Adenosine Stress Cardiovascular Magnetic Resonance With Variable Density Spiral Pulse Sequences Accurately Detects Coronary Artery Disease: Initial Clinical Evaluation

Salerno et al: Spiral Stress CMR Accurately Detects CAD

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Abstract

**Background**—Adenosine stress CMR perfusion imaging can be limited by motion-induced dark-rim artifacts (DRA), which may be mistaken for true perfusion abnormalities. A high-resolution variable-density spiral (VDS) pulse sequence with a novel density compensation strategy has been shown to reduce DRA in first-pass perfusion imaging. We aimed to assess the clinical performance of adenosine stress CMR using this new perfusion sequence to detect obstructive coronary artery disease (CAD).

**Methods and Results**—CMR perfusion imaging was performed during adenosine stress (140μg/kg-min) and at rest on a Siemens 1.5T Avanto scanner in 41 subjects with chest pain scheduled for coronary angiography (CA). Perfusion images were acquired during injection of 0.1mmol/kg Gd-DTPA at 3 short-axis locations using a saturation recovery (SR) interleaved VDS pulse sequence. Significant stenosis was defined as >50% by quantitative CA (QCA). Two blinded reviewers evaluated the perfusion images for the presence of adenosine-induced perfusion abnormalities and assessed image quality using a 5 point scale (1 – poor to 5-excellent). The prevalence of obstructive CAD by QCA was 68%. The average sensitivity, specificity, and accuracy were 89%, 85%, and 88% respectively with a positive predictive value and negative predictive value of 93% and 79% respectively. The average image quality score was 4.4±0.7 with only one study with more than mild DRA. There was good inter-reader reliability with a kappa statistic of 0.67.

**Conclusions**—Spiral adenosine stress CMR results in high diagnostic accuracy for the detection of obstructive CAD with excellent image quality and minimal DRA.

**Key Words:** CMR, adenosine stress perfusion, coronary artery disease
It is estimated that 17.6 million Americans have coronary artery disease (CAD) and approximately 10.2 million Americans suffer from angina pectoris. CAD is a leading cause of morbidity responsible for approximately 1 in 6 deaths in the US. Greater than 10 million stress tests are performed annually to evaluate known or suspected coronary artery disease resulting in a significant economic burden to the US. As recent studies have demonstrated low rates of obstructive coronary artery disease of patients undergoing cardiac catheterization, improvement in stress imaging techniques can potentially impact down-stream costs of additional non-invasive and invasive evaluation and treatment of CAD.

There is a significant body of evidence demonstrating the high diagnostic and prognostic utility of adenosine stress CMR imaging. Recent head-to-head comparisons between stress CMR and SPECT have demonstrated equivalent or superior accuracy of CMR. Despite these advantages, CMR perfusion imaging is still limited by artifacts which may be mistaken for perfusion abnormalities and has limited spatial and temporal resolution. Recent studies have extended the capabilities of CMR improving spatial coverage or spatial resolution using k-t acceleration but these techniques have limitations in the setting of inadequate breath-holding.

 Clinically available CMR pulse sequences for perfusion imaging utilize Cartesian trajectories which are robust but are not efficient in collecting the data and are particularly susceptible to ringing artifacts in the phase-encoding direction of the image. Non-Cartesian pulse sequences such as spiral imaging collect the required data in a spiral trajectory which is more efficient and may be less susceptible to motion induced dark-rim artifacts. Non-Cartesian techniques can also be combined with parallel imaging techniques and hold potential for large gains in spatial-temporal resolution. To date there have been relatively few studies evaluating these techniques. We have previously demonstrated that spiral pulse sequences with
short readout durations, and optimized sequence parameters can efficiently produce perfusion images with high spatial resolution, SNR, and minimal artifacts.\textsuperscript{15} By extending this technique to the use of variable-density spiral trajectories with a novel density compensation strategy, high-resolution perfusion images with reduced-imaging artifacts could be produced with a further increase in efficiency as compared to standard spiral techniques.\textsuperscript{14} However, these techniques need to be tested in a realistic clinical setting for the evaluation of known or suspected CAD as compared to a reference standard.

The goal of this study was to assess the clinical performance of VD spiral perfusion pulse sequences for adenosine stress CMR to detect obstructive CAD disease as compared to quantitative coronary angiography (QCA).

