1. Introduction

Advances in X-ray computed tomography (CT) over the past 20 years have enabled non-invasive imaging of the coronary arteries, as well as cardiac structure and function. Coronary computed tomography angiography (CTA) has emerged as an accurate non-invasive imaging modality for identifying the anatomic severity of coronary stenoses.1–3 Similar to other anatomic coronary imaging, coronary CTA alone has been limited in its ability to define the hemodynamic significance of coronary stenoses.4 Since the identification of the presence and severity of ischemia are important parameters for selecting between invasive and medical management of coronary artery disease,5–7 the assessment of both coronary anatomy and myocardial perfusion is needed in some clinical scenarios.

The development of X-ray CT-based myocardial perfusion imaging to determine myocardial ischemia began in the late 1980s. Early investigators used electron beam computed tomography and a fast multislice CT scanning platform to perform quantitative myocardial perfusion imaging with good results.8,9 However, the introduction of multidetector CT and the proven feasibility of coronary CTA over 10 years ago10–13 also allowed for development and refinement of myocardial CT perfusion (CTP) imaging.4,14–16 In single center studies, myocardial CTP imaging has demonstrated high accuracy when compared with single photon emission computed tomography (SPECT), cardiovascular magnetic resonance (CMR), invasive coronary angiography (ICA), positron emission tomography (PET), and invasive fractional flow reserve (FFR).5,14,17–25 Multicenter studies have also established the accuracy of myocardial CTP with coronary CTA.26,27 These studies suggest that CTP is particularly accurate when interpreted in the context of coronary CTA findings.

Currently, there is large body of evidence that establishes myocardial CTP diagnostic accuracy and incremental value over coronary CTA.28 However, an important limitation to myocardial CTP implementation is the heterogeneity within the literature of pharmacologic stress agents, imaging sequences, scanner types, acquisition protocols, post-processing, and interpretation of CTP results. Clinical adoption of myocardial CTP is further hindered by the absence of expert consensus regarding when and how CTP should be performed. The goal of this document is to bring together international experts in myocardial CTP imaging to provide a consensus document that can be used as a resource for clinical implementation, resource allocation, and future investigations.

2. General overview of myocardial CTP, patient selection, and logistics

Myocardial CTP imaging is the contrast enhanced imaging of myocardial perfusion using qualitative, semi-quantitative, or quantitative methods. Myocardial CTP imaging may be performed at rest and during pharmacologically induced stress. An additional acquisition can
be performed 5–10 minutes after vascular contrast washout to detect myocardial scar. The two primary methods of acquisition are static CTP and dynamic CTP. Static CTP, which has been more extensively studied, involves acquisition of a single image during an infusion of iodinated contrast to allow qualitative and/or semi-quantitative CTP assessments. Dual energy CTP is another approach to performing static CTP, which is less widely used, but utilizes different energy photons to better visualize iodine contrast within the myocardium. Dynamic CTP imaging involves acquisition of multiple data sets during the first pass of iodinated contrast from the coronary arteries into the myocardium. Dynamic CTP allows for a qualitative, semi-quantitative, as well as fully quantitative assessment of myocardial perfusion.

Regardless of CTP acquisition mode, patient selection is of utmost importance. Coronary CTA alone has a very high negative predictive value to exclude myocardial ischemia in the presence of no CAD or a non-obstructive stenosis (≤50% severity). Therefore, selection of a myocardial CTP protocol should generally be reserved for situations where the determination of the presence or absence of ischemia can be helpful such as in the presence of coronary artery stenoses of unknown hemodynamic significance, severe coronary calcification, or coronary stents. In the setting of an uninterpretable coronary segment from any cause, myocardial CTP can improve diagnostic accuracy for both stenosis and ischemia. While it is conceivable that patients who have a higher risk of obstructive CAD are more likely to benefit from CTP, models to calculate the probability of obstructive CAD are not widely used and such models often over-estimate the probability of obstructive disease.

If CTP is used to evaluate for myocardial ischemia, pharmacologic stress is required. Resting myocardial blood flow is only decreased by the most severe stenosis, and can be difficult to differentiate from myocardial infarction, making the use of rest CTP alone non-specific for ischemia.

Although stress CTP is safe, there are some circumstances where it should be avoided altogether or only used with caution. Absolute and relative CTP contraindications are listed in Table 1.

Summary: We recommend that myocardial CTP may be added to coronary CTA when patients are at high atherosclerotic risk for obstructive coronary artery disease, including those with prior coronary intervention or significant calcification, or when there is a stenosis of indeterminate functional significance. In such cases, myocardial CTP is recommended if knowledge regarding the presence and severity of ischemia would impact patient management and CTP is feasible.

2.1. Stress CTP procedure logistics

Myocardial CTP imaging with pharmacologic stress testing requires supervision by a trained medical provider who is experienced in the administration of pharmacologic stress agents and stress testing. These clinicians should also be trained in dealing with emergencies related to contrast injection and vasodilator stress testing. Proper resuscitative equipment such as a code cart, defibrillator with transcutaneous pacing capabilities, aminophylline as a reversal agent, bronchodilator therapy, beta-blockers, sublingual nitroglycerin, and epinephrine and diphendydramine should be available in the immediate vicinity.

Prior to starting the study, a focused patient history and physical exam, review or performance of a 12-lead ECG, and informed consent are required to determine suitability of stress testing, similar to other stress testing guidelines. Appropriate intravenous access should then be obtained, typically a 20 gauge or larger IV that can handle the high flows required for contrast injection. During the administration of the pharmacologic stress agent, continuous heart rate/ rhythm monitoring and intermittent blood pressure monitoring are required. Continuous 12-lead ECG monitoring may be performed using radiolucent electrodes and leads. Alternatively, 12-lead ECG monitoring can be interrupted during scan acquisition while continuous rhythm is still being recorded and monitored by the scanner console. Upon the completion of imaging, a 12 lead ECG should be performed to ensure there are no significant changes from baseline suggestive of post-stress myocardial ischemia or injury.

2.2. The use of pharmacologic stress agents, aminophylline and nitroglycerin

Myocardial CTP stress testing uses only vasodilator stress agents at present. Exercise and dobutamine are not practical options for CTP due to the elevated heart rates that would preclude diagnostic imaging with most currently available CT platforms. While there are no agents approved for myocardial CTP, adenosine, dipyridamole, and regadenoson are FDA approved for radionuclide myocardial perfusion imaging. Therefore, their use in CTP imaging is off-label. These agents, their actions and adverse reactions have been extensively reviewed elsewhere. Specific considerations for vasodilator stress CTP include the need for two IV’s for both continuous infusion of adenosine and contrast injection, while regadenoson and dipyridamole require only one IV for alternating injections. A potential disadvantage of regadenoson is the higher heart rate compared with other vasodilators, which may lead to more motion artifacts during CTP acquisition. However, regadenoson tends to be better tolerated and has been tested in single center CTP studies and a randomized diagnostic accuracy study that compared CTP and SPECT myocardial perfusion imaging. Overall, regadenoson was similarly tolerated in regards to adverse events between CTP and SPECT imaging.

Nitroglycerin is commonly used prior to coronary CTA to dilate the coronary arteries and improve coronary artery visualization. Since it is also a vasodilator, simultaneous administration of nitroglycerin and a vasodilator stress agent can lead to hypotension. A 10–20 minute delay between the administration of the two agents is recommended to avoid hypotension. Adequate preload will also decrease the risk of hypotension. The mean elimination half-life of nitroglycerin is 2–3 minutes.

2.3. CT contrast agents

In general, during myocardial CTP, images are acquired during the transit of contrast from the coronary arteries to the myocardium. Because iodinated contrast attenuates x-rays proportionally to the concentration of iodine, hypoattenuated myocardial areas typically represent regions with low blood flow, or hypoperfusion. Typically, 50–70ml of iodinated contrast is injected at a rate of 5–6 ml/sec. A saline bolus (40–50ml) following the contrast bolus with the same injection rate is recommended to assist with contrast delivery to the myocardium. Patients should be warned and educated about the ‘hot flash’ sensation caused by contrast injection. This sensation can be uncomfortable and cause breathing or patient movement that in turn leads to motion artifacts and deterioration of image quality.

3. CTP imaging strategies overview

Myocardial CTP perfusion protocols typically include a rest and a stress CT scan. The rest portion of the scan allows for assessment of the coronary anatomy in addition to rest myocardial perfusion, thus rest images should be acquired according to coronary CTA performance and acquisition guidelines and include the use of beta-blockers and nitrates. However, the optimal sequence of scans (rest first versus stress first) has not been determined and either sequence has advantages and disadvantages. When stress CT imaging is performed first, the myocardium does not have residual contrast in the myocardium from an earlier contrast injection potentially making it easier to detect ischemia. In addition, beta-blocker administration may potentially lead to some underestimation of the ischemic burden, and a stress-first acquisition will allow for delay of beta-blocker administration until after the stress acquisition has been performed. Alternatively, if rest coronary CT angiography acquisition is evaluated first (e.g. prior to stress), patients...
without an obstructive or questionable coronary stenosis would avoid stress CT perfusion. However, areas of myocardial infarction may have delayed contrast enhancement which can potentially be misinterpreted as “normally perfused” myocardium on the stress CTP images. Neither sequence of testing has been shown to be superior. Regardless, delaying 10–20 minutes between the rest and stress CT acquisitions is recommended to minimize myocardial contrast agent contamination and to eliminate the effects of pharmacologic stress or nitroglycerin administration.

**Summary:** Our committee suggests assessment of factors that would impair exclusion of obstructive CAD on coronary CTA (e.g. significant coronary calcium or known CAD) prior to decision to perform CTP. Those patients with known significant coronary disease or severe amount of CAC may undergo stress myocardial perfusion imaging first; whereas, patients who lack the above features may undergo coronary CTA first (Fig. 1). The routine use of coronary calcium scoring prior to stress or resting imaging has been tested and compared against standard of care in a prospective randomized trial and may be a practical, cost-effective approach to design a patient-specific imaging protocol.47 The optimal order of a comprehensive CT perfusion study has not been determined and is a topic of debate.

4. CTP image acquisition

CTP image acquisition is most commonly performed using either static, dynamic, or dual energy approach. Discussion of each of the acquisition modalities is described in detail below and summarized in Table 2.

4.1. Static CTP image acquisition

Static CTP refers to imaging all or portions of the left ventricular myocardium during a single period in time as the contrast transits the myocardium. This method uses retrospective ECG-gating (most often with 64 detector scanners) or prospective ECG-triggering to ensure imaging during specific cardiac phases. Static CTP provides a qualitative or semi-quantitative assessment of myocardial perfusion.14,18,48,117 Conveniently, every coronary CTA is a resting static CTP study. Several studies have demonstrated that a resting CTP has a high sensitivity and specificity for the detection of prior myocardial infarction ranging from 77 to 91% and 79–97%, respectively compared with the reference standard MRI.49–53

Static stress myocardial CTP imaging has been well validated for the detection of coronary stenosis and myocardial ischemia compared to various reference standards including pre-clinical validation, invasive coronary angiography (ICA), single photon emission computed tomography (SPECT), magnetic resonance perfusion, and fractional flow reserve.4,14,15,19,20,117 Advantages of static CTP are its relative simplicity of image acquisition, reduced radiation dose, and ease of image interpretation. Disadvantages include the potential of imaging myocardial contrast off peak enhancement, imaging different myocardial regions at different time points during CT table movement, presence of imaging artifacts, and limitations of only qualitative or semi-quantitative ischemia assessment.

4.1.1. ECG-gating strategy

To date, there is no definitive data available to provide guidance on whether prospective or retrospective ECG gating is preferred for all patients. The consensus of this committee is that retrospective ECG gating is favored when smaller z-axis detectors (<8 cm) are utilized to allow for whole heart coverage in order to reduce artifacts at the transition zones. Alternatively, prospective ECG triggering is favored for large z-axis coverage scanners (≥8 cm) and if the phase acquisition window can be widened to allow for the acquisition of additional cardiac phases (i.e. at least 20% of the RR interval). There is currently no definitive data to recommend the optimal portion of the cardiac cycle to acquire images. CTA is generally imaged at 65–75% of the R to R interval relative cardiac motion quiescence, or “diastasis”. As the heart
rate increases, such as during the administration of a pharmacological stressor, diastasis becomes shorter and occurs later in the cardiac cycle. In heart rates over 80 beats per minute, the phase of relative cardiac quiescence may occur during end-systole (approximately 30–50% of the R to R interval). The systolic phase may be preferred at higher heart rates due to a shorter and more stable duration of about 200 msec and it may be less affected by extrasystolic events. In addition, the intraventricular amount of contrast is lower compared with the diastolic phase, which may reduce beam-hardening artifacts and fluctuations in myocardial CTP measurements.54,55

There is no consensus about whether imaging should be performed at end-systole or during diastole although most larger trials to date have selected diastole. When performing stress CTP, a multiphase acquisition which includes phases from both systole and diastole can be considered so that the phase with the least amount of artifact can be selected for analysis retrospectively.

4.1.2. Contrast timing

Optimal CTP contrast timing is determined manually by contrast timing bolus or using an automated bolus-tracking algorithm.56 If an automated bolus-tracking algorithm is utilized, a region of interest should be defined in either the proximal-ascending or mid-descending thoracic aorta. The automated trigger should be set to a Hounsfield Unit (HU) threshold that is ~80-100HU above the baseline HU of the reference area immediately prior to the contrast injection. After the scanner is triggered, a short pause (~5 seconds) is required to allow for breath-hold instructions to be given. Contrast dose and flow rate is typically ~60–70ml injected at 5–6ml/sec. Higher doses of contrast may be required if a single source 64 slice CT scanner is being used. Imaging is performed during suspended breathing after peak hyperemia is achieved.

4.1.3. Static CTP minimum scanner requirements

Static CTP imaging requires a CT system capable of acquiring high spatial resolution images of the entire heart within a short time interval while patients are holding their breath. This includes virtually all contemporary 64 slice or greater CT scanners. The temporal resolution of a CT scan is determined by the time required to acquire the data for reconstruction of a single transverse section or “slice”. The speed of gantry rotation is one of the primary determinants of the temporal resolution of the CT scan. In CTP, high temporal resolution minimizes motion artifacts related to a fast heart rate or cardiac contractility that typically occurs during the administration of a pharmacological stressor. The minimum gantry rotation time on current generation scanners (the time required to complete a 360° rotation) is between 250 and 400 ms, depending on the manufacturer and model. Software and hardware improvements have further increased temporal resolution. The routine use of half-scan reconstruction results in an effective temporal resolution of approximately one half the time required for the typical 360° CT rotation, or a reduction to approximately 125–200 ms per rotation. Dual-source CT scanners equipped with 2 sets of x-ray sources and detectors offset by ~90° from each other achieve temporal resolution of approximately 65 ms. Disadvantages of partial- or half-scan reconstructions are decreases in the stability of Hounsfield units within the images due to geometrical and misregistration artifacts. Hybrid reconstruction protocols utilizing a combination of half-scan data for image detail and full-scan (360°) data for contrast resolution

<table>
<thead>
<tr>
<th>Imaging Modality</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static CTP perfusion</td>
<td>Single image taken at peak myocardial perfusion to visualize hypoattenuation (hypoperfusion)</td>
<td>• Technically simple</td>
<td>• Qualitative to semiquantitative analyses only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can use CCTA images for rest CTP</td>
<td>• Timing of CTP acquisition critical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low radiation exposure</td>
<td>• Need normal segment to identify abnormal perfusion</td>
</tr>
<tr>
<td>Dynamic CTP perfusion</td>
<td>Repeated images over time to create time attenuation curves (TACs)</td>
<td>• Semiquantitative myocardial blood flow (MBF) and volume (MBV) assessment possible</td>
<td>• Increased scanner hardware requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Modeled, fully quantitative myocardial blood flow (ml/min/g) assessment possible</td>
<td>• Lower detector systems may require shuttle mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Potential to detect balanced and microvascular ischemia</td>
<td>• CTP artifacts common</td>
</tr>
<tr>
<td>Dual Energy CTP perfusion</td>
<td>Separate energy X-ray beams used to distinguish myocardium, contrast attenuation, and other structures</td>
<td>• Higher contrast differentiation than other CTP modalities</td>
<td>• Higher radiation exposure when compared to static CTP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Beam hardening correction possible</td>
<td>• Additional software requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Additional quantification approaches possible</td>
<td>• Specific scanner hardware requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Additional software requirements</td>
</tr>
</tbody>
</table>
may provide an advantage. The high, nearly isotropic, spatial resolution with most modern scanner are less important for visualizing perfusion defects in the myocardium as discussed later in the CTP reconstruction methods.

4.2. Dynamic CTP image acquisition

Dynamic CT perfusion imaging refers to the imaging of myocardial contrast enhancement by taking multiple sequential CTP images over time as the contrast transits through the heart. The myocardial contrast enhancement images can be analyzed visually or their enhancement over time can be quantified in order to create time-attenuation curves (TAC). These TACs are proportional to myocardial blood flow and can be evaluated in various ways as explained below. Advantages of dynamic CTP include the ability to quantify myocardial blood flow (MBF), myocardial blood volume, and potentially other hemodynamic parameters by applying mathematical models to vascular contrast enhancement and the tabulated myocardial TACs (Table 3). The parameters used and how accurately they can be determined depends strongly on the temporal sampling rate. The disadvantages of dynamic CTP protocols are the radiation exposure is higher than that of static CTP, cardiac and patient motion, and lack of standardized models to quantify blood flow. To reduce radiation dose, automatic tube current modulation can be useful with spiral dynamic perfusion CT and iterative reconstruction techniques to maintain image quality with lower radiation exposure (58) can be used. Myocardial misregistration from patient and cardiac motion during the relatively long dynamic CTP image acquisition can be reduced using motion correction algorithms.

4.2.1. Dynamic CTP minimal scanner requirements

Dynamic perfusion imaging requires a system capable of acquiring repeated moderate spatial resolution images that cover the entire myocardium (which in adults is about 7–10cm) within the 20–30 second breath hold required for contrast transit. High temporal resolution is required to minimize motion artifacts related to a fast heart rate during pharmacologic stress or patient breath hold. Sufficient temporal sampling is required for TAC generation and quantification or semi-quantification of myocardial perfusion. Second and third generation dual-source computed tomography (CT) systems and later generation single-source CT systems fulfill these requirements. The number of longitudinal detector rows/data channels that can simultaneously measure x-ray attenuation determines the volumetric z-axis coverage of the CT scanner. Both 64-detector CT and first-generation dual-source CT have limited z-axis coverage per gantry rotation (~4 cm), if the table remains in the same position. For these scanners, the CT table and patient need to move back and forth through time (shuttle mode) to cover the entire myocardium. In second- and third-generation dual-source CT and z-axis coverage of 38–40 mm, ECG-triggered sequential-scanning with table movement back and forth between the two scanning positions provides a final coverage of 7.3–8cm. This coverage is limited but large enough to collect information about myocardial perfusion in the end-systolic phase, when the size of the heart is smaller and the thickness of the myocardial wall is higher (compared with diastolic phase).

Using higher slice systems with larger z-axis coverage (detector width of 12–16 cm) provides whole heart coverage per gantry rotation. However, the lower temporal resolution of these systems increases the risk of motion artifacts with higher heart rates. This may be mitigated, to some extent, by the use of multisector reconstruction.

4.2.2. Timing of the scan and frequency of temporal sampling

Dynamic perfusion relies on accurately measuring arrival, peak and washout of the first pass of myocardial contrast and aorta or left ventricle over time. CTP images should be acquired during the early portion of first-pass circulation, when the iodinated contrast is mainly intravascular. Images are then acquired repeated at different time points yielding the various temporal frames of the dynamic dataset, generally 1–3 seconds apart. Each frame of the dynamic dataset generates a point of the TAC in each voxel of the myocardium, as well as a point of the arterial input function in the aorta. Other crucial time points include at least one baseline (pre-contrast) frame including the point of the arterial input function in the aorta. Other crucial time points include at least one baseline (pre-contrast) frame including the whole myocardium, and adequate frames to define the upslope, peak and early portion of the downslope of the time-attenuation curves.

4.2.3. Dual-source CT

Dual source CT with detector coverage that cannot cover the entire myocardium requires “shuttling” the patient back and forth to image the myocardium over time. With the shuttle mode technique, CT data

<table>
<thead>
<tr>
<th>CTP Measure</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Static CTP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualitative</td>
<td>Visual analysis of perfusion defects (fixed vs reversible, transmural vs endocardial)</td>
<td>• Simple</td>
<td>• May be more susceptible to artifact and interpretation errors</td>
</tr>
<tr>
<td>Transmyocardial perfusion ratio (TPR)</td>
<td>Ratio of endocardial to epicardial attenuation.</td>
<td>• Simple analysis</td>
<td>• Dependent on good image quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Simple adjunct</td>
<td>• Susceptible to artifact</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Semiquantitative</td>
<td>• Unclear if added value over qualitative assessment</td>
</tr>
<tr>
<td>Dynamic CTP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualitative</td>
<td>Visual analysis of transit of contrast over time</td>
<td>• Simple</td>
<td>• May be susceptible to artifact and interpretation errors</td>
</tr>
<tr>
<td>Myocardial Perfusion Reserve Index</td>
<td>Ratio of stress-over-rest myocardial peak attenuation or upslope of myocardial attenuation curves normalized to the corresponding arterial TAC parameter.</td>
<td>• Rapid analysis</td>
<td>• Semiquantitative</td>
</tr>
<tr>
<td>Quantitative myocardial blood flow (MBF) or myocardial blood volume (MBV)</td>
<td>Modeled calculation of absolute MBF or MBV from arterial and myocardial time attenuation curves</td>
<td>• Simple calculation</td>
<td>• Questionable accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Shorter imaging time</td>
<td>• Imaging of peak attenuation critical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fully quantifiable flow (ml/min/gram)</td>
<td>• Longer scan and more susceptibility to artifacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Higher quantification accuracy</td>
<td>• Requires dynamic CT imaging</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Errors within model are possible</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Higher radiation than other CTP</td>
</tr>
</tbody>
</table>

Table 3 Approaches for assessment and quantification of myocardial perfusion.
are acquired at two alternate table positions by moving the table back and forth covering the entire myocardium in the end-systolic phase. Each stack contains attenuation data of the blood pool in the descending aorta or left ventricular cavity as well as attenuation data of the myocardium. Second and third generation dual-source technology allows CTP acquisition at every heart beat for up to 63 beats per minute, and every second heart beat above 63 beats per minute, in keeping with a temporal sampling of 2–3 s under pharmacological stress conditions. These are generally sufficient to allow the estimation and fit of the TAC while limiting radiation exposure to patients. This allows construction of the arterial input function with double temporal sampling compared to the myocardium, and provides sufficient time points for the construction and fitting of the TACs for both in left ventricle or aorta (arterial input function) and in each voxel of the myocardium (tissue). The scan typically acquires 10–15 whole myocardial volumes corresponding to 10–15 time points (or frames) over 20–30s.

4.2.4. Single source CT

Single source CT with smaller (<8 cm) coverage also requires "shuttling" the patient back and forth over time, similar to dual source CT, but may not have the temporal resolution to obtain all needed data points for TAC generations. Larger coverage scanners (>8 cm) image the whole heart every rotation without table motion. This is achieved with the 320-detector CT scanner that can provide up to 16 cm of coverage along the z-axis. This allows image acquisition of the heart within a fraction of a single heartbeat, with more homogeneous contrast attenuation of the myocardium and no reconstruction slab artifacts. Single source scanner generally require a minimum number of scans (~10–15) to generate robust TAC although more recent data are challenging this requirement. Contemporary acquisition protocols can also vary the sampling rate during the passage of contrast, to obtain more data points during the important upslope portion of the TAC.

4.2.4.1. Image artifacts for static and dynamic CTP

Beam hardening is a well-known artifact which occurs when x-ray beams pass through high-density objects, in which lower energy beams are absorbed, leading to a hypoenhanced region that may appear as a falsely-positive perfusion defect. This commonly occurs in the basal inferolateral wall, which is adjacent to the contrast-enhanced descending aorta. There are a number of reconstruction algorithms that have been described in an effort to correct for beam hardening, but it remains a problematic artifact in CT-MPI imaging.

The visual interpretation of perfusion defects in CT-MPI can be limited by suboptimal image quality and relatively poor signal-to-noise ratio due to patient body habitus and the desire to minimize radiation exposure to the patient. Iterative reconstruction algorithms have been developed in an effort to reduce image noise in CT. These algorithms provide improved signal-to-noise and contrast-to-noise ratios without requiring an increase in radiation. This new reconstruction strategy is especially promising for CTP imaging, as it offers an effective way to acquire additional images with only minimal radiation exposure, without compromising imaging quality and diagnostic accuracy.

4.3. Dual energy CTP

Overview. Dual energy CT (DECT) imaging produces a spectrum of photon strengths (kVp) during CT acquisition that, when measured with modern CT scanners, are processed into different imaging spectra. DECT has the ability to differentiate iodinated contrast from background tissue, water and fat by utilizing the reactions of each of these substances to photons at the so called "k-edge". DECT has the advantage of overcoming some challenges of interpreting CTP images such as beam hardening artifacts and the relatively low contrast to noise ratio needed to keep radiation exposure judicious over several heartbeats. DECT scanning techniques vary according to the type of scanner whether it has one or two x-ray tube sources.

Dual Source DECT. In the dual source scanners, two tubes are placed perpendicular in the same gantry with an angle offset of ~90°. One of the tubes operates at 140 kV and the other at 80–100 kV. A limitation of this approach is that when both sources are active at the same time, cross-scatter can result in artifacts and degraded contrast-to-noise ratio. The best achievable temporal resolution in this configuration is 165 milliseconds; however, reconstruction algorithms have been described that may further improve this. DECT perfusion studies with dual source are acquired with retrospective ECG-gating and ECG-dependent tube current modulation.

Single Source DECT. There are currently two approaches for dual energy CT using only one x-ray tube source: the rapid kV switching during rotation and the dual layer detector approach. With the first approach, rapid KV switching occurs within a single tube between low and high tube potentials every 0.5 milliseconds and are generally 80 and 140 keV. Each pair of 80 and 140 keV projections are basically obtained from an identical view angle. DECT using this approach only operates in a prospective ECG-triggered mode and a wider padding is required for imaging both systolic and diastolic phases. With the second approach, a dual layer detector system utilizes two different scintillating materials fused together with a single source CT gantry. The upper layer detects the lower energy photons and permits higher energy X-ray photons to pass through it to be detected by the lower layer. The two signals for the two detectors would resemble two x-rays in two different energy ranges. Advantages of this design is that at each view the high- and low-energy projections are exactly registered with respect to each other. A potential disadvantage is less spectral separation between low and high energy projections that can lead to an inadequate material decomposition and beam hardening correction.

4.3.1. Image reconstruction and analysis using DECT

DECT allows for two types of analyses, either monochromatic examination or material decomposition, to reduce beam hardening and other artifacts. The monochromatic examination renders each image at a monochromatic energy level over a wide spectrum of energies that ranges between 40 keV and 140 keV. This means that for each image, there are several possible energy levels for discrimination of chemical composition by mapping the differing interactions with x-ray photons. Those with high atomic number has inverse conspicuity, or HU density, to photon energy with DECT. High atomic numbers result in higher density (HU) at lower energy levels (for example, 40 keV) and lower density (HU) at higher energy levels (140 keV). Iodinated contrast has a high atomic number and thus has a higher density at low energy levels and a relatively lower conspicuity at high energy level reconstructions. While low energy levels depict higher contrast enhancement in the myocardium, they are associated with increased noise, and are subject to increased beam hardening artifacts that can mimic perfusion abnormalities and increase false positive readings unless dedicated algorithms are used. Conversely, higher energy levels yield lower myocardial and intravascular contrast but lower image noise, and decreased beam hardening artifacts. Thus, DECT may reduce or even eliminate beam hardening by generating monochromatic images. Once the optimal energy level is determined, grayscale, color mapped, or color-overlaid images can be utilized for analysis. Semi-quantitative and quantitative analysis can be complemented in a similar manner to single energy CT as described below.

The second type of DECT evaluation is material decomposition (MD). MD is based upon different attenuation coefficients of various tissues, which in turn depend on the energy levels of the X-ray beam.
MD yields information about tissue atomic number and can provide “mass density maps” for basic materials such as water or iodine. MD allows the visual isolation of a material as well measurement of its concentration in a given voxel (mg/Ugr/mm³). In myocardial CTP, the amount of iodine can be measured in order to establish normal or an abnormal perfusion. MD can be portrayed in grayscale or in color scale.

5. CTP image analysis Overview

We recommend interpretation of coronary CTA and myocardial CTP images be performed concomitantly. Accordingly, workstations used for CTP interpretation should possess all requirements for standard coronary CTA interpretation. This constitutes the ability to facilitate two and three-dimensional display of the coronary arteries and the myocardium subtended in all conventional reconstruction formats. These include axial and multiplanar reformations (MPR), maximum intensity projections (MIP), minimal intensity projections (MinIP), and average projections. If dynamic CTP is performed, then software that allows visualization of myocardial enhancement over time is also required.

CTP images should be viewed using the available cardiac phases to reduce motion-related artifacts. Diagnostic accuracy may be improved by the use of additional image reconstructions performed at a phase with the least cardiac motion. For this reason, images may be reconstructed from multiple phases of the cardiac cycle, typically at 5–10% intervals. Raw CTA and CTP data files should be retained until image interpretation is complete. Images may be viewed in systolic and/or diastolic phases, depending on acquisition parameters.

CTP images may be viewed in static and/or dynamic CTP modes, depending on the acquisition. If available, qualitative and quantitative ventricular function should be reported including regional wall motion abnormalities to correlate with the CTP findings.

5.1. Static CTP image analysis

In static visual CTP interpretation, myocardial images are typically arranged using three standard orthogonal views - the short axis, vertical long axis, and horizontal long axis (Fig. 2). CTP images usually use a narrow window width of 200–300 and level setting of 100–150 with an average slice thickness of 5–8 mm. Images may be viewed in minimal intensity projection (MinIP) or average intensity projections, although the former may be more sensitive. CTP images should be automatically or visually divided into standard American Heart Association 17 myocardial segment model. Dedicated perfusion software platforms should also allow side by side display and comparison of rest and stress images to examine the presence and extent of reversibility of perfusion defects. The ability to review the perfusion images acquired during different cardiac phases in order to determine if a potential perfusion defect persists during multiple phases of the cardiac cycle can help improve diagnostic confidence. In the event a true perfusion defect has

Fig. 2. Potential display for static CTP images. A surface rendered image (bottom left) suggests the presence of a stenosis in the left anterior descending artery. Stress CTP images are shown in the 2-chamber (top left), 3-chamber (top middle), and short axis (bottom middle) imaging planes and demonstrate the presence of an apical anterior perfusion defect. The finding is verified on the quantitative bullseye plots (top and bottom right).
been identified, visual coronary CTA analysis or automated software should enable the interpreter to track the stenosis in the major epicardial coronary artery or branch that subtends the myocardial segment with the corresponding perfusion defect.

5.1.1. Semi-quantitative analysis for static CTP

Qualitatively, perfusion defects are visually evaluated using the American Heart Association 17-segment model. We recommend that perfusion defects be “scored” using the following:

1) Severity. Hypoperfusion severity should be scored by whether hypoperfusion is present (binary). In addition, it may be useful to describe the severity of the defect using a continuous scale of mild, moderate, or severe.

2) Size. The size of the perfusion defect (small, medium, or large) should be described, as well as whether it is transmural (>50%) or non-transmural (<50%).

3) Reversibility. Perfusion defects should also be described as reversible (perfusion defect present only on the stress CTP images), fixed (perfusion defect present and similar on both rest and stress CTP images), or partially reversible (perfusion defect present on both the stress and rest CTP images but less pronounced of the rest images).

CTP software is also available which permits evaluation of other semi-quantitative metrics such as the transmural perfusion ratio (TPR), absolute contrast map and various other types of perfusion indexes. TPR is the ratio of the subendocardial attenuation of a specific segment of myocardium and the entire epicardial attenuation. This index has been validated using quantitative coronary angiography and fractional flow reserve, and can be used to guide visual reads. This can be displayed as an average for the entire myocardial segment or within each pixel of the segment using a 17-myocardial segment polar plot which effectively presents a 34 segment model. Another proposed CTP index normalizes myocardial subendocardial perfusion to the LV cavity HU density resulting in a segmental myocardial perfusion index. This allows for different “normal” CTP attenuation in certain segments that are prone to more attenuation due to adjacent structures, such as the basal inferior wall. A related semi-quantitative CTP method measures the 3-dimensional myocardial attenuation in volumetric myocardial segments, which is normalized to the LV cavity but also compared to a histogram of a reference normal myocardial segment from a library of normal individuals. The hypoenhanced voxels in a myocardial segment reflects the relative volume of perfusion defect, and the defect severity is estimated by the difference in the positions of peaks of the attenuation histogram of the particular segment of interest and the reference segment. Together, these indices are used to estimate an overall defect volume and severity. This normalized voxel assessment has been shown to have good agreement with SPECT MPI for rest CT-MPI, with improved detection for CAD noted with the addition of stress CT-MPI. Despite the number of available methods for semi-quantitative assessment of myocardial perfusion for static CTP, there is no clear benefit of using one method over another and the authors can make no recommendations for preferential use of any technique at present.

5.2. Semi-quantitative analysis for dynamic CTP

The result of the dynamic perfusion acquisition is a sequence of volumetric CT scans, each consisting of overlapping axial slices usually with a thickness of 1.5–3mm. The individual CT images are characterized by a low contrast-to-noise ratio. Although more difficult to interpret than static perfusion scans, enhancement heterogeneity may readily be observed on the source images. From the time-resolved data and temporal changes in CT attenuation it is possible to investigate a range of myocardial perfusion parameters. The measured CT attenuation values show a linear relation with the iodine concentration. Sampling the myocardium or myocardial region of interest and then charting the myocardial attenuation values over time create time-attenuation curves (TACs). The time-attenuation curves provide a semi-quantitative measure of myocardial perfusion by normalizing against slope or peak of the attenuation curve measured in the left ventricle or aorta which is related to the arterial blood flow supplying the myocardium and can be compared between different myocardial regions. Ischemic myocardium will demonstrate a shallower upslope and lower peak compared to normal myocardium.

5.2.1. Post-processing for quantitative analysis for dynamic CTP

Depending on the CT scanner and myocardial perfusion package used, a number of pre-processing steps may be required. Correction of myocardial displacement between phases is essential to measure changes in attenuation. Phases with non-correctable displacement, perhaps due to arrhythmia, may be entirely deleted from the analysis. To measure the change in myocardial attenuation, it is important to acquire one or more non-enhanced datasets, that serve as the baseline, non-enhanced image for the TAC. To quantify the myocardial blood flow, both a measure of the arterial input function and myocardial flow are needed to model blood flow calculations in absolute blood flow units (ml/min/gram of myocardial tissue). The arterial input function can be approximated by placing a region of interest in the descending thoracic aorta or left ventricular cavity and sampling the attenuation over time. For shuttle-mode acquisitions, it is important to place a region of interest both in the upper and lower part of the scan to increase the sampling rate. The software application may require further preparation steps, such as isolation of the myocardial volume, or adjustment of the image filtering to avoid excessive image noise. Semi-automated software applications exist to perform these functions, but require visual conformation and possibly manual adjustments by experienced users to optimize quantitative measures.

5.2.2. Quantitative analysis for dynamic CTP

Calculation of absolute parameters of myocardial perfusion requires more complex iodinated contrast kinetic modeling. Generally, two-compartment models are applied that consider the blood flow into the myocardium, the myocardial blood flow itself, and the extra-vascular extraction rate of the contrast into the interstitial space. The most investigated method is the deconvolution model. By this approach, the arterial input function, the tissue TACs, and the assumed temporal exchange of contrast between the vessel and the interstitial space over time (assuming a short contrast bolus) are deconvoluted with a CTP model to derive quantitative flow. Preferably the sampling interval should be less than the shortest transit time, although the number of CTP images is limited by the scanner configuration and radiation dose. The duration of scanning is further limited by the time of the breath hold.

Other processing techniques have been reported although none have not been widely validated. Patlak plot analysis was reported as an approach to calculate myocardial blood flow. To overcome the limited number of images over time and specifically designed for the shuttle-mode perfusion imaging technique, is a hybrid model combining a simplified deconvolution algorithm with the maximum-slope method. Using this method, myocardial blood flow can be calculated by dividing the maximum slope of the fit model curve by the peak of the arterial input function. In addition to myocardial blood flow, myocardial blood volume may also be calculated. While other independent or derived hemodynamic parameters may be calculated, which have established value in non-myocardial dynamic contrast enhanced imaging applications, these parameters have not been extensively investigated for myocardial perfusion imaging. The most
commonly used approaches for assessing myocardial perfusion using static and dynamic CTP are summarized in Table 3.

5.2.3. Image display for dynamic CTP

For qualitative assessment, the dynamic perfusion images may be displayed in the same orthogonal cardiac imaging planes as static CTP with similar settings. Dynamic CTP images should be viewed during contrast enhancement as a cine loop to qualitatively view of myocardial contrast uptake over time. This also allows for visual confirmation of significant patient or cardiac motion that may affect myocardial co-registration over time. The results may also be displayed using color-coded maps, where the shading represent particular myocardial perfusion values, such as myocardial blood flow or volume. The voxel-based functional imaging maps may be sampled for (averaged) regional perfusion values. While quantification of myocardial perfusion values should be used to differentiate normal, ischemic, and infarcted myocardium, there is no accepted positivity criterion with threshold values that may be applied for interpretation. Thus, currently, relative differences in perfusion values between different myocardial segments has been adopted in clinical practice.

6. CTP clinical studies

6.1. Static CTP clinical studies

Current evidence on the feasibility (efficacy) of static myocardial CT perfusion imaging using contemporary CT scanners is summarized in Table 4. Overall, studies range from proof-of-concept studies to multicenter studies demonstrating a promising performance by static perfusion CT for the detection of functionally relevant CAD, with incremental diagnostic value over CT angiography alone. The reference standard varied significantly among the studies and included SPECT, MRI, PET, invasive angiography, and invasive measurement of FFR for hemodynamically significant lesions.

Table 4
Summary of available studies validating static CTP.

<table>
<thead>
<tr>
<th>Scanner type</th>
<th>Imaging protocol</th>
<th>Reference standard</th>
<th>N</th>
<th>Radiation Dose (mSv)</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurata et al.</td>
<td>Retrospective</td>
<td>SPECT-MPI</td>
<td>12</td>
<td>Not reported</td>
<td>90</td>
<td>79</td>
</tr>
<tr>
<td>George et al.</td>
<td>Retrospective</td>
<td>QCA/SPECT-MPI</td>
<td>27</td>
<td>16.8 (64 CT)</td>
<td>81</td>
<td>85</td>
</tr>
<tr>
<td>Blankstein et al.</td>
<td>Retrospective</td>
<td>QCA/SPECT-MPI</td>
<td>33</td>
<td>9.1</td>
<td>93</td>
<td>74</td>
</tr>
<tr>
<td>Rocha-Filho et al.</td>
<td>Retrospective</td>
<td>QCA</td>
<td>34</td>
<td>9.8</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>Okada et al.</td>
<td>Retrospective</td>
<td>QCA</td>
<td>47</td>
<td>10.0</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>Cury et al.</td>
<td>Retrospective</td>
<td>QCA</td>
<td>26</td>
<td>3.4</td>
<td>88</td>
<td>79</td>
</tr>
<tr>
<td>Ko S. et al.</td>
<td>Retrospective</td>
<td>MRA-MPI</td>
<td>41</td>
<td>8.6</td>
<td>91</td>
<td>72</td>
</tr>
<tr>
<td>Tamarapoo et al.</td>
<td>Retrospective</td>
<td>MRA-MPI</td>
<td>30</td>
<td>15.7</td>
<td>92</td>
<td>86</td>
</tr>
<tr>
<td>Fechtner et al.</td>
<td>Retrospective</td>
<td>MRA-MPI</td>
<td>30</td>
<td>0.9</td>
<td>96</td>
<td>95</td>
</tr>
</tbody>
</table>

* Number of patients in the study who underwent both CTP and reference standard imaging modality.
* Radiation dose only for the stress perfusion acquisition.
* Only the radiation dose for both stress and rest perfusion was reported.
* Assuming a summed stress score of 4.
* Per patient results available only.

6.2. Dynamic CTP clinical studies

Current evidence on the feasibility of dynamic myocardial CT perfusion imaging using contemporary CT scanners is summarized in Table 5. Overall, studies were proof-of-concept studies demonstrating a promising performance by dynamic perfusion CT for the detection of functionally relevant CAD, with incremental diagnostic value over CT angiography alone. The reference standard varied significantly among the studies and included SPECT, MRI, PET, invasive angiography, and invasive measurement of FFR with different FFR thresholds (0.75 vs. 0.80) for hemodynamically significant lesions. Also, derived myocardial perfusion parameters (i.e. myocardial blood flow and volume) were not employed in a standardized fashion to serve as a positivity criterion. The reported associated radiation exposure varied but ranged from 5.3 to 13.1 mSv. Reported technical limitations included limited coverage of the perfusion volume and cardiac and patient motion during long breath holds of up to 30 seconds.

6.3. Dual energy clinical studies

Current evidence on the feasibility (efficacy) of dual energy myocardial CT perfusion imaging is summarized in Table 6.

7. CTP interpretation and reporting

The components of a CTP structured report should include information regarding the following:

7.1. Clinical history and indications

This section should include the main clinical indication for the study and specific signs and symptoms to support the clinical indication.

7.2. Technique or procedure description

This section should include pertinent information of image
acquisition and image reconstruction of coronary CTA and myocardial CT perfusion. Several aspects of image acquisition should be included, such as:

- type of studies (including calcium score, CCTA, rest and stress myocardial CT perfusion, delayed enhancement CT),
- equipment (scanner type – 64-slice, 128-slice, 256-slice, 320-slice or dual-source),
- technical acquisition protocol (with reference to both stress and rest/CTA acquisition as well as acquisition modes: prospective vs retrospective, static vs dynamic perfusion),
- type and amount of contrast (for both stress and rest/CTA acquisitions),
- medications use (including stress vasodilator agent and sequence of testing, such as rest then stress CTP),
- clinical parameters during the procedure, including heart rate and any complications or side effects (particularly symptoms or side effects during the administration of stress vasodilator agent).
- Image Reconstruction should include all the performed reconstruction modes and descriptions for any semi-quantitative or quantitative methods used.

7.3. Findings

The study quality needs to be described for each component of the examination and the presence of any significant artifacts that may affect image quality and study interpretation. The artifacts specific to coronary CTA and myocardial CTP should be included in the report, such as beam hardening artifacts, motion artifacts, misalignment, etc.

Perfusion defects should be assessed qualitatively by comparing the rest and stress acquisitions based on the severity (mild, moderate and severe), extent (small, medium and large) and reversibility (reversible, partially reversible and fixed) as described above. Quantitative or semi-quantitative information can be included, if such techniques were utilized. When available, global and regional ventricular function assessment should be included, particularly in association with any myocardial perfusion abnormality.

Coronary CTA findings should be described separately in a per-vessel and per segment distribution for stenosis and plaque assessment following the updated SCCT guidelines for interpretation and reporting. This includes a complete report of the non-coronary cardiac structures.

### Table 5

Summary of available studies on the diagnostic accuracy of dynamic myocardial CT perfusion imaging. CAD: coronary artery disease; cMRI: cardiac magnetic resonance imaging; FFR: invasive measurement of fractional flow reserve; PET: positron emission tomography; DSCT: dual-source computed tomography.

<table>
<thead>
<tr>
<th>Author name</th>
<th>Scanner type</th>
<th>Imaging protocol</th>
<th>Reference standard</th>
<th>N</th>
<th>Radiation Dose [mSv]</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bastarrrika et al. 92</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>cMRI</td>
<td>10</td>
<td>1290.4 ± 233.3 mGy cm</td>
<td>86.1</td>
<td>98.2</td>
</tr>
<tr>
<td>Ho et al. 93</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>SPECT</td>
<td>35</td>
<td>9.15 ± 1.32 mSv (stress)</td>
<td>83</td>
<td>78</td>
</tr>
<tr>
<td>Weininger et al. 94</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>SPECT</td>
<td>20</td>
<td>12.8 ± 2.4 mSv</td>
<td>86</td>
<td>98</td>
</tr>
<tr>
<td>Kono et al. 95</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>FFR</td>
<td>42</td>
<td>9.4 mSv</td>
<td>97.8</td>
<td>69.6</td>
</tr>
<tr>
<td>Bamberg et al. 96</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>FFR</td>
<td>33</td>
<td>10 ± 2</td>
<td>93</td>
<td>87</td>
</tr>
<tr>
<td>Kurata et al. 97</td>
<td>256 detector rows</td>
<td>Stationary</td>
<td>Invasive Angiography</td>
<td>11</td>
<td>10.4</td>
<td>100</td>
<td>78.6</td>
</tr>
<tr>
<td>Bamberg et al. 98</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>eMRI</td>
<td>38</td>
<td>11.08 ± 2.0</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Wang et al. 99</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>SPECT</td>
<td>30</td>
<td>12.8 ± 1.6</td>
<td>90</td>
<td>81.4</td>
</tr>
<tr>
<td>Kim et al. 100</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>eMRI</td>
<td>33</td>
<td>5.7 ± 1.0</td>
<td>82</td>
<td>84</td>
</tr>
<tr>
<td>Ebersberger et al. 101</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>SPECT</td>
<td>37</td>
<td>9.6 ± 4</td>
<td>86</td>
<td>96</td>
</tr>
<tr>
<td>Greif et al. 102</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>FFR</td>
<td>65</td>
<td>9.7 ± 2.2</td>
<td>95.1</td>
<td>74.7</td>
</tr>
<tr>
<td>Kikuchi et al. 103</td>
<td>Shuttle</td>
<td>Single Temporal Volume O-H2O-PET</td>
<td>O-H2O-PET</td>
<td>32</td>
<td>12.8 ± 2.9</td>
<td>85.7</td>
<td>92.3</td>
</tr>
<tr>
<td>Rossi et al. 104</td>
<td>DSCT</td>
<td>Shuttle</td>
<td>FFR</td>
<td>80</td>
<td>9.4</td>
<td>84</td>
<td>81</td>
</tr>
<tr>
<td>Huber et al. 105</td>
<td>256 detector rows</td>
<td>Stationary</td>
<td>FFR</td>
<td>32</td>
<td>9.5</td>
<td>75.9</td>
<td>100</td>
</tr>
<tr>
<td>Pontone et al. 106</td>
<td>256 detector rows</td>
<td>Stationary</td>
<td>FFR</td>
<td>85</td>
<td>5.3 ± 0.7 mSv</td>
<td>73%</td>
<td>86%</td>
</tr>
</tbody>
</table>

### Table 6

Summary of CT Perfusion studies validating dual energy CTP.

<table>
<thead>
<tr>
<th>Author name</th>
<th>Scanner type</th>
<th>Imaging protocol</th>
<th>Reference Standard</th>
<th>N</th>
<th>Average CT Dose [mSv]</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruzsics 2009 107</td>
<td>DSCT</td>
<td>Shuttle, Rest</td>
<td>SPECT</td>
<td>36</td>
<td>14</td>
<td>97</td>
<td>67</td>
</tr>
<tr>
<td>Bauer 2010 108</td>
<td>DSCT</td>
<td>Shuttle, Rest</td>
<td>CMR</td>
<td>36</td>
<td>9.7</td>
<td>77</td>
<td>97</td>
</tr>
<tr>
<td>Nagao 2010 109</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>SPECT, ICA</td>
<td>10</td>
<td>NR</td>
<td>86</td>
<td>75</td>
</tr>
<tr>
<td>Nance 2011 110</td>
<td>DSCT</td>
<td>Shuttle, Rest</td>
<td>ICA</td>
<td>12</td>
<td>NR</td>
<td>91</td>
<td>95</td>
</tr>
<tr>
<td>Ko 2011 111</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>CMR</td>
<td>41</td>
<td>8.6</td>
<td>89</td>
<td>78</td>
</tr>
<tr>
<td>Wang 2011 112</td>
<td>DSCT</td>
<td>Shuttle, Rest</td>
<td>SPECT</td>
<td>31</td>
<td>10.5</td>
<td>81</td>
<td>92</td>
</tr>
<tr>
<td>Meyer 2012 113</td>
<td>DSCT</td>
<td>Shuttle, Rest/Stress/Delayed</td>
<td>CMR</td>
<td>50</td>
<td>13.4</td>
<td>90</td>
<td>71</td>
</tr>
<tr>
<td>Ko 2012 114</td>
<td>DSCT</td>
<td>Shuttle, Rest/Stress</td>
<td>ICA</td>
<td>45</td>
<td>16.5</td>
<td>89</td>
<td>74</td>
</tr>
<tr>
<td>Weininger 2012 115</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>SPECT</td>
<td>20</td>
<td>12.8</td>
<td>94</td>
<td>98</td>
</tr>
<tr>
<td>Delgado 2013 116</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>CMR</td>
<td>56</td>
<td>8.2</td>
<td>76</td>
<td>99</td>
</tr>
<tr>
<td>Ko 2014 117</td>
<td>DSCT</td>
<td>Shuttle, Rest/Stress</td>
<td>CMR, ICA</td>
<td>40</td>
<td>4.2</td>
<td>82</td>
<td>83</td>
</tr>
<tr>
<td>Ko 2014 118</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>CMR</td>
<td>100</td>
<td>4.2</td>
<td>97</td>
<td>36</td>
</tr>
<tr>
<td>Kim 2014 119</td>
<td>DSCT</td>
<td>Shuttle, Stress/Rest</td>
<td>CMR</td>
<td>50</td>
<td>11.4</td>
<td>94</td>
<td>71</td>
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<td>Zhao 2014 120</td>
<td>DSCT</td>
<td>Shuttle, Rest</td>
<td>ICA</td>
<td>60</td>
<td>NR</td>
<td>94</td>
<td>91</td>
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<tr>
<td>Kido 2014 121</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>ICA</td>
<td>21</td>
<td>7.7</td>
<td>67</td>
<td>92</td>
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<tr>
<td>De Cecco 2014 122</td>
<td>DSCT</td>
<td>Shuttle, Rest/Stress</td>
<td>SPECT</td>
<td>29</td>
<td>5.8</td>
<td>95</td>
<td>50</td>
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<tr>
<td>Delgado 2016 123</td>
<td>DSCT</td>
<td>Shuttle, Stress</td>
<td>CMR</td>
<td>36</td>
<td>5.4</td>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>
Table 7
Key consensus statements for CTP.

1. We recommend that myocardial CTP may be added to coronary CTA when there is a high likelihood of ischemic heart disease, known CAD, prior coronary intervention, or significant calcifications. Additionally, CTP may be added when there is a known stenosis of indeterminate functional significance. In such cases, myocardial CTP is recommended if knowledge regarding the presence and severity of ischemia would impact patient management and CTP is feasible.
2. Myocardial CTP imaging with pharmacologic stress testing requires supervision by a trained medical provider who is experienced in the administration of pharmacologic stress agents and stress testing.
3. Continuous 12-lead ECG monitoring may be performed using radiolucent electrodes and leads. Alternatively, 12-lead ECG monitoring can be interrupted during scan acquisition while continuous rhythm is still being recorded and monitored by the scanner console. Upon the completion of imaging, a 12 lead ECG should be performed to ensure there are no significant changes from baseline suggestive of post-stress myocardial ischemia or injury.
4. If an automated bolus-tracking algorithm is utilized, a region of interest should be defined in either the proximal-ascending or mid-descending thoracic aorta. The automated trigger should be set to a Hounsfield Unit (HU) threshold that is ~80-100 HU above the baseline HU of the selected reference area immediately prior to the contrast injection. After the scanner is triggered, a short pause (~5 seconds) is required to allow for breath-hold instructions to be given. Contrast dose and flow rate is typically ~60-70 ml injected at 5-6 ml/sec.
5. The optimal sequence of scans (rest first versus stress first) has not been determined and either sequence has advantages and disadvantages. Our committee suggests assessment of factors that could impair exclusion of obstructive CAD on coronary CTA (e.g., significant coronary calcium, prior coronary event or coronary revascularization, high pre-test probability of obstructive CAD) prior to decision to perform CTP. Those patients with a high likelihood or known significant coronary disease or severe amount of CAC may undergo stress myocardial perfusion imaging first; whereas, patients who lack the above features may undergo coronary CTA first.
6. A delay of 10-20 minutes between the rest and stress CT acquisitions is recommended to minimize myocardial contrast agent contamination and to eliminate the potential adverse interaction of pharmacologic stress agents and nitroglycerin administration.
7. There is no consensus about whether imaging should be performed at end-systole or during diastasis although most larger trials to date have selected diastole. A multiphase acquisition which includes phases from both systole and diastole can be considered so that the phase with the least amount of artifact can be selected for analysis retrospectively.
8. For optimal image interpretation, images may be reconstructed from multiple phases of the cardiac cycle, typically at 5–10% intervals of the R–R image acquisition window and raw CTP and CTA data files should be retained until image interpretation is complete.
9. In static visual CTP interpretation, myocardial images are typically arranged using three standard orthogonal views - the short axis, vertical long axis, and horizontal long axis. CTP images usually use a narrow window width of ~200–300 and level setting of ~100–150 with an average slice thickness of 5–8 mm. Images may be viewed in minimal intensity projection (MinIP) or average intensity projections.
10. Perfusion defects should be described in terms of size, transmurality, and reversibility in the context of the degree of stenosis in the supplying coronary artery.

7.4. Impression or conclusion

It is recommended to start the impression with an overall statement summarizing the findings: For example, “severe coronary atherosclerosis with significant 3-vessel anatomic disease and a medium size area of reversible ischemia in the LAD territory only”. It is important to relate any perfusion deficits to the culprit vessel since this may have treatment implications.

Subsequently, all other available information should be reported, such as: 1) total calcium score, 2) presence or absence of significant coronary stenosis, 3) presence or absence of myocardial perfusion defects, 4) information related to global and regional LV function, 5) Any other relevant cardiac or extra-cardiac findings.

7.5. Images

Attaching representative images of important pathology for myocardial CT Perfusion and CCTA imported from the workstation is suggested. For referring physicians, short-axis images of myocardial CT perfusion are often preferable.

8. Summary and final conclusions

Myocardial CTP provides incremental value over coronary CTA. This document provides some consensus regarding the heterogeneity that currently exists about the use of pharmacologic stress agents, imaging sequences, scanner types, acquisition protocols, post-processing, and interpretation of CTP results. This document represents the consensus opinion of international experts in myocardial CTP imaging and is meant to serve as a resource for clinical implementation, resource allocation, and future investigations related to CTP. Key statements selected by the committee are shown in Table 7.

Conflict of Interest

Grants and Research for the authors:
Amit Patel: General Electric; Philips; Astellas, Speaker's Bureau: Astellas - stress testing; Alnylam - amyloidosis.

Ron Blankstein: Astellas Inc; Amgen, Inc., Consultant: Amgen Inc. Fabian Bamberg: Bayer; Siemens Healthineers, Speakers Bureau: GE; Siemens Healthineers; Bracco.
Kelley Branch: Bayer; Kresta; Astellas; Eli Lilly, Consultant: Bayer; Janssen; Astra Zeneca.
Brian Ghoshhajra: Siemens Healthineers, Stocks: Apple, Inc.
Brian Ko: Canon Medical, Speakers Bureau: Medtronic; St. Jude Medical.
Koen Nieman: Siemens Healthineers; GE; Bayer; HeartFlow.
Francesca Pugliesi: Siemens Healthineers.
Joseph Schoeptf: Astellas; Bayer; GE; Siemens, Consultant: Guerbet, Speaker's Bureau: HeartFlow.
Gianluca Pontone: GE Healthcare; Bracco; HeartFlow, Speakers Bureau: GE Healthcare; Bracco; Bayer; Medtronic; HeartFlow.
Gianluca Pontone: GE Healthcare; Bracco; HeartFlow, Speakers Bureau: GE Healthcare; Bracco; Bayer; Medtronic; HeartFlow.

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