

# THE HEART

REVEALED

RADIOLOGY IN THE DIAGNOSIS AND  
MANAGEMENT OF CARDIAC CONDITIONS

Editors: Jens Bremerich & Rodrigo Salgado



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# EDITORIAL

BY JENS BREMERICH AND RODRIGO SALGADO

*“a hot, dry organ –  
the centre of vitality of the body”*

That is how Aristotle described the heart in the fourth century B.C. Although it was then thought to be a three-chambered structure, the heart was already identified as being the most important organ of the body. Our understanding of the anatomy and physiology of the heart has evolved since then, but it remains without question one of the most cherished human structures, a marvel of nature’s engineering, and the referenced source of so much more than its role as the engine behind our blood circulation.

With such a central place in our existence, it was inevitable that humans would soon try to uncover its structure and function, and from there its relationship with human wellbeing. Mankind had, however, to wait until William Harvey’s 1628 publication *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus (An Anatomical Study of the Movement of Heart and Blood in Animals)*, commonly referred to as *De Motu Cordis*, for the discovery of the blood circulation. Today, scientific research and education focusing on the pathophysiology of the heart forms one the most important pillars of modern medicine, and for good reason.

Ever since the Framingham Heart Study commenced in 1948, in the city of Framingham (Massachusetts, USA), modern medicine has tried to understand how heart disease affects our physical condition, quality of life and long-term survival, being constantly motivated by the devastating effects of unrecognised and/or untreated disease. Cardiovascular disease remains the main global cause of death, currently accounting for about 17 million deaths annually; this number is expected to increase to more than 23 million by 2030. 80% of these deaths occur in low- to middle-income countries. Heart disease accounts for almost 52% of the total \$7.28 trillion cumulative economic loss from non-communicable disease (which also includes respiratory disease, cancer and diabetes).

Considering the rise in risk factors such as obesity and arterial hypertension, together with the increasingly ageing Western population, it is evident that cardiac and cardiovascular disease will remain at the forefront of the global healthcare agenda for the foreseeable future. Several trials and registries are currently running to provide better insights through imaging (chapters 3, 13).

Nevertheless, the progress that has been made in the last 50 years is nothing short of astonishing. Procedures like heart transplants, complex valvular interventions and treatment of coronary artery disease have, among others, made such spectacular advances that they are now routinely performed in specialised centres all over the world. However, timely detection of disease, correct evaluation of its extension, and the outlining of possible treatment options still predicate the eventual success of many procedures. It is here that cardiac imaging plays an often-pivotal role, guiding the referring physician to the best possible patient outcome. For the cardiac radiologist, computed tomography (CT) and magnetic resonance imaging (MRI) are the main tools for non-invasive cardiac imaging (chapter 1).

While there has been continuous development of imaging techniques in other subspecialties, the progress made during the last decade in non-invasive cardiac imaging stands out among other achievements. Today, we can routinely and safely investigate potential coronary artery disease in patients; earlier, classic invasive angiography was the only available method for direct coronary artery visualisation (chapter

8). Our understanding of risk stratification and prognosis prediction, even in asymptomatic patients, using simple tools like the non-invasive quantification of coronary calcium is developing significantly as the results of large trials come in (chapter 2). The integration of CT during the triage of patients with acute chest pain has proven beneficial, resulting in quicker and safer discharge of patients in selected cases (chapter 4).

Beyond coronary arteries, MR imaging today provides valuable information for correctly characterising myocardial tissue, as such helping the clinician with, among other things, the evaluation of athlete’s heart, infectious/inflammatory disease, prevention of sudden death, and the evaluation of ischaemic heart disease (chapters 5–7, 16–17). Also, this book will shed more light on, what may at first glance appear as, unsuspected connections like the heart-brain axis (chapter 12).

Radiology has always been one of the first specialties to incorporate new technologies to achieve better results. New tissue mapping MRI techniques, evolving application like pre- and post-procedural evaluation of prosthetic heart valves, and of course the introduction of artificial intelligence as diagnostic tool will be addressed (chapters 9–11, 15).

Finally, since there is no ‘I’ in a team, several chapters further explain insights from and the important role of radiographers and medical physicists, who form an essential part of every radiology department (chapters 18–21).

The European Society of Cardiovascular Radiology (ESCR) is, as always, devoted to promoting cardiac radiology and assuring the high-quality performance of our members through accreditation (chapter 14). With this book, together with the European Society of Radiology (ESR), we thank you for your interest in the International Day of Radiology 2018, and we hope that you enjoy reading this publication.

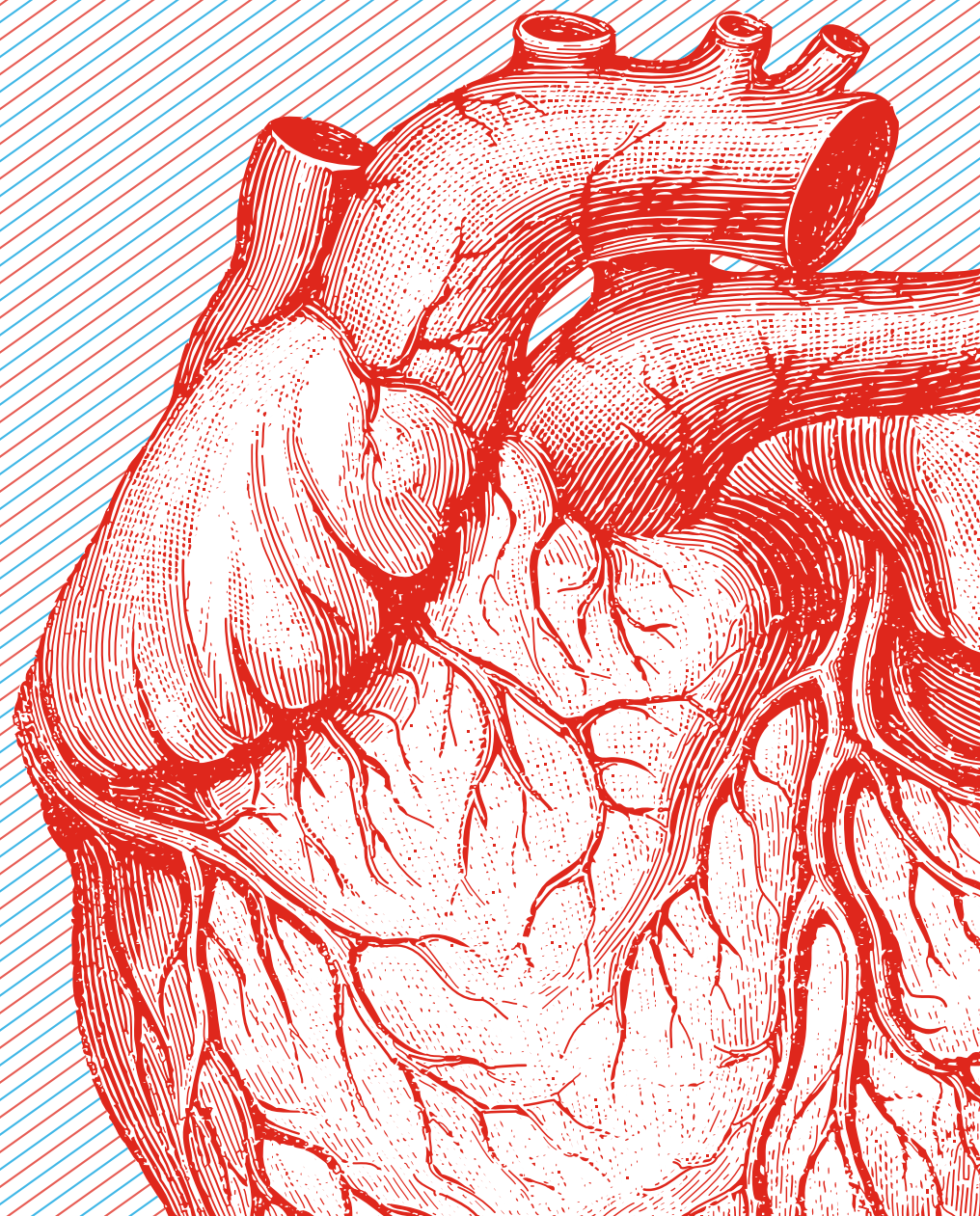
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# 1

## BASIC BUILDING BLOCKS IN NON-INVASIVE CARDIAC IMAGING

In the last decade, computed tomography (CT) and magnetic resonance imaging (MRI) have gained a prominent role in the non-invasive imaging of cardiac and cardiovascular disease, and as such have become the two most important non-invasive imaging modalities for a cardiac radiologist. As their underlying physical principles and therefore clinical application differs significantly, this first chapter offers an introduction into what constitutes the ‘basic building blocks’ of each imaging modality with regards to cardiac imaging. Specific applications will later be described in detail in dedicated chapters.

## BASIC BUILDING BLOCKS IN NON-INVASIVE CARDIAC IMAGING

### Part I:

# WHAT CAN WE EXPECT FROM A BASIC CARDIAC CT EXAMINATION

BY GORKA BASTARRIKA

### WHY CARDIAC CT?

Cardiovascular disease (CVD), and in particular coronary artery disease (CAD), is the leading cause of morbidity and mortality in developed countries. According to the European cardiovascular disease statistics in 2017, it is estimated that CVD causes 3.9 million deaths in Europe each year and accounts for 45% of all deaths in Europe<sup>1</sup>. Conventional coronary angiography is the gold standard to image the coronary vasculature and to assess the presence and severity of CAD. However, this technique is not without complications. It is estimated that coronary catheterisation causes major complications in 1.3% of cases and has a 0.05% in-lab mortality rate<sup>2</sup>.

Advances in cardiac computed tomography (CT) and significant improvements in spatial and temporal resolution have allowed for accurate and rapid, yet non-invasive evaluation of the coronary vasculature. In particular, since the advent of 64-row multidetector computed tomography scanners, coronary CT angiography (CCTA) holds the key to replacing diagnostic cardiac catheterisation in various clinical scenarios.

## BASIC ASPECTS OF CARDIAC CT

Adequate patient selection and preparation are mandatory factors to obtain optimal image quality cardiac CT examinations<sup>3</sup>. From a clinical perspective, CCTA is currently mostly indicated in symptomatic patients with a low to intermediate risk of CAD (Figure 1). There are some contraindications to cardiac CT. These include renal insufficiency, a known history of severe contrast reaction, clinical instability and pregnancy. Other patient-related variables that may also affect the diagnostic accuracy of the test include morbid obesity, an inability to collaborate with breath-hold instructions and/or scan acquisition, heart rate variability and arrhythmia, and contraindications to beta-blocker medication or nitrates.

Even if more recently developed CT systems allow for the scanning of patients with high and irregular heart rates, slow heart rates are preferred for cardiac CT imaging, not just because of the improved image quality. This approach also allows significant dose savings by applying sequential or even single heart-beat CCTA acquisition techniques (Figure 2).

In general, beta-blocker premedication is used to lower the heart rate below 60 beats per minute. Among different drugs, metoprolol has become the standard. In subjects weighing less than 80 kg an initial dose of 50 mg of metoprolol is administered, whereas for heavier subjects, 100 mg of metoprolol is administered one hour before the examination<sup>4</sup>. If the heart rate remains high, additional metoprolol may be given intravenously. An alternative approach to oral premedication

Figure 1

Coronary CT angiography performed on a 58-year-old man with atypical chest pain. (A) 3D-cinematic rendering. Curved planar reformats of the right coronary artery (B), left circumflex coronary artery (C), and left anterior descending coronary artery (D). The study showed mild luminal irregularities and allowed to exclude significant coronary artery stenosis.

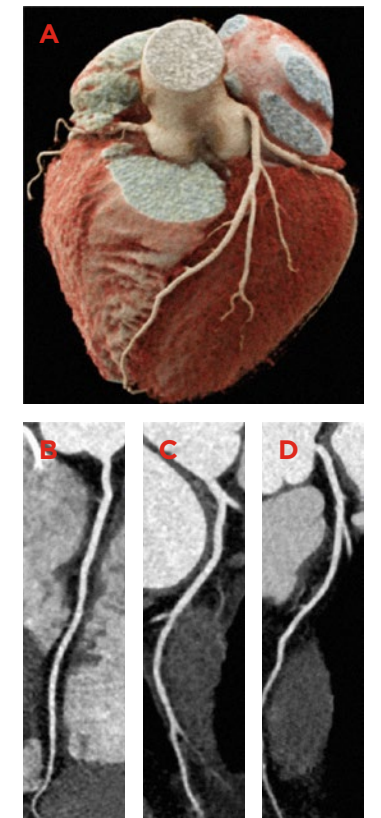
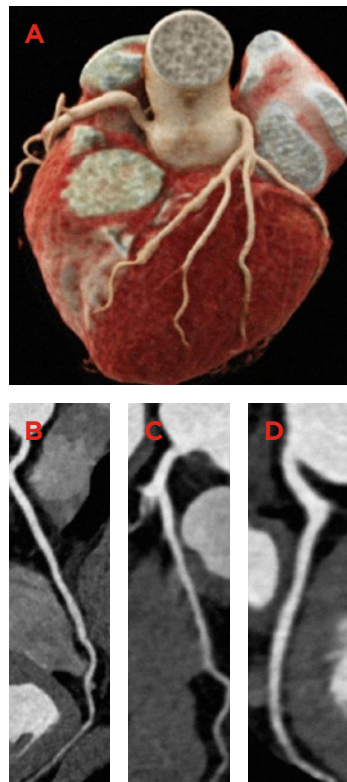


Figure 2

Coronary CT angiography performed using single-heartbeat high-pitch spiral acquisition in a 46-year-old woman with atypical chest pain and shortness of breath. (A) 3D-cinematic rendering. Curved planar reformats of the right coronary artery (B), left anterior descending coronary artery (C), and left circumflex coronary artery (D). The study allowed for the exclusion of significant coronary artery disease. A radiation dose of 0.65 mSv was employed in this study.



is the intravenous administration of the drug, usually starting with 5 mg. In patients with contraindications to beta-blockers, short-acting calcium channel blockers or ivabradine may be viable alternatives. The use of nitrates (400–800 mg of sublingual nitro-glycerine) just before the CT examination is also highly recommended in the absence of contraindications, so as to achieve coronary vasodilatation<sup>4</sup>.

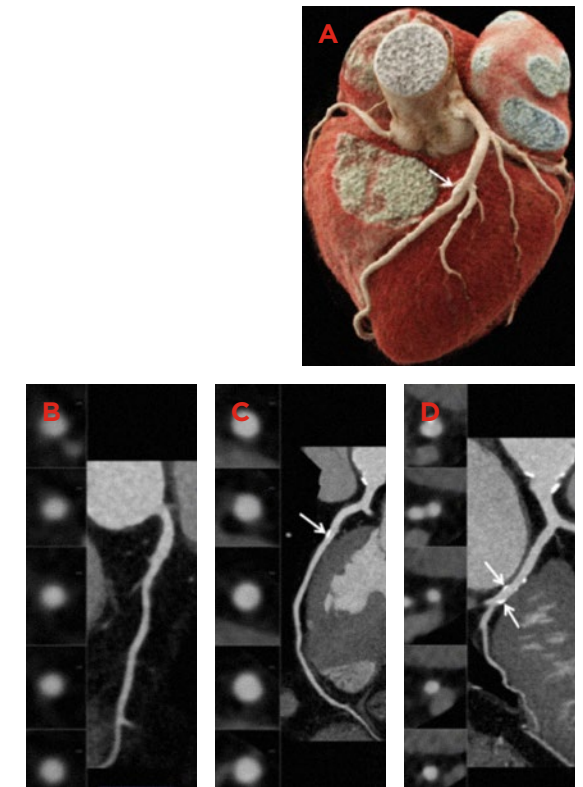
Cardiac CT should only be performed in cases where the results have the potential to influence patient management or prognosis<sup>5</sup>. Thus, besides the clinical benefit, radiation exposure should also be considered when ordering the test and carrying out the examination. From a technical perspective, the radiation dose should be kept to a minimum and all available strategies to avoid the use of unnecessary radiation should be applied. These include tailoring the tube voltage<sup>6</sup> and tube current<sup>7</sup> to patient habitus and using automated radiation exposure control techniques (i.e. ECG-based tube current modulation), limiting the scan range to the clinical indication, and using the optimal cardiac ECG-gating technique for each case (retrospective, prospective or single-heartbeat acquisition)<sup>8</sup>.

## CARDIAC CT IN THE CLINICAL SETTING

The clinical indications of cardiac CT are predominantly based on its high negative predictive value. CCTA allows for CAD to be ruled out with great certainty in symptomatic individuals, thus avoiding

Figure 3

Coronary CT angiography performed on a 57-year-old man with atypical chest pain and intermediate pre-test probability of CAD. (A) 3D-cinematic rendering. Curved planar reformats of the right coronary artery (B), left anterior descending coronary artery (C), and left circumflex coronary artery (D). The study showed scattered calcified and non-calcified plaques (arrows) predominantly involving the left anterior descending and left circumflex coronary arteries. The study allowed ruling out significant coronary artery stenosis.



unnecessary conventional coronary angiography procedures<sup>9</sup>.

Initial recommendations for when the use of CT in cardiac imaging was considered appropriate were endorsed by American and European cardiac and cardiac imaging societies<sup>10, 11</sup>, noting that, in general, cardiac CT should be performed in symptomatic subjects, especially if the symptoms, age and sex were suggestive of a low or intermediate probability of suffering significant coronary stenosis.

