematic, perfusion, and delayed gadolinium enhanced image quality was most reliable in the CMR-conditional devices, with only two subjects out of 16 who had any segments with suboptimal visualization due to artifact (one with a leadless right ventricular pacemaker obscuring the apical septal segment and the other with a 3.0 Tesla conditional ICD obscuring the basal to mid segments of the anterior and anteroseptal walls). Patients with CMR nonconditional ICDs had several segments affected by artifact from the device generator, most pronounced in the anterior/anteroseptal walls but extending in some cases to more remote myocardial segments. Green: ≥90% diagnostic; yellow: 80%–89% diagnostic; red: <80% diagnostic, CMR, magnetic resonance imaging; ICD, implantable cardioverter-defibrillator.

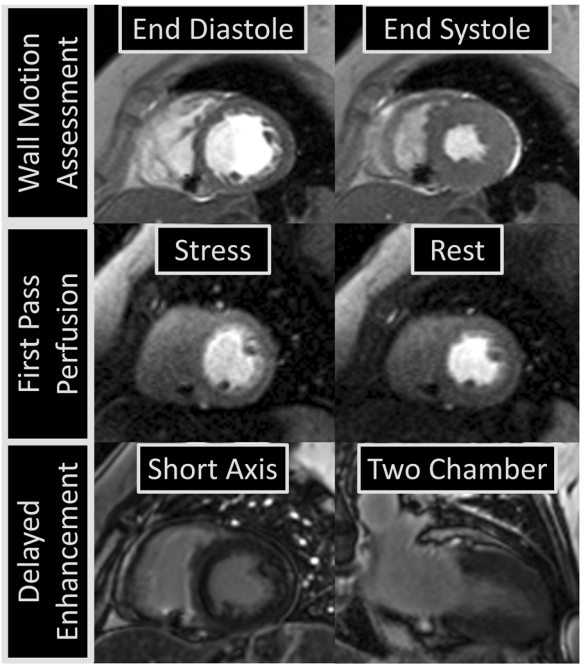

FIGURE 3 Example of stress CMR in a conditional pacemaker. Adenosine stress CMR in a patient with new chest pain symptoms and risk factors for coronary artery disease. The patient had a 3 Tesla conditional pacemaker implanted for sick sinus syndrome, and the study was performed on a 3 Tesla CMR system. Cinematic, perfusion, and delayed enhancement sequences were without significant artifact from the device components. CMR, magnetic resonance imaging.

of the two modalities have shown superiority of CMR.[9] Many patients with PPMs or ICDs may be inappropriate for stress electrocardiography (uninterpretable tracings for ischemic findings) or echocardiogram (pacing-induced dyssynchrony and baseline wall motion abnormalities). As such, clinicians may be forced to choose among myocardial perfusion-based stress imaging or invasive options.

However, published experience toward the use of vasodilator stress CMR is highly limited. Klein-Wile et al. reported on a retrospective analysis of 24 patients with CMR conditional devices at their center who underwent adenosine stress CMR, in which devices were reprogrammed at the time of scan with settings based on indication for device, atrial rhythm at the time of the scan, and underlying sinus rate above or below 45 bpm.[3] They similarly did not report any safety or adverse events. A subsequent investigation from the group described a pretesting protocol in which patients with CMR conditional PPMs and intermittent atrioventricular block (32% of their cohort) underwent adenosine challenge under a supervised setting before entering the magnetic resonance environment.[4] In doing so, they identified a subset (one-third of the tested patients) who developed higher degree block, suggesting the need for asynchronous pacing.

These efforts are to be applauded for creating a highly individualized reprogramming plan for each patient upon entering the stress CMR environment. However, widespread implementation of this pretesting approach would add to patient discomfort with an additional exposure to adenosine, impair workflow, prolong the

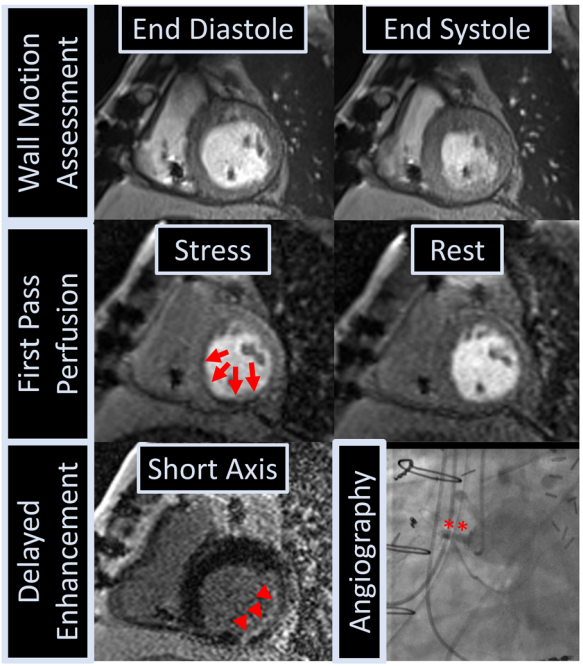

FIGURE 4 Example of stress CMR in a conditional defibrillator. Adenosine stress CMR in a patient with decompensated heart failure and a history of coronary artery bypass grafting. The patient had a 3 Tesla conditional ICD for a history of ventricular fibrillation cardiac arrest, and the study was performed on a 1.5 Tesla system. Cinematic, perfusion, and delayed enhancement images were largely without significant artifact from the device components. A reversible perfusion defect was identified on stress perfusion (arrows), which was out of proportion to the degree of subendocardial scar (arrowheads) and corresponded to a chronic total occlusion of the right coronary artery (asterisks) which was not revascularized due to an occluded vein graft to the territory. CMR, cardiovascular magnetic resonance; ICD, implantable cardioverter-defibrillators.

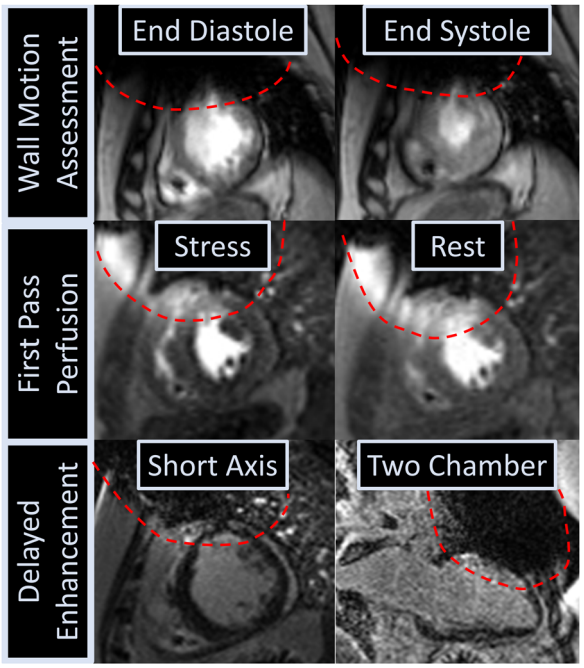

FIGURE 5 Example of stress CMR in a nonconditional defibrillator. Regadenoson stress CMR in a patient with chest pain and multiple prior percutaneous coronary interventions. The patient had a CMR nonconditional ICD for a history of cardiac arrest, and the study was performed on a 1.5 Tesla system. Cinematic, perfusion, and delayed enhancement imaging all were affected by significant artifact, predominantly affecting the anterior and anteroseptal walls (outlined in the dashed lines), rendering those segments nondiagnostic. CMR, cardiovascular magnetic resonance; ICD, implantable cardioverter-defibrillators.

duration of the patient encounter, and in doing so reduce availability of an imaging resource that already faces challenges in providing patient access. A more universal device reprogramming protocol would have appeal in streamlining tests for this patient population. To this end, Pavon et al recently described a more universal approach of asynchronous pacing in all individuals with >1% pacing on device interrogation, set to 10 bpm above the resting heart rate.[5] The group reported safety of this approach with good image quality in CMR-conditional devices and high correlation with subsequent coronary angiography in cases of perfusion defects identified. They further reported no changes in heart rate or systolic blood pressure and a significant decrease in diastolic blood pressure.

Indeed, while our case-by-case approach to temporary device settings varied during stress CMR, our data further supports the notion that high rates of asynchronous pacing during stress CMR may be effective and safe, as we also did not observe any instances of competitive pacing in our cohort. The patients who were programmed to asynchronous pacing were set to rates approximately 10 bpm above baseline rates during stress CMR, and despite observing accelerations of >10 bpm above baseline in the SPECT cohort, competitive pacing events were nonetheless absent in this experience. One downside to a high rate of asynchronous pacing includes a limitation on assessment of hyperemic response, which can be overcome with assessing the splenic "switch off" sign only if the patients receive adenosine.[7] Diastolic blood pressure decrease might be another manner in which hyperemic response is assessed given our experience as well as that of Pavon et al.[5] Some of the factors to consider when choosing between stress SPECT versus CMR are summarized in Table 4.

Even if it competitive ventricular pacing were to occur, the theoretical risk includes that of the "R-on-T" phenomenon, whereby a ventricular depolarization stimulus occurring at the apex of the T wave could trigger malignant ventricular arrhythmias. However, the risk of this phenomenon appears largely restricted to high-risk cohorts such as postmyocardial infarction, Brugada syndrome, malignant long QT syndrome, and syndromes of idiopathic ventricular fibrillation. Asynchronous pacing has been historically incorporated into electrophysiology clinics through in-person and even remote interrogations without an apparent risk of triggering malignant ventricular arrhythmias. Indeed, there are exceedingly few case reports of pacemaker-induced ventricular fibrillation as a result of R-on-T events, almost all involving epicardial pacing wires in the

TABLE 4 Considerations of stress SPECT versus CMR in patients with CIEDs

	SPECT	CMR
Temporary device reprogramming	• Not required	• Required
Information available from the test	• Myocardial perfusion • Left ventricular volumes/function	• Myocardial perfusion • Volumes/function of all cardiac chambers • Tissue characterization (e.g., late gadolinium enhancement) • Additional information if required: o Valvular functional assessment o Vascular anatomy o Thrombus evaluation
Confirmation of hyperemia with vasodilator	• Symptoms • Heart rate response • Blood pressure response	• Symptoms • Heart rate response (not if asynchronously paced) • Blood pressure response • Splenic switch-off sign (adenosine only)
Potential imaging artifacts	• Inferior perfusion defect (males) • Apical perfusion defect (females) • Septal artifact (left bundle branch block or right ventricular pacing)	• Anterior/anteroseptal wall obscured (if nonconditional ICD or patient unable to raise arm above shoulder level)
Device specific considerations	• All devices can be scanned	• CMR nonconditional ICDs and subcutaneous ICDs with poor image quality (limited data) • Abandoned/fractured leads remain contraindications (emerging data to challenge this)

Abbreviations: CIEDs, Cardiovascular implantable electronic devices; CMR, cardiovascular magnetic resonance; ICD, implantable cardioverter defibrillator; SPECT, single photon emission computed tomography.

post-cardiac surgery setting.[10–15] As such, the risk of this occurring from endocardial leads within the CMR environment may be clinically inconsequential.

Of note, only two patients with CMR nonconditional ICDs were attempted for stress CMR, with image artifact from the generators causing the anterior and anteroseptal walls (and in the case of the perfusion images, additional segments) to be nondiagnostic. This degree of artifact was rather consistent with other nonstress CMRs performed in patients with nonconditional ICDs. Thus, following these two cases, patients with CMR nonconditional ICDs were excluded from stress CMR studies. Further wideband pulse sequence development may improve upon this limitation, though not currently available for widespread clinical use.[16]

Limitations to this study include its retrospective and single center design with a relatively small sample size and variability in device programming. The majority (63%) of patients undergoing stress CMR received adenosine, compared to all patients receiving regadenoson in the nuclear cohort, and recent data have suggested that higher doses of adenosine might be required to result in adequate hyperemia in patients with reduced systolic function.[17] Nonetheless, it is the first published cohort to include patients with CMR nonconditional devices, studies performed on a 3.0 Tesla system, and use of regadenoson in patients with ICDs or PPMs undergoing stress CMR. Additionally, we were able to provide hemodynamic insights with supplemental data from our nuclear stress testing laboratory. Further studies are needed to validate the safety of a streamlined and uniform device programming approach in this patient cohort and to confirm the diagnostic and prognostic performance of stress CMR in these individuals.

5 | CONCLUSION

In conclusion, the majority of patients with PPMs and ICDs can be expected to have a tachycardic response to vasodilator stress agents in the nuclear stress testing environment. Nonetheless, in our center's experience, high rates of asynchronous device programming for patients with a history of sinus node dysfunction, high-grade atrioventricular block, and higher pacing requirements were without adverse events. In those with CMR conditional devices, image quality was generally high, including on scans performed at 3 Tesla field strengths. Further experience is needed to validate these findings and confirm that stress CMR is of sufficient diagnostic quality in patients with PPMs and ICDs.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Cory R. Trankle https://orcid.org/0000-0002-3891-7004

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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