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REVIEW ARTICLE

Cardiac CT for myocardial ischaemia detection and characterization—comparative analysis

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ABSTRACT

The assessment of patients presenting with symptoms of myocardial ischaemia remains one of the most common and challenging clinical scenarios faced by physicians. Current imaging modalities are capable of three-dimensional, functional and anatomical views of the heart and as such offer a unique contribution to understanding and managing the pathology involved. Evidence has accumulated that visual anatomical coronary evaluation does not adequately predict haemodynamic relevance and should be complemented by physiological evaluation, highlighting the importance of functional assessment. Technical advances in CT technology over the past decade have progressively moved cardiac CT imaging into the clinical workflow. In addition to anatomical evaluation, cardiac CT is capable of providing myocardial perfusion parameters. A variety of CT techniques can be used to assess the myocardial perfusion. The single energy first-pass CT and dual energy first-pass CT allow static assessment of myocardial blood pool. Dynamic cardiac CT imaging allows quantification of myocardial perfusion through time-resolved attenuation data. CT-based myocardial perfusion imaging (MPI) is showing promising diagnostic accuracy compared with the current reference modalities. The aim of this review is to present currently available myocardial perfusion techniques with a focus on CT imaging in light of recent clinical investigations. This article provides a comprehensive overview of currently available CT approaches of static and dynamic MPI and presents the results of corresponding clinical trials.

Clinical impact of myocardial ischaemia

The current World Health Organization rating attributes 30% of deaths worldwide to cardiovascular diseases (CVD).¹ In the USA, every third death was attributed to CVD in 2009,² while coronary artery disease (CAD) was considered the cause of every sixth death.² Per year 915,000 new and recurring myocardial infarctions are estimated to occur with an additional 150,000 silent infarctions. The total estimated cost for CVD and stroke in 2009 ranged at 312.6 billion dollars.²

The assessment of patients presenting with symptoms of myocardial ischaemia remains one of the most common and challenging clinical scenarios faced by physicians. Despite considerable advances in treatment, >50% of cardiac mortality from acute myocardial infarction (AMI) occurs before reaching cardiac catheterization. Risk stratification

plays a central role in averting cardiac events. The current imaging modalities of nuclear imaging, echocardiography, CT and cardiac MRI (cMRI) can provide three-dimensional, functional and anatomical views of the heart and as such offer a unique contribution to understanding and managing the pathology involved.

The aim of this review is to present currently available myocardial CT perfusion techniques in light of recent clinical investigations.

CURRENT ANATOMICAL MODALITIES FOR DETECTION OF MYOCARDIAL ISCHAEMIA

Invasive coronary angiography

Selective invasive coronary angiography (ICA) was first described by Sones et al³ in 1959 and has since been recognized as the gold standard in the evaluation of patients

with CAD. The prognostic value of ICA has been established in large, long-term survival studies such as the Coronary Artery Surgery Study registry.⁴ Significant stenosis on ICA as one-, two- or three-vessel disease is associated with a 12-year survival rate of 74%, 59% and 50%, respectively, compared with 91% for patients without significant coronary stenosis.⁴ ICA enjoys a unique position in clinical workflow because it is linked to interventional treatment access and allows for further catheter-based modalities.⁵

Reported radiation dose of ICA has generally been lower than single photon emission CT (SPECT) but higher than coronary CT angiography (cCTA).⁶ Recently, however, the radiation dose associated with ICA could be reduced to submillisievert levels.⁷

By design, ICA carries all the risks associated with invasive coronary catheterization, such as stroke, bleeding and dissection of the vessels within the access route. There are, however, several limitations with ICA related to its simple planar silhouette visualization of the lumen. ICA does not comprehensively represent complex luminal shapes as seen on necropsy studies, so that the extent of atherosclerotic disease is generally underestimated.⁸ Furthermore, the identification of significant stenosis is confounded by coronary remodelling and by extraluminal plaque location.⁹ Trials, such as the recently published Providing Regional Observations to Study Predictors of Events in the Coronary Tree study have shown that ICA by itself fails to accurately assess high-risk plaque features. High-risk, vulnerable coronary artery plaques, often described as thin-cap fibroatheromas with a lipid-rich core, are expected to be more likely to rupture and cause AMI. The vulnerability of coronary plaques, however, seems to be inadequately reflected by absolute luminal narrowing, the parameter routinely detected by ICA. Especially, detection of lipid-rich extraluminal components is believed to be essential in the attempt to accurately define high-risk coronary artery plaques. Lastly, visual assessment of significant stenosis by ICA suffers from high observer variability. Quantitative invasive angiography has hence introduced an array of standardized parameters, such as lesion length, area of obstruction, area of plaque and minimal stenosis diameter, which provide observer-independent measurements.¹⁰ The closely related measurement of fractional flow reserve (FFR) is discussed in the section on functional modalities.

Coronary CT angiography

cCTA is the preferred non-invasive test for morphological evaluation of the coronary anatomy. cCTA has the additional capacity for plaque characterization,¹¹ and unlike ICA, cCTA can detect lipid-rich, extraluminal components, one of the features associated with high-risk coronary artery plaques. Technical advances in CT technology over the past decade have progressively moved cCTA into the clinical workflow. A recent meta-analysis comparing cCTA to the standard of ICA has demonstrated a sensitivity of 96%, specificity of 86%, positive likelihood ratio of 6.38 and negative likelihood ratio of 0.006 for detection of CAD.¹² Likewise cCTA has recently been shown to provide excellent predictive value from 5-year follow-up.¹³

Owing to its high sensitivity, cCTA has been used as a risk stratification tool for exclusion of CAD in mid- to low-risk patients,

where negative CAD images are associated with <1% probability for a major adverse cardiac event.¹⁴ Implementation of cCTA has been evaluated in critical patient care for suspected acute coronary syndrome, where it expedited safe discharge of patients with low-to-intermediate risks.¹⁵ Successful integration of cCTA in the emergency department has been proposed in a step-based model.¹⁶ An improved cost effectiveness when using cCTA as gatekeeper before ICA was confirmed in a recent study on 550 patients.¹⁷

Limitations of cCTA are that it is currently only indicated in the cases of low-to-intermediate-risk patients;¹⁸ its visualization is limited by calcified structures adjacent to target regions, *i.e.* the coronary vessels; it delivers a dose of ionizing radiation to the patient; it has been investigated in fewer large multicenter trials than comparative modalities, despite the growing body of evidence supporting its diagnostic accuracy.

Why add perfusion imaging?

Evidence has accumulated that visual anatomical coronary evaluation does not adequately predict haemodynamic relevance.¹⁹ Ischaemia-guided therapy on the other hand has proven beneficial for prognosis. Compared with patients with localized ischaemia, those with extensive ischaemia were shown to be more likely to benefit from invasive treatment in addition to optimal medical therapy.²⁰ When revascularization was guided by a functional test, an improved outcome was shown from follow-up data in the Fractional Flow Reserve versus Angiography for Guiding PCI in Patients with Multivessel Coronary Artery Disease (FAME) trial.²¹ Likewise, selection of patients through a functional test (SPECT) in a substudy of the Clinical Outcomes Utilizing Revascularization and Aggressive Drug Evaluation (COURAGE) trial resulted in increased reduction of ischaemia by percutaneous coronary intervention on top of optimal medical therapy.²² This indicates the necessity to complement an anatomical coronary assessment with physiological tests. Without functional data, ICA and cCTA can only provide limited correlation with myocardial perfusion defects.^{23,24}

COMMON FUNCTIONAL MODALITIES FOR DETECTION OF MYOCARDIAL ISCHAEMIA

Numerous imaging tests exist for physiological assessment of CAD, including stress echocardiography, cardiac MR and nuclear SPECT and positron emission tomography, which have been utilized with excellent diagnostic accuracy.²⁵ These modalities assess wall motion abnormalities or regional differences in coronary flow reserve as a surrogate for ischaemia. However, along with their inherent individual limitations, most modalities that detect ischaemia lack the ability to define coronary anatomy or to evaluate subclinical atherosclerosis.

Single photon emission CT

SPECT is a nuclear, non-invasive imaging modality. The injectable tracer substances contain the radioactive isotopes thallium-201 or technetium-99 or a combination of both. Both rest and stress acquisitions are possible. Three-dimensional tomographic reconstruction of the data from a rotating gamma camera is then performed. Through electrocardiography (ECG)-gating, reconstruction at different time points over the cardiac cycle allows calculation of ventricular volumes and ejection fraction.²⁶

According to the current joint American Heart Association and American College of Cardiology guidelines, SPECT is recognized for diagnosis of CAD, risk stratification, myocardial viability and left ventricular function,¹⁸ where risk stratification is best applied to patients with an intermediate clinical risk of having a cardiac event. The independent prognostic value of SPECT was demonstrated in comparison with ICA.²⁷ In a recent meta-analysis on 11,862 patients, SPECT had a sensitivity of 88.3% and specificity of 75.8% for detection of CAD, as defined by ICA.²⁸ The extent of ischaemia on SPECT images has repeatedly been identified as a strong predictor of prognosis.^{20,27} SPECT had generally been regarded as unmatched in its ability to detect the extent of infarcted myocardium.²⁹

More recently, delayed enhancement cMRI has found acceptance as the gold standard for viability imaging.³⁰ Furthermore, SPECT does not produce quantitative perfusion measurements. Symmetric reductions in myocardial perfusion are one example in which semi-quantitative and qualitative assessments are limited in their diagnostic ability.

Cardiac MR perfusion imaging

Current MR scanners typically use either 1.5- or 3.0-T magnetic fields and offer anatomical and detailed functional cardiac assessment. Characterization of myocardial tissue is possible in any tomographic plane. Images are usually acquired over several heartbeats using ECG gating. Cardiac sequences generally include a scout series next to "Cine", T_2 weighted series, perfusion imaging and delayed gadolinium enhancement.³¹

Stress perfusion cMRI has shown high diagnostic accuracy for the detection of CAD.³² A recent meta-analysis found an overall sensitivity of 89% with a specificity of 80% compared with the reference standard of ICA.³³ cMRI also provides excellent prognostic risk stratification for patients with known or suspected CAD. A negative stress study is associated with a low risk of cardiovascular death or myocardial infarct, whereas a positive study or delayed gadolinium enhancement is predictive of an increased risk.³⁴

The Clinical Evaluation of MRI in Coronary Heart Disease study confirmed a higher sensitivity with cMRI than was found with SPECT, independent of the patient's gender.³⁵ Subanalysis of the original study indicated that cMRI is a cost-effective test and supported more widespread use of the modality.³⁶ Direct comparison to SPECT further benefits cMRI for its lack of ionizing radiation dose and higher spatial resolution. Increased sensitivity over SPECT has been shown in the IMPACT 1 study³² especially for small, non-transmural or subendocardial infarcts.

cMRI, however, is not without limitations, including insufficient spatial resolution for diagnostic imaging of the coronary arteries, long image acquisition time and limited availability. MRI is therefore not currently recommended for the screening of high-risk populations.³⁷

Fractional flow reserve

FFR is combined with ICA to provide additional functional information and to guide revascularization.³⁸

Measurements of mean arterial post-stenotic pressure and mean aortic pressure are taken during induction of maximal hyperaemia and then related, in order to produce a FFR-derived index.³⁹ This invasive FFR measurement has been accepted as a surrogate for non-invasive testing of inducible myocardial ischaemia.⁴⁰ FFR is suggested as the preferred test by the appropriate use criteria for diagnostic catheterization³⁸ within intermediate lesions (50–69% stenosis) for patients without prior non-invasive imaging, or for cases with discrepancies of clinical presentation and non-invasive findings.

Cut-off values >0.80 are clinically accepted to indicate non-relevant stenosis (predictive accuracy of 95%³⁸) and have been correlated accordingly in the FAME trials.⁴¹ An index <0.75 has been adopted for indication of revascularization with high specificity (100%), sensitivity (88%) and overall accuracy (93%).³⁸ Yet, index values between these leave treatment options up to individual evaluation.⁴² Aiming to improve accuracy and reproducibility while eliminating technical and operator-related artefacts, an updated standard methodology was recently proposed for data acquisition.¹⁰

Correlations of FFR measurements with reversible ischaemia were extensively proven in clinical trials.^{40,43} FFR indexing has been clinically proven to improve the outcome for multivessel CAD patients on 2-year follow-up²¹ and provide incremental prognostic value and diagnostic accuracy over coronary catheter angiography alone.⁴⁴ In fact, to date, revascularization on the basis of FFR is the only physiological test that has been clinically validated against a true gold standard in a prospective multi-testing Bayesian approach.⁴⁵ Results from the FAME 2 trial indicate reduced rates of urgent revascularization when adding FFR-guided revascularization to optimal medical therapy.⁴⁶

However, invasive FFR has a significant rate of complications, which include coronary dissection and retroperitoneal haemorrhage. Furthermore, the model of the FFR index relies on several assumptions that require independent validation from clinical correlation. Assuming maximal vasodilation after administration of a standard dose of adenosine has been identified as a commonly problematic element in FFR measurement.⁴⁰

NOVEL CT TECHNIQUES FOR ASSESMENT OF MYOCARDIAL ISCHAEMIA

General considerations

Myocardial blood pool imaging vs dynamic perfusion imaging

Recent technological advances in cardiac CT have provided a new perspective to the imaging of myocardial ischaemia since its early approaches. Single energy (SE) or dual energy (DE) CT myocardial blood pool imaging and dynamic myocardial CT perfusion imaging (MPI_{CT}) can potentially combine morphological and functional diagnosis within a single imaging modality and could additionally limit false-positive results of cCTA.

Approaches to evaluate myocardial ischaemia generally use the distribution of contrast material as an indicator of myocardial blood flow (BF). The underlying principle assumes myocardial areas with reduced amounts of contrast material to be indicative

of perfusion defects. A static image of myocardial attenuation during first pass perfusion gives a snapshot of myocardial iodine distribution (hence static myocardial blood pool imaging), while attenuation followed over several consecutive time points provides dynamic myocardial perfusion (DMP).

CT acquisition under pharmacological stress

Since the reversible myocardial perfusion defects occur prior to fixed myocardial perfusion defects,⁴⁷ additional sensitivity in perfusion imaging is expected by stress testing. Pharmacological stress is induced by the vasodilative substances adenosine, regadenoson, dobutamine, dipyridamole or adenosine triphosphate.⁴⁸ Compensatory dilation of diseased coronaries is limited, since they are already operating within dilatory reserve capacity to compensate for reduced perfusion. The response from healthy coronary vessels in contrast induces hyperaemic myocardium. Hypoattenuated myocardium during pharmacological stress is classified by comparison with images in rest conditions. Areas with constant hypoattenuation during both phases correspond to irreversible ischaemia. Reversible ischaemia can be suspected if hypoattenuation is present only in the stress phase or if the hypoattenuated area increases significantly.

While adenosine is usually injected over a minimum duration of 2–3 min during ECG monitoring, with a dose ratio of $140 \mu\text{g kg}^{-1} \text{min}^{-1}$, the selective, agonistic profile of regadenoson on A2A receptors has shown reduction of systemic side effects⁴⁹ in patients with asthma or chronic obstructive pulmonary disease.⁵⁰ However, to take into account the longer effect duration of regadenoson, sufficient time needs to be allowed before rest acquisition (15–20 min). Ultimately, theophylline can be administered as a countermeasure.⁵¹ The use of regadenoson showed higher time efficiency over dipyridamole and adenosine in a stress/rest protocol.⁴⁸ This was attributed mostly to administration of the substance because a pre-filled single dose is available for regadenosone.

CT acquisition at rest

Resting myocardial perfusion is impaired when sudden occlusion occurs in case of a myocardial infarction or when critical coronary stenosis limits the autoregulatory capacity for coronary dilation.⁴⁷ Rest-phase CT series have also been reported to detect non-critical perfusion deficits (ischaemia not infarct).⁵² In one such study, half of the 16 myocardial perfusion defects, detected in resting conditions on CT studies, were not detected by SPECT on rest studies and could only be confirmed by SPECT on stress studies.⁵³ Two mechanisms have been selected to explain this discrepancy. First, iodinated contrast media could produce a relevant vasodilative effect analogous to the action of pharmacological stress agents.^{54,55} Second, the higher spatial resolution of CT might produce findings that cannot be detected by SPECT.^{52,56}

Myocardial viability assessment with delayed CT acquisition

Similar to delayed gadolinium enhancement on cMRI, image acquisition with cardiac CT 5–10 min after administration of iodinated contrast material can display hyperattenuating patterns indicative of non-viable myocardium.⁵⁷ Compared with

MRI, cardiac CT has a rather low signal-to-noise ratio, since “nulling” of the myocardium is not possible with CT. Furthermore, contrast medium (CM) volume for delayed enhancement exceeds volumes regularly given for CTA. Acquisition utilizing this delayed enhancement has been performed after invasive revascularization by percutaneous coronary intervention (PCI) procedures without additional administration of CM.⁵⁸

Order of the series: rest/stress or stress/rest

Variation exists in the order of rest and stress series acquisition: placing the stress phase before rest imaging avoids contamination of contrast material and enables maximal contrast difference between ischaemic and non-affected myocardium.⁵⁹ A persisting elevated heart rate, however, could impair the quality of the rest acquisition.⁵¹ If rest acquisition is placed first, it effectively supplies a CTA study, taking advantage of its high negative-predictive value (NPV).⁶⁰ Patients with obstructive disease could then selectively undergo stress testing to assess physiological significance of the stenosis (Figure 1).

Single energy first pass CT—myocardial blood pool imaging

SE first-pass CT (SE FP_{CT}) uses static distribution of contrast material during early arterial attenuation, as the CM is travelling through the myocardial microvasculature, to detect myocardial blood perfusion irregularities.

Acquisition parameters, radiation dose and scan times for SE FP_{CT} are identical to those for cCTA. Lowering the tube voltage from 120 to 100 kV with prospective ECG triggering significantly lowers the radiation dose and has not shown any negative impact on diagnostic accuracy,⁶¹ even when reducing the CM volume to 35–70 ml.

Image acquisition is performed at peak coronary contrast. Volumes of contrast medium generally range between 60 and 70 ml. A flow rate of 5 ml s^{-1} or above is desirable and appropriate intravenous catheter access is necessary. Proper timing of the scan within the window of first-pass enhancement is essential to capture enhancement differences. Acquisition triggered by an attenuation threshold of 100 HU in the proximal ascending aorta should ideally image the myocardium within an 8-s time frame, 8 s after the threshold is exceeded. The maximum difference in contrast enhancement between ischaemic and non-ischaemic myocardium has been reported approximately 10 s after exceeding the threshold.⁵⁹

Reconstruction at several phases of the cardiac cycle, if corresponding data are available, can help in distinguishing suspected defects from artefacts. A real perfusion defect should persist as hypoattenuation throughout the cardiac cycle.³⁰

Qualitative/semi-quantitative assessment

Myocardial blood pool defects (MBPDs) on SE FP_{CT} have mostly been qualitatively assessed. As a comparable quantifiable measure, the transmural perfusion ratio, the ratio between mean subendocardial and mean subepicardial attenuation, has shown good predictive value in comparison with SPECT and invasive angiography.⁶²

Figure 1. Flow chart of cardiac CT protocol for visualization of myocardial ischaemia. CaSc, calcium scoring; CM, contrast medium; ECG, electrocardiography; IV, intravenous.

Single energy post-processing techniques

Dedicated post-processing applications have been used to enhance the diagnostic accuracy of SE FP_{CT} data sets. Furthermore, quantification of myocardial blood pool using automated segmentation has been explored. Colour coding of the attenuation range within the myocardium combined with automated segmentation of the left ventricle improved detection of hypoperfusion.⁶³ Adding to pure visual assessment, semi-quantitative measurements can be produced from SE FP_{CT} using a semi-automated method for the indexing of signal density.⁶⁴ Indexes for transmural, subendocardial and myocardial perfusions provided incremental diagnostic accuracy when using control group measurements as a standard (sensitivity 87%–96%, accuracy 84%–88% and specificity 79%–68%).⁶⁵ Using an automated 16-segment model with corresponding subepicardial, mid-myocardial and subendocardial layers, George et al⁶⁰ calculated the corresponding transmural perfusion ratios. Recently, a novel application has been described to quantitatively compare standardized segments between rest and stress images in an automated fashion.⁶⁶

Clinical studies using single energy first-pass CT rest acquisition

In their clinical study in 2005, Nikolaou et al⁶⁷ described a good correlation for identification of myocardial infarction between rest SE FP_{CT} series on a 16-detector row CT and cMRI (sensitivity, 91%; specificity, 79%; and accuracy, 83%), but only fair detection of hypoperfusion (three of six cases; sensitivity, 50%; specificity, 92%; and accuracy, 79%). A recent study⁶⁸ on 140 individuals confirmed high accuracy (sensitivity, 90%; specificity, 94%; and NPV, 91%) for visual identification of myocardial infarction from SE FP_{CT} rest series. Similar results were reported in a substudy using a dedicated software tool [sensitivity, 92%; specificity, 73%; NPV, 91%; and positive-predictive value (PPV), 76%].⁶⁸ A closer investigation into myocardial ischaemia visible on SE FP_{CT} included stratification by degree of coronary stenosis, as defined by quantitative coronary angiography, in 131 patients. MBPDs were identified on rest cCTA studies in 60% of patients with severe coronary stenosis (70–90%), in 47.3% of patients with stenosis >50%, and only 4.8% of patients with

stenosis <50%.⁵² After angioplasty, these defects resolved in all but three patients, suggesting that these hypoattenuations had been correctly identified as myocardial ischaemia. Nagao et al⁶⁹ had earlier described myocardial ischaemia as a characteristic enhancement pattern, by correlating colour-coded rest cCTA studies to SPECT images and had correctly identified myocardial ischaemia in 36 of 40 patients (90%), with a specificity of 83%, a PPV of 86% and a NPV of 88%. In a separate investigation in a population of 20 patients, the same group reported 16 perfusion defects at rest CTA that were not detected on resting SPECT, 8 of which, however, became apparent on stress SPECT.⁵⁶ Results from a study on 100 consecutive patients found myocardial hypoenhancements, reflective of myocardial ischaemia owing to significant stenosis defined by ICA, on SE FP_{CT} in as

Figure 2. First-pass cardiac CT imaging for detection of myocardial ischaemia. Contrast-enhanced, retrospectively ECG-gated first pass, arterial phase CT study of a 61-year-old patient with prior history of myocardial infarct and stent insertion. (a) Curved multiplanar reformat view of the right coronary artery delineates occluded distal stent (arrow). (b) In dedicated three-chamber reconstruction, a dark rim of basal inferior hypoattenuation (arrow) delineates myocardial ischaemia/infarction in the corresponding inferior myocardial segment. (c) Segmental wall motion is depicted in this three-dimensional, left ventricle reconstruction. Blue and purple colour was assigned to the inferior myocardial segment, indicating decreased myocardial wall motion. Green represents good, and orange and yellow represent excellent wall motion. (d) The polar map, using a 17 myocardial segment model, also confirms reduced wall motion of the inferior wall (blue colour). For colour images please see online: <http://www.birpublications.org/doi/full/10.1259/bjr.20140159>.

many as 72% of patients with identified MBPD. Previous MI was underlying the myocardial hypoenhancements in only 28% of the cases⁶⁵ (Figure 2).

Clinical studies using single energy first-pass CT stress acquisition

Incremental benefit of SE FP_{CT} stress series was not initially evident. In an early feasibility study on 12 patients in 2005, using adenosine triphosphate as a stress agent, no benefit could be reported.⁴⁸ Rocha-Filho *et al*⁷⁰ demonstrated considerable improvements in sensitivity (91% from 83%), specificity (91% from 71%), PPV (86% from 66%) and NPV (87% from 93%) by adding a stress phase SE FP_{CT} to cCTA for detection of stenosis >50% against a standard of invasive angiography in 35 patients with a high risk of CAD. By adding visual assessment of stress SE FP_{CT} to cCTA on a 320-detector row CT scanner, Ko *et al*⁷¹ found an increase in per patient accuracy for detection of FFR-significant stenosis from 83% to 92%. This addition of visual perfusion assessment to cCTA increased specificity for FFR-significant stenosis from 78% to 95%, with a sensitivity of 87% from formerly 95%.

Clinical studies using a comprehensive CT protocol: rest, stress and delayed CT acquisition

Cost benefit and the additional radiation dose need to be considered to justify a more extensive three-part cardiac CT protocol. A recent study on 42 patients, presenting with at least 1 coronary stenosis on ICA >50%, showed significant improvement of diagnostic accuracy by addition of stress phase. However, all delayed enhancement series were free of defining enhancement patterns, even if previous infarction was present. The authors found that the combination of a MBPD in SE FP_{CT} and a >50% coronary stenosis on cCTA was indicative for a FFR ≤0.8 with 98% specificity. A normal perfusion on SE FP_{CT} and coronary stenosis <50% on cCTA, on the other hand, excluded significant FFR findings with 100% specificity.⁷² The delayed enhancement series accounted for 1.2 mSv and stress phase SE FP_{CT} for 5.3 mSv of the average patient dose of 11.3 mSv. Blankstein *et al*⁷³ demonstrated diagnostic accuracy for myocardial perfusion defects comparable to SPECT in an earlier study when using a comprehensive three-phase CT protocol. The authors reported a sensitivity of 82%, specificity of 81%, PPV of 82% and NPV of 81% for delayed enhancement series alone; however, all perfusion defects were also present on rest series. A recent study on 105 patients with intermediate-to-high pre-test probability for CAD found no benefit in accuracy for detection of significant CAD by the addition of delayed enhancement series. Good accuracy for the detection of ischaemic scarring on delayed enhancement images was confirmed (90%).⁷⁴ Although it might be too early to rule out clinical use of delayed enhancement CT series altogether, current data for detection of significant ischaemia point towards a flexible, two-part perfusion protocol, making use of rest cCTA first, with potential addition of stress SE FP_{CT}.

Limitations of single energy first-pass CT

Interpretation of SE FP_{CT} is challenging because of the relatively subtle attenuation difference in the areas of perfusion defects (as

low as 10%⁶¹) and because of several factors interfering with ideal image quality. As one example, the visual quality of perfusion studies is highly dependent on bolus timing.⁵⁹ Furthermore, high susceptibility to beam-hardening artefacts, especially in the basal part of the left ventricle, bears the risk for false-positive readings.⁶⁹ Additional relevant image artefacts include motion artefacts and partial scan reconstruction artefacts.^{75,76}

Dual energy first-pass CT—myocardial blood pool imaging

DE static first-pass CT (DE FP_{CT}) makes mapping of iodine distribution possible, which in turn serves as a surrogate for myocardial perfusion. This feature utilizes the differences in attenuation of iodine between both energy spectra, since a tube voltage closer to the k-edge of iodine (33.2 keV) results in higher attenuation of iodine content.⁷⁷ This makes quantification of myocardial blood pool from iodine concentration possible with DE FP_{CT}.⁷⁸

Dual source CT scanners make use of independent tube regulation, while single source CT scanners are able to produce DE images through rapid tube current switching.⁷⁹ Cardiac applications, however, have mostly been assessed using dual source CT, with synchronized acquisitions at both energy levels.^{73,80,81}

Both prospectively ECG-triggered and retrospectively ECG-gated protocols are available for DE CT acquisition. Previous challenges in temporal resolution have been overcome with second-generation dual source scanners (75 ms),⁸⁰ and third-generation scanners are promising to further decrease temporal resolution. Additionally, hybrid image reconstruction enables imaging even at high heart rates.⁸⁰ Scan time and radiation dose for prospectively ECG-triggered and retrospectively ECG-triggered acquisition are equivalent to those of SE cardiac CT acquisition⁸² (Tables 1–3).

Dual energy CT post-processing technique

Dedicated software typically generates a colour-coded iodine distribution map overlay on top of a virtual non-contrasted image (Figures 3–5). A calibration of the iodine map can be performed by marking a normally perfused myocardial region as a reference.⁹¹ Yet, the non-standardized windowing represents one of the current challenges, as it makes calibration of colour-coded maps highly user dependent and can easily mask or simulate MBPDs.

Clinical studies using dual energy first-pass CT

Comparisons of DE FP_{CT} to cMRI and PCI,⁹² cMRI and SPECT,^{53,85} as well as PCI and SPECT⁸⁸ have demonstrated its accuracy. Ko *et al*⁹² found that DE FP_{CT} could diagnose reversible ischaemia identified by cMRI with 89% sensitivity, 78% specificity and 82% accuracy. Using ICA as the reference standard, sensitivity was 89%; specificity, 76%; and accuracy, 83%. Compared with the reference standard of SPECT, Wang *et al*⁸⁶ showed that sensitivity in, specificity of and accuracy of detecting coronary stenosis >50% by addition of DE FP_{CT} increased from 82%, 91% and 86% with cCTA alone to 90%, 86% and 88%, respectively.⁸⁸ A recent trial of 50 patients comparing

Table 1. Example scan protocols

Series	CT angiography ^{59,83}	SE FP ⁸³	SE FP ⁷²	SE FP ⁸⁴
CT scanner	Second-generation dual source CT	Second-generation dual source CT	320-row CT	64-row CT
ECG-gated scan mode	Adaptive sequential ⁵⁹ Prospective, high pitch ⁸³	Prospective, high pitch	Prospective	Prospective/retrospective
Tube current (mAs)	320	320	300–500	500–700 ^a
Tube voltage ^a (kVp)	100/120 ^{a,59} 100 ⁸³	100	100/120 ^a	100/120 ^a
Gantry rotation time (ms)	330 ⁵⁹ 280 ⁸³	280	350	350
Detector collimation (mm)	2.0 × 64.0 × 0.6	2.0 × 64.0 × 0.6	320.0 × 0.5	64.000 × 0.625
Contrast volume (ml)	50 ⁵⁹ 84 ⁸³	84	70	80
Reconstructed section thickness (mm)	0.75 ^{59,83}	5 ^b	3 ^b	8 ^b

SE FP, single energy first-pass CT.

^aDependent on body mass index of the patient,^{59,72,73} that is, if $\geq 30 \text{ kg m}^{-2}$ or $\geq 25 \text{ kg m}^{-2}$.^bShort axis view.

DE CT and SPECT for the detection of obstructive CAD against a gold standard of cMRI reported higher sensitivity (90% vs 85%) and specificity (71% vs 58%) with DE FP_{CT} rather than SPECT (Figures 2 and 3).⁸⁹

Dual energy rest and stress acquisition

The incremental benefit of DE FP_{CT} stress series was demonstrated in an early feasibility study by Blankstein et al⁷³ in which sensitivity was increased from 76% to 92% and specificity was similar with 67% compared to 85%, against a standard of PCI. Diagnostic accuracy was found to be comparable to that of SPECT. Ko et al⁹³ reported increases in sensitivity, specificity, PPV, and NPV from 91.8%, 67.7%, 73.6% and 87.5% to 93.2%, 85.5%, 88.3% and 91.4%, respectively, by adding DE FP_{CT} to DE CTA (Figure 4).

Studies have suggested the ability of DE FP_{CT} to detect MBPDs in rest series alone. In these trials, most perfusion defects on rest and stress SPECT studies were detected from rest DE FP_{CT} series.^{53,88} Although DE FP_{CT} has often been performed as part

of a three-part acquisition series, the additional diagnostic value of each series has not been conclusively investigated. Likewise, in SE FP_{CT}, a recent study has proposed that delayed enhancement might not be necessary in all cases, reducing patient radiation exposure.⁹⁴

Additional cost-effectiveness benefits of substituting SPECT with DE FP_{CT} have been shown, while accuracy for identifying myocardial ischaemia in acute chest pain patients was constant compared with the standard of cMRI.⁸⁹

Dual energy first-pass CT vs single energy first-pass CT

Benefits of DE FP_{CT} over SE FP_{CT} are expected by (1) reduction of beam-hardening artefacts (2) improved detection of myocardial perfusion defects by colour-coded visualization of iodine content and (3) improved visualization of delayed enhancement.⁸² Benefits in detection of fixed and mixed perfusion defects were shown in a systematic comparison with SE FP_{CT} on 47 patients.⁸¹ In a porcine model, beam-hardening reduction through prospectively ECG-triggered DE CT, by rapid tube potential switching, has been

Table 2. Example scan protocols

Series	Dynamic myocardial perfusion ⁵⁹	Dual energy first pass ⁸⁵
Scanner	DSCT	DSCT
Scan mode	Shuttle	Retrospective
Tube current (mAs)	300	165 and 150
Tube voltage ^a (kVp)	100	140 and 100
Gantry rotation time (ms)	280	330
Detector collimation (mm)	2.0 × 64.0 × 0.6	2.0 × 64.0 × 1.5
Contrast volume (ml)	50	70
Reconstructed section thickness ^b (mm)	3	3

DSCT, dual source CT.

^aDependent on body mass index of the patient.^bShort axis view.

Table 3. Comparison between techniques

Variables	Dynamic CT perfusion			Single energy first-pass CT			Dual energy first-pass CT		
	Weininger et al ⁸⁵	Wang et al ⁸⁶	Greif et al ⁸⁷	Ko et al ⁷²	Feuchtnet et al ⁸³	Feuchtnet et al ⁸⁴	Wang et al ⁸⁸	Meyer et al ⁸⁹	Delgado et al ⁹⁰
Study									
Scanner		First-generation DSCT		320-row (Toshiba; Tokyo, Japan)	DSCT	64-slice CT	DSCT	64- slice DSCT	DSCT
Scan mode		Dynamic shuttle mode		Prospective	High pitch/prospective	Prospective/retrospective	Retrospective	Prospective	Retrospective
Radiation dose ^d Stress (rest) (mSV)	12.8 ± 2.4	9.5 ± 1.3	9.7 ± 2.2	5.3 ± 2.2 (4.8 ± 2.6)	0.93 ± 0.18 (1.59 ± 1.3)	N/A	10.5 ± 1.5	13.4 ± 2.6 ^b	5.2 ± 1.2
Quantification	Visual, qualitative	Quantitative	Quantitative	Visual, qualitative	Visual, qualitative	Automated, semi-quantitative	Visual, qualitative	Visual, qualitative	Visual, qualitative
Contrast ^d (ml)	50	50	50	70	70	80	60–90	50	60
Time of acquisition (s)	30	30	30	0.31	0.35–0.7	NR	NR	NR	NR
Number of patients	20	30	67	40	42	76	34	50	56
Population characteristic	Known or high-risk CAD	Known or high-risk CAD	Chest pain	Suspected or known CAD	Chest pain	Chest pain	SPECT and CTA	Referral to SPECT for CAD	Suspicion of ischaemia by stress ECG
Reference standard	cMRI	SPECT	FFR	cMRI	FFR	SPECT	SPECT	cMRI	cMRI
Accuracy (%)	NR	NR	81.5 ^c	93 ^d	NR	99.1 ^c	85 ^e	87 ^c	NR
Sensitivity (%)	86 ^c	85 ^c	97 ^c	96 ^d	96 ^c	89 ^c	68 ^e	90 ^c	76 ^c
Specificity (%)	98 ^c	92 ^c	65.6 ^c	88 ^d	71 ^c	99 ^c	93 ^e	71 ^c	99 ^e
Negative-predictive value (%)	94 ^c	98 ^c	95.5 ^c	94 ^d	91 ^c	99.6 ^c	86 ^e	NR	98 ^c
Positive-predictive value (%)	96 ^c	55 ^c	74.4 ^c	93 ^d	87 ^c	82 ^c	83 ^c	NR	89 ^e
Area under the curve	NR	NR	NR	0.93 ^d	NR	NR	NR	NR	NR

CAD, coronary artery disease; cMRI, cardiac MRI; DSCT, dual source CT; FFR, functional flow reserve; NR, not reported; SPECT, single positron emission CT.

^aDose per series.^bCombined dose for rest, stress and delayed enhancement series.^cOn a per patient basis.^dOn a per vessel basis.^eOn a per segment basis.

Figure 3. Dual energy CT for detection of reversible perfusion defect. Imaging studies of a 68-year-old female presenting with chest pain. (a) Myocardial stress perfusion cardiac MRI reveals hypoperfusion (low-signal enhancement) in the anterior segments (arrow). In addition, there is no hyperenhancement on delayed gadolinium enhancement, viability MRI (b), which is indicative for reversible myocardial ischaemia without the presence of non-viable, irreversibly injured myocardium. (c) This dual energy first-pass CT image shows subendocardial perfusion deficit in antero-septal segment on the corresponding short axis view (arrow).

demonstrated.⁷⁹ Furthermore, creation of a virtual monochromatic image can reduce beam-hardening artefacts. In a head-to-head comparison against a standard of SPECT, DE FP_{CT} was superior to SE FP_{CT} for detection of mixed perfusion defects in sensitivity (91% vs 55%), NPV (97% vs 86%) and accuracy (93% vs 85%), whereas specificity was highest with SE FP_{CT} (98% vs 94%). Unfortunately, little clinical evidence exists to date for direct comparison of SE and DE FP perfusion and confirmation of these results from larger studies is currently unavailable.

Dynamic myocardial CT perfusion

Through ECG-synchronized, repetitive scanning of the myocardium and cardiac blood pool, time attenuation curves (TACs) are generated while the contrast bolus is undergoing first pass, arterial phase and microcirculation (Figures 6 and 7). Further analysis of these data can produce quantifiable measurements of myocardial perfusion.

Although early results of dynamic myocardial perfusion CT (DMP_{CT}) were demonstrated on a 16-slice scanner,⁹⁵ adequate volume coverage is considered a major factor for clinical feasibility of DMP_{CT}. On 320-slice CT-scanner systems, the detector coverage makes dynamic imaging of the heart possible without table movement. On scanners in which detector width offers only partial coverage of the heart, use of a shuttle mode, which alternates between two table positions, increases the coverage.

Both semi-quantitative and quantitative analysis methods have been used with DMP_{CT} (Table 4). Several methods exist, and these have mostly been adapted from perfusion imaging of other modalities, such as electron beam CT and cMRI.

Semi-quantitative analysis

The “upslope-analysis” method can produce semi-quantitative measurements from the upslope portion of the TACs. These parameters include time to peak, peak enhancement, attenuation upslope and area under the TAC. Ischaemic myocardial regions correspond to decreased peak enhancement and upslope values, and increased time to peak values.

Since data acquisition during attenuation upslope is sufficient for the upslope analysis method, the high radiation dose currently associated with complete first-pass coverage can be avoided. Normalizing the attenuation to the arterial input function indicated by the left ventricular blood pool is possible, which can further improve accuracy. In an early clinical study, including the comparison of 149 myocardial segments from 10 patients, BF quantification by upslope analysis has shown good correlation with myocardial BF from cMRI perfusion.⁹⁹

Quantitative analysis

Quantitative measurement of myocardial perfusion, however, requires the extraction of absolute perfusion parameters through mathematical model fitting. This includes recognition of input and output functions of BF and extraction rate of the contrast agent from the intravascular space.

Among the available techniques used with DMP_{CT} are deconvolution methods and derivatives of the deconvolution method.

Figure 4. Dual energy CT for detection of fixed myocardial perfusion defect. Imaging studies of a 66-year-old patient who presented with chest pain. (a) Myocardial MR perfusion imaging study at rest in dedicated mid-ventricle short axis view shows fixed septal perfusion defect with the presence of low signal intensity (arrow). (b) Delayed enhancement viability image confirms the finding of delayed contrast accumulation (hyperenhancement) in the corresponding myocardial septum, confirming the presence of myocardial infarction (arrow). (c) This corresponding short axis dual energy first-pass CT image at rest delineates septal hypoattenuation (septal myocardial blood pool defect) (arrow) induced by myocardial infarction in good agreement with findings of clinical standard myocardial perfusion and viability MR images.

While other methods, such as Patlak plot analysis, maximum enhancement method and gamma variate curve fitting, have been applied to electron beam CT, these have not been utilized in current multidetector CT systems. Technical limitations, such as sampling rates of the scanner and total radiation dose, are limiting factors when comparing available methods. The amount of required sampling points has a direct influence on the patient's radiation dose and has been estimated in the area of 1 mSv per sampling point.¹⁰⁰

Deconvolution methods have previously been used in cMRI perfusion¹⁰¹ and rely on the entire data of first pass to derive a perfusion estimate. Based on a two-compartment model, blood-attenuation and tissue-attenuation curves are used. So et al¹⁰² used this method for DMP_{CT} in comparison with a standard of ICA on 26 patients. The combined average radiation dose for rest and stress series averaged 19.4 mSv.

Patlak et al¹⁰³ plot analysis on the other hand uses a limited number of sampling points during upslope of the TAC and estimates perfusion on the assumption of a constant unidirectional efflux of contrast medium from the vasculature into the extracellular space. This method has been used in an early animal study,¹⁰⁴ but no clinical trials are currently available for DMP_{CT}.¹⁰⁵

As most available clinical trials have used a dual source CT system, a modified deconvolution method, compatible with the slower sampling rate of shuttle mode, has been most frequently used in available studies to date.^{96,97,99,100,102}

Since dynamic myocardial CT perfusion is a rather recent development, available clinical data are sparse and cut-off values have not been conclusively established. Challenges specific to DMP_{CT}, next to high radiation exposure from dynamic acquisition, include the requirement for breath holding over 30–40 s. Since shuttle mode is necessary, depending on detector width, data from two separate table positions are combined, which makes acquisition more sensitive to extra systole and arrhythmia. Susceptibility to artefacts lead to as many as 51% of the false-positive findings in basal myocardial segments illustrating these difficulties.⁸⁶

Several solutions have addressed these challenges, and more are to be expected. Statistical image reconstruction¹⁰⁶ can improve accuracy while reducing image noise. Beam-hardening correction algorithms can further improve myocardial assessment.¹⁰⁷ Motion correction can significantly increase spatial alignment and reduce imaging noise.¹⁰⁸ Semi-automated three-dimensional software has been used to produce quantification with substantially reduced processing times,¹⁰⁹ which is a beneficial step for integration into clinical workflow.

Studies using dynamic myocardial CT perfusion

Dynamic perfusion from stress series compared with SPECT has shown comparable accuracy for detection of myocardial ischaemia.⁸⁶ Several early clinical studies found good diagnostic value for dynamic myocardial CT perfusion imaging compared with the reference standards of SPECT and cardiac MR,⁸⁵ SPECT alone,⁸⁶ FFR,^{72,89,96} ICA^{97,98} and cMRI.⁹⁹ Summaries of these studies are provided in Table 4.

Figure 5. Dual energy CT for detection of partially reversible perfusion defect. Imaging studies of a 67-year-old male with medical history of myocardial infarct, stent insertion and coronary artery bypass graft surgery with new onset of chest pain. (a) Invasive angiography shows significant mid-to-distal right coronary artery stenosis with the presence of sternotomy wires. Corresponding significant mid-to-distal right coronary artery stenosis (arrow) proximal to right coronary artery stent is confirmed by curved multiplanar reconstruction (b), using dual energy CT data set at rest, which shows good agreement with clinical standard invasive angiography. The three-dimensional volume rendered dual energy reconstruction at rest (c) delineates the presence of significant stenosis in the same mid-to-distal segment, proximal to the right coronary artery stent. The patent left internal mammary artery (LIMA) to left anterior descending artery graft is visible with surgical clips around repositioned LIMA (arrowhead). Clinical standard single photon emission CT (SPECT) perfusion imaging shows the partially reversible perfusion defect in the inferior mid-ventricle myocardial segment at stress (d) and rest (f) (arrows). The contrast-enhanced dual energy CT studies in short axis at stress (e) and rest (g) show corresponding inferior myocardial blood pool defect (arrows) in good correlation with partially reversible perfusion defect at SPECT.

In a porcine model on six country pigs, diagnostic accuracy of hypoperfusion by DMP_{CT} was superior to $SE\ FP_{CT}$ for coronary stenosis of 50%, while results were similar for high-grade stenosis. Furthermore, diagnostic accuracy of DMP_{CT} was increased by inclusion of pharmacological stress imaging in both high- and medium-grade stenoses.¹¹⁰ In their clinical feasibility study on 33 patients, Bamberg et al⁹⁶ established a cut-off value of $75\text{ ml}/100\text{ ml min}^{-1}$ for quantified BF with an odds ratio of 86.9 for haemodynamic significance of stenosis. While the accuracy of detecting functionally significant coronary artery

stenoses ($FFR \leq 0.75$) was low with cCTA alone, incremental accuracy by DMP_{CT} increased PPV from 49% to 78% on a per segment level, sensitivity was 91%, specificity was 98.2% and NPV was 99.4. As a similar optimal cut-off value of $78\text{ ml}/100\text{ ml min}$ was used by Rossi et al⁹⁸ on a population of 80 stable patients with chest pain. The authors further demonstrated improvement of specificity over visual and quantitative ICA for patients with intermediate coronary stenosis (30–70% by ICA), compared with the reference standard of FFR .¹⁰⁰

Figure 6. Dynamic CT perfusion study for detection of myocardial ischaemia. ECG-gated dynamic CT perfusion study of a 66-year-old female patient with a medical history of hypertension and hyperlipidaemia. (a) Curved multiplanar reconstruction of the left anterior descending artery using rest CT angiography series reveals significant mixed, calcified and non-calcified stenosis in the proximal segment (arrows). Dynamic CT perfusion at stress using grey scale (b) and colour-coded images (c) delineates corresponding anterior transmural ischaemia (arrows). In colour-coded dynamic perfusion image: cold colours (including blue and green) have been assigned for ischaemic myocardium with low iodine inflow. Warm colours (red) represent normal, healthy myocardium with preserved perfusion and normal iodine distribution. For colour images please see online: <http://www.birpublications.org/doi/full/10.1259/bjr.20140159>.

In a small study of 20 patients with acute chest pain, head-to-head comparison suggested excellent diagnostic accuracy of DMP_{CT} in comparison with cMRI (86% sensitivity, 98% specificity, 94% PPV and 96% NPV) and SPECT (93% sensitivity, 99% specificity, 92% PPV and 96% NPV).⁸⁵

Studies comparing quantitative vs semi-quantitative analysis

Few data are available for direct comparison of available parameters. In their trial involving 10 patients, Bamberg et al⁹⁶ showed moderate correlation between absolute myocardial blood flow

Figure 7. Dynamic CT perfusion study for detection of myocardial ischaemia. This ECG-gated dynamic CT perfusion study was acquired from a 57-year-old male patient presenting with acute chest pain. Both qualitative (a) and quantitative (b) evaluations detect perfusion defects on the two-dimensional perfusion map of blood flow (BF) at the mid-cavity level; on the correlating single photon emission CT image an inferior transmural perfusion defect is visible at mid-cavity level (c). On three-dimensional visualization on the 17-segment polar map of BF (d) the perfusion defects are represented by colour coding corresponding to the anatomic regions of the inferior and inferoseptal wall (segments 3, 4, 9, 10 and 15). Max, maximum; Min, minimum; SD, standard deviation.

Table 4. Clinical studies comparing dynamic CT myocardial perfusion imaging

Study	Reference modality	Patients included	Sensitivity (%)	Specificity (%)	Positive-predictive value (%)	Negative-predictive value (%)	Radiation dose dynamic myocardial perfusion CT (mSv) (total CT dose)
Weininger et al ⁸⁵	SPECT	20	84.0	92.0	88.0	92.0	15.2
	cMRI		86.0	98.0	94.0	96.0	
Wang et al ⁸⁶	SPECT	30	85.0	92.0	55.0	98.0	9.5 ± 1.3 (12.8 ± 1.6)
Ko et al ⁷²	FFR	42	76.0	84.0	82.0	79.0	5.3 (11.30)
Bamberg et al ⁹⁶	FFR	33	91.0 ^a	98.2 ^a	78.0 ^a	99.4 ^a	N/A
Ho et al ⁹⁷	ICA	35	83.0	78.0	79.0	82.0	18.24
Rossi et al ⁹⁸	ICA	80	N/A	89.0	N/A	N/A	N/A
Bastarrika et al ⁹⁹	MRI	10	86.1	98.2	93.9	95.7	733.5 ± 139.6 mGy cm (1290.4 ± 233.3 mGy cm)

cMRI, cardiac MRI; FFR, fractional flow reserve; ICA, invasive catheter angiography; N/A, not available; SPECT, single positron emission CT.

^aOn a per segment basis.

(MBF) quantification and semi-quantitative upslope values with both hypoperfused ($r = 0.41$; $p < 0.01$) and normal myocardial segments ($r = 0.43$; $p < 0.01$). In a recent study on 32 patients, time to peak, area under the curve, upslope and peak enhancement were compared against measurements from CTA and FFR. The results showed a similar high area under the receiver operating characteristic curve, sensitivity and specificity between quantitative MBF (0.86%, 75.9% and 100%) and the semi-quantitative parameters upslope (0.87%, 82.8% and 88.1%) and peak enhancement (0.83%, 82.8% and 89.6%).¹¹¹

Radiation dose consideration

Although further decreases of associated radiation dose are to be expected with dynamic CT perfusion, currently static perfusion imaging compares favourably with regard to radiation exposure. Also data acquired for DMP_{CT} series might require additional cCTA series for anatomical evaluation, unlike static SE FP_{CT} and DE FP_{CT} series. Comprehensive protocols containing delayed acquisition and unenhanced calcium scoring next to rest and stress static perfusion series have generally been reported in the range of 12–14 mSv.⁶⁰ This is comparable to the radiation dose delivered by SPECT imaging. For static first pass CT, Feuchtner et al⁸³ recorded combined patient doses of 2.5 mSv of both rest CTA and stress SE FP_{CT} in their study on 30 patients, with a high sensitivity (96%), specificity (88%), PPV (93%) and NPV (94%) compared with cMRI. As radiation doses <1 mSv on cCTA studies are becoming a reality, radiation doses for first-pass CT can be expected to decrease further.⁸³

Comparison of three dynamic myocardial CT perfusion protocols showed a reduction of radiation dose from 12.1 ± 1.6 to 3.8 ± 1.3 mSv through use of automated tube current modulation and reduction of acquisition time from 30 to 14 s, on a 128-slice dual source CT scanner. Thus, acquisition was essentially reduced to the most relevant portions of the TAC, while diagnostic accuracy was maintained.¹¹²

CONCLUSION

CT-based MPI has shown excellent diagnostic accuracy compared with available reference modalities.

Currently available trials have not shown clear benefits of quantitative dynamic myocardial CT perfusion measurements over static first-pass CT and semi-quantitative dynamic myocardial CT perfusion measurements.

At this time, large clinical trials are not available to confirm a positive impact on patient outcome and evaluate the economic effect of integrating myocardial CT perfusion in clinical workflow. Furthermore, future clinical trials for DMP_{CT}, testing the effectiveness of available quantitative analysis methods, refinement of technical workflow and reduction of delivered radiation dose could increase clinical usability of DMP_{CT} in comparison with SE and DE FP_{CT}.

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