Methods

Study population

Forty-three patients who were scheduled for coronary angiography for evaluation of chest pain with known or suspected CAD were prospectively recruited to undergo a research adenosine stress study between March 2010 and June 2013. Patients with a known history of prior CAD, MI, or prior PCI were eligible for the study; however, patients with prior coronary artery bypass surgery (CABG) were excluded as adenosine stress CMR has been shown to have different test characteristics in this population.\textsuperscript{18} Exclusion criteria included known EF<45%, evaluation for workup of cardiomyopathy, significant valvular pathology, pulmonary hypertension, or transplant vasculopathy, GFR < 45 mL/min/1.73m\textsuperscript{2}, contraindications to MRI including implantable cardiac devices, contraindications to adenosine infusion (asthma or severe COPD), or a history of prior gadolinium contrast reaction. All patients had their renal function assessed.
within 30 days prior to the CMR study. All CMR imaging studies were performed on the morning of the scheduled cardiac catheterization. A detailed history and physical exam was performed by a physician prior to the CMR study. The research was performed under an IRB approved protocol.

**Stress CMR protocol**

All stress CMR studies were performed on a 1.5 T scanner (Avanto, Siemens Medical Systems) using the standard spine and body phased-array coils. An EKG was obtained before the CMR study and resting heart rate and blood pressure were recorded. CMR protocol included anatomic imaging using a single-shot SSFP pulse sequence, ventricular function imaging using a cine SSFP pulse sequence, and late gadolinium enhancement (LGE) using a phase-sensitive inversion recovery pulse sequences following standard published methodology. For the vasodilator stress imaging, adenosine (Astellas Pharmaceuticals) was infused at 140 mcg/kg/min through a peripheral IV for 3 minutes. A bolus of 0.1mmol/kg of Gadolinium contrast (Magnevist, Bayer Pharmaceuticals) was injected via power injector (Medrad Continuum, Warrendale PA) through a second IV in the other arm at 4cc/second. Three short axis slice locations were imaged per heart beat over a 50 heart beat acquisition using a saturation recovery (SR) variable-density spiral (VDS) perfusion pulse sequence. The technical details of the pulse sequence have been described previously. Pulse sequence parameters included: SR time of 80 ms (to first RF pulse of the readout, echo time (TE) 1 ms, repetition time (TR) 9 ms, slice thickness 10 mm, flip angle 30 degrees, field of view 320mm, 8 spiral interleaves, 6.1 ms readout duration per spiral and nominal spatial resolution of 2 mm². Low resolution field maps were obtained using two single-shot spiral images for off resonance correction with each perfusion image. The time to acquire each image was 176 ms. Images were reconstructed with a fast conjugate-phase semi-automatic
reconstruction with Chebyshev approximation of the off-resonance phase term.\textsuperscript{20} Images were reconstructed with a novel density compensation function which improves signal-to-noise and reduces ringing (dark-rim artifact) as previously described.\textsuperscript{14} After a 10 minute washout delay following the stress perfusion acquisition, resting perfusion imaging was performed during a second injection of 0.1 mmol/kg of Magnevist using the same imaging protocol as described above. SSFP functional imaging was performed between the perfusion acquisitions, and LGE imaging was performed 5 minutes following resting perfusion imaging using standard methodology.\textsuperscript{19} The protocol took on average 35-45 minutes.

**Image Analysis**

Two reviewers blinded to the coronary angiography data evaluated the CMR images to assess for the presence of perfusion abnormalities consistent with myocardial ischemia on a per-patient basis. Image quality was graded on a 5 point scale (1 – poor to 5 excellent). Images were also assessed for the presence and severity of DRA (0-none, 1-mild, 2-moderate, 3 severe). The perfusion images were read off-line in Image J (http://rsbweb.nih.gov/ij/) after conversion of the images to animated gifs. In cases of perfusion abnormalities, LGE images were assessed to determine if the region of perfusion abnormality was larger than the area of scar. A positive study was considered one with evidence of a perfusion abnormality exceeding the area of scar on LGE indicating evidence of ischemia.