Most recent recommendations extend the appropriate use of cardiac CT to different clinical scenarios, confirming the previously

established indications and increasing their number<sup>12</sup>. In the field of detection of CAD in symptomatic patients without known heart disease, CCTA is appropriate in patients with interpretable ECG, who are able to exercise and who are presenting with an intermediate pre-test probability of CAD. Similarly, it is appropriate in individuals with uninterpretable ECG or who are unable to exercise and have low or intermediate pre-test probability of CAD (Figure 3). In patients with acute symptoms, CCTA is appropriate in cases of normal ECG and cardiac biomarkers and low or intermediate pre-test probability of CAD, and in patients with uninterpretable ECG or non-diagnostic or equivocal cardiac biomarkers and low or intermediate pre-test



Figure 4

Coronary CT angiography performed on a 69-year-old man with chest pain and prior history of coronary artery bypass surgery. (A) 3D-cinematic rendering. (B) Colour-coded perfusion map of the left ventricle in the three-chamber view. (C) Colour-coded perfusion map of the left ventricle in the short axis view. (D) 3D-volume rendered perfusion reconstruction. The study revealed occlusion of the saphenous vein to left anterior descending coronary artery graft (arrow in A). Myocardial perfusion images demonstrated hypoperfusion of the mid and apical inferolateral segments (arrow in B) and the apical anterior segment (arrow in C) in keeping with prior myocardial infarction. The patient also had a left apical thrombus (\*). Volume rendered images nicely showed the perfusion deficit (arrowheads in D).

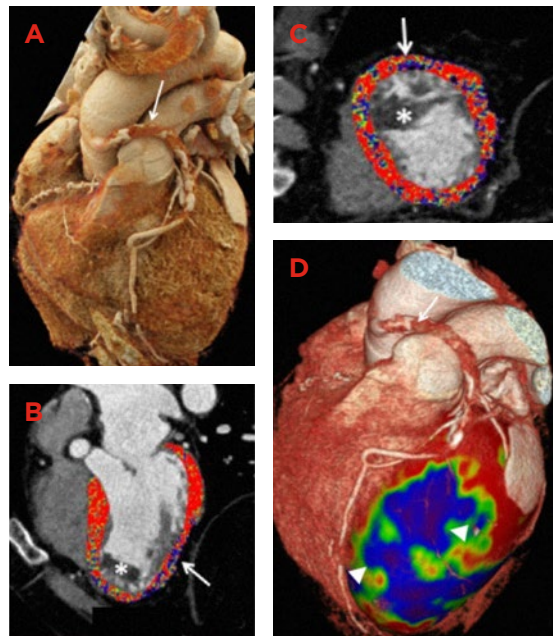
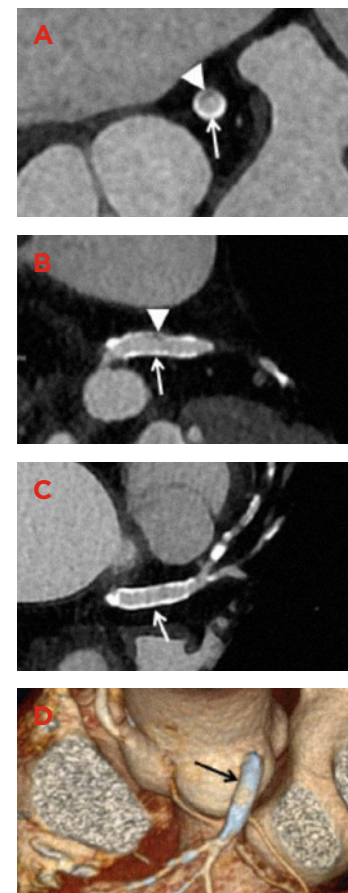


Figure 5

Coronary CT angiography performed on a 64-year-old asymptomatic patient with prior stent implantation in the left main coronary artery. (A) Cross-sectional image of the left main coronary artery. (B) Para-sagittal view of the left main coronary artery. (C) Oblique axial view of the left main coronary artery. (D) 3D-volume rendered image. The stent was patent (arrows) and only showed mild intimal hyperplasia causing less than 25% coronary stenosis (arrowhead).



probability of CAD. Non-contrast cardiac CT performed to quantify coronary artery calcification is appropriate to detect CAD and to assess risk in asymptomatic patients with a family history of premature coronary heart disease and in individuals with no known CAD and intermediate global coronary heart disease risk.

CCTA is also encouraged to detect CAD in other clinical scenarios, such as newly diagnosed or newly established clinical heart failure in patients without known coronary disease and low or intermediate pre-test probability of CAD, and in the preoperative evaluation of the coronary arteries in patients with intermediate pre-test probability of CAD undergoing non-coronary cardiac surgery.

After prior test results, CCTA should be performed when exercise ECG and imaging results are discordant, when stress imaging results are equivocal or in cases with normal previous stress imaging results and new or

worsening clinical symptoms. In the clinical scenario of risk assessment after surgical or percutaneous coronary revascularisation, CCTA is considered appropriate in the evaluation of graft patency after CABG in symptomatic patients (Figure 4), and in the assessment of prior left main coronary stent with stent diameter  $\geq 3$  mm (Figure 5).

Finally, CCTA is considered appropriate in the assessment of coronary anomalies and complex adult congenital heart disease, in the evaluation of left ventricular function following acute myocardial infarction or in heart failure patients when inadequate images have been obtained from other non-invasive methods, in the assessment of morphology and quantification of right ventricular function, in the characterisation of native and prosthetic cardiac valves in cases of clinical suspicion of significant valvular dysfunction with non-diagnostic images from other techniques (Figure 6), and in other clinical scenarios, such as the evaluation of cardiac

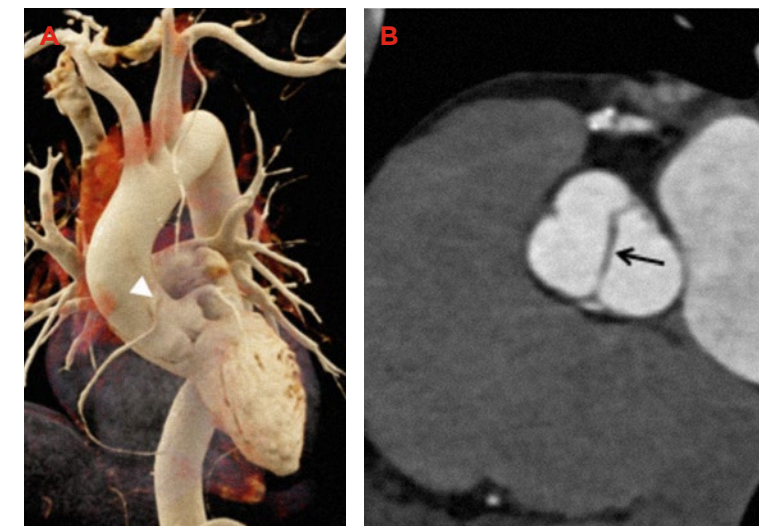
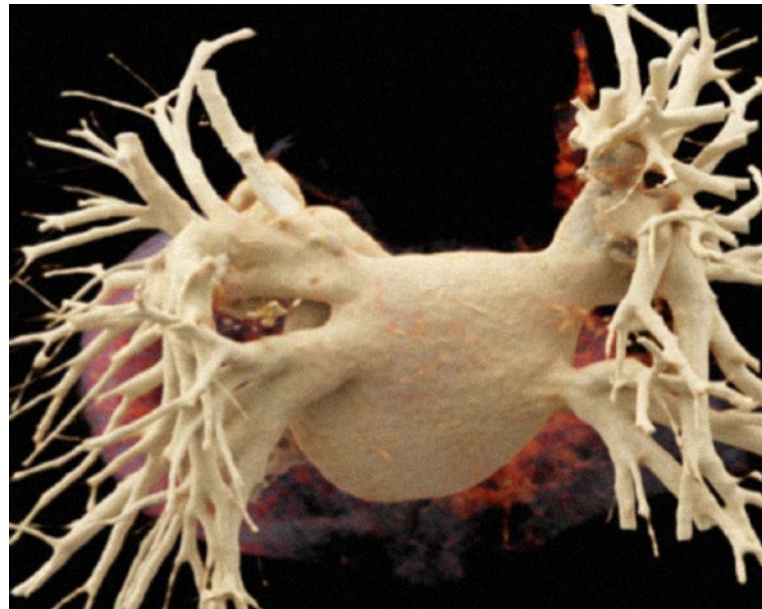


Figure 6

CT angiography of the aorta performed on a 37-year-old man. (A) 3D-cinematic rendering. (B) Multi-planar reformat of the aortic valve. The study revealed mild dilation of the ascending aorta and a bicuspid aortic valve (arrow in B). Incidentally, a coronary anomaly consisting of abnormal origin of the right coronary artery from almost the sinotubular junction was also noted (arrowhead).

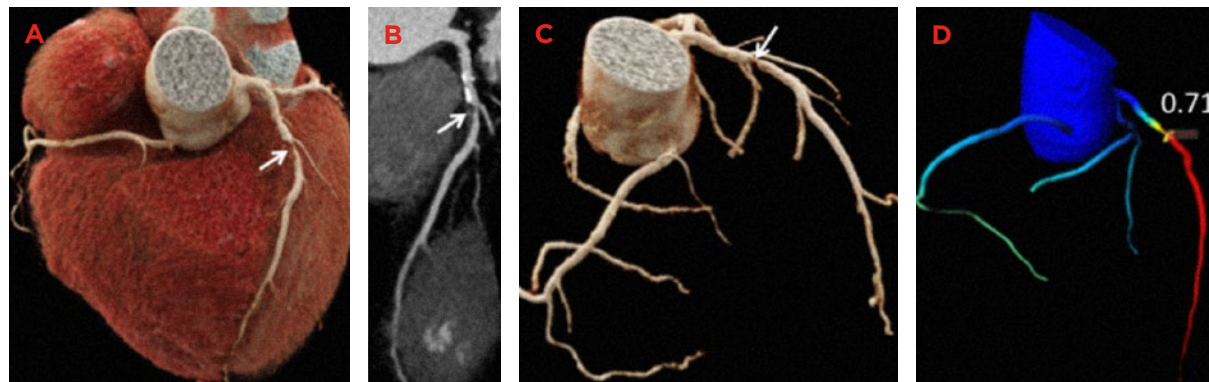


**Figure 7**

Cardiac CT performed on a 74-year-old man with paroxysmal atrial fibrillation requiring pulmonary vein ablation. Normal anatomy of the pulmonary veins was observed.

**Figure 8**

Coronary CT angiography performed on a 56-year-old man with atypical chest pain and prior inconclusive stress test. (A) 3D-cinematic rendering. (B) Curved planar reformat of the left anterior descending coronary artery. (C) 3D-cinematic rendering of the coronary vasculature. (D) CT-derived fractional flow reserve (CT-FFR). A 70–99% stenosis was depicted in the mid left anterior descending coronary artery segment (arrows) (CAD-RADS 4A). CT-derived FFR value obtained with a research prototype (ctFFR, syngo.via Frontier, Siemens Healthineers) was 0.71, reflecting that the coronary stenosis was likely haemodynamically significant.



masses, evaluation of pericardial anatomy, assessment of pulmonary and coronary vein anatomy prior to interventional procedures, such as radiofrequency ablation or pacemaker implantation (Figure 7), and previous redo cardiac surgery<sup>12</sup>.

## CONCLUSION AND FUTURE PERSPECTIVES

Recent development has allowed a widespread use of cardiac CT. From the beginning, CCTA showed its usefulness in a certain number of clinical scenarios in individuals with known or suspected CAD. Nowadays, clinical indications are mostly based on its high negative predictive value, i.e. on its ability to confidently rule out significant coronary artery stenosis. Besides evaluating the coronary vasculature, cardiac CT has also been shown to be useful in the evaluation of cardiovascular anatomy and morphology. Ongoing research points towards comprehensive assessment of ischaemic heart disease. Strategies based on complex computational methods (i.e. CT-derived fractional flow reserve) (Figure 8) and CT myocardial perfusion may fulfil this integrative approach to coronary artery disease. Furthermore, recent publications also emphasise the prognostic value and cost-effectiveness of cardiac CT. Significant research is still warranted to further evaluate the full clinical potential of this imaging technique.

## References

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## BASIC BUILDING BLOCKS IN NON-INVASIVE CARDIAC IMAGING

### Part II:

# WHAT CAN WE EXPECT FROM A BASIC CARDIAC MR EXAMINATION

BY FARAH CADOUR, AXEL BARTOLI AND ALEXIS JACQUIER

### WHY CARDIAC MR?

With technical progress, cardiac magnetic resonance (CMR) imaging has become part of mainstream cardiology imaging practice. The development of increasing magnetic field strengths and surface coil channels, rapid k-space sampling, postprocessing techniques, and sophisticated sequences for myocardial characterisation have made cardiac MR a powerful tool in the workup of many complex cardiac disorders. Consensus statements from several international cardiac associations include cardiac MR as a primary imaging technique. In this chapter, we will outline the CMR biomarkers assessable in clinical practice that give an optimal evaluation of anatomy, function, perfusion, flow, and tissue characterisation. This chapter will also provide an overview of the CMR capabilities in cardiac imaging, but it does not intend to be exhaustive.

### BASIC MR ANATOMY EVALUATION

All cardiac imaging sequences are acquired using electrocardiographic gating to overcome image-blurring secondary to cardiac

contraction. In clinical practice, all sequences could be useful to detect anatomical abnormalities. However, anatomical parameters are particularly crucial in defining thoracic aorta aneurysm and the indications to treat thoracic aorta aneurysm are based on anatomical measurements. To assess the ascending aortic anatomy, 3D bright blood free breathing steady state free precession sequences yield multiplanar reconstructions. Ascending aortic aneurysm measurements should be taken perpendicular to the vessel of interest. The largest diameter perpendicular to the great axis is considered as the reference diameter (Figure 1). Exploration of the ascending aorta should include exploration of the aortic valve in particular to detect constitutional

abnormalities such as bicuspid valves or valvular regurgitation or stenosis.

### MR FUNCTIONAL ASSESSMENT

Left ventricular (LV) volumes and mass assessment are well-known markers of LV systolic function. Steady state free precession (SSFP) sequences are the gold standard for assessing chamber volume and mass. SSFP sequences require k-space sampling over several heartbeats and must be performed with short breath holds (usually from 8-12 seconds). SSFP sequences have a high signal to noise ratio and provide a T2/T1

Figure 1

This figure shows an example of a 3D bright blood sequence (free breathing, 6 min acquisition time). (A) A native image of the 3D stack is displayed. (B) shows a reconstructed view perpendicular to the great axis of the aortic root. Note that the aortic valve is bicuspid without raphe. A 3D volume rendering of the ascending aorta is displayed in (C).



signal. Furthermore, SSFP also quantifies chamber volume and LV mass; for that purpose, a stack of short-axis SSFP cine sequences should be acquired from the annulus to the apex. Interobserver and intraobserver variability is around 5% and 3% respectively for volume quantification. Expert consensus panels consider CMR to be the most precise and reproducible technique to assess LV volume, mass and ejection fraction. Other cardiac chamber volumes can also be assessed using SSFP sequences. Cine sequences are the basis of all cardiac magnetic resonance images (Figure 2). Besides the functional parameters, cine sequences can also depict abnormal segmental contraction or any

abnormal aspect of the left ventricle such as excessive trabeculation phenotypes.

## MR FLOW QUANTIFICATION

Velocity-encoded cardiac magnetic resonance measures flow in vessels of the cardiovascular system without the use of intravascular catheterisation, ionising radiation radioactive tracers or gadolinium injection. Velocity maps are generally displayed on a grey scale with stationary tissue shown in mid-grey, velocities in forward (positive) and reverse (negative) directions being represented as higher (towards white)

and lower (towards black) pixel intensities (Figure 3). Velocity-encoded CMR measures valvular regurgitation accurately and is used if echocardiography has yielded unsatisfactory results.

## MYOCARDIAL PERFUSION IMAGING

Myocardial perfusion imaging assesses the blood supply to the myocardium and plays an increasing role in the diagnosis of ischaemic heart disease. In order to assess myocardial perfusion, blood passing into the myocardium needs to alter the image

signal intensity so that areas of reduced perfusion can be detected. This is typically achieved using a signal enhancing contrast agent. The contrast agent is injected intravenously whilst multiple images of the heart in the same anatomical position and at the same point in the cardiac cycle are acquired in successive heartbeats. Typically, short-axis images are acquired but a long axis image is sometimes also acquired in order to cover the apex of the heart. In general, the acquisition of a dynamic series of MR images during the passage of contrast agent through the body is known as dynamic contrast-enhanced MRI (DCE-MRI). DCE-MRI can be used after the injection of a vasodilator drug at rest and

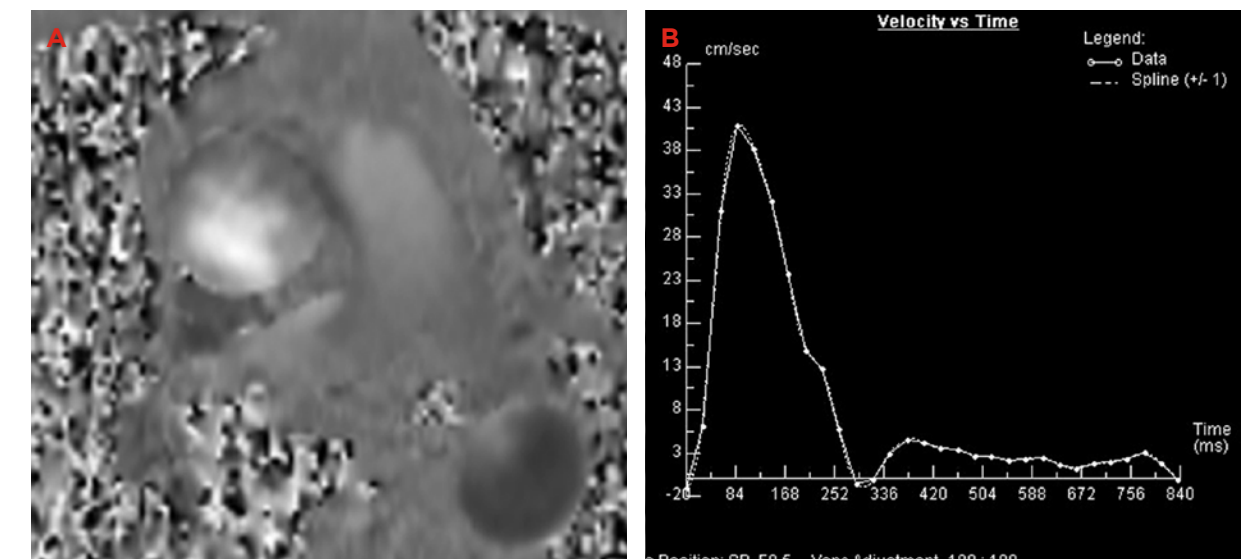
Figure 2

This figure shows a four chamber view steady state free precession (SSFP) image in the diastolic phase. Note the high contrast between blood and myocardium.



Figure 3

This figure shows velocity-encoded images in (A) and the corresponding aortic flow profile in (B).



under stress to detect myocardial ischaemia. Recent European recommendations consider DCE-MRI as precise as other reference technique such as SPECT or PET for ischaemia diagnosis.

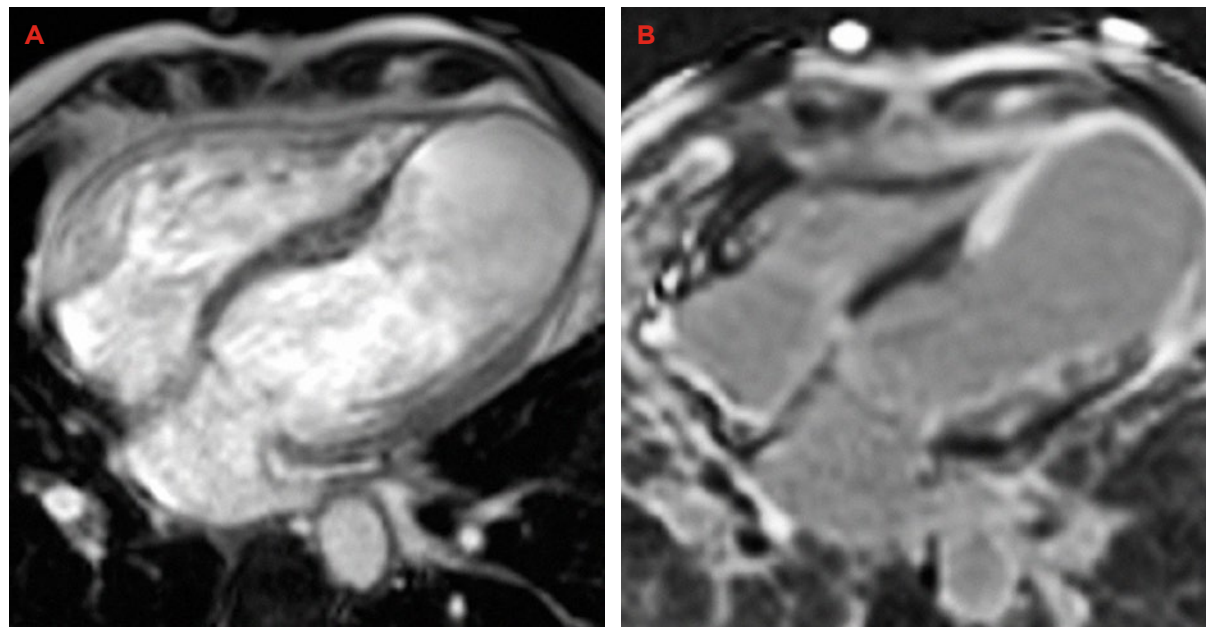
## LATE GADOLINIUM ENHANCEMENT

Late gadolinium enhancement (LGE) imaging has revolutionised the role of CMR for both ischaemic and

non-ischaemic disease. LGE involves intravenous administration of 0.1 to 0.2 mmol/kg gadolinium-based contrast agent followed by the acquisition of T1 weighted images of the myocardium using an inversion recovery technique. In ischaemic disease, LGE depicts areas of myocardial infarct that typically involve the sub-endocardium, and depending on the size of the infarct, extend up to the epicardium. This method is referred to as 'viability imaging', as the absence of scar indicates that the myocardium is viable, retaining a capacity to recover its contractile function

Figure 4

This figure shows a patient with a huge left ventricular (LV) apical aneurysm in (A) with transmural enhancement after late gadolinium enhancement (LGE) in (B).



following revascularisation (Figure 4). LGE not only defines the location and extent of infarction, but also differentiates areas that show failure of tissue perfusion after revascularisation, the so-called no-reflow phenomenon. In non-ischaemic disease, LGE characterises hyper-enhancement patterns that are characteristic of several disorders such as hypertrophic cardiomyopathy (Figure 5), inflammatory or storage diseases such as cardiac sarcoidosis (Figure 6) or amyloidosis (Figure 7).

## PARAMETRIC MAPPING AND TISSUE CHARACTERISATION

Parametric mapping is a new technology in clinical CMR practice. On conventional MR imaging techniques, signal intensity is expressed on an arbitrary scale that differs from one imaging examination to another and therefore is unsuitable for direct signal quantification. T1 and T2 mapping, in contrast, yields signal quantification in milliseconds on a standardised scale. In T1 and T2 mapping techniques, after preparation, pulse signal recovery is sampled from a series of multiple measurements, and the associated T1 or T2 relaxation time is calculated for every pixel of a parametric image referred to as a T1 or T2 map. T1 maps yield measurements of myocardium and blood T1 values before and after gadolinium contrast enhancement. The native T1 value (without contrast) is used to characterise myocardial infiltration by fibrosis or protein such as in amyloidosis (Figure 7). T1 mapping has demonstrated its value

Figure 5

This figure shows a patient with a sarcomeric hypertrophic cardiomyopathy. The maximal end diastolic thickness of the interventricular septum is 21mm (A). T1 mapping in (B) showed up an area of higher signal, matching with area of highly fibrosed myocardium on late gadolinium enhancement (LGE) (C).

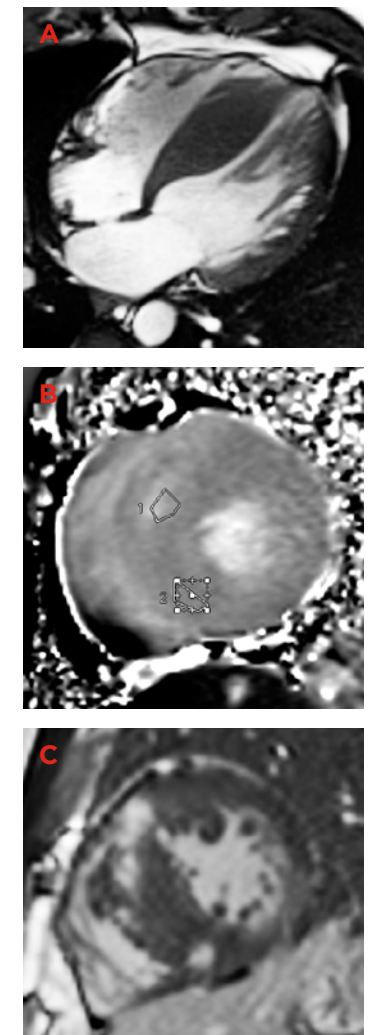


Figure 6

This figure shows a patient with an acute cardiac sarcoidosis involvement depicted by a large oedema shown as an orange area on the T2 mapping sequence in (A) and matching with the late gadolinium enhancement (LGE) myocardial area on (B).

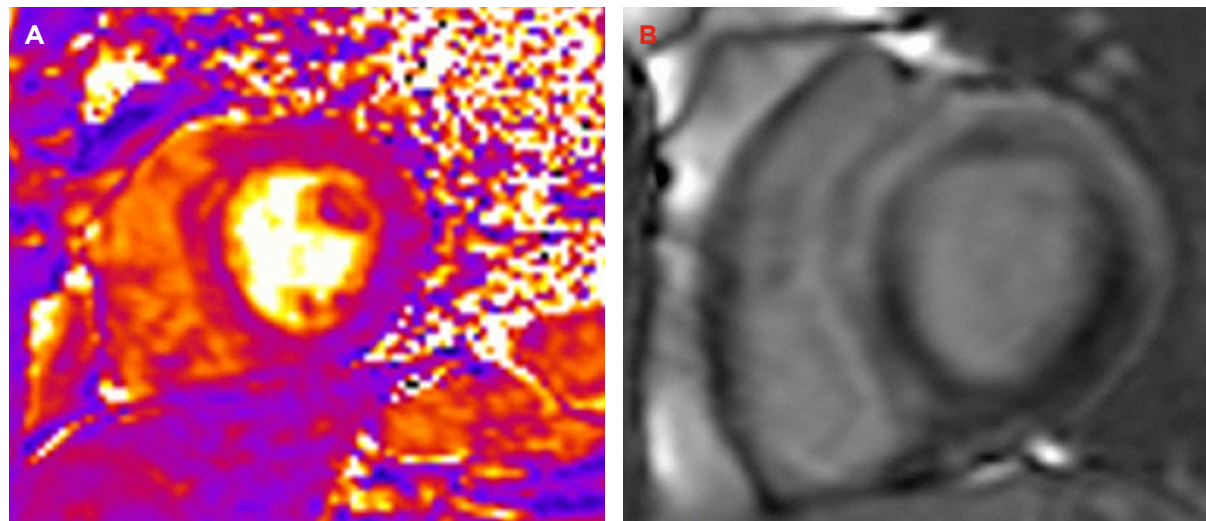


Figure 7

This figure shows a patient with overall myocardial hypertrophy involving the left ventricular (LV), right ventricular (RV) and both atrial walls on (A). On (B) the T1 map shows high signal intensity of the entire LV whole with a T1 value measured at 1542ms (normal 1150ms (3T machine)). The LGE image in (C) depicts diffuse myocardial enhancement with a higher signal in comparison to LV blood. Amyloidosis was confirmed on biopsies.

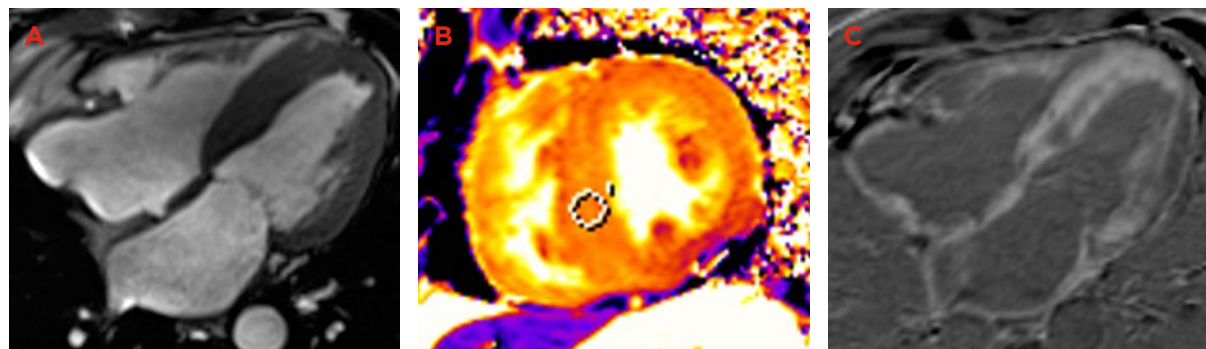
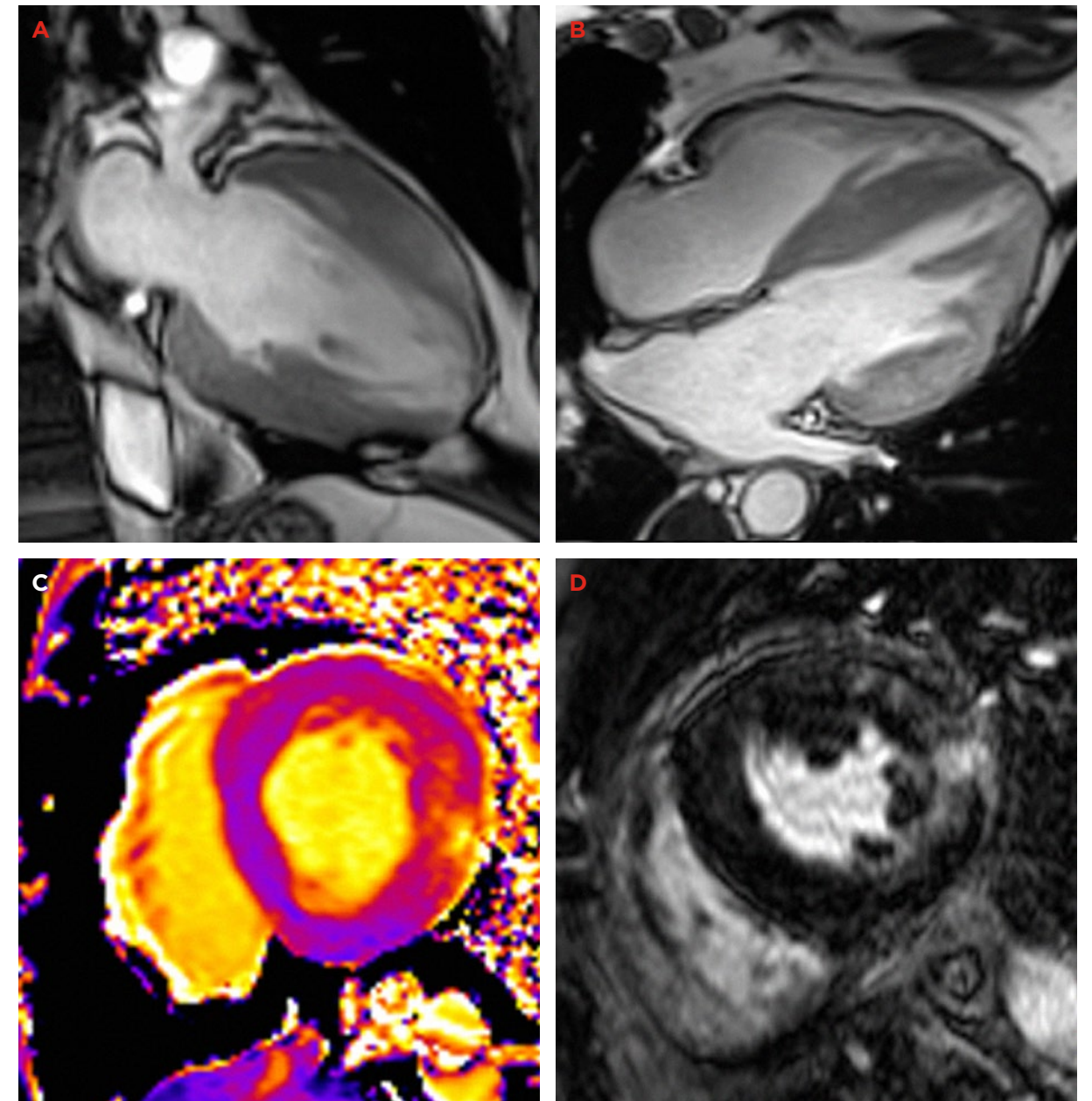


Figure 8

This figure shows a patient with a global disseminated left ventricular (LV) hypertrophy in (A) and (B). In (C) T1 mapping revealed a low value at the level of the septum with a T1 value measured at 798ms and a high signal area on the lateral wall matching with area of LGE on (D).



in assessing myocardial involvement in Fabry's disease and shown a decrease in T1 value in the myocardium (Figure 8). T2 mapping is less sensitive to motion and coil artefact compared to T2 weighted images and is used to quantify oedema and for follow-up (Figure 6).

## CONCLUSION

Over the past decade, CMR has developed from an exciting novelty to become an integral part of today's clinical routine. The unique ability of CMR to comprehensively assess cardiac morphology, function, and tissue structure has provided new pathophysiologic insights, improving our understanding of ischaemic cardiomyopathies and non-ischaemic cardiomyopathies and facilitating early diagnosis.



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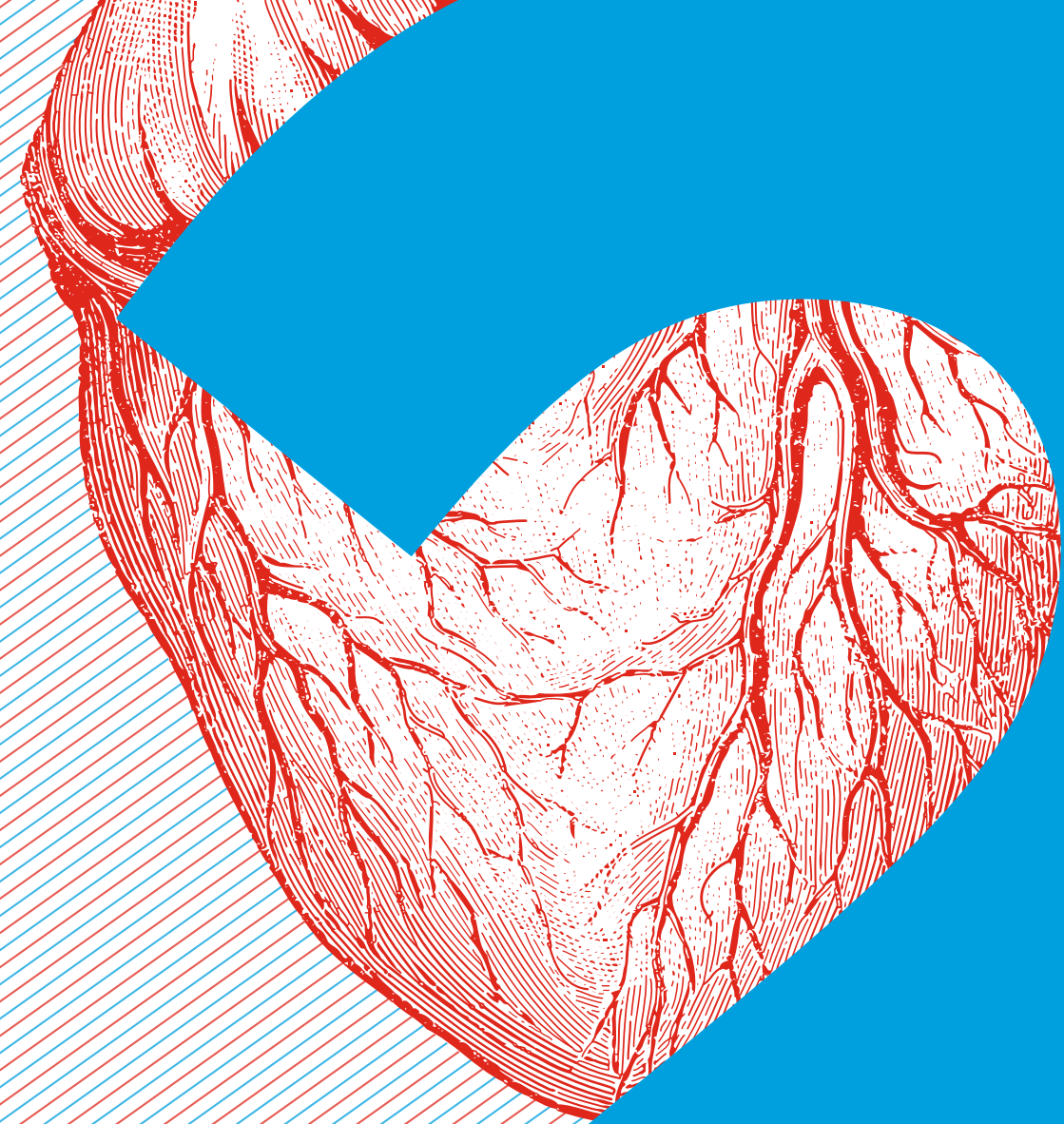


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2

RISK  
STRATIFICATION



# MY FUTURE AND I: CARDIOVASCULAR RISK STRATIFICATION OF ASYMPTOMATIC INDIVIDUALS

BY ROZEMARIJN VLIEGENTHART

In the coming decades, a continuing increase in the number of cases of coronary heart disease (CHD) is expected. This is caused by, amongst others, the increasing prevalence of obesity and diabetes, and the rising numbers of elderly citizens. The morbidity and mortality toll of CHD is high. In many cases, a coronary event occurs acutely, without earlier signs suggesting CHD. So how can we identify individuals in the asymptomatic population at high risk of CHD, and prevent coronary events? Cardiovascular risk estimation in the general population is based on determining risk factors such as hypertension and smoking. Risk factor levels can be used to calculate a risk-scoring algorithm, like the European SCORE, and guide medical therapy. Unfortunately, risk factor based algorithms are neither highly sensitive nor specific. Accurate identification of asymptomatic individuals who will develop a coronary event is challenging.

Evaluation of the extent of atherosclerotic plaque, which underlies CHD, can improve cardiovascular risk evaluation. Amongst the non-invasive measures of atherosclerosis, focus has turned to assessment of coronary calcification by non-contrast-enhanced computed tomography

(CT). Coronary calcium scanning was first made possible in the late eighties with electron-beam tomography. Nowadays, any CT system with at least 16 detectors can be used for this purpose. The CT calcium scoring protocol is highly standardised (Figure 1) and involves an electrocardiographically (ECG)-triggered CT scan. A CT scan for calcium scoring involves a radiation dose of typically 1 mSv or less. This dose is insignificant compared to annual background radiation.

The amount of coronary calcification is typically expressed as a calcium score according to Agatston's method (Figure 2). With the use of semi-automated software, a calcium score can be calculated within a couple of minutes by radiology technicians. The variability in calcium scores within and between observers is low. However, there are differences in calcium scores between CT systems from different vendors that can result in a difference in risk classification in some individuals. At the very least, it is important to perform repeated calcium scoring as much as possible on the same CT system.

A positive calcium score indicates the presence of coronary atherosclerosis. While CT-detected coronary calcification only allows evaluation of the calcified component of coronary plaques, a good correlation has been found between the calcium score and the total coronary plaque burden as determined by intravascular ultrasound and histology. Therefore, the calcium score is a good measure for the total extent of coronary atherosclerosis, including stable and vulnerable plaque.

Figure 1

Standardised protocol for CT calcium scoring

## CALCIUM SCORING: METHODOLOGY

- **At least 16-MDCT system**
- **Standardised protocol**
  - Axial scan mode
  - Prospective ECG triggering
  - Tube voltage 120 kVp
  - Reconstructed slice thickness 3 mm
  - Calcium score according to Agatston
- **Radiation dose typically 1 mSv (< 3 mSv)**

Figure 2

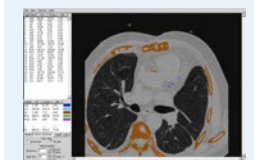
Calculation of the calcium score according to Agatston's method

## CALCIUM SCORING: AGATSTON'S METHOD

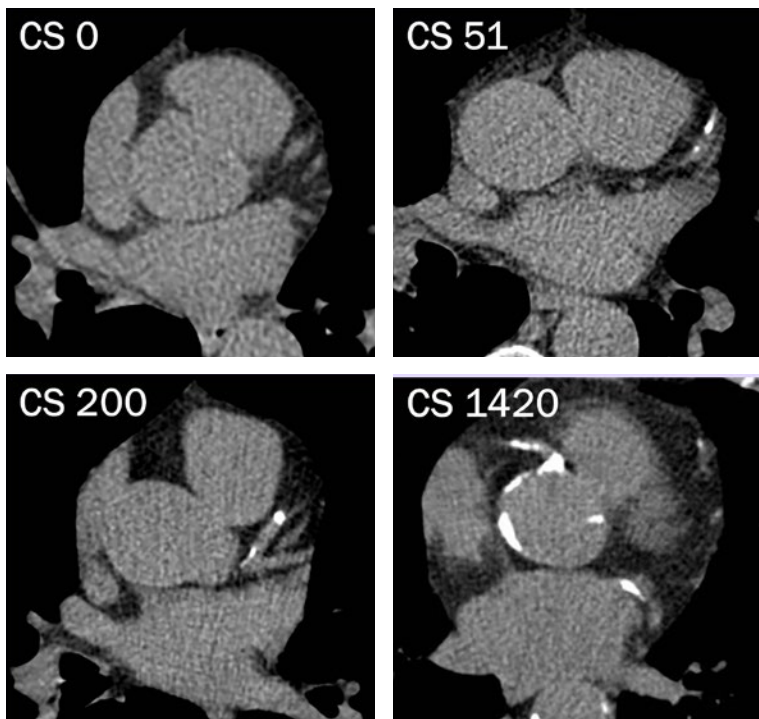
### Score per calcified lesion:

Area of voxels	$\left\{ \begin{array}{l} 1 = 130-199 \text{ HU} \\ 2 = 200-299 \text{ HU} \\ 3 = 300-399 \text{ HU} \\ 4 = \geq 400 \text{ HU} \end{array} \right.$
$\geq 130 \text{ HU}$	
x	
Factor (voxel with highest HU)	

**Total score:** add score for all calcified lesions



Agatston, JACC 1990



**Figure 3**

Calcium score scan results for four individuals with no, mild, moderate and severe coronary calcification

Figure 3 shows some examples of CT calcium score scan results.

The calcium score increases with age, and is generally higher for men than for women. About 50% of men have some detectable coronary calcification at age 50 years, compared to approximately 25% of women. Often, the calcium score is divided into four categories (Figure 4): 0 (none), 1–99 (mild), 100–299 (moderate), and at least 300 (severe coronary calcification). These cut-points were chosen based on the risk of significant coronary artery disease at invasive coronary angiography. Another commonly used approach is to calculate an age- and gender-matched percentile, where a calcium score of at

least the 75<sup>th</sup> percentile indicates premature or accelerated plaque development.

Multiple screening and population-based studies have shown the strong prognostic value of the calcium score for coronary events. The calcium score predicts the occurrence of CHD in men and women, and in younger and older populations. Already in individuals with a positive, low calcium score (1–100), the risk of coronary events is doubled compared to those with a zero calcium score. Around two thirds of coronary events are concentrated in the quarter of the population with a calcium score above 100. Compared to individuals without coronary calcification, those with a calcium score above 1,000 have more than 10 times the risk

of CHD. These individuals should be considered high risk. The relative risks for increasing calcium score categories are much higher than those reported for cardiovascular risk factors or other non-invasive measures of atherosclerosis.

When considering the utility of calcium scoring, it is important to assess the ability of the test to improve discrimination between those who do and who do not develop an event. There is clear evidence that calcium scoring improves this discrimination, in particular in the intermediate risk category (based on risk factors). Studies have shown that up to two thirds of those with intermediate risk were more correctly classified in the low- or high-risk category when the calcium score was added to risk stratification. Thus, the calcium score can have a major impact in risk stratification of the asymptomatic population.

Apart from a high calcium score, a clinically very relevant finding is a calcium score of 0. In over 70,000 individuals, a zero calcium score conferred a risk of CHD of only 0.5% in four years, suggesting that the risk of coronary events is negligible in case of absent coronary calcification. A calcium score of 0, in asymptomatic individuals and in symptomatic patients, is a very reassuring finding with a warranty period of up to 15 years. Whether it is safe to downregulate preventive medication in case of a calcium score of zero is still unknown.

So far, randomised controlled trials on the impact of calcium scoring on CHD are lacking. This information is generally considered essential to determine the value of a new

diagnostic marker for integration in risk assessment. However, this evidence is similarly lacking for currently used risk scoring algorithms based on risk factors and other non-invasive markers of atherosclerosis such as the ankle-brachial index. Currently, a randomised trial on the role of calcium scoring in primary prevention is ongoing in the Netherlands (ROBINSICA trial).

What do current guidelines mention about the calcium score? Recent guidelines on cardiovascular risk assessment and CHD prevention (ACC/AHA 2013; ESC 2016) agree on an indication of calcium scoring in asymptomatic individuals at intermediate risk based on risk factors. In these cases, adding

**Figure 4**

Classification of calcium score into cardiovascular risk categories

CALCIUM SCORING: RISK CATEGORISATION	
Score	Cardiovascular risk
0	very low
1–99	mildly increased
100–299	moderately increased
≥ 300	moderate to severely increased
Score	Cardiovascular risk
> 75%	increased risk compared to persons of same sex and age

the calcium score as a risk modifier can lead to upward or downward risk reclassification. This assists in decision-making regarding the start of preventive medication. In the US guideline, the recommendation is to reclassify an individual into the higher-risk category in case of a calcium score of at least 300, or at least 75% percentile for their age and gender. The 2016 SCCT/STR guideline states that because of its strong prognostic value, coronary calcification should be evaluated and reported on all routine non-contrast, non-ECG-triggered chest CT scans. In this setting, the amount of coronary calcium can be visually estimated as none, mild, moderate and severe (Figure 3).

In conclusion, CT calcium scoring is an increasingly important radiological examination. CT calcium scoring is limited to a very low radiation dose, can be performed in a high throughput fashion, is a technician only examination, and has virtually no contraindications. Strengths of CT calcium scoring include the high level of standardisation, the extensive evidence base for its risk stratification potential in the general population and its role in cardiovascular prevention guidelines.

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#### References

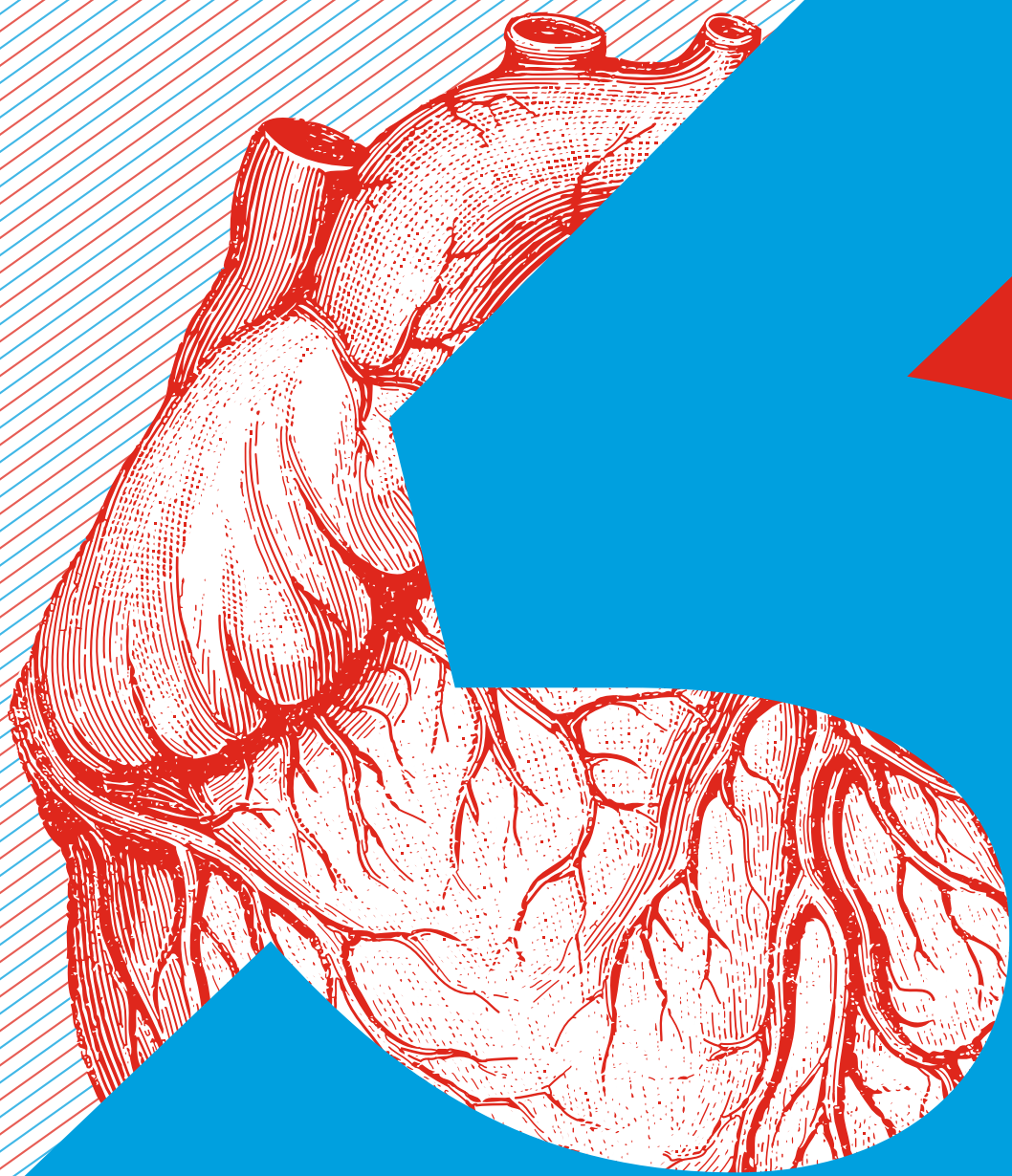
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3

CARDIAC  
IMAGING  
TRIALS

# IMAGING TRIALS: THE FUTURE OF CARDIAC IMAGING LOOKS BRIGHT

BY MARC DEWEY

## INTRODUCTION

The future of cardiac imaging will be greatly influenced by the results of imaging trials. This is because health insurers mainly rely on evidence from randomised imaging trials when deciding about the coverage of novel imaging techniques. In such trials, patients are randomly (by chance) assigned to undergo the novel imaging technique or the previous standard of care, which may or may not include imaging. To give a broad overview of recent and current cardiac imaging trials, we invited all trialists to provide a graphical abstract of their trial. The figures in this chapter are graphical abstracts, mainly from the trials' chief investigators, and provide an easy-to-understand overview of how these trials will shape the future of cardiac imaging.

## THE BEACON TRIAL<sup>1</sup>

*Better Evaluation of Acute Chest pain with computed tomography angiography - a randomised cONtrolled trial*

The BEACON trial included 500 patients at seven sites in the Netherlands with low-to-intermediate risk chest pain at the emergency department.

Patients were randomised to either cardiac computed tomography (CT) or standard care. Results showed that cardiac CT led to reductions in diagnostic costs (Figure 1).

## THE CATCH I TRIAL<sup>2</sup>

*CArdiac cT in the treatment of acute CHest pain*

The CArdiac cT in the treatment of acute CHest pain (CATCH) trial included 600

patients admitted to Hvidovre hospital, Copenhagen with acute onset chest pain, but normal electrocardiogram and troponins. Patients were randomised to either outpatient evaluation with computed tomography (CT) or a functional stress test (exercise bicycle test or single photon emission computed tomography (SPECT)). Results showed that cardiac CT identified more patients with significant coronary artery disease (CAD) and more coronary revascularisations were performed. Cardiac CT reduced subsequent cardiac events within a median follow-up period of 18.7 months (Figure 2).

Figure 1

The BEACON trial

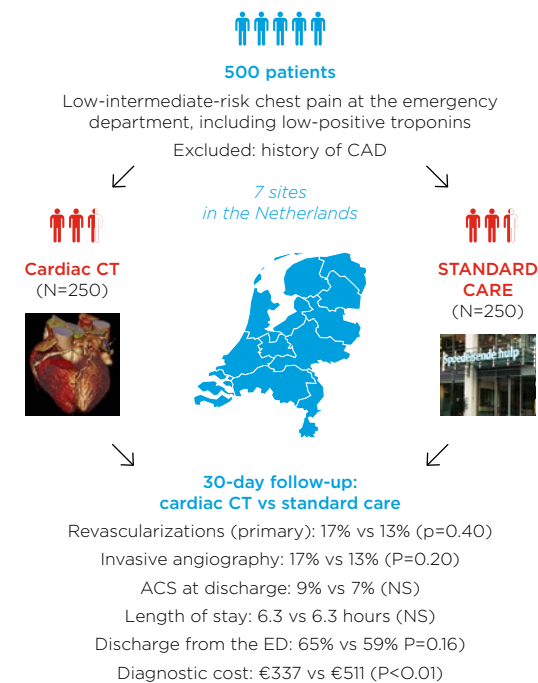
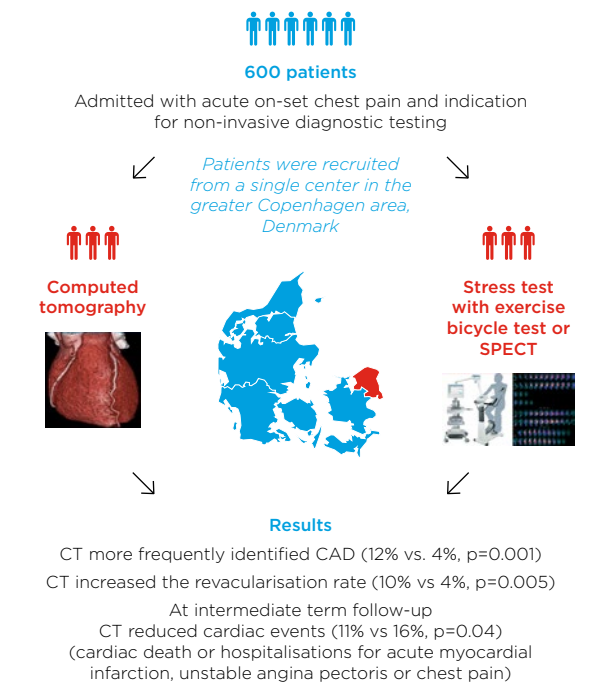


Figure 2

The CATCH I trial



## THE CATCH II TRIAL<sup>3</sup>

*Cardiac cT in the treatment of acute Chest pain – myocardial CT perfusion II*

The CARDiac cT in the treatment of acute Chest pain 2 (CATCH II) trial included 600 patients admitted to a hospital in the Greater Copenhagen area with acute onset chest pain for either computed tomography (CT) or computed tomography in combination with myocardial CT perfusion (CTP). Results showed a significant reduction in the referral rate for invasive coronary angiography and reduced revascularisation rate in the CT + CTP group. However, the revascularisation rate among patients referred for invasive coronary angiography was similar in the two groups. Follow-up will be conducted to

examine the implications of the diagnostic approaches (Figure 3).

## THE CE-MARC II TRIAL<sup>4</sup>

*Clinical Evaluation of MAgnetic Resonance imaging in Coronary heart disease II*

The CE-MARC II trial randomly assigned more than 1,200 patients to either magnetic resonance (MR) imaging, the procedure according to the UK NICE guideline, or to myocardial perfusion scintigraphy (MPS). There were fewer angiographies after MR and MPS, reducing unnecessary angiographies, while major adverse cardiovascular events were similar in the three groups (Figure 4).

## THE CRESCENT II TRIAL<sup>5</sup>

*Comprehensive Cardiac CT Versus Exercise Testing in Suspected Coronary Artery Disease Randomized Controlled trial*

The CRESCENT II trial randomly assigned 268 patients with a pre-test probability (PTP) of more than 10% to either a tiered CT protocol including calcium score, CT angiography and CT perfusion or functional testing. This resulted in a greater proportion of invasive angiograms with an ESC class I indication in the CT group and less secondary non-invasive testing (Figure 5).

## THE DISCHARGE TRIAL<sup>6</sup>

*Diagnostic Imaging Strategies for Patients with Stable Chest Pain and Intermediate Risk of Coronary Artery Disease: comparative effectiveness research of existing technologies*

The DISCHARGE trial randomly assigns more than 3,500 patients across Europe to undergo either computed tomography (CT) or invasive coronary angiography. Outcomes that matter to patients will be collected at follow-up in a blinded fashion to generate highest levels of evidence (Figure 6).

Figure 3

The CATCH II trial

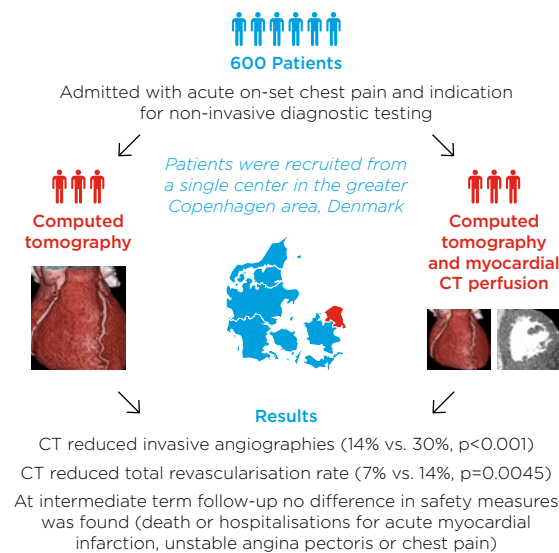


Figure 4

The CE-MARC II trial

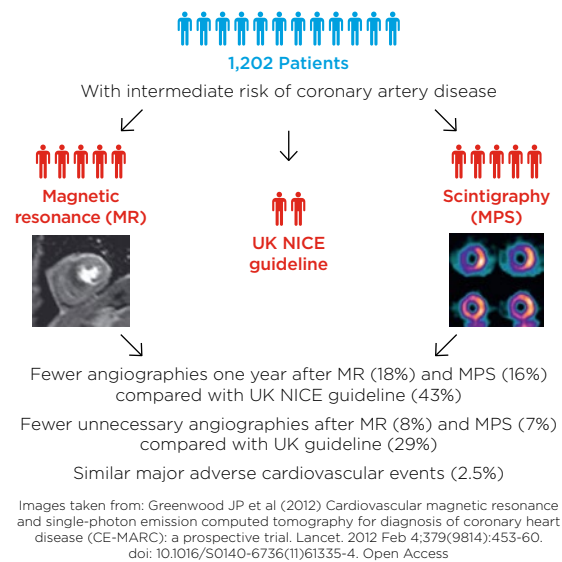


Figure 5

The CRESCENT II trial

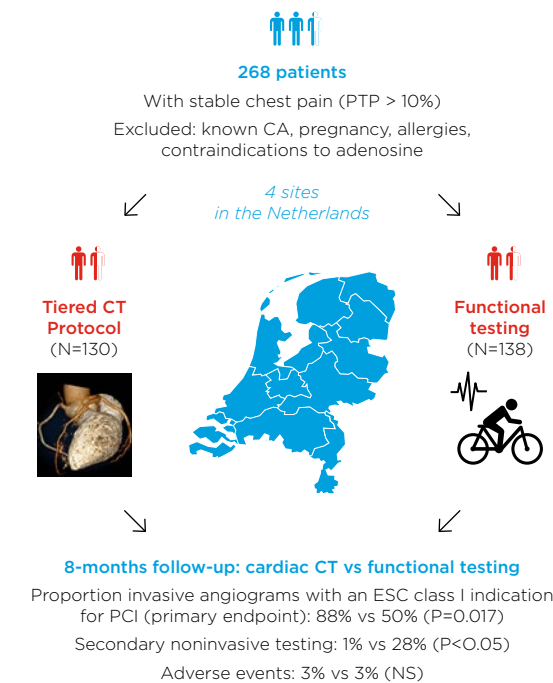
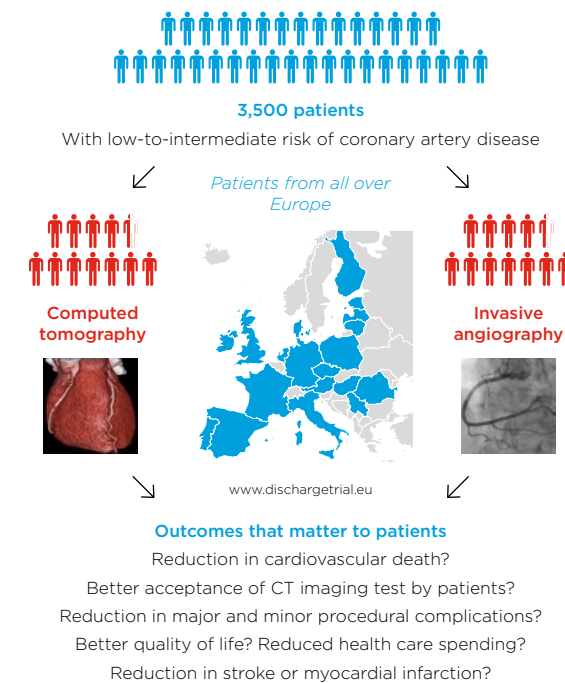


Figure 6

The DISCHARGE trial



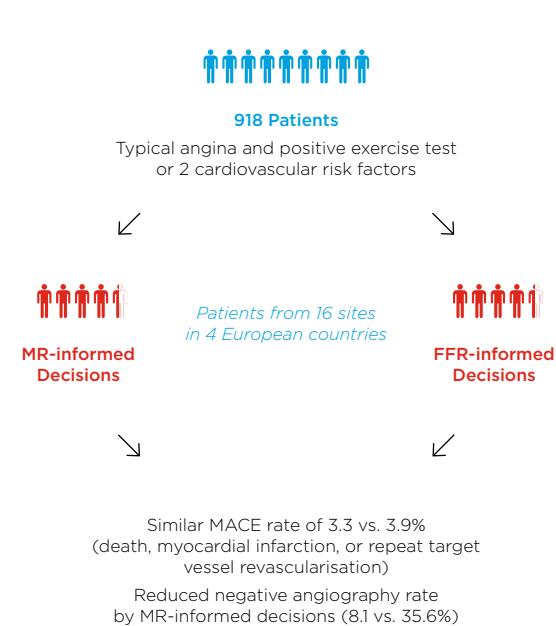
## THE MR-INFORM TRIAL<sup>7, 8</sup>

*Randomised Non-inferiority Multicenter Trial Comparing MR Perfusion Imaging and Fractional Flow Reserve (FFR) to Guide Management of Patients With Stable Coronary Artery Disease*

The MR-INFORM trial randomly assigned more than 900 patients to undergo decision making informed by either magnetic resonance (MR) or invasive fractional flow reserve (FFR). There were similar major adverse cardiovascular event (MACE) rates while MR reduced negative angiography rates (Figure 7).

Figure 7

The MR-INFORM trial



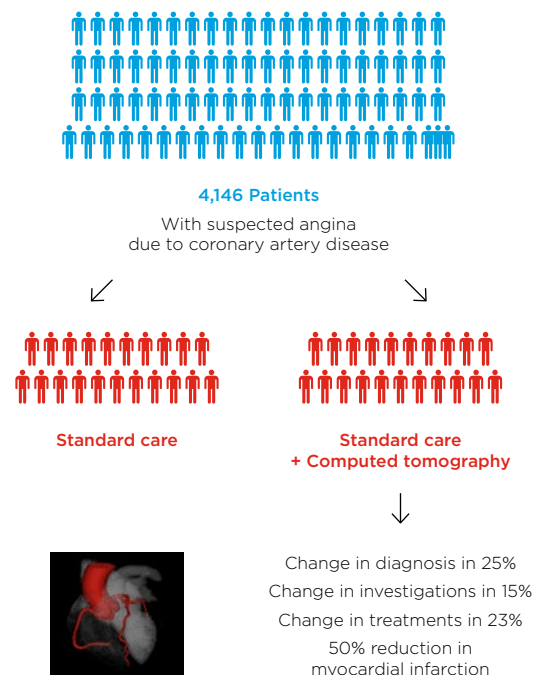
## THE SCOT-HEART TRIAL<sup>9, 10</sup>

*Role of Multidetector Computed Tomography in the Diagnosis and Management of Patients Attending a Rapid Access Chest Pain Clinic*

The SCOT-Heart trial randomly assigned 4,146 patients in Scotland to undergo either standard care or standard care plus computed tomography (CT). There was a relevant change in diagnosis, investigations, and treatments in the CT group leading to a 50% reduction in myocardial infarction (Figure 8).

Figure 8

The SCOT-Heart trial



## CONCLUSION

The randomised imaging trials outlined above show that the future of cardiac imaging looks bright. Cardiac CT is expected to play a central role in the management of patients with suspected coronary artery disease while cardiac MRI will enable us to better understand the clinical implications of myocardial ischaemia and infarction for individual patients, thus allowing 'personalised radiology' to become a clinical reality.

### References

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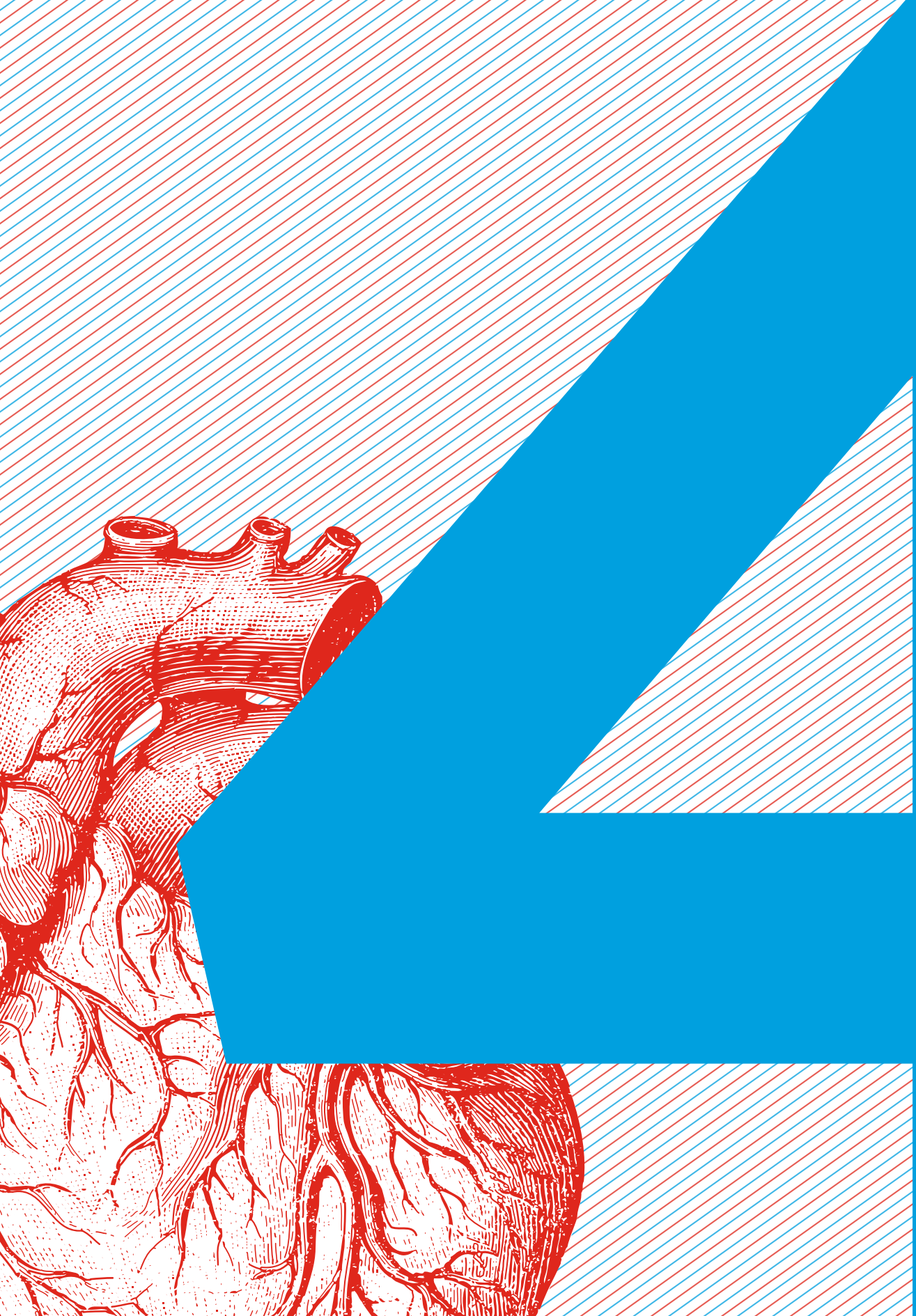
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*Professor Dewey received the two highest scientific awards of the German Röntgen Society; the Röntgen Award in 2009 and the Curie Ring in 2012.*

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4

CARDIAC CT  
IN THE  
EMERGENCY  
ROOM



# I WANT TO LIVE ANOTHER DAY: HOW CARDIAC CT CAN HELP PATIENTS IN THE EMERGENCY ROOM

BY HAROLD GOERNE AND SUHNY ABBARA

## INTRODUCTION

Chest pain is the second most common cause of admission to emergency departments (ED) in the United States after abdominal pain according to data from the National Center for Health Statistics. It is estimated that around 9 million patients per year are admitted to the ED for this reason, costing up to \$15 billion. One of the biggest concerns for doctors and patients is to ascertain whether the chest pain is due to a life-threatening cardiovascular condition, such as acute coronary syndrome (ACS) (ST segment elevation myocardial infarction = STEMI, NSTEMI = non-STEMI, unstable angina), acute aortic syndrome (dissection, intramural haematoma, penetrating atherosclerotic ulcer) or acute pulmonary embolism. In most of these scenarios, prompt intervention is essential, especially in STEMI, in which early identification and treatment is fundamental to changing the course of the disease, which could otherwise be fatal.

In the context of ACS, clinical suspicion is supported by early risk stratification through clinical history, electrocardiogram, cardiac biomarkers and criteria such as the TIMI risk score. However, this doesn't make it possible to detect patients who can be discharged from ED earlier and safely. This leads to prolonged stays, saturation of hospital services and high costs for patients who do not really require it, since up to 85% of patients with chest pain do not have ACS.

Recent efforts have focused on the reduction of the length of stay as a result of accurate early identification of patients who can safely be discharged from ED versus those who require in-hospital observation. Of particular interest is the group of patients with ACP, negative first troponin, negative/non-diagnostic ECG and low to intermediate risk (TIMI risk score <4).

Coronary CT angiography may help to reach this goal, since it has proven to be clinically useful as an alternative or in addition to functional tests (according to several prospective trials such as PROMISE and SCOT-HEART) and has also proved to be a powerful tool in safely identifying patients who can be discharged from ED (supported in 4 large randomised trials: CT-STAT, ACRIN-PA, ROMICAT II and CT-COMPARE), due to its high sensitivity (86-100%) and a high negative predictive value (93-100%).

Up to 8% of patients with ACS may have negative ECG and negative cardiac biomarkers, which leads to a missed diagnosis and an increase not only in morbidity and

mortality but also in malpractice litigation. In these cases, coronary CT angiography may help clinicians to guide management. In this chapter, we are going to focus on coronary CT angiography rather than aortic or pulmonary CT angiography.

## EVOLUTION OF CARDIAC CT

Imaging the heart using CT is a technological challenge, since it requires scanning very small vessels (coronary arteries) that are in constant motion, therefore a high spatial and temporal resolution is needed. In the 1980s, the use of electron beam CT made it possible to obtain images of the heart with a high temporal resolution but low spatial resolution, even so it was the essential modality to establish the basis for a calcium score. In the 1990s, single-slice helical CT systems were introduced, utilising new slip-ring technology. Multi-detector row CT (also known as MDCT or multi-slice CT) followed soon thereafter, increasing the coverage in z-plane, and since then, the number of detectors has increased from 4 (1998) to 320 (2008) allowing a coverage of up to 16cm within a single rotation, which has made it possible to scan the entire heart in a single gantry rotation. At the same time, rotation speed increased from 1 to 0.25 seconds which increases the temporal resolution significantly. Dual source CT further improves the temporal resolution by a factor of 2, without increasing the rotation speed. New detector systems allow spatial resolutions closer to conventional angiography. These incredible technological

advances make it possible for CT coronary angiography to be used routinely in clinical practice today.

## TECHNICAL CONSIDERATIONS

For coronary CTA, it is recommended to use at least a 64 detector CT scanner, but the quality of the study depends not only on the number of detectors and rotation speed, but also on multiple technical factors. These include aspects relating to the patient such as their ability to maintain apnoea breath hold, which is essential to perform the study, otherwise it would be an absolute contraindication; their weight, which will determine the kVp and the amount of contrast medium; their heart rate, which ideally should be less than 60 beats per second, for which it is necessary to use  $\beta$ -blockers (oral or intravenous metoprolol) and the use of vasodilators such as nitro-glycerine, which helps to better visualise coronary arteries. It is important to check for possible contraindications with these medications.

Prospective ECG-triggering is currently the most common acquisition mode; it obtains images in one or several phases of the cardiac cycle with a step and shoot method. It has the advantage of emitting a low dose and the disadvantage of not recording all phases of the cardiac cycle. In contrast, retrospective ECG-gating collects data throughout the entire cardiac cycle, making it possible to evaluate ventricular function and wall

motion abnormalities. This mode is ideal for patients with high HR or arrhythmias; it is also the mode of choice when assessing motion of mechanical prosthetic valves. Its disadvantage is the higher radiation dose need, this can, however, be significantly reduced with tube current modulation technique. A third mode, high-pitch helical, has a very low radiation dose but can only be performed on second and third generation dual-source scanners and most sites only use this mode at HR <60bpm. Iterative reconstruction is an option offered by all vendors as a strategy for significant dose reduction without sacrificing signal to noise ratio.

## CORONARY CTA IN EMERGENCY DEPARTMENTS

It is very important to establish strategies between the ED team and the cardiovascular imaging team to ensure the correct use of coronary CTA, which in turn allows for more efficient patient care. The oral  $\beta$ -blocker can be administered in ED one hour prior to the study (usually metoprolol 50–100mg) or intravenously in the CT room (metoprolol 5mg every 5 minutes for up to 5 doses) until reaching a heart rate of less than 60bpm. Sublingual nitro-glycerine (0.8mg) is given in the CT room 5 minutes prior to the scan acquisition. Serum creatinine value is necessary to evaluate renal function. Good intravascular access is important because high injection flow rates of contrast medium are used (usually 6 ml/s). The iodine

concentration should usually be high, at about 350–370 mg/ml.

CT acquisition should be performed by cardiac trained technical and nursing staff and reviewed by an expert in cardiovascular imaging. Once the study is done, communication between the cardiovascular radiology staff and the emergency department staff is important, so as to make decisions and establish management of the condition as soon as possible.

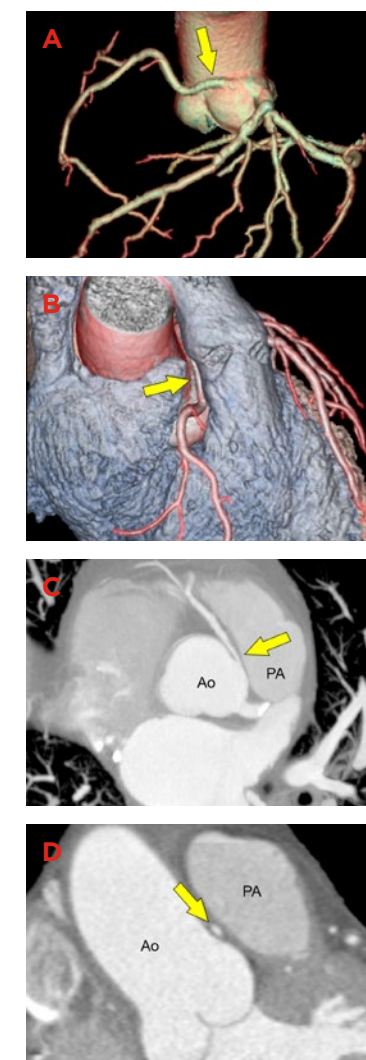
The study should be reviewed in a dedicated workstation with adequate post-processing software for coronary CT angiography, allowing for evaluation of DICOM data in axial plane, multiplanar reformation (MPR), maximum intensity projection (MIP), curved planar reconstruction (CPR), volume rendering technique (VRT) and cardiac function analysis for retrospective mode scans.

Coronary arteries are evaluated at their origin and course; coronary CTA is an excellent modality to demonstrate anomalous origins that may be cause of ischaemia, such as the interarterial course (Figure 1). A normal CTA coronary confirms the absence of coronary disease. The presence of atherosclerosis requires the assessment of two parameters: the degree of stenosis and the characteristics of the plaque.

Recently, the introduction of CAD-RADS as a standardised system for reporting coronary CTA makes it possible to avoid a lexicon variability, in addition to the fact that it provides management recommendations.

Figure 1

50-year-old male with recurrent chest pain after exercise. (A) VRT of coronary tree, (B) VRT of the heart, (C) MIP, (D) MPR, shows anomalous origin of right coronary artery from left sinus of Valsalva with interarterial course and extrinsic compression in proximal segment with severe stenosis (arrows). (PA: Pulmonary Artery, Ao: Aorta).



CAD-RADS classifies cardiac CT results into five categories depending on the degree of maximal coronary stenosis:

- CAD-RADS 0 confirms the absence of coronary artery disease (0% stenosis) ACS highly unlikely (Figure 2)
- CAD-RADS 1 (minimal, 1-24% stenosis) ACS highly unlikely (Figure 3)
- CAD-RADS 2 (mild, 25-49% stenosis) ACS unlikely
- CAD-RADS 3 (moderate, 50-69% stenosis) ACS possible (Figure 4)
- CAD-RADS 4A (severe, 70-99% stenosis) or 4B (left main >50% or 3-vessel >70%

obstructive disease) ACS likely (Figures 5 and 6)

- CAD-RADS 5 (100% total occlusion) ACS very likely (Figure 7)
- A CAD-RADS N is reserved for non-diagnostic studies. Some factors are taken into account and added to the category as modifiers, which include not fully evaluable (N), stent (S) (Figure 8), graft (G) (Figure 9), vulnerable plaque (V)

Coronary CTA provides information not only for coronary arteries, but also allows to evaluate the structure of the cardiac chambers, integrity of atrial and ventricular septum, aorta (Figure 10), pericardium, pulmonary vessels and lungs. There is a

Figure 2

47-year-old male, acute chest pain, low risk for ACS. (A) Cinematic rendering, (B) Curved planar reconstructions and cross-section of RCA, LAD and LCX, shows normal coronary arteries with no plaque or stenosis (CAD-RADS 0).



Figure 3

60-year-old male, acute chest pain, intermediate risk for ACS. (A) VRT of coronary tree shows multiple calcified plaques in coronary arteries. Calcified plaques with minimal stenosis in (B) RCA, (C) LAD and (D) LCX.

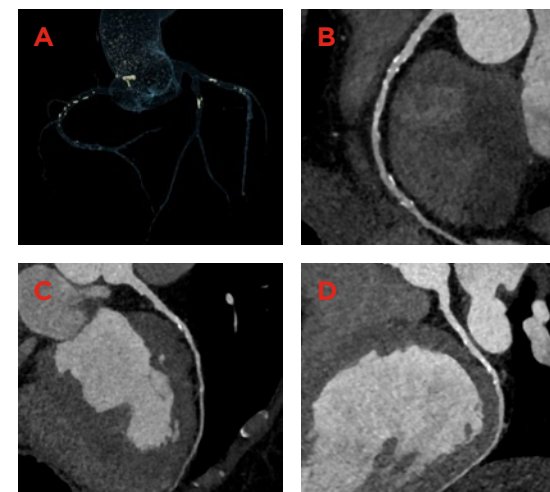


Figure 4

Two different patients with acute chest pain. (A) Obtuse marginal branch with non-calcified plaque with 50-69% moderate stenosis (yellow arrow), (B) Mid segment RCA with partially calcified plaque with 50-69% moderate stenosis (green arrow).

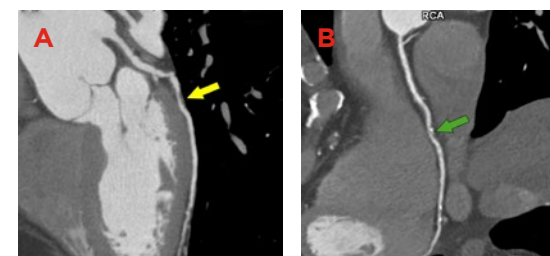


Figure 5

56-year-old male, stable chest pain. (A) VRT of coronary tree shows high take-off of RCA (yellow arrow), anomalous origin of LCX from right sinus of Valsalva with retroaortic course (red arrow), LAD from left sinus of Valsalva (blue arrow). (B) CPR of RCA shows high take-off (yellow arrow), severe stenosis in distal RCA (orange arrow) and PDA (green arrow), (C) subocclusive predominant non-calcified plaque in mid LAD (blue arrow), (D) retroaortic LCX with diffuse partially calcified plaques with severe stenosis (red arrow). 3 vessel obstructive disease (CAD-RADS 4B).

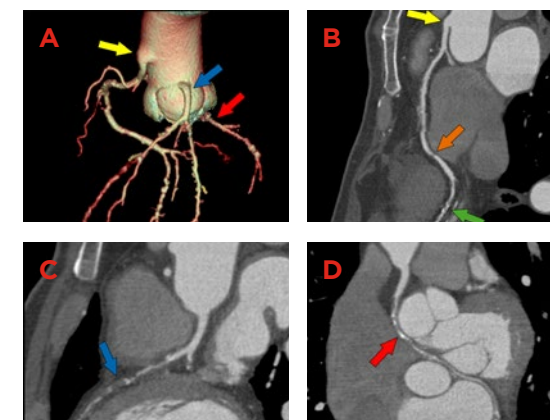


Figure 6

61-year-old female, recurrent chest pain even after recent stent placement. (A) MIP and (B) VRT shows severe stenosis of LM (yellow arrow), stent in proximal LAD (green arrow), severe reduced flow in mid LAD (blue arrow). (CAD-RADS 4B/S).

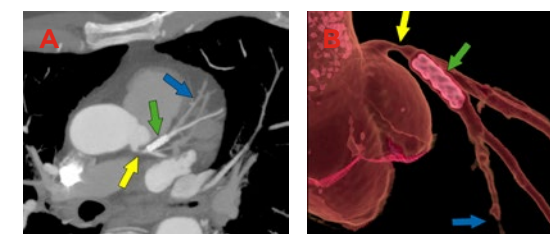


Figure 7

70-year-old female with shortness of breath. (A) Cinematic rendering and (B) CPR of LCX shows occluded stent (yellow arrow), absence of contrast in distal LCX (blue arrow), (C) thickening polar map shows akinetic inferolateral wall (CAD-RADS 5/S).



Figure 8

55-year-old male with chest tightness. (A) VRT and (B) CPR shows normal appearance of patent stent in mid LAD (yellow arrow), calcified plaque with minimal stenosis in proximal LAD (green arrow) (CAD-RADS 1/S).

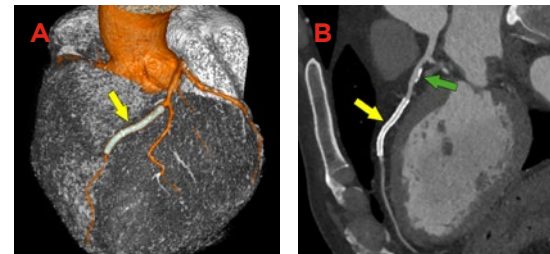
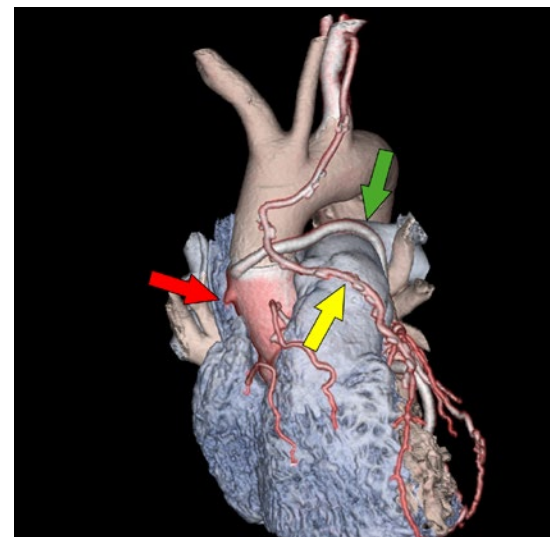


Figure 9

69-year-old male with prior history of 3 coronary grafts. Patent arterial LIMA graft to mid LAD (yellow arrow). Patent venous graft to OM1 (green arrow). Occluded venous graft to PDA (red arrow).



triple-rule-out protocol for the assessment of coronary arteries, thoracic aorta and pulmonary artery at the same time, providing good intravascular contrast in both right and left side of the heart, but it is not routinely used because it requires a greater amount of contrast medium, longer breath hold times and a higher radiation dose, while studies have not shown significant incremental yield.

## THE FUTURE OF CARDIAC CT IN THE EMERGENCY ROOM

The latest advances allow us to obtain images of the heart and coronary arteries with no or little motion artefact even at higher heart rates. The objective in the future

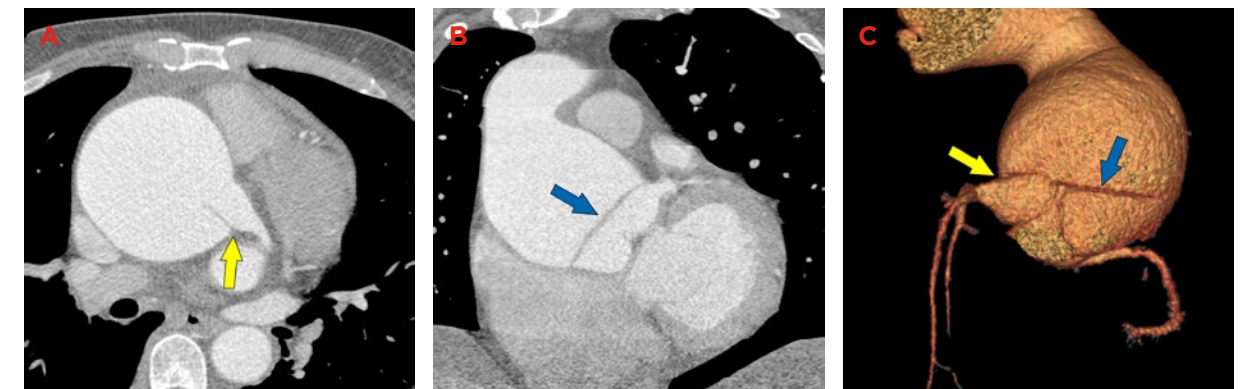
will be to achieve images without motion artefact at any heart rate, even greater than 100bpm, or with arrhythmias. This represents an important technological challenge related to the improvement of the temporal resolution. Spectral CT is a technique promising to be useful in cardiovascular applications allowing for tissue characterisation (such as in plaques) and for quantification of enhancement such as in the myocardium. In summary, cardiac computed tomography is poised to be a modality for evaluation of cardiac structure, function, and myocardial perfusion and tissue characterisation, an all in one study with a low dose of radiation and performable in approximately 5 minutes.

### References

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Figure 10

21-year-old male with Marfan syndrome. (A) axial MPR, (B) coronal oblique MPR and (C) VRT shows type A aortic root dissection (blue arrow) with flap at the ostial border of left coronary artery (yellow arrow).





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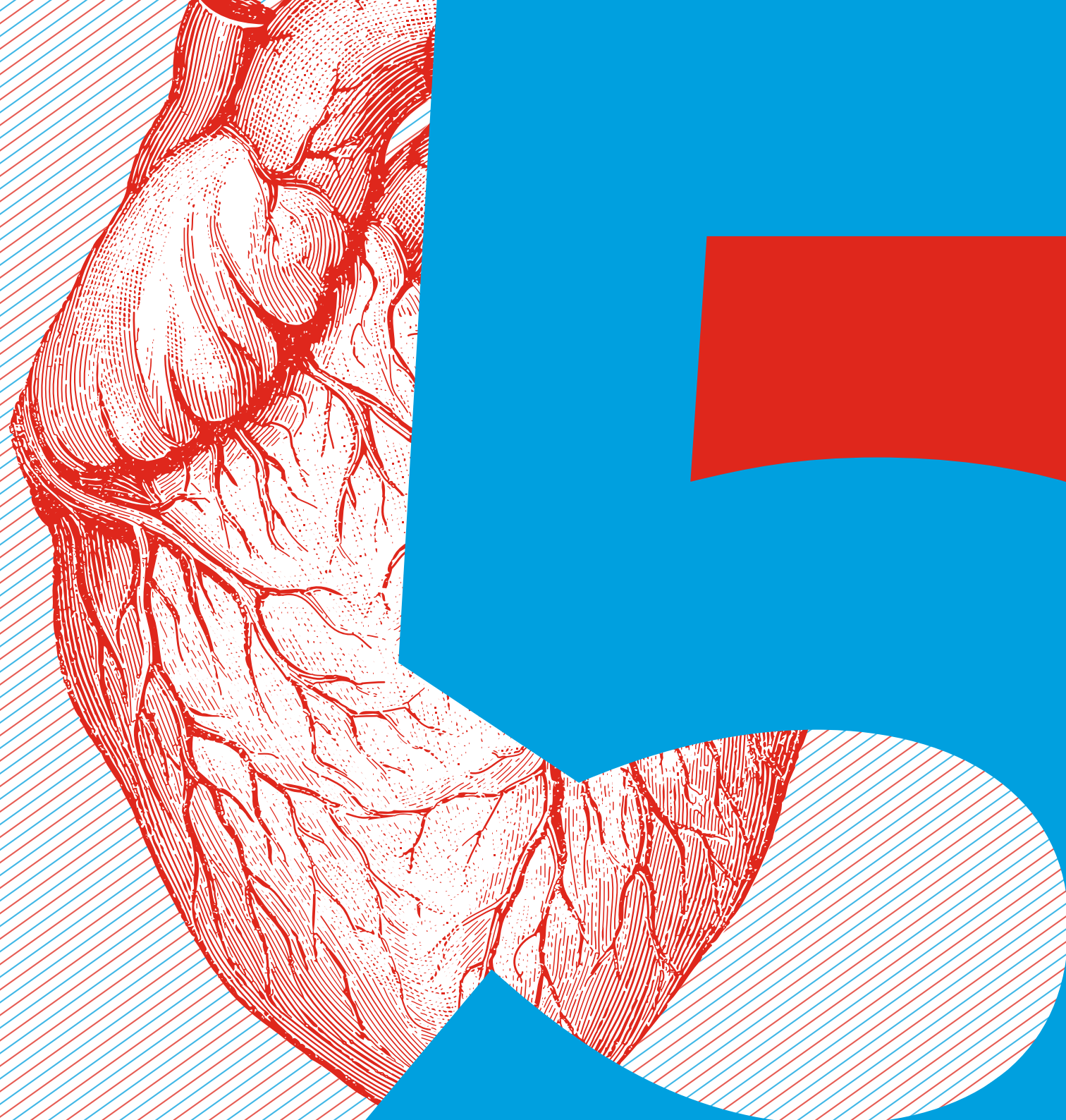


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*Professor Abbara served on several scientific journal editorial boards and he was chosen to lead the RSNA journal Radiology: Cardiothoracic Imaging as the Editor. He has co-authored 250 peer-reviewed PubMed-referenced articles resulting in an h-index of more than 50. He has authored several textbooks and numerous book chapters and clinical guidelines. He chairs the cardiac panels for the ACR Appropriateness criteria. Professor Abbara has served as president of the Certification Board of Cardiac CT (CBCCT) and is President of the Society for Cardiovascular Computed Tomography (SCCT).*



5

THE  
ISCHAEMIC  
HEART

# TOO LITTLE TOO LATE: IMAGING OF THE ISCHAEMIC HEART

BY JEAN-NICOLAS DACHER

## Coronary artery disease (CAD) remains a major cause of mortality in the western world.

During the twentieth century, radiology as a medical specialty was barely involved in the detection and treatment of CAD. Technical innovation in MRI and CT has completely changed the situation on the turn of the century.

Coronary artery disease/stenosis can induce ischaemia. Ischaemia is defined as an insufficient delivery of oxygen to the myocardium. Until recently, gated SPECT (a relatively expensive technique delivering ionising radiation) was the only diagnostic tool available to reach this diagnosis.

Since 2013 and the new statement on stable angina issued by the European Society of Cardiology<sup>1</sup>, MRI was recognised as a valid and at least equivalent alternative to isotope studies. A number of studies and meta-analyses even claim that MR is superior to SPECT. The absence of radiation and radioactive effluent are strong arguments for using MRI in addition to its spatial and temporal resolution, while its main drawback lays in its limited availability.

This recommendation was grounded on multiple studies<sup>2-4</sup> that showed correlation between MRI and the reference studies of CAD that are coronary angiography and fractional flow reserve.

Cardiac MRI is now a standardised examination<sup>5</sup>. It includes at least the following pulse sequences:

- Multiplanar CINE imaging, allowing the evaluation of ejection fraction and other ventricular functional parameters including volumes and myocardial mass
- First-pass perfusion imaging under vasodilator stress (stress perfusion imaging)
- Delayed enhancement pulse sequences are acquired, in order to detect myocardial infarction or fibrosis

The principle of stress first-pass perfusion MR imaging is to induce a vasodilatation of healthy coronary arteries pharmacologically. Adenosine or regadenoson are mainly used for this purpose after contra-indications have been excluded. They are being used off-label for this purpose. At the peak effect of the vasodilator, a bolus of gadolinium chelate is administered while a real-time T1-weighted sequence is run.

In case of stenosis of one or several of the three main coronary arteries, the blood flow is redirected towards the healthy territories (vascular steal phenomenon) and decreased perfusion of the subendocardial myocardium is observed in the diseased segments.

Analysis of first-pass perfusion is usually qualitative, although quantification is possible. This may allow for microvascular disease to be detected.

It is also possible to complete the examination with a rest first-pass study after the vasodilator effect was suppressed (spontaneously after adenosine or after aminophylline injection for regadenoson).

Rest perfusion imaging is normal in case of reversible ischaemia.

The results of perfusion imaging need to be compared to other pulse sequences and in particular to delayed enhancement imaging that can detect the scar of a myocardial infarction. Hence, it is possible to assess both myocardial ischaemia and viability during the same 30–40 minutes MR session. Comparing the results of the MR scan to the coronary angiogram (if available) is also helpful for the management of the patient.

If substantial areas of inducible ischaemia are detected by stress MR, this represents a strong argument for revascularisation (either by percutaneous transluminal coronary angioplasty or by bypass grafting). Inducible ischaemia and/or myocardial infarction have a high prognostic value regarding cardiac death or major cardiovascular events.

Obviously, this examination needs to be performed under optimal safety conditions. Pre-procedural ECG is required as well as continuous monitoring of the patient's vital parameters during the examination and particularly during the stress test. In our institution, two physicians attend the examination; one takes care of the patient's safety, while the other one pilots the examination with the technician.

Considering all those advantages, we wonder why stress MRI is not practised more often worldwide to detect coronary artery disease. We already mentioned its limited availability. While MR scans are routinely used for brain studies, this is not currently the case for the heart. Another reason is probably that physical exercise, the most physiological stress, cannot

Figure 1

Normal stress perfusion imaging in a 45-year-old female patient with chest pain and normal systolic function. Vasodilation occurred after an intravenous injection of 400 µg Regadenoson for 10 seconds. Heart rate increased from 70 to 90 beats per minute. Four successive short axis views of the same dynamic sequence (saturation recovery) are shown.

(A) Baseline image (prior to gadolinium chelate bolus). (B) Enhancement of the right ventricle. (C) Enhancement of the left ventricle and lung. (D) Synchronous (normal) enhancement of the myocardium. Both CINE and delayed enhancement pulse sequence (not shown) were normal.

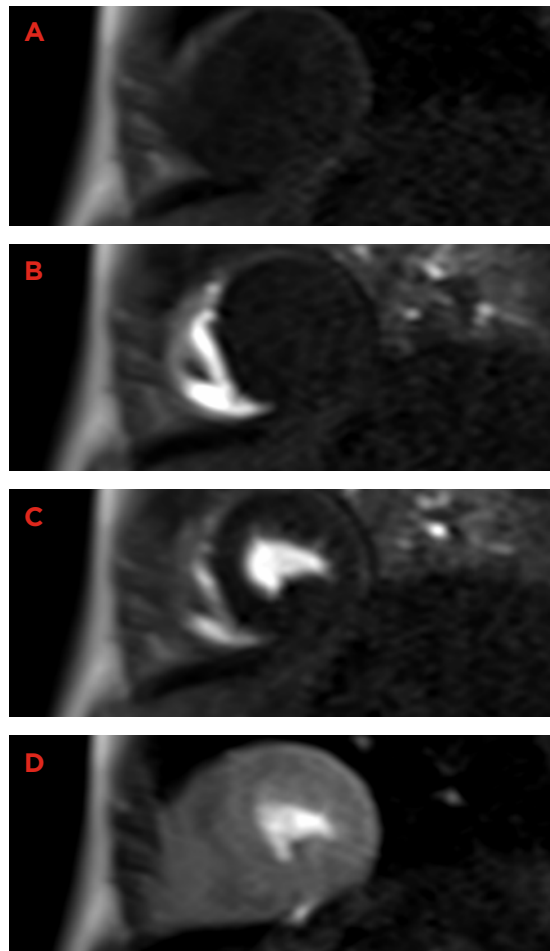
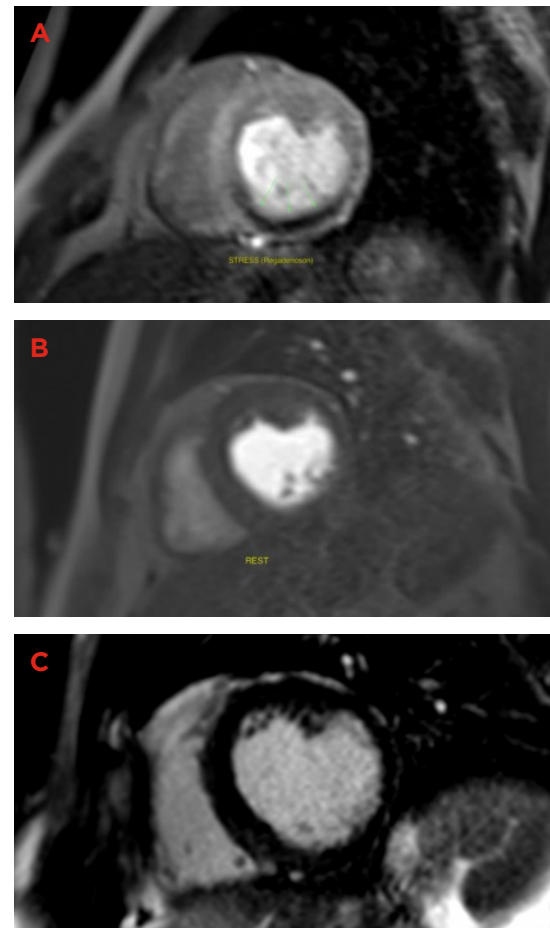


Figure 2

Abnormal stress perfusion imaging in a 48-year-old male patient complaining of chest pain while exercising. Systolic function was impaired (ejection fraction: 35%). Stress perfusion imaging showing decreased signal in the sub endocardium of the inferior basal segments (right coronary artery territory) (green arrows) (A). Vasodilation had been obtained after intravenous injection of 400 µg Regadenoson for 10 seconds. Subsequent rest perfusion (B) after an injection of 125mg IV aminophylline was normal. Delayed enhancement did not show scarring (C). Percutaneous angioplasty of the right coronary artery was performed. Six months later, the patient was free of symptoms and ejection fraction had increased by 7%.



yet be used in MRI. Also, there is a large and old amount of scientific evidence pleading for gated SPECT. Many cardiologists still consider MRI as a research tool. Finally, cardiac MRI is insufficiently recognised and reimbursed by health systems in Western countries and this is probably one of the most problematic features.

## CONCLUSION

In summary, nowadays a stress cardiac MRI is a safe alternative to other stress tests in cardiology used to detect ischaemia. The examination is quite short, requires the use of a vasodilator drug and its diagnostic capabilities are excellent. The limited costs, the absence of radioactive effluent and the absence of radiation are unique advantages of cardiac MRI over gated SPECT. Cardiac MR should definitely be employed more often by cardiologists worldwide.

Figure 3

This 32-year-old man with a long history of hypertension was referred to CT for chest pain. A severe dual stenosis of the left anterior descending artery (LAD) was disclosed (A). Stress MR (400 µg Regadenoson) was positive in the apical septum (B). Based on this result, revascularisation was performed.



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Professor Dacher is a member of the Société Française de Radiologie (SFR), Société Française d'Imagerie Cardiovasculaire (SFICV), European Society of Radiology (ESR) and European Society of Cardiovascular Radiology (ESCR). Author of 200 articles referenced in PubMed and several book chapters, Jean-Nicolas Dacher is an active teacher of cardiac imaging in the French-speaking community and outside it. Currently, he acts as a member of the Cardiac Scientific Committee of European Radiology and Diagnostic and Interventional Imaging.

## References

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6

CARDIAC  
MRI IN  
MYOCARDITIS



# THE HEART CAUGHT A COLD: CARDIAC MRI IN MYOCARDITIS

BY CHARLES PEEBLES

## INTRODUCTION

Chest pain is a common cause of presentation to medical services with a wide differential diagnosis. Patients are triaged according to the nature of the chest pain, clinical findings, ECG, and cardiac biomarkers<sup>1</sup>. Those with ST elevation and positive troponin levels (5–10%) follow an established clinical pathway for acute myocardial infarction with early revascularisation strategies involving Primary Percutaneous Coronary Intervention (PPCI) or thrombolysis (if PPCI is unavailable). At the other end of the spectrum, many patients are diagnosed with non-cardiac chest pain and are managed appropriately. A significant proportion of patients (40%) will have troponin positive chest pain but no ST elevation and the differential lies between non-ST elevation MI, unstable angina, or other forms of acute myocardial injury such as myocarditis. Prior to the widespread availability of cardiac MR (CMR), most of these patients would undergo an invasive coronary angiogram with 10–15% having normal coronary arteries. The ability of CMR to identify and characterise myocardial inflammation has revolutionised the diagnosis of myocarditis. This chapter will illustrate the appearance of myocarditis with standard and more advanced CMR techniques.

## MYOCARDITIS AETIOLOGY

The causes of myocarditis include three main groups; infection, immune mediated, and toxic myocarditis. Viral infections are thought to be the most

common cause of myocarditis in Europe and North America, with Parvovirus B19 and human herpes virus 6 (HHV 6) being the most frequent in myocardial biopsy. Unfortunately, the rate of endomyocardial biopsy (EMB), which is required for definitive diagnosis, is relatively low, so the true prevalence, aetiology and outcome for viral myocarditis is poorly understood. The diagnosis is usually suspected in younger patients without risk factors for coronary artery disease who present with chest pain and malaise, often following a prodromal viral illness. Clinical findings are often absent or non-specific, ECG changes are variable, and biomarkers such as cardiac troponin do not differentiate from ischaemic myocardial disease and may be normal. The European Society of Cardiology guidelines<sup>2</sup> have, none-the-less, recommended clinical and diagnostic criteria for the diagnosis of myocarditis. The diagnostic criteria include ECG, troponin, functional or structural abnormalities on imaging, and tissue characterisation by CMR.

## CARDIAC MRI CRITERIA FOR THE DIAGNOSIS OF MYOCARDITIS (LAKE LOUISE CRITERIA)

The ability of CMR to identify myocardial inflammation and scar as well as function has given it a unique role in establishing the diagnosis of myocarditis<sup>3</sup>. These diagnostic tools include;

### 1. Function

Steady-state free precession (SSFP) cine imaging is the gold standard to assess cardiac morphology and function. Patients

with myocarditis may show regional wall motion abnormalities involving the right ventricle (RV) and the left ventricle (LV) or more global ventricular dysfunction. When present, impaired ventricular function has a worse prognosis. Cine MRI plays an important role in the exclusion of other causes of raised troponin such as hypertrophic cardiomyopathy. Transient increases in myocardial thickness are however seen in myocarditis and reflect myocardial inflammation and increased intra- and extracellular volume.

Cine images are also useful in identifying pericardial thickening and effusion, indicating pericarditis, which is present in 30–50% of patients with myocarditis.

### 2. Oedema

Tissue characterisation sequences, such as T2 weighted imaging, with or without fat suppression, visualise myocardial oedema. A myocardial signal intensity (SI) to skeletal muscle SI ratio of >2.0 is consistent with myocardial oedema. These sequences tend to be susceptible to artefact and field inhomogeneity which can make achieving diagnostic image quality challenging (Figure 1).

### 3. Hyperaemia

Early post gadolinium contrast images (EGE) help identify myocardial inflammation. T1 weighted images early post gadolinium, showing a global SI enhancement ratio of myocardium over skeletal muscle of >4.0 or an absolute myocardial enhancement of >45% is consistent with myocarditis.

Figure 1

This illustrates the typical appearances of acute myocarditis. (A) SSFP cine image following gadolinium showing areas of increased signal indicating hyperaemia. (B) and (C) T2 weighted images showing increased myocardial signal compared to skeletal muscle indicating myocardial oedema. (D) and (E) LGE images showing a diffuse mid myocardial scar typical of myocarditis.

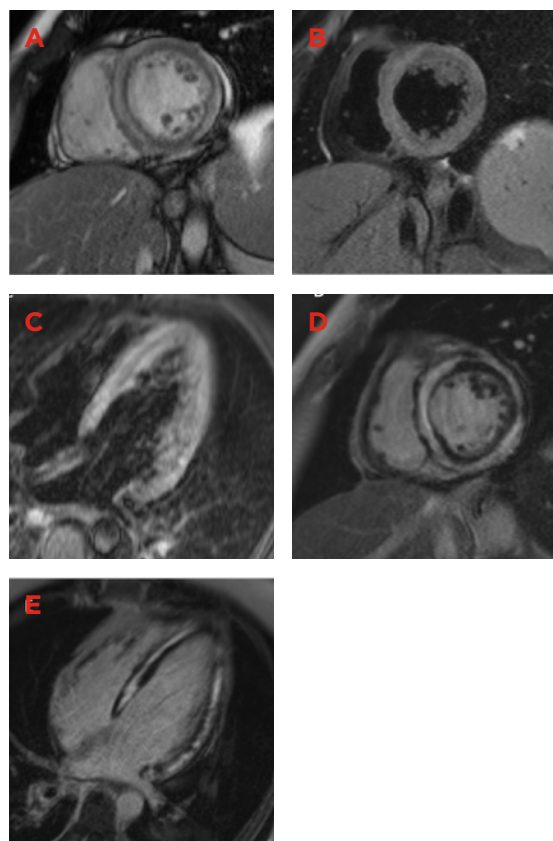
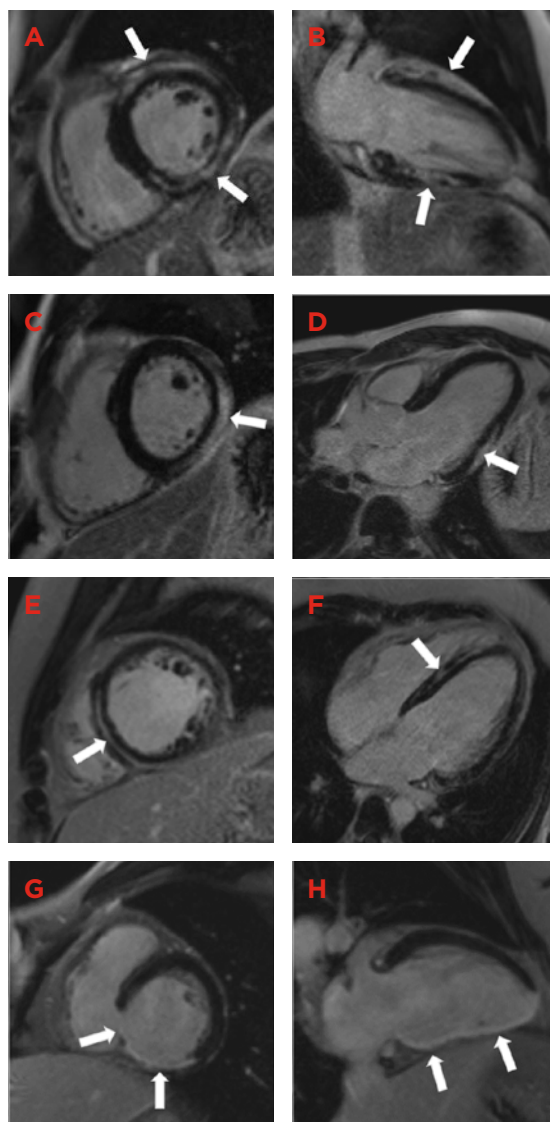


Figure 2

Typical LGE appearances of myocarditis in 3 cases (A) and (B), (C) and (D), (E) and (F), with patchy areas of scar sparing the subendocardium (white arrows). Conversely case (G) and (H) shows an inferior wall MI with transmural and subendocardial scar (white arrows) in a typical coronary territory distribution.



In practice, cine images obtained following contrast often demonstrate areas of increase myocardial signal reflecting EGE and myocardial hyperaemia (Figure 1).

#### 4. Necrosis/Fibrosis

Late post gadolinium enhanced images (LGE) visualise the presence and distribution of myocardial scar/fibrosis. Images are obtained 8–10 minutes after administration of contrast using an inversion-recovery prepared T1 weighted sequence to suppress normal myocardial signal. In theory high signal on LGE images denotes irreversible myocardial necrosis and scarring, however, in practice, areas of myocardial oedema may also show increased signal on LGE sequences in acute myocardial injury with subsequent resolution during recovery.

The pattern of LGE in myocarditis is typically patchy and predominantly involves the sub-epicardial myocardium and the mid myocardium. Importantly, it usually spares the sub-endocardium allowing differentiation from an ischaemic myocardial injury (Figure 2).

Pericardial inflammation may also be demonstrated on LGE images (Figure 3).

The Lake Louise Criteria allow for a diagnosis of myocarditis in the appropriate clinical context if two or more of the diagnostic tissue markers (oedema, EGE or typical scar) are present. A diagnostic accuracy of 78% is quoted.

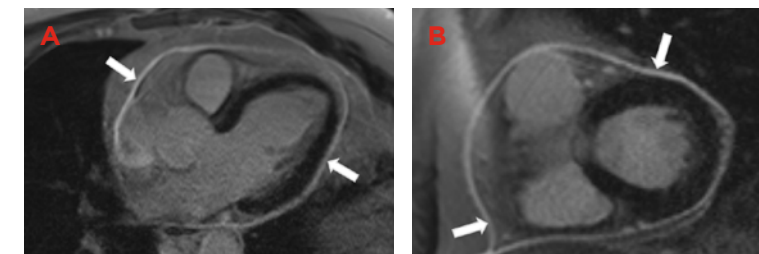
### NEWER CMR TECHNIQUES

Techniques to identify myocardial oedema are currently hampered by issues with signal to noise ratio and image quality. In addition, myocardial oedema is often diffuse, making it difficult to visualise as all of the myocardium may be affected. The Lake Louise Criteria therefore used the degree of signal intensity compared to adjacent skeletal muscle as a quantitative cut off for myocardial oedema. Likewise, the distribution of EGE may be very diffuse and subsequently not easily discernible to visual assessment.

The re-introduction of quantitative techniques to measure myocardial T1 and T2 relaxation times in the form of 'parametric mapping' sequences has significantly added to diagnostic accuracy as they are able to identify global (and regional) changes in myocardial signal with greater sensitivity.

Figure 3

LGE images showing pericardial enhancement consistent with pericarditis (white arrows).



There are a plethora of sequences and measurement parameters available including native T1, T1 post contrast, T2, extracellular volume (ECV) and synthetic ECV. In addition, the values for each technique vary with field strength and individual scanners making universally comparable results difficult to obtain. None-the-less, numerous authors have shown an improvement in diagnostic accuracy and confidence if mapping sequences are applied to this patient cohort. Diagnostic accuracy for myocarditis improved from 79% with the Lake Louise Criteria to 90% when combining ECV and LGE<sup>4</sup>. It seems likely that new diagnostic criteria incorporating parametric mapping techniques will be published shortly (Figure 4).

## PROGNOSIS AND TEMPORAL CONSIDERATIONS

The majority of patients with acute myocarditis show spontaneous resolution in the first 2–4 weeks, but about 25% will develop persistent cardiac dysfunction and 12–25% may acutely deteriorate or develop DCM<sup>1</sup>. Myocarditis is diagnosed in up to 20% of cases of unexpected sudden death and viral myocarditis is implicated in up to 60% of cases of dilated cardiomyopathy. These factors have a number of implications for clinicians investigating possible myocarditis; firstly, making a positive diagnosis of myocarditis is important as it will allow appropriate therapy and follow up, and avoidance of risk factors such as vigorous exercise in the acute phase. Secondly,

myocardial inflammation associated with myocarditis is usually transient and will reduce over time in the majority of patients (Figure 4). Timing of the initial MRI scan is therefore important in achieving a positive diagnosis. There is some evidence that patients scanned within the first 24–48 hours of presentation may have not elicited enough inflammatory response to be visible on CMR. Likewise, patients scanned more than six weeks following presentation will have a lower diagnostic rate as both oedema and LGE subside over time. Ideally therefore a scan time of 5–10 days following presentation is ideal. Follow up CMR at three months is also recommended in order to assess resolution and identify those patients at risk of progressing to DCM and chronic cardiac dysfunction.



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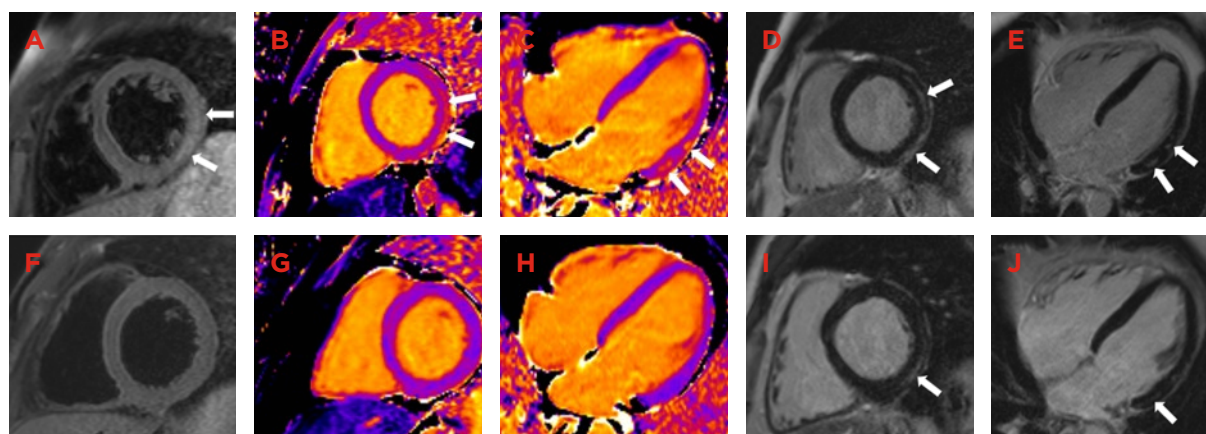
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*He is widely published in the field of cardiac imaging and has been on the National Institute for Health and Care Excellence (NICE) guideline development groups for stable angina and acute chest pain. He has a particular interest in education and has run successful Cardiac MRI courses at Southampton since 2009.*

**Figure 4**

A case of acute myocarditis performed 5 days after presentation (A–E) and 3 months later (F–J). The myocardial oedema seen on T2 weighted images (A) and T1 mapping sequences (B) and (C) has resolved after 3 months (F–H). Likewise, the extent of LGE (D) and (E) has shown significant improvement compared with follow-up images (I) and (J).

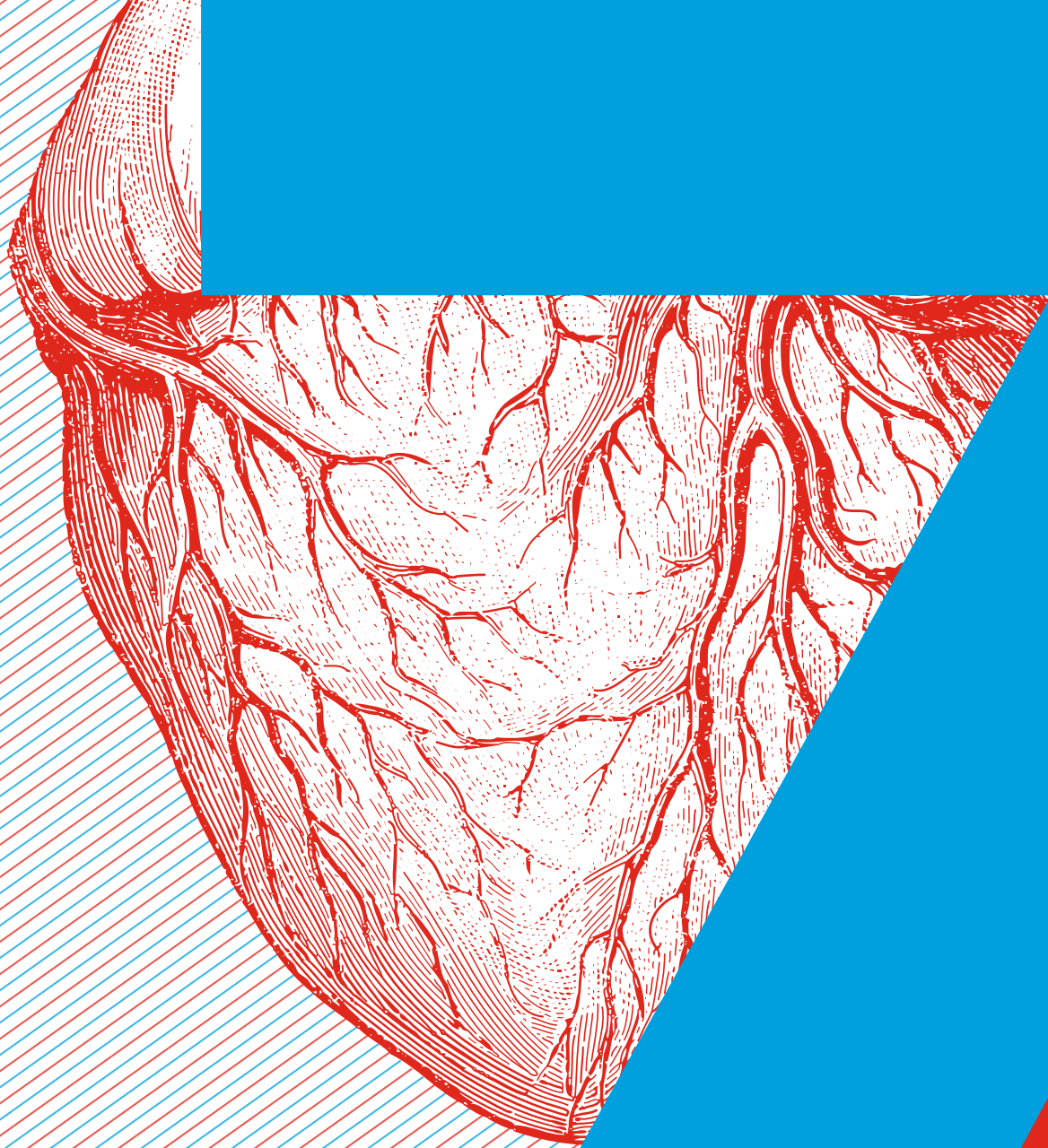


## CONCLUSION

Myocarditis is an important cause of chest pain and, whilst most patients recover well, a minority result in sudden cardiac death and dilated cardiomyopathy. CMR has an established pivotal role in the diagnosis and management of patients with myocarditis. The advent of parametric mapping techniques will further enhance the role of CMR with improved diagnostic accuracy and confidence.

## References

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7

THE  
ATHLETE'S  
HEART

# THE ATHLETE'S HEART: BALANCING PERFORMANCE AND POTENTIAL RISKS

BY MARCO FRANCONI, ANNA PALMISANO AND ANTONIO ESPOSITO

## INTRODUCTION

Sudden cardiac death (SCD) prevention in athletes has been an object of extensive debate among the media, scientists and sports communities (Figure 1), due to the tremendous social impact of those events usually occurring in healthy and well-trained individuals.

Initial general conviction that elite competitors would represent a special cohort of healthy individuals with negligible cardiovascular risk has been gradually replaced by the evidence that athlete's heart is a sort of separate entity in which cardiovascular adaptations to sport often lead to overlapped manifestations with a series of pathological conditions.

There is, in particular, an increasing demand for systematic screening of young competitive athletes (i.e. <35 years old), who are deemed to be the paradigm of health. The heart of a young athlete has been clearly recognised to differ from the heart of a non-athlete and these changes have been structured into the definition of athlete's heart syndrome, in which differentiation from potentially lethal pathological conditions requires careful global assessment.

A completely different clinical setting concerns the so-called population of adult athletes (i.e. >35 years old), usually including middle-aged or elderly participating in informal or recreational sports, on either a regular or an inconsistent basis!

In this cohort of individuals, cardiovascular screening should predominately aim to rule out coronary arteries disease, which is the main cause of events occurring during physical activity.

The present article aims to review morphological and functional features of athlete's

heart, with particular emphasis on the importance and respective strengths of CT and MR imaging which have been recognised as novel central tools for cardiovascular prevention in young and adult athletes.

## THE ATHLETE'S HEART

The observation that the cardiovascular system of highly trained athletes would differ structurally and functionally from the general population has been known for more than 100 years.

Figure 1

Sudden cardiac death (SCD) occurrence in top-level athletes is a rare but highly exposed event, producing significant media interest and social awareness, with subsequent social pressures on the medical community.

### Sudden Cardiac Death: Should Young Athletes Be Screened?

For most people, regular exercise is associated with cardiovascular health. But doctors have long noted a troubling tendency among the ultra-fit: an athlete has a greater chance than the average person of suddenly dropping dead. As physicians and sporting organizations learn more about the condition known as sudden cardiac death (SCD), their research has opened an



'Athlete's heart' was firstly described in 1899<sup>2</sup> when Dr. Henschen empirically reported the enlargement of the heart in a cohort of cross-country skiers, by simply using chest percussion. He concluded that both dilatation and hypertrophy were present.

The impact of training on cardiac remodelling was better defined in the last two decades, as a result of greater accessibility to large populations of trained athletes studied with advanced non-invasive imaging techniques, but, unfortunately, a certain degree of overlap exists between the normal adaptation to intensive training and pathological conditions that may lead to increased risk of sport-related SCD.

Athlete's heart is generally regarded as a benign physiological adaptation with an increase in cardiac mass and volume, with normal systolic function, diastolic function and high-energy phosphates (PCr, ATP) content<sup>3</sup>. Different types of conditioning usually induce different degrees and forms of cardiovascular system remodelling. Endurance training, sometimes also described as dynamic, isotonic or aerobic training, such as long-distance running and swimming, predominantly produces a volume overload. Strength exercises, also referred as static, isometric, power or anaerobic training, such as weightlifting, cause largely a pressure overload. Finally, sports such as cycling and rowing are examples of combined endurance and strength exercises.

Left (LV) and right ventricles (RV) remodelling develop relatively rapidly and are most impressive in endurance athletes.

Remodelling is dynamic in nature, being reversible with cessation of training. Cross-sectional studies of endurance athletes demonstrate that LV wall thickness is 15% to 20% greater than in sedentary controls, and LV volume is 10% larger. The RV is also enlarged, with elite athletes demonstrating 10% increases in RV dimensions. These structural changes are favourable and necessary to compete (Figure 2).

Training-induced cardiovascular remodelling may be associated with ECG abnormalities, occurring in approximately 40% of trained athletes. Most common ECG abnormalities include early repolarisation patterns, increased QRS voltages, diffuse T-wave inversion, and deep Q waves. The heightened vagal tone that accompanies training may lead to innocent arrhythmias and conduction alterations (sinus bradyarrhythmias, junctional rhythm, and first-degree AV block), but it is fundamental to be aware that exercise may act as a trigger for lethal ventricular tachyarrhythmias in patients with susceptibility due to underlying and unsuspected cardiac diseases.

## PREVENTION OF SCD IN YOUNG ATHLETES

SCD of young trained athletes, usually during sport activity, is an event with an impressive media resonance due to a devastating emotional impact to the community at large; it leads subsequently to a substantial increase in awareness about the underlined clinical conditions, although it represents a minor cause of death in a

young population, considering the significantly larger impact of road accidents, infections, suicide and many other causes.

It is estimated that approximately 3.6/100,000 young athletes die per year, among which 1/100,000 is a result of cardiovascular death, which is more common in males. SCD in young athletