Adenosine Stress High-Pitch 128-Slice Dual-Source Myocardial Computed Tomography Perfusion for Imaging of Reversible Myocardial Ischemia

Comparison With Magnetic Resonance Imaging

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Background—Coronary computed tomography angiography (CTA) enables accurate anatomic evaluation of coronary artery stenosis but lacks information about hemodynamic significance. The aim of this study was to evaluate 128-slice myocardial CT perfusion (CTP) imaging with adenosine stress using a high-pitch mode, in comparison with cardiac MRI (CMR).

Methods and Results—Thirty-nine patients with intermediate to high coronary risk profile underwent adenosine stress 128-slice dual source CTP (128\times0.6 \text{ mm}, 0.28 \text{ seconds}). Among those, 30 patients (64±10 years, 6% women) also underwent adenosine stress CMR (1.5T). The 2-step CTP protocol consisted of (1) adenosine stress-CTP using a high-pitch factor (3.4) ECG-synchronized spiral mode and (2) rest-CTP/coronary-CTA using either high-pitch (heart rate <63 \text{ bpm}) or prospective ECG-triggering (heart rate >63 \text{ bpm}). Results were compared with CMR and with invasive angiography in 25 patients. The performance of stress-CTP for detection of myocardial perfusion defects compared with CMR was sensitivity, 96%; specificity, 88%; positive predictive value (PPV), 93%; negative predictive value (NPV), 94% (per vessel); and sensitivity, 78%; specificity, 87%; PPV, 83%; NPV, 84% (per segment). The accuracy of stress-CTP for imaging of reversible ischemia compared with CMR was sensitivity, 95%; specificity, 96%; PPV, 95%; and NPV, 96% (per vessel). In 25 patients who underwent invasive angiography, the accuracy of CTA for detection of stenosis >70% was (per segment): sensitivity, 96%; specificity, 88%; PPV, 67%; and NPV, 98.9%. The accuracy improved from 84% to 95% after adding stress CTP to CTA. Radiation exposure of the entire stress/rest CT protocol was only 2.5 mSv.

Conclusions—Adenosine-induced stress 128-slice dual-source high-pitch myocardial CTP allows for simultaneously assessment of reversible myocardial ischemia and coronary stenosis, with good diagnostic accuracy as compared with CMR and invasive angiography, at a very low radiation exposure. (Circ Cardiovasc Imaging. 2011;4:540-549.)

Key Words: adenosine stress myocardial perfusion ■ CT ■ CMR ■ CAD

Multislice coronary computed tomography angiography (CTA) is an accurate tool in the noninvasive workup of patients with suspected coronary artery disease (CAD). Its strengths include a high sensitivity in detecting coronary stenosis >50%, with an excellent negative predictive value. For clinical use, coronary CTA is recommended in patients with low to intermediate pretest probability of CAD. However, CTA is limited to anatomic grading of coronary stenosis, lacking information regarding the hemodynamic significance of a stenosis. This limitation often necessitates additional testing for myocardial ischemia, as coronary revascularization by percutaneous coronary intervention or coronary artery bypass graft (CAGB) surgery is indicated in the presence of ischemia.

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Myocardial perfusion imaging (MPI) using either single-photon emission tomography (SPECT), positron emission tomography, or cardiac MRI (CMR) are the reference methods for imaging of myocardial ischemia.

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The advantage of CMR over myocardial SPECT encompasses a high spatial resolution of \( \approx 1 \) to 2 mm.\(^5\) Initial data in animals\(^6\) and humans\(^7\)–\(^9\) indicate that myocardial computed tomography perfusion (CTP) enables the detection of myocardial ischemia and infarct,\(^7\)–\(^9\) with good accuracy as compared with SPECT, at a radiation exposure of \( \approx 12.7 \) mSv.\(^7\)

Recently, a 128-slice dual-source CT (DSCT) system was introduced, providing a spatial resolution of \( \approx 0.3 \) to 0.4 mm\(^3\), improved temporal resolution of 75 ms, and a new prospective ECG-synchronized high-pitch spiral mode allowing for fast image acquisition within \( <0.4 \) seconds, at a low radiation dose of \( \approx 1 \) mSv.\(^{10,11}\) The advantage of cardiac CT is complementary evaluation of coronary arteries and myocardial perfusion, permitting the visualization of both coronary anatomy and physiology.

Therefore, the primary aim of the present study was to evaluate the accuracy of adenosine stress 128-slice high-pitch CTP for assessment of myocardial perfusion, including the detection of reversible myocardial ischemia or infarction, as compared with CMR. The secondary aim was to compare coronary CTA as part of a comprehensive stress CT protocol with invasive angiography (IA).

### Methods

#### Study Population and Design

This prospective study was approved by a local ethics committee. Each participating subject gave written informed consent. Patients with an intermediate to high coronary risk profiles were prospectively enrolled.

#### Inclusion Criteria

The CT and CMR examinations were performed on the same day. Patients were recruited if they had suspected or known CAD and were able to sign informed consent. Patients were advised to stop caffeine intake for at least 12 hours before the study. No \( \beta \)-blockers or nitroglycerin premedication were given before the study. Metformin was discontinued for at least 48 hours. A 12-lead ECG was taken. The creatinine was determined. In patients in whom CTP and coronary CTA were directly compared with IA, the time interval between CT and IA was 6 weeks, maximum.

#### Exclusion Criteria

Exclusion criteria included severe aortic stenosis, long-QT syndrome (heart rate–corrected QT \( >440 \) ms), AV block grade II/III, sick sinus syndrome, New York Heart Association heart failure class III/IV, left ventricular ejection fraction \( <30\% \), renal dysfunction (creatinine \( >110 \) \( \mu \)mol/L), glomerular filtration rate [GFR] \( <60 \) mL/min per 1.73 m\(^2\)), severe left main stenosis, chronic obstructive pulmonary disease, asthma, acute coronary syndrome (ACS) within \( <48 \) hours, unstable angina, and atrial fibrillation.

During adenosine injection, the patient’s ECG, heart rate, blood pressure, and symptoms were monitored. Adenosine injection was stopped if a cessation criterion occurred. Cessation criteria were severe chest pain, drop in blood pressure \( >40 \) mm Hg, ECG signs of arrhythmia, and new onset of ST-segment depression or elevation.

### Cardiac CT Examination

A 128-slice dual-source CT system was used (Somatom Definition Flash, Siemens Healthcare, Germany). In each patient, 2 intravenous cannulas (1 on each side) were placed. Baseline heart rate (HR) and systolic and diastolic blood pressure (BP) during adenosine injection were noted at 30 seconds, 2 minutes, and after completing injection. The CT scan protocol consisted of 2 steps (Figure 1). First, stress-myocardial CTP was performed. Adenosine was injected intravenously with an infusion pump at a dosage of 140 \( \mu \)g/kg per minute for 3 minutes, at which point the stress CTP scan was initiated. Adenosine injection continued during the CT examination. For stress CTP, a bolus of 60 mL nonionic iodine contrast agent with 370 mg/mL iodine concentration (ipromide, Ultravist 370 Bayer Schering, Germany) was injected using an injector (Medtron, Germany) at a flow rate of 5 mL/s, followed by 60 mL mixed contrast agent/saline solution (20%/80%). The CT scan was triggered using “bolus tracking technique,” after 100 Hounsfield Units (HU) were reached in the ascending aorta. Patients were holding the breath at midinspiration. The scan length extended from the pulmonary artery bifurcation to the apex of the heart. Prospective ECG synchronization was applied. The scan start was triggered at 60% of the R-R interval, resulting in end-diastolic image acquisition from 60% to 80%. Scan parameters were slice acquisition, \( 2 \times 128 \times 0.6 \) mm; gantry rotation time, 280 ms; and tube potential, \( 100 \) kilovoltage (kV) if body mass index (BMI) was \( <30 \) kg/m\(^2\) and \( 120 \) kV if BMI was \( >30 \) kg/m\(^2\). Tube current-time product was set at 320 mA/rotation. Pitch factor was 3.4.

Second, after a delay of at least 5 minutes, rest myocardial CTP/Coronary CTA (Figure 1) was performed using a second iodine contrast bolus injection with the same contrast bolus volume of 60 mL and flow rate as for stress CT. Identical scan parameters as described for the stress CT were used. High-pitch mode (pitch, 3.4) was applied if HR was \( <63 \) bpm, or prospective ECG-triggering (“dual-step pulsing”)\(^\text{12}\) was performed if HR was \( >63 \) bpm.

Automated computed tomography dose index (CTDI\(_{\text{vol}}\)), dose-length-product (DLP), and effective dose calculated as = DLP/\( \times \) conversion factor, 0.014\(^\text{13}\) were collected.

CT images were reconstructed at 0.75-mm slice width (increment=0.5) and with a medium-to-smooth image reconstruction kernel. CT images were transferred to a workstation (LeonardoTM, Siemens). Short-axis views of the left ventricle (LV) were generated from 4- and 2-chamber views in thick average (5-mm slice width, multiplanar reconstruction). Two independent reviewers (with 7 years and 9 months of experience) performed myocardial CTP readouts independently and blinded. Reader 1 repeated readouts after 6 weeks. The latter consensus was used.

LV myocardium was evaluated using the 16-segment American Heart Association (AHA) model\(^\text{14}\) for the presence of hypoenhancing perfusion defects during stress and rest. The type of myocardial perfusion defects was defined as completely reversible (CR) if...
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midventricular, and apical regions for perfusion MRI. Representative short-axis sections were obtained in each in the basal, myocardium were generated from a series of scout images. Three 

Cardiac Magnetic Resonance Imaging

Cardiac MR exams were performed on a 1.5-T unit (Philips Achieva, Best, The Netherlands), using a 5-element cardiac phased-array receiver coil and during breath-hold in end-inspiration. A stack of short-axis steady-state free precession slices of the LV myocardium were generated from a series of scout images. Three representative short-axis sections were obtained in each in the basal, midventricular, and apical regions for perfusion MRI.

For stress MR perfusion imaging, adenosine was injected intravenously at 140 μg/kg during a minimum of 2.5 minutes and continued during the examination. Sequences were acquired immediately after Gadoterate meglumine (Gd-DOTA) (Dotarem; Guerbet Research, Aulnay-sous-Bois, France) injection (concentration=0.1 mmol/kg), using an automated injector (MR Spectris; Medrad, Pittsburgh, PA) (flow rate, 5 mL/s and 40-mL saline flush). Heart rate and blood pressure were noted before, after 30 seconds, and after 2 minutes of adenosine injection (as in the CT study).

MR rest perfusion was performed 10 minutes after stress, using the same sequence and image orientation, and a second bolus of 0.1 mmol Gd-DOTA. SENSE (k-t sensitivity encoding) imaging was used with a saturation recovery gradient-echo pulse sequence for both of these sequences (repetition time/echo time, 3.1/1.1 ms; flip angle, 20°; saturation prepulse delay, 110 ms; partial Fourier sampling, acquisition window, 120 ms; section thickness, 10 mm; k-t factor of 5 with 11 k-t interleaved training profiles; effective acceleration, 3.7; 3 sections acquired sequentially during a single R-R interval), providing an in-plane resolution of 1.25×1.25 mm.

Delayed enhancement (DE) was performed in a continuous short-axis view using an inversion-recovery gradient-recalled echo MR sequence (field of view, 350 to 400 mm; repetition time/echo time, 7.4/4.3 ms; inversion time, 200 to 350 ms; flip angle, 20°; matrix, 240×240; slice thickness, 10 mm). The inversion time was chosen individually according to a Look-Locker sequence to optimize myocardial nulling.

CMR readouts were performed by 2 independent observers (8 and 3 years of experience). Consensus was applied. Rest and stress were evaluated for myocardial perfusion defects according to the modified 17-segment AHA-16-segment classification by an experienced observer. Coronary stents were included.

Invasive Angiography

IA was performed on average in 7 projections (4 views of the left and 3 views of the right coronary artery). Quantitative coronary angiography was performed. Hemodynamically significant coronary stenosis was considered present if there was ≥70% luminal narrowing, as depicted with coronary angiography.

Statistical Analysis

Statistical analysis was performed using SPSS Software (SPSS, Version 14, Chicago, IL). Quantitative data are expressed as
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mean±standard deviation. For comparison of CTP with CMR, the sensitivity, specificity, positive predictive value (PPV), and negative predictive values (NPV) were calculated. Receiver operating curve (ROC) analysis and the area under the curve (AUC) were calculated. The intraclass correlation coefficient (ICC) was calculated to express intraindividual variations and interpreted as 0 to 0.2 indicates poor; 0.25 to 0.39, fair; 0.4 to 0.59, moderate; 0.6 to 0.79, strong; and >0.8, almost perfect agreement. A generalized estimating equation (GEE) was performed to test for independency among myocardial segments and vessel territories for both the “reversible” and “all-defect” analysis. A probability value of >0.05 was regarded as criterion to rule out correlation and to proof independency. Quasi-likelihood under Independence Model Criterion was applied to determine goodness of fit of GEE. A hierarchical linear model is presented for vessel-based analysis, variance was calculated, and \( P<0.05 \) was regarded as significant.

For interobserver and intraobserver variability, Cohen \( \kappa \) value was applied.

The diagnostic accuracy of CTP compared with invasive angiography for detection of stenosis >70% was calculated per vessel and those of CTA per vessel (left anterior descending coronary artery, left circumflex, and right coronary artery) and segment (n=16). The accuracy of using combined CTP/CTA for detection of >70% stenosis on IA was calculated per vessel territory and its incremental value over CTA and CTP defined with Cohen \( \kappa \).

Results

Of 73 patients recruited, 33 were excluded because of contraindications: ACS within 48 hours or unstable angina (n=4), long-QT interval (n=6), severe aortic stenosis (n=4), severe left main stenosis (n=2), renal dysfunction (n=10), AV block II/III (n=2), severe obstructive pulmonary disease (n=2), LV dysfunction/heart failure (n=4), or refused consent (n=3). One patient agreed to CMR but refused CT; 9 patients were examined with stress CTP only but not with CMR; 39 subjects completed stress CTP; 30 patients were examined with stress CTP and CMR; and 25 patients had IA within 6 weeks. The study population is shown in Table 1.

Radiation Dose Estimates

The 2-step myocardial CTP protocol resulted in an effective radiation dose of 2.5±2.1 mSv (range, 1.3 to 6.7), CTDIvol was 10.94±9 mGy (range, 4.8 to 42.3), and DLP was 191±128 mGy/cm (range, 95 to 698). Scan time for high-pitch stress CTP was 0.31 seconds (range, 0.24 to 0.37) and scan length 14.3 cm (range, 10.9 to 17.4). Effective radiation dose for stress and rest was 0.93±0.18 mSv (range, 0.75 to 1.48) and 1.59±1.3 mSv (range, 0.53 to 5.8 mSv), respectively. For rest CTP, high-pitch was applied in 28 of 39 (72%) patients with HR <63 bpm and prospective ECG-triggered dual-step-and-shot12 in the remaining 11.

Examinations and HRs

All patients were in sinus rhythm. Mean HR during stress CTP was 69±11 bpm (range, 51 to 99). During rest, HR was 58±11 bpm (range, 44 to 86). In 4 of 30 patients, adenosine was stopped before reaching 3 minutes because of cessation criteria (n=2 at 2 minutes; n=1 at 1:45 minutes because of angina; and in n=1 at 2:50 minutes because of angina/ST-depression). During CMR, adenosine was stopped in 5 patients before reaching 3 minutes because of cessation criteria (angina).

In 30 patients who underwent both stress CTP and CMR, among 480 myocardial segments, there were 103 with complete reversible (CR) (Figure 2), 41 with partial reversible (PR) ischemia (Figure 3), and 52 with myocardial infarcts (Figure 4) (43 fixed defects and 9 with myocardial thinning) by CTP.

Accuracy of Adenosine Stress-CTP for Detection of All Myocardial Perfusion Defects (Reversible and Fixed) Versus CMR

The accuracy of CTP is presented in Table 2. For detection of any myocardial perfusion defects during adenosine, stress CTP had a sensitivity of 78%, a specificity of 87%, and NPV of 84% per myocardial segment compared with combined CMR stress perfusion and DE as reference standard (ROC: AUC, c=0.84). Per coronary vessel, sensitivity was 96%;
specificity, 88%; and NPV, 94% (AUC, c=0.93). The ICC for intraindividual variations among myocardial segments was very low, with 0.105 (95% confidence interval, 0.06–0.19) and moderate with 0.59 (95% confidence interval, 0.13–0.79) for vessels. GEE showed independency for segments (mean, $P=0.310$). For vessels, the hierarchical model showed significant variance ($P=0.002$).

**Accuracy of Adenosine Stress CTP for Detection of Reversible Myocardial Ischemia Versus CMR**

The diagnostic accuracy of CTP is shown in Table 3. Per myocardial segment, the diagnostic accuracy of CTP for detection of reversible defects ($n=144$) on CT during adenosine, as compared with adenosine stress perfusion CMR, was sensitivity, 68%; specificity, 88%; NPV, 85% (AUC, 0.82), and on per-vessel–based analysis, sensitivity, 95%; specificity, 96%; NPV, 96% (AUC, c=0.93). The ICC for intraindividual variations was very low, with 0.085 (95% confidence interval, 0.033–0.21) for segments and fair, with 0.49 (95% confidence interval, 0.18–1.32) for vessels, respectively. GEE showed independency for segments (mean, $P=0.390$). Hierarchical model showed a significant variance ($P=0.04$) for vessels.

The confidence scores for perfusion defects during stress CT were mean, 1.3±0.3, and those by CMR, 2.1±0.9.

Intraobserver agreement for CTP was good, with $\kappa=0.66±0.17$ (range, 0.48 to 0.80) for rest, and stress CTP and interobserver agreement was $\kappa=0.48±0.2$ (range, 0.41 to 0.63) and 0.61 (range, 0.25 to 1), respectively. Interobserver agreement for CMR was $\kappa=0.72±0.19$ (range, 0.28 to 1) for DE and 0.68±0.2 for perfusion.

**Accuracy of Adenosine Stress CTP and CTA for Detection of Significant Stenosis Versus IA**

Of 39 patients who underwent CTP, 25 patients had IA within 6 weeks (mean, 26.0 days) (Figure 5). The accuracy of coronary CTA for detection of >70% stenosis (mean, 86.1%) as compared with IA per-vessel and per-segment is presented in Table 4; 8 segments with stents (Figure 3) were included.

The accuracy of CTP for the detection of stenosis >70% per vessel is shown in Table 5. Of 75 vessel territories, there...
Table 2. Diagnostic Accuracy of Adenosine Stress CTP for Detection of All (Reversible and Fixed) Myocardial Perfusion Defects Versus CMR Perfusion and Delayed Enhancement

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Per vessel (n=90)</th>
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<td><strong>Sensitivity</strong></td>
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<td><strong>PPV</strong></td>
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<td>94% (CI: 80–98)</td>
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<td><strong>NPV</strong></td>
<td>85% (CI: 81–89)</td>
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CTP indicates CT perfusion; CMR, cardiac MRI; CI, confidence interval; PPV, positive predictive value; and NPV, negative predictive value.

Table 3. Accuracy of Adenosine Stress CTP for Diagnosis of Reversible Myocardial Ischemia Versus Stress CMR

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CTP indicates CT perfusion; CMR, cardiac MRI; CI, confidence interval; PPV, positive predictive value; and NPV, negative predictive value.

Discussion

Our data demonstrate a good diagnostic accuracy of adenosine stress myocardial CTP imaging with 128-slice CT in high-pitch mode for the detection of reversible myocardial ischemia, as compared with the reference standard CMR. The accuracy of stress CTP was higher in a per-vessel territory as compared with a per-segment analysis, probably because of misregistration of myocardial segments between CTP and CMR. We also demonstrate that the diagnostic accuracy of CTA is maintained as compared with IA, even using a comprehensive stress CT protocol. Adenosine stress myocardial perfusion imaging with 128-slice CT in high-pitch mode has the potential to overcome current limitations of coronary CTA, in terms of providing simultaneously evaluation of reversible myocardial ischemia and coronary anatomy from the same datasets with low radiation exposure.

In contrast to previous studies,7,8 our study has 2 novelities: First, we compared between stress CTP and stress CMR, whereas other studies compared SPECT.7,8 Second, we applied new CT technology, 128-slice dual-source CT, using high-pitch ECG-synchronization,10,11 leading to a substantial decrease in radiation exposure to 2.5 mSv. High-pitch mode allows for an ultrafast scan time of <0.4 seconds within 1 end-diastolic phase while maintaining uniform contrast enhancement throughout the myocardium and avoiding different timing of contrast perfusion of the myocardium.

Our study results are in line with previous studies,7,8 reporting a sensitivity of 93% and specificity of 74% for CT compared with SPECT and invasive angiography (>50% stenosis), for first-generation 64-slice dual source CT in 33 patients.7 Our data show a higher specificity of CTP on a per-vessel-basis, which may be attributed to the improved spatial resolution of CMR as compared with SPECT and to the fact that the pharmacokinetics of iodine and gadolinium-containing contrast agents used for CTP and CMR is closer related.

The second novel aspect of our study encompasses the implementation of a new CT technology, second-generation 128-slice DSCT10,11 using high-pitch spiral image acquisition at a pitch factor of 3.4, which resulted in about 6-fold lower radiation dose as compared with adenosine stress CT MPI imaging using first-generation 64-slice DSCT (12.7 mSv),7 and resulted in 10-fold lower radiation dose as compared with the dynamic myocardial perfusion “shuttle-mode” with alternating table positions (9.6 mSv×2).16 In contrast to our “1-shot” technique, the “shuttle-mode” provides the advantage of dynamic real-time imaging of myocardial perfusion over a time frame of up to 30 seconds,16 similar to MR, but does not allow for complementary CTA evaluation. Moreover, presently the z-axis coverage is limited to only 7.3 cm,16 and imaging is contained to systole.

The total radiation exposure of 2.5 mSv observed in our series for the combined stress and rest CTP/coronary CTA protocol indeed provides a very reasonable approach in practice; 320-detector volume CT enables imaging of the heart within 1 heart beat at 16 cm z-axis coverage and allows for myocardial perfusion imaging at higher radiation dose and preserved homogenous attenuation of the myocardium, as shown by George et al.8
Figure 5. Reversible myocardial ischemia: 70-YOF, angina Canadian Cardiovascular Society class III. Reversible myocardial perfusion defect anterior, septal, inferior, and lateral (arrows, A through D) during stress CT perfusion (CTP) (A and B) and rest CTP (C and D). Lower HU units indicate hypoperfused myocardium (right-sided). Left anterior descending coronary artery occlusion and high-grade circumflex stenosis by CT angiography (CTA) (E) and invasive angiography (IA) (F). Right coronary artery occlusion distally (arrow) by CT and IA (G and H). False-positive proximal stenosis by CTA (G) is not significant on IA (H). During rest (C and D), streak-like beam hardening artifact inferior.
The optimal time point of image acquisition was chosen at 1 time point, as suggested by a myocardial blood flow quantification study showing that the difference in upslope between ischemic and remote myocardium remains relatively constant for several seconds during the entire arterial phase after a minimum delay of 12 seconds. Further, the high-pitch mode is a spiral technique and hence provides the advantage that misregistration step artifacts, as observed for prospective ECG-triggering, are avoided.

The potential advantage of CTP over CMR is the complementary acquisition of CT angiography datasets allowing for both imaging of coronary anatomy and myocardial perfusion. This is of particular interest for 2 different patient groups: First, in patients with intermediate or high-pretest probability of CAD scheduled to undergo coronary revascularization, knowledge about any and which myocardial segments exhibit reversible ischemia provides prognostic information and can aid surgical planning in terms of defining which territories will probably benefit from revascularization. This applies for both planning of percutaneous interventions such as chronic total occlusions (CTO) or of CABG surgery, for which characterization of lesion and distal vessel morphology, can be provided by CTA. Potentially, CTP may solve another limitation of CTA, the detection of in-stent restenosis (Figure 2), which has a sensitivity and specificity of 79% and 81%, respectively, because of artifacts from stent struts causing variable (44% to 48%) artificial luminal narrowing.

Second, in patients presenting with intermediate stenosis of 50% to 70% on coronary CTA, an MPI study (CMR, SPECT, or ECG-treadmill) is required to determine whether a post-IA is necessary. In these patients, the addition of an adenosine stress CTP examination may provide this information while adding only little time and efforts for the patient and physician. Another recent study has shown added value of adenosine stress CTP over CTA by increasing the specificity from 71% to 91% and the PPV from 66% to 86%, respectively, for detection of significant stenosis on invasive angiography.

Our study corroborates this data by revealing similar results. Using our 2-step CTP protocol, it was possible to obtain diagnostic image quality of coronary arteries during rest CTP, allowing for accurate detection of significant coronary artery stenosis (>70%) without additional contrast or radiation exposure. The moderate PPV of CTA compared with IA is in line with the literature and can be explained by a high prevalence of severely calcified coronary arteries in our study population with high probability of CAD. Overall diagnostic accuracy of CTA for detection of coronary stenosis using a combined CTA and CTP protocol is maintained.

The PPV of stress CTP was 91% improved, compared with CTA, with 67% and 84% per segment and per vessel, respectively. More importantly, the intermodality agreement between CT and IA, as well as the accuracy of combined CTP and CTA readouts, improved from 90% to 95%, and the number of false-positive findings decreased from 11 to 4, which is in line with the literature. For the rest-CT, high-pitch mode was used if HR was <63 bpm, because motion artifacts for coronary imaging occur at higher HR, particularly in the right coronary artery. Therefore, we applied prospective dual-step ECG triggering for the rest scan if HR was >63 bpm, which allows for cardiac function analysis and could potentially be used for comprehensive evaluation of regional wall motion abnormalities. For stress CT, high-pitch mode was used in all patients. Despite mean HR during adenosine injection being too high to permit...
reliable analysis of coronary arteries, image quality of the myocardium is less susceptible to motion artifacts than the coronary arteries, and CTP could be assessed in all patients.

Interobserver agreement for CTP was moderate, which can be attributed to the learning curve, because the level of experience between the CT observers was variable.

Study Limitations
We acknowledge a selection bias because our study population exhibited high prevalence of CAD affecting interpretation of specificity. High disease prevalence is a study limitation, which does not permit calculating the accuracy per patient. However, the number of diseased versus nondiseased vessels and segments for the stress CTP versus CMP myocardial perfusion analysis was well balanced and independent. Further studies on patients with low to intermediate likelihood and a higher prevalence of intermediate stenosis are needed.

Second, we did compare CTA and CTP with invasive angiography in a subset of 25 patients who had a high prevalence of diseased vessels; hence, a bias is introduced for the per-vessel–based analysis for the specificity, and NPV lacks statistical power.

Further, some patients had totally occluded or collateralized vessels. In those patients, the myocardial perfusion defects may not strictly be aligned with the AHA segment-based coronary artery territory classification. Therefore, we highlight the direct comparison of myocardial perfusion defects by CTP with CMR.

A high percentage of patients had to be excluded because of contraindications, such as renal dysfunction or arrhythmia.

Contrast volume for 1 CT scan was \( \approx 70 \) mL, resulting in a total of \( \approx 140 \) mL, which is generally well tolerated in patients with normal kidney function but not appropriate in those with dysfunction.

The additional use of CT delayed enhancement could improve the accuracy of CT for the detection of myocardial infarctions but was not included.

Conclusion
Adenosine stress myocardial CTP imaging with 128-slice high-pitch DSCT allows for accurate detection of myocardial ischemia and coronary stenosis, using CMR and IA as the reference standard. Reversible myocardial ischemia can be detected at a very low radiation dose.

In summary, 128-slice dual-source CT is able to overcome shortcomings of coronary CTA, in terms of providing information about reversible myocardial ischemia and infarcts in addition to coronary stenosis. There may be 2 potential clinical applications: First, in patients with high coronary risk profile, known CAD, or those with a high calcium score (>400 Agatston Units), the stress CTP could be performed first. Second, in patients exhibiting intermediate (50% to 70%) stenosis on coronary CTA or in those with in-stent restenosis, CTP could be used. The adenosine stress CT scan could be added after CTA and awaiting elimination of the first contrast bolus (20 to 30 minutes). Further, in patients scheduled for coronary revascularization such as CTO intervention or CAGB surgery, information about both coronary lesion characteristics and myocardial segments with reversible ischemia or infarcts is helpful to plan the procedure.

Disclosures
None.

References


**CLINICAL PERSPECTIVE**

Adenosine stress myocardial CT perfusion imaging with 128-slice dual-source CT in high-pitch mode allows for accurate detection of myocardial ischemia at a very low radiation dose by providing complementary coronary CT angiography. Its clinical utility may be significant in patients with a high coronary risk profile, known coronary artery disease, those with a high calcium score (e.g., >400 Agatston Units), or those with suspected in-stent restenosis in whom severe coronary calcification or artifacts prevent accurate quantification of coronary stenosis by CT angiography. Additionally, in patients exhibiting intermediate (50% to 70%) coronary stenosis on coronary CT angiography, CT perfusion may be able to determine the hemodynamic significance of these lesions. Finally, in patients scheduled for coronary artery bypass surgery or percutaneous revascularization, information about both coronary lesion characteristics and myocardial segments with reversible ischemia or infarcts could be helpful to plan the procedure and provide prognostic information.
Adenosine Stress High-Pitch 128-Slice Dual-Source Myocardial Computed Tomography Perfusion for Imaging of Reversible Myocardial Ischemia: Comparison With Magnetic Resonance Imaging

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