**Coronary Angiography**

Immediately following the CMR examination the patients were brought to the cardiac catheterization laboratory for their clinically indicated coronary angiography. Angiograms were performed using standard techniques. The severity of stenosis was performed by an independent blinded reviewer using quantitative coronary analysis (QCA). QCA was performed using
automatic edge detection software at an end-diastolic frame based on the demonstration of the most severe stenosis with minimal foreshortening or branch overlap. The minimal lumen diameter was recorded in each coronary branch with a reference diameter > 2 mm. A QCA percent diameter stenosis greater than 50% was used as the reference standard.

**Statistical Analysis**

Continuous data were expressed as mean ± standard deviation, and categorical data were expressed as percentages. The mean sensitivity, specificity and accuracy of visual analysis of the CMR stress images to detect obstructive CAD as defined by a >50% stenosis by QCA were determined for each of the reviewers. The inter-reader variability was assessed by determining the kappa-statistic. Statistical analysis was performed using SPSS 19 (IBM, Armonk, NY). Ninety five percent confidence intervals were determined using an exact binomial method based on the F-distribution.21

**Results**

**Patient characteristics**

Forty-one of the 43 patients successfully completed the CMR study and were included in the final analysis. One subject could not tolerate the CMR procedure due to claustrophobia, and the other subject developed a long run of non-sustained ventricular tachycardia immediately prior to initiation of adenosine stress and the stress study was not completed. This patient was subsequently found to have a 99% proximal stenosis of his LAD during coronary angiography.

In 40 of the 41 subjects coronary angiography was performed immediately following the CMR stress protocol. One subject was found to have thrombocytopenia and his catheterization was not
performed on the same day, but the patient underwent coronary angiography 7 months later.

Table 1 summarizes the patient characteristics of the subjects included in the study.

Table 2 summarizes the hemodynamic data from the stress CMR studies. With adenosine
the average heart rate increased by 10 beats per minute without a change in systolic blood
pressure. All patients successfully underwent both adenosine stress and rest imaging without any
complications. The average left ventricular ejection fraction as determined from cine-CMR was
61±7, and the lowest EF was 49%. 14 patients (34%) had evidence of LGE in a CAD pattern,
and two patients had evidence of mid-wall fibrosis.

Table 3 shows the results of QCA. Coronary angiography demonstrated significant
coronary artery stenoses (>50% luminal diameter reduction in vessels with >2mm diameter) in
28 patients (68%). Eight patients (20%) had single-vessel, 6 (15%) had two-vessel disease, and
14 (34%) had three-vessel disease. Two (5%) patients had left-main disease (as well as three-
vessel disease). In the patients with single-vessel disease, 6 were in the left anterior descending
(LAD) territory and 2 in the right coronary artery territory (RCA).

Diagnostic Performance and Image Quality

All CMR perfusion imaging studies were of diagnostic quality. Figure 1 shows (a) stress and (b)
rest spiral perfusion images from a subject who had normal LV function and no LGE. There is a
reversible perfusion abnormality in the anterior wall and anteroseptum (arrows). Coronary
angiography (c) demonstrated 85% stenosis of his LAD at cardiac catheterization. Figure 2
shows (a) stress and (b) rest perfusion images from another subject with a normal LV function
and no LGE. There is a subendocardial perfusion abnormality in the anterior and lateral walls
(arrow). Coronary angiography (c) showed a 80% stenosis in the LAD, a 80% stenosis in the
LCx, and a 70% stenosis in a non-dominant RCA. Figure 3 shows (a) stress and (b) rest
perfusion images from a 3rd subject with normal LV function and no LGE demonstrating a large perfusion abnormality in the inferior wall. An exercise Nuclear SPECT study (c) did not identify any quantitative evidence of myocardial ischemia. Coronary angiography (d) demonstrated a 90% stenosis in an RCA. These CMR images demonstrate high SNR, minimal blurring, and no dark-rim artifact. Figure 4 demonstrates (a) an adenosine stress perfusion abnormality in the LAD territory, RCA and a milder defect in the LCX territory in the setting of a prior inferior myocardial infarction. Evidence of enhancement in the inferior wall (b) early in the resting perfusion image series and a lack of a (c) resting perfusion defect are expected since stress imaging is performed before rest imaging and the infarct is already demonstrating LGE from the first contrast bolus. The (d) LGE images confirm an inferior myocardial infarction but no infarction in the other coronary territories. The (e) Coronary angiogram demonstrated 80% mid LAD, 50% LCX, 99% RCA stenosis.

The diagnostic accuracy for adenosine stress perfusion by patient and by coronary territory is presented in Table 4. For the detection of a 50% stenosis by coronary angiography the average sensitivity, specificity, and accuracy and 95% confidence intervals (CI) of the two readers were 89% (CI 71%-98%), 85% (CI 55%-98), and 88% (CI 74%-96%) respectively on a per-patient basis. The positive predictive value was 93% (CI 75%-99%) and the negative predictive value was 79% (CI 49%-95%). There was good inter-reader reliability with a kappa statistic of 0.67. For detection of a 70% stenosis the average sensitivity, specificity, accuracy, PPV and NPV were 91%, 67%, 80%, 78%, and 86% respectively. In the one case that was read as a false positive by both readers, there was a perfusion abnormality and LGE, but the patient had a patent stent in the RCA and history of a prior STEMI in this territory. In the one case that
was read as a false negative by both readers, there was a 54% stenosis in the LAD territory by quantitative QCA.

In 5 of the cardiac catheterizations fractional flow reserve (FFR) was performed at the discretion of the operator (12.5% of cases). Of these 5 cases, 3 had an FFR<0.75 and 2 had an FFR>0.75. CMR agreed with FFR in 4 of the five cases (80%). The one discordant case was a patient with known CAD, prior RCA STEMI with LGE, and diffusely diseased coronary arteries with a 60% LAD lesion by QCA who had an FFR>0.75 but an abnormal CMR perfusion study.

**Image quality**

The mean image quality score was 4.4±0.7 with only one study demonstrating more than minimal dark rim artifact yielding a DRA score of 0.37. Diagnostic quality images were obtained and could be interpreted in all subjects.

**Discussion**

Our study is the first to clinically evaluate spiral pulse sequences for adenosine stress CMR. We demonstrate that these sequences produce high quality images with minimal dark-rim artifacts and demonstrate high diagnostic accuracy for assessment of coronary artery disease. There are a number of advantages to spiral pulse sequences including high efficiency, high SNR efficiency, robustness to motion, and isotropic spatial resolution. The novel density compensation strategy utilized in this study further reduces ringing artifacts and improves SNR by underweighting the high spatial frequencies. While most clinically utilized pulse sequences use parallel imaging techniques to achieve high temporal and spatial resolution, the variable density spiral technique described in this manuscript has 2.2mm isotropic spatial resolution (after apodization) and high temporal resolution with data collected over an 80 ms acquisition window without the use
of any parallel imaging techniques. While this study began before we started using parallel-imaging techniques for spiral perfusion imaging, the choice not to add parallel imaging techniques had multiple advantages for this study in that all images were reconstructed in real-time on the scanner console using non-iterative techniques, and it allowed us to evaluate the clinical performance of spiral pulse sequences without any additional artifacts that could result from parallel imaging. However, when VD spiral trajectories are combined with parallel imaging techniques, complete ventricular coverage with high spatial resolution is achievable. The clinical evaluation of such techniques is currently underway.

The diagnostic performance of the spiral technique described in this manuscript compares favorably with the data reported from a large meta-analysis of stress CMR perfusion imaging. Nandalur et. al. reported a sensitivity of 91% and a specificity of 81% from a total of 24 published studies of vasodilator stress CMR imaging studies with variation in the definition of a positive study. The largest prospective evaluation of adenosine stress CMR imaging, the CE-MARC trial, demonstrated a sensitivity of 82% and a specificity of 79% with a positive study defined by a multicomponent composite which included any regional wall motion abnormality, hypoperfusion, or presence of LGE. The MR-IMPACT II study demonstrated a more modest performance of stress CMR with a sensitivity of 72% and a specificity of 59%. Notably 6% of the studies were deemed unevaluable. The specificity for the MR-IMPACT-II study may be lower due to the fact that only perfusion images were used to define a positive study. Klem et. al. demonstrated that only using the perfusion images only to define a positive study resulted in a sensitivity of 82% but with a specificity of only 63%; however, adding LGE to the interpretation algorithm increased specificity to 88%. A major contributor to the lower specificity of CMR perfusion imaging has been the presence of dark-rim and other motion induced artifacts on the
perfusion imaging, and may contribute to the discrepancy in specificity between CE-MARC and MR-IMPACT II. The important implication is that better CMR perfusion imaging techniques could further improve the specificity of adenosine stress CMR particularly when the goal of the evaluation is to assess for the presence of a flow-limiting stenosis rather than establishing the diagnosis of CAD. In this setting, the presence of LGE does not help define whether the vessel is causing ischemia in myocardium which could benefit from revascularization.

Non-Cartesian techniques such as spiral and radial trajectories have the potential to reduce dark-rim artifact by multiple mechanisms. We have previously demonstrated that non-Cartesian trajectories inherently have reduced cardiac-motion induced dark-rim artifacts as compared to conventional Cartesian acquisition strategies.\textsuperscript{25,27} In addition, the acquisition efficiency and benign aliasing artifacts enable acquisition of higher resolution images for a given acquisition time. Some of this increased spatial resolution can be traded for reduction in ringing artifacts (both Gibbs and cardiac-motion induced) using apodization or windowing of the raw data.

Apodization is well-established technique for reducing Gibbs-ringing.\textsuperscript{28} Di Bella et al. demonstrated the utility of windowing data in the phase-encoding (PE) direction to reduce Gibbs-ringing in Cartesian perfusion imaging, but this results in a significant loss of spatial resolution in the PE direction which can only be compensated for by increasing the time to acquire each perfusion image.\textsuperscript{8} We previously described the use of a density-weighted acquisition and apodizing-DCF for VD spiral perfusion imaging to both increase SNR and reduce DRA.\textsuperscript{26} By using a variable-density spiral trajectory, a larger extent of k-space (higher spatial resolution) can be sampled in the same or shorter readout duration. By using a DCF which intentionally “under-weights” the variable-density data, the k-space data is effectively
apodized, reducing ringing (either due to motion or Gibbs-ringing) and increasing SNR with only a slight loss of spatial resolution. Overall the resolution is higher than that which could be achieved with a conventional spiral with a 25% increase in acquisition efficiency and significantly less ringing artifacts.

The recently described radial technique by Sharif et. al. utilizes a similar approach. A higher readout bandwidth is used to achieve a higher spatial resolution with the same readout duration at the cost of a reduction in SNR. The data is apodized (in their case by a Gaussian filter) to remove residual ringing artifacts, effectively under-weighting the high spatial frequencies and recovering SNR.

Spiral pulse sequences have some inherent efficiency and SNR advantages over radial techniques, although they may be more sensitive to off-resonance and both techniques require accurate scanner calibration and special image reconstruction techniques. Both non-Cartesian techniques show potential for improving image quality and improving acquisition efficiency for first-pass myocardial perfusion imaging.

This study has several limitations. The sample size is relatively small, and there is a high prevalence of CAD. Given the latter, we defined a positive study based on the presence of an adenosine-induced perfusion abnormality rather than using LGE or wall motion abnormalities to define a positive study. This is more consistent with the goal of trying to define the presence of ischemia rather than infarction. However, the population in this study is representative of patients undergoing coronary angiography at our institution which increasingly includes patients with known CAD and prior PCI. Another limitation is the use of quantitative coronary angiography as the reference standard instead of fractional flow reserve (FFR). As the patients were undergoing clinically ordered CA studies, the use of fractional flow reserve was at the
discretion of the operator. While multiple studies have demonstrated the superiority of FFR
guided interventions, data from the National Cardiovascular Data Registry suggest that in the
US, even among patients who were undergoing PCI, FFR was only used in 6.1% of patients.\textsuperscript{30}
Furthermore we did not directly compare the spiral pulse sequence to a standard Cartesian pulse
sequence as it was not feasible to have patients undergo multiple research adenosine stress
perfusion studies prior to cardiac catheterization.

Spiral pulse sequences have a number of potential drawbacks which require careful
consideration to create the high-quality images presented in this study. Spiral pulse sequences
are more sensitive to gradient hardware fidelity and eddy current effects. We utilize an
anisotropic gradient delay and eddy current model of the theoretical k-space trajectory to correct
these effects.\textsuperscript{31} Spiral sequences are sensitive to off-resonance effects which can result in image
blurring. We have carefully optimized the spiral trajectory design to balance between off
resonance artifacts and SNR efficiency. Secondly we obtain a field-map with each image
acquisition to measure field homogeneity and utilize a rapid conjugate reconstruction technique
with a Chebychev polynomial approximation of the off-resonance phase.\textsuperscript{20} The image
reconstruction occurs in real-time on the MRI scanner during image acquisition and no off-line
processing is required. The combination of these two factors minimizes off-resonance artifacts.
With our current readout duration we on occasion see off-resonance artifacts in regions of prior
myocardial stents or occasionally near the inferior cardiac vein, but these are confined to the
epicardium and thus do not significantly impact the evaluation of ischemia. While spiral pulse
sequences appear to be relatively robust to dark-rim artifacts the additional apodization produced
by the density compensation function further reduces ringing artifacts from Gibbs-ringing and
motion.
Recent studies have demonstrated the potential for 3D coverage of the ventricle using highly accelerated 3D k-t PCA techniques. 3D spiral perfusion pulse sequences are feasible and may enable 3D imaging with higher spatial coverage than that achievable with Cartesian techniques due to the increased efficiency afforded by spiral trajectories. Initial results from our group and others have demonstrated significant potential for 3D spiral techniques such as stack-of spirals. When combined with parallel-imaging techniques, 2D-spiral perfusion imaging techniques can also produce images with high temporal and spatial resolution enabling full ventricular coverage by interleaving multiple slices following each saturation pulse. With further shortening of the readout duration per interleaf, similar image quality can be obtained at 3T. In conclusion, variable-density spiral pulse sequences represent a new avenue of research in the quest for high spatial and temporal resolution adenosine stress CMR imaging, with minimal dark-rim artifacts. This technique demonstrates high diagnostic accuracy in a single-center study, but further validation in a larger population in a multi-center setting will be necessary to confirm the diagnostic accuracy of this promising technique in a broader clinical setting.

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Disclosures
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References


Table 1. Demographic Data and Patient Characteristics

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<th>Clinical Characteristics</th>
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<tr>
<td>Age (years)</td>
<td>62±9</td>
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<tr>
<td>Male Sex</td>
<td>68%</td>
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<tr>
<td>Weight (lbs)</td>
<td>201±44</td>
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<tr>
<td>Height (inches)</td>
<td>67±5</td>
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<tr>
<td>Body Mass Index (kg/m²)</td>
<td>31±6</td>
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<td>Hypertension</td>
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<td>Hyperlipidemia</td>
<td>95%</td>
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<td>Diabetes</td>
<td>46%</td>
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<td>Current Smoker</td>
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<tr>
<td>Prior Smoker</td>
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<tr>
<td>Chest Pain</td>
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<td>Dyspnea</td>
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<td>History of CAD</td>
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<tr>
<td>Prior PTCA</td>
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<tr>
<td>Prior Myocardial Infarction</td>
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<td>Aspirin</td>
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<td>Beta-Blocker</td>
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<td>ACE Inhibitor/ARB</td>
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<td>Statin</td>
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<td>Other Cholesterol Medication(s)</td>
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<td>Oral Hyperglycemic Agent</td>
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<td>Insulin Therapy</td>
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### Table 2. Hemodynamic data

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<th>Rest</th>
<th>Stress</th>
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<tr>
<td>Heart rate (beats/min)</td>
<td>66±11</td>
<td>76±15</td>
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<tr>
<td>Systolic Blood Pressure (mmHg)</td>
<td>138±13</td>
<td>139±19</td>
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<tr>
<td>Diastolic Blood Pressure (mmHg)</td>
<td>76±11</td>
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<tr>
<td>Rate Pressure Product (HR*SBP)</td>
<td>9101±1395</td>
<td>10548±2614</td>
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### Table 3. Quantitative Angiography Findings

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<tr>
<td>No Coronary Disease</td>
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<th>Significance Criteria</th>
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<tr>
<td>&gt;50%</td>
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<tr>
<td>Any Significant Disease</td>
<td>28 (68%)</td>
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<tr>
<td>Single Vessel</td>
<td>8 (20%)</td>
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<tr>
<td>Two Vessel</td>
<td>6 (15%)</td>
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<tr>
<td>Three Vessel</td>
<td>14 (34%)</td>
</tr>
<tr>
<td>Left Main</td>
<td>2 (5%)</td>
</tr>
<tr>
<td>&gt;70%</td>
<td></td>
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<tr>
<td>Any Significant Disease</td>
<td>23 (58 %)</td>
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<tr>
<td>Single Vessel</td>
<td>8 (20%)</td>
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<tr>
<td>Two Vessel</td>
<td>7 (17)</td>
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<tr>
<td>Three Vessel</td>
<td>8 (20%)</td>
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<tr>
<td>Left Main</td>
<td>1 (2%)</td>
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### Table 4. Diagnostic Performance of Adenosine Stress Perfusion

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<th>TP</th>
<th>FP</th>
<th>FN</th>
<th>TN</th>
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<tr>
<td>50%</td>
<td>22</td>
<td>2</td>
<td>3</td>
<td>11</td>
<td>0.89 (0.72-0.98)</td>
<td>0.85 (0.55-0.98)</td>
<td>0.88 (0.74-0.96)</td>
<td>0.93 (0.76-0.99)</td>
<td>0.79 (0.49-0.95)</td>
</tr>
<tr>
<td>70%</td>
<td>21</td>
<td>6</td>
<td>2</td>
<td>12</td>
<td>0.91 (0.72-0.99)</td>
<td>0.67 (0.41-0.81)</td>
<td>0.80(0.65-0.91)</td>
<td>0.78(0.58-0.91)</td>
<td>0.86(0.57-0.98)</td>
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<th>50% Stenosis by territory</th>
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<td>LAD</td>
<td>20</td>
<td>2</td>
<td>5</td>
<td>14</td>
<td>0.80 (0.59-0.93)</td>
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<td>6</td>
<td>2</td>
<td>22</td>
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<td>0.79 (0.59-0.92)</td>
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Figure Legends

Figure 1. (a) Stress and (b) rest spiral perfusion images from a subject who had normal LV function and no LGE demonstrates a reversible perfusion abnormality in the anterior wall and anteroseptum. Coronary angiogram (c) shows an 85% stenosis of his LAD.

Figure 2. (a) Stress and (b) rest perfusion images from a second subject with a normal LV function and no LGE demonstrates a subendocardial perfusion abnormality in the anterior and lateral walls. Coronary angiogram (c) shows multi-vessel CAD with an 80% stenosis in the LAD, an 80% stenosis in the LCx, and a 70% stenosis in a non-dominant RCA.

Figure 3. (a) Stress and (b) rest perfusion images from a third subject with normal LV function and no LGE demonstrates a large perfusion abnormality in the inferior wall. A SPECT study (c) demonstrated no quantitatively significant perfusion abnormality. The numbers in each sector of the 17 segment model denote the relative percent tracer activity at stress (upper) and rest (lower). Relative counts for all sectors were within normal limits as compared to a normal database. (d) Coronary angiogram demonstrated a 90% stenosis in the mid RCA. This case demonstrates the challenge of inferior attenuation in the interpretation of SPECT studies.

Figure 4. (a) Stress images from a fourth subject demonstrate extensive perfusion abnormalities in the LAD and RCA and a milder defect in the LCx territory. (b) Early in the series of rest perfusion images before myocardial enhancement, there is contrast enhancement of the inferior perfusion defect, which is consistent with the inferior infarct which is confirmed with (e) LGE images. (d) Later in the series of rest images an inferior defect is not seen, as this region has already began to show late enhancement. The lack of a resting defect in the setting of infarction is expected since stress imaging is performed before rest imaging and the infarct is already demonstrating LGE from the first contrast bolus. This is an important distinction as compared to SPECT where resting defects indicate infarction. (e) Coronary angiogram demonstrated 80% mid LAD, 50% LCX, 99% RCA stenosis.
Adenosine Stress Cardiovascular Magnetic Resonance With Variable Density Spiral Pulse Sequences Accurately Detects Coronary Artery Disease: Initial Clinical Evaluation
Michael Salerno, Angela Taylor, Yang Yang, Sujith Kuruvilla, Michael Ragosta, Craig H. Meyer and Christopher M. Kramer

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Supplemental Material

Video Legends

Video 1. Stress perfusion images from a subject who had normal LV function and no LGE demonstrates a reversible perfusion abnormality in the anterior wall and anteroseptum. The coronary angiogram demonstrated an 85% stenosis of his LAD. Video corresponds to figure 1 in the manuscript.

Video 2. Resting perfusion images from the same subject do not demonstrate any perfusion abnormality.