Magnetic resonance myocardial perfusion imaging at 3.0 Tesla for the identification of myocardial ischaemia: comparison with coronary catheter angiography and fractional flow reserve measurements

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Aims
To assess image quality and diagnostic performance of 3.0 Tesla (3T) cardiac magnetic resonance (CMR) myocardial perfusion imaging with a dual radiofrequency source to detect functional relevant coronary artery disease (CAD), using coronary angiography and invasive pressure-derived fractional flow reserve (FFR) as reference standard.

Methods and results
We included 116 patients with suspected or known CAD, who underwent 3T adenosine myocardial perfusion CMR (resolution 2.97 × 2.97 mm) and coronary angiography plus FFR measurements in intermediate lesions. Image quality of myocardial perfusion CMR was graded on a 4-point scale (1 = poor to 4 = excellent). Diagnostic accuracy was assessed by ROC analyses using a 16-myocardial segment-based summed perfusion score (0 = normal to 3 = transmural perfusion defect) and by determining sensitivity, specificity, positive and negative predictive value on the coronary vessel territory and the patient level. Diagnostic image quality was achieved for all stress myocardial perfusion CMR studies with an average quality score of 2.5, 3.1, and 3.0 for LAD, LCX, and RCA territories. The ability of the myocardial perfusion CMR perfusion score to detect significant coronary artery stenosis yielded an area under the curve of 0.93 on ROC analysis. Values for sensitivity, specificity, positive and negative predictive value on a vessel territory level and the patient level were 89, 95, 87% and 85, 87, 77% and 92%, respectively.

Conclusion
In patients with suspected or known significant CAD, 3T myocardial perfusion CMR with standard perfusion protocols provides consistently high image quality and an excellent diagnostic performance.

Keywords
Coronary artery disease • Fractional flow reserve • Magnetic resonance imaging • Myocardial perfusion • 3.0 Tesla
Introduction

Owing to steady technical evolution, cardiac magnetic resonance (CMR) imaging has become a powerful and increasingly used modality for the assessment of myocardial function, perfusion, and viability. Current data show promising results for the applicability of CMR perfusion imaging for the assessment of myocardial ischaemic states. Myocardial perfusion CMR can be used as a first-line imaging modality for the exclusion of haemodynamic relevant coronary artery stenosis in patients with suspected coronary artery disease (CAD). Patients with negative myocardial perfusion CMR results were shown to have an excellent prognosis.\(^1,2\) Myocardial perfusion CMR can also be used to assess the haemodynamic relevance of coronary stenosis and thus guide revascularization. Recent studies demonstrate good diagnostic performance at 1.5 Tesla (1.5T) as well as at 3.0 Tesla (3T) when compared with pressure-derived myocardial fractional flow reserve (FFR).\(^3-5\) the current reference standard for assessing functional relevance of coronary lesions (Figure 1). However, most of these studies were performed in patients with angiographically severe lesions, which are not the primary targets for FFR measurements under real-world conditions, because of the high likelihood of haemodynamic changes and an increased risk of adverse events when passing high-degree stenosis with the flow wire.

The FAME study strengthened the importance of functional assessment in coronary stenosis \( \geq 50\% \). It was shown that coronary intervention guided by FFR results in superior outcomes with significantly lower mortality.\(^6,7\) The observed effect was mainly due to a systematic overestimation of the haemodynamic severity of intermediate lesions by angiography alone and a subsequent higher number of index percutaneous interventions in the non-FFR group. However, the invasiveness of FFR makes alternative non-invasive methods for haemodynamic assessments of intermediate coronary lesions desirable. Myocardial perfusion CMR may serve as such an alternative.

The increasing availability of 3T cardiac MR systems has spurred efforts to further improve myocardial perfusion CMR protocols, mainly by exploring advanced techniques for increased in-plane spatial resolution or employing 3-D whole-heart acquisition.

![Myocardial perfusion CMR vs. coronary angiography](https://example.com/image.png)

**Figure 1** Myocardial perfusion CMR vs. coronary angiography. Left panel: Patient with two intermediate lesions of the left anterior descending coronary artery (A). Fractional flow reserve (FFR) within both stenoses was measured and lesions were found to be non-obstructive (B: proximal LAD stenosis). Myocardial perfusion CMR (C) revealed normal perfusion. Right panel: Patient with a proximal intermediate LAD lesion (A). The FFR measurement (B) as well as myocardial perfusion CMR (C) demonstrate haemodynamic significance.
strategies. However, perfusion imaging at 3T can be limited by B₀ and B₁ artefacts as the latter can lead to insufficient suppression of the myocardium by the saturation pre-pulse. The recent introduction of multi-transmit radiofrequency MR techniques reduces dielectric shading, improves homogeneity of the MRI signal, and thus improves image quality at 3T. So far, the clinical feasibility of a robust standard myocardial perfusion CMR sequence using this new technology has not been evaluated.

Hence, the goals of the current investigation were: (i) to assess the real-world routine feasibility and image quality of a standard 3T myocardial perfusion CMR sequence using dual transmit radiofrequency technology and (ii) to assess the diagnostic accuracy of 3T myocardial perfusion CMR for the detection of myocardial ischaemia using a clinical algorithm with FFR evaluation of intermediate lesions and visual assessments of high-grade stenosis as the standard of reference.

Methods

Patients

In the time period from June 2010 until July 2012, 120 consecutive patients with suspected or known CAD who were referred for coronary angiography and also underwent myocardial perfusion CMR due to clinical reasons within 5 days of coronary angiography were included. In patients who had coronary angiography first and revealed significant stenosis, ad hoc angioplasty was usually done and these patients were excluded. Staged angioplasty was only done as per clinical decision of the interventionalist. Patients gave informed consent and agreed that their anonymized clinical data are used for scientific purposes. The protocol was approved by the Ethics Committee of the Bavarian Chamber of Physicians (Bayerische Landesarztekammer). Exclusion criteria were contraindications to CMR due to claustrophobia or metallic implants, obstructive pulmonary disease, atrio-ventricular block grade I, myocardial infarction within 7 days, acute coronary syndrome, New York Heart Association class IV heart failure, and kidney disease with a GFR of <45 mL/min. Patients were instructed to refrain from caffeine, nicotine, and beta-blocking medication for 24 h prior to the examination. Clinical characteristics are provided in Table 1.

CMR imaging

Myocardial perfusion CMR scans were performed on a 3T system (Achieva 3.0T TX; Philips Healthcare; Best; the Netherlands) equipped with dual source parallel RF excitation and transmission technology (MultiTransmit; Philips) using a 32-channel cardiac phased array receiver coil for signal detection. Perfusion imaging was performed using three parallel short-axis sections in end-inspiration. A T1-weighted fast field echo sequence [repetition time/echo time 2.7 ms/0.8 ms, flip angle 18°, acquired in-plane spatial resolution 2.97 × 2.97 mm (reconstructed 1.48 × 1.48 mm), 8 mm section thickness] was used. At an acceleration factor of 2.3 (SENSE in right/left encoding direction for coronal planes and in anterior/posterior encoding direction for sagittal or transversal planes), image data were obtained after 3 min of adenosine (170 μg/kg/min Adenoscan®, Astellas, Tokyo, Japan) induced hyperaemia using a continuous venous infusion, which was repeated 15 min later at rest. Forty-five dynamics were acquired. Both perfusion studies used 0.05 mmol/kg Gd-DOTA (Dotarem®, Guerbet, Paris, France) at 4 mL/s followed by a 25 mL saline flush. The contrast agents and adenosine were administered separately using two 18-gauge intravenous lines.

Visual myocardial perfusion CMR image analysis

Images were evaluated independently by two experienced observers, using dedicated software (Extended MR WorkSpace 2.6.3.2.; Philips). The observers had no knowledge of the patient’s characteristics, history, or angiographic results. Perfusion defects were determined qualitatively using the 16-segment model of the American Heart Association for left ventricular assessments. Myocardial segments were deemed to have perfusion defects if the contrast signal was reduced over at least three or more consecutive image frames in comparison to non-ischaemic myocardial segments and the perfusion defect was not located within scar tissue as determined by corresponding LGE studies. Stress perfusion images in each segment were scored on a 4-point Likert scale ranging from 0 to 3 (0 = normal, 1 = probably normal, 2 = probably abnormal or subendocardial defect, 3 = abnormal or transmural defect). The perfusion score was then calculated as the sum of all 16 segmental scores for each patient and used for ROC analysis. In addition, we assessed diagnostic accuracy (Sensitivity, Specificity, PPV, NPV) of myocardial perfusion CMR on a coronary vessel perfusion territory level and on a patient level. Three short-axis image sections at basal, mid-ventricular, and apical levels during rest and during hyperaemia-perfusion were evaluated for image quality in a blinded and random order in each patient. The perfusion territories of each coronary artery LAD, LCX, and RCA during rest and during hyperaemia-perfusion were evaluated for image quality in a blinded and random order in each patient. The perfusion territories of each coronary artery LAD, LCX, and RCA during rest and during hyperaemia-perfusion were evaluated for image quality in a blinded and random order in each patient.
Coronary angiography and FFR measurements

Coronary angiography was performed by a femoral or radial artery approach using a 6-F sheath. Lesions with a diameter stenosis of 50–75% in at least two orthogonal views as visually assessed by the angiographers were defined as intermediate. Lesions >75% or intermediate lesions with an FFR value of ≤0.80 were defined as significant. In addition, images were transferred to an off-line workstation (CAAS II, Pie Medical, Maastricht, The Netherlands) for quantitative analysis. In analogy to clinical practice, FFR measurements were performed on intermediate lesions only. In those lesions, a pressure wire that allowed simultaneous measurement of ostial and peripheral coronary pressure was placed across the target lesion. For FFR measurements, intracoronary nitroglycerine and 5000 IE of heparin were administered. If multiple intermediate stenoses in the same coronary artery branch were observed, FFR was measured distally to the most distal lesion using a commercially available and well validated system (PressureWire™ Certus FFR Measurement System St Jude Medical, USA). Hyperaemia was induced by the same adenosine protocol that was used for CMR perfusion imaging. A bolus of 170 μg adenosine/kilogram body weight/minute was administered. FFR measurements were started 3 min after the start of the infusion.

Statistical analysis

Categorical data were presented as frequencies and percentages and were compared by using the χ²-test. Normally distributed continuous data were presented as means ± standard deviations and were compared by using the two-tailed t-test for independent samples. Analysis for interobserver reliability was performed with Cohen’s kappa statistics. The diagnostic accuracy of visual myocardial perfusion CMR analysis to detect significant coronary stenoses was determined by using receiver–operator characteristics analysis with calculation of the area under the ROC curve (AUC). A P ≤ 0.05 was considered statistically significant. All statistical analyses were performed by using the SPSS software (SPSS, release 18.0; SPSS, Chicago, IL, USA).

Results

Of 120 (71 men, age 63 ± 14 years) patients undergoing coronary angiography and myocardial perfusion CMR, 4 patients were excluded from the analysis (one patient was excluded because the scan was aborted due to claustrophobia and three patients were excluded because coronary revascularisation was performed prior to myocardial perfusion CMR) thus resulting in 116 patients in the final patient cohort. Eight-four patients (70%) underwent myocardial perfusion CMR before coronary angiography. A total of 348 perfusion territories were analysed. Due to scaring, 74 territories (21%) could not be evaluated for myocardial perfusion.

Coronary angiography and FFR measurements

Coronary angiography was successfully performed in all patients without adverse events. On offline quantitative coronary angiography measurements, CAD (>50% diameter stenosis) was found in 135 vessels (39%), significant stenosis (>75% diameter stenosis) was found in 54 vessels (16%), and total occlusions were present in 25 vessels (7%). Twenty-six patients (22%) were found to have no significant CAD (<50% diameter stenosis), 46 patients (40%) had one-vessel disease, 27 patients (23%) had two-vessel disease, and 17 patients (15%) had three-vessel disease (Table 2). Coronary artery disease was present in the LAD in 40%, in the LCX in 29%, and in the RCA in 31% (Table 2).

Intermediate lesions (50–75% diameter stenosis) were found in 56 of 348 vessels (16%), prompting the performance of FFR measurements. Fractional flow reserve values ranged from 0.61 to 0.99 and correlated moderately (r = 0.66, P < 0.001) with diameter stenosis on quantitative coronary angiography. Among these intermediate lesions, 14 (25%) had FFR values ≤0.80. The average diameter stenosis of lesions with an FFR ≤0.8 was 67.2 ± 8.1%.

CMR imaging

Clinical feasibility and image quality

Intravenous adenosine application at 170 μg/kg/min was well tolerated by all patients. Due to myocardial scaring on late enhancement imaging, 74 segments had to be excluded. Per segment image quality is shown in Table 3. There was no image data set with non-diagnostic image quality. The mean image quality scores for LAD, LCX, and RCA territories during rest perfusion and adenosine stress perfusion were 2.8, 3.1, 3.0 and 2.5, 3.1, 3.0, respectively. The agreement between both readers was good. The values for Kappa ranged between 0.66 and 0.89 (Table 3).

Diagnostic accuracy of myocardial perfusion CMR

The calculated CMR perfusion score ranged from 0 to 12 (Q1 = 0, Q3 = 6) with an overall mean of 2.6 ± 3.5. The ability of myocardial perfusion CMR using the summed perfusion score to detect significant coronary artery stenosis on a per-patient base was 0.93 AUC using ROC analysis (Figure 2).

Sensitivity, specificity, positive and negative predictive value of myocardial perfusion CMR to detect significant coronary stenoses on a vessel territory basis was 89%, 95%, 87%, and 96%, respectively (Table 4). When evaluating our results on a patient level, we found a
sensitivity of 85%, specificity of 87%, a PPV of 77%, and a NPV of 92% (Table 5).

Patients with single vessel disease were found to have a sensitivity and specificity of 81 and 83%, and those with multi-vessel disease of 88 and 89%, respectively.

Diagnostic accuracy of myocardial perfusion CMR in intermediate stenosis compared with FFR

In patients with intermediate lesions and an FFR threshold of 0.80 as the standard of reference, myocardial perfusion CMR correctly classified 38 of 56 coronary perfusion territories as normal and 12 of 56 as pathologic. Two coronary perfusion territories were falsely classified as pathologic and four false negative results were observed. Hence, performance characteristics of myocardial perfusion CMR were evaluated.

Hence, performance characteristics of myocardial perfusion CMR for detecting ischaemia in lesions with FFR values ≤0.80 were as follows: sensitivity 75%, specificity 95%, PPV 86%, and NPV 90%. Per-patient based performance showed a sensitivity of 80%, a specificity of 93%, a PPV of 86%, and a NPV of 90%. For results regarding an FFR threshold of 0.75, please see our Supplementary data.

Discussion

The objective of this study was to evaluate the performance of 3T myocardial perfusion CMR with dual RF transmission technique for diagnosing myocardial ischaemic states with a clinical algorithm consisting of coronary angiography and FFR measurements as reference standard. For this purpose, we used routine clinical perfusion protocols in a large, unselected patient cohort with various severity of CAD. Myocardial perfusion CMR at 3T was demonstrated to be a

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**Table 3** Image quality of myocardial perfusion CMR during rest and stress

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<tr>
<td></td>
<td>LAD</td>
<td>RCX</td>
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<td>Mean ± SD</td>
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<td>3.1 ± 0.5</td>
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<td>Median</td>
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<td>Cohen’s κ</td>
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Table shows mean, median, and interobserver reproducibility (Cohen’s κ) of image quality scores on a four-point grading system (4 = excellent to 1 = non-diagnostic). The perfusion territories of each coronary artery (left anterior descending (LAD), left circumflex artery (LCX), right coronary artery (RCA)) during rest and stress myocardial perfusion CMR were evaluated.

**Figure 2** The receiver–operator characteristic curve shows the performance of the CMR perfusion score to detect haemodynamically significant coronary stenosis on a per-patient base (FFR ≤0.80 or >75% stenosis on quantitative coronary angiography). The area under the ROC curve is 0.93.

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**Table 4** Vessel based diagnostic accuracy of 3T myocardial perfusion CMR using coronary angiography and FFR as standard of reference

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<tr>
<th>Vessel lumen stenosis</th>
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<td>Pathologic 3T myocardial perfusion CMR</td>
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**Table 5** Patient-based diagnostic accuracy of 3T myocardial perfusion CMR using coronary angiography and FFR as standard of reference

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robust imaging technique with excellent diagnostic accuracy for the evaluation of significant and intermediate coronary lesions.

**Myocardial perfusion CMR**

Myocardial perfusion CMR for the detection of myocardial ischaemia is increasingly incorporated into clinical practice. Myocardial perfusion CMR using 1.5T and, more recently, also 3T systems have previously been compared with nuclear imaging methods and invasive techniques such as coronary angiography and FFR. A meta-analysis by Hamon et al. analysed 1658 patients from 20 studies, which compared adenosine vasodilator myocardial perfusion CMR with coronary angiography. A pooled sensitivity of 90% (88–92%) and a specificity of 81% (78–84%) were found. However, most prior studies used a cut-off threshold of 50% coronary lumen stenosis on coronary angiography which may incur a possible inflation of false-negative myocardial perfusion CMR findings. Conversely, those studies which used 70–75% as a cut-off do not account for pathologic perfusion findings caused by intermediate lesions, leading to an artificially high frequency of false-positive myocardial perfusion CMR results. In addition, the few studies which compared myocardial perfusion CMR with FFR measurements were mainly performed in patients with angiographically severe lesions. In clinical practice, such lesions are not the primary targets for FFR evaluation, as there is an elevated risk of complications when passing high-degree stenosis with FFR wires and little incremental benefit for patient management, as the likelihood of haemodynamic relevance is high. Thus, we evaluated 3T myocardial perfusion CMR compared with a clinical routine algorithm in which only coronary stenoses exceeding 75% were deemed pathologic on coronary angiography and FFR measurements were performed in patients with intermediate lesions.

Overall, the performance of 3T myocardial perfusion CMR using our proposed approach is encouraging: of all significant stenoses, only six were missed by myocardial perfusion CMR. In four of these cases, three vessel-disease with possible balanced ischaemia was present. When investigating intermediate lesions, we similarly found good diagnostic performance of 3T myocardial perfusion CMR when compared with invasive FFR. Upon comparison with FFR measurements of 56 intermediate lesions, there were 2 false-positive and 4 false-negative myocardial perfusion CMR findings, resulting in a sensitivity of 75% and a specificity of 95%.

Our results are especially promising as this patient population is clinically most challenging. For the interventional cardiologist, it can be difficult to evaluate the haemodynamic relevance when relying only on visual assessment. It was shown that cardiologists routinely overestimate such lesions and tend to perform more percutaneous interventions compared with operators who performed additional FFR measurements. The 5-year outcome of the DEFER (Deferral vs. Performance of PTCA in Patients Without Documented Ischemia) trial showed that stenting of haemodynamically non-significant intermediate lesions (FFR > 0.75) did not improve outcomes. The study also confirmed the poor correlation between the degree of coronary stenosis of intermediate lesions and functional relevance as measured by FFR, thus emphasizing the importance of functional assessments.

Despite using a routine clinical perfusion protocol, the diagnostic performance of myocardial perfusion CMR in our investigation was similar, with an AUC of 0.93, to that reported by Manka et al. with an AUC of 0.94, and Plein et al. with an AUC of 0.89. These latter investigations used dedicated, proprietary image acquisition sequences with high spatial resolution of up to 1.1 × 1.1 mm which are thought to be superior for reducing dark-rim artefacts by virtue of their reduced voxel size. Our lower spatial resolution standard protocols thus compare quite favourably with these prior results. However, our relatively high diagnostic accuracy could in part be explained by our more granular reference standard which did not rely on stenosis severity by coronary angiography alone, as most previous investigations, but also used FFR for assessing the haemodynamic relevance of intermediate lesions.

Considering the excellent NPV and thus the ability to reliably exclude haemodynamically significant stenosis, 3T myocardial perfusion CMR could serve most beneficially as an upstream test prior to coronary angiography in patients with suspected CAD. Pilz et al. already showed in 176 patients that myocardial perfusion CMR prior to CA could reduce the frequency of merely diagnostic coronary angiography studies from 34 to 6%. In addition, large investigations demonstrated that patients with non-pathologic myocardial perfusion CMR enjoy an excellent prognosis, underlining the incremental value of myocardial perfusion CMR for guiding patient care. As demonstrated here, myocardial perfusion CMR is also capable as a secondary gatekeeper to assess the clinical relevance of intermediate lesion detected at coronary angiography and can thus guide decisions regarding revascularization, especially in clinical settings where FFR is not desirable or feasible to perform.

In addition, we were able to show the safe and effective use of an adenosine perfusion protocol using 170 μg adenosine/kilogram body weight/minute. We did not encounter any negative side-effects and all patients showed an elevation of the heart rate indicating vasodilation.

**Clinical feasibility of RF multi-transmission technology at 3T**

Due to the high field strength, cardiac imaging at 3 Tesla is hampered by imaging artefacts, including magnetic field inhomogeneities, dielectric shading, and restrictions related to local energy deposition. The use of multiple RF sources promises to overcome some of these limitations. Improvements for imaging of the spine and the liver have already been demonstrated. In addition, it was shown that B1 inhomogeneities in dual-source transmission systems are improved over settings where FFR is not desirable or feasible to perform.

In our patient collective, accelerated image acquisition could be achieved without penalties arising from dielectric shading or B1 inhomogeneity. This is reflected by the overall high image quality in most of our patients. Image quality was graded excellent in 12.0% of myocardial segments and good in 70.4%. None of the studies was deemed non-diagnostic. Particularly, the image quality of the posterior wall, a region that is prone to artefacts at 3.0 Tesla, was high in our cohort. These results demonstrate that 3T myocardial perfusion CMR using dual RF transmission provide high image quality and sufficient robustness in clinical real-world settings.
Study limitations

Our study has several limitations, which have to be taken into account. First, true quantitative myocardial perfusion CMR myocardial blood flow measurements were not performed, as the purpose of this study was to evaluate this modality in a clinical setting and to date most of the relevant prognostic studies were based on visual assessment. However, by using semi-quantitative measures such as myocardial perfusion indices, the accuracy of myocardial perfusion CMR may be further improved. Furthermore, we used a ‘standard’ 2.9 × 2.9 mm spatial-resolution perfusion protocol, as our goal was to investigate the clinical performance of more ubiquitously reproducible techniques. However, a high-resolution protocol may have further improved image quality. In order to evaluate perfusion defects, including those on a subendocardial level we excluded all myocardial segments with scarning. Furthermore, ideally all patients should have undergone myocardial perfusion CMR before coronary angiography. However, due to clinical workflow requirements, this was not always feasible in all of our patients. We do not believe that this significantly limits our study findings; however, there may a minor bias towards non-significant coronary lesions. Lastly, we did not compare perfusion data acquired with multi-transmit technology with data acquired without this novel approach.

Conclusion

3T myocardial perfusion CMR is an accurate, safe, and robust tool for the routine clinical evaluation of myocardial ischaemia in patients with intermediate and significant coronary lesions. This suggests a potential beneficial role of this test as a first-line diagnostic modality prior to coronary angiography for excluding obstructive disease. Additionally, myocardial perfusion CMR could be used to guide decisions regarding revascularization of intermediate lesions observed at coronary angiography in cases where invasive measurements are a less desirable option.

Supplementary material

Supplementary data are available at European Journal of Echocardiography online.

Conflict of interest: B.S. is an employee of Philips Health Care; Hamburg, Germany. There are no financial or other relations that could lead to a conflict of interest.

References

1. Bingham SE, Hachamovitch R. Incremental prognostic significance of combined cardiac magnetic resonance imaging, adenosine stress perfusion, delayed enhancement, and left ventricular function over preimaging information for the prediction of adverse events. Circulation 2011;123:1509–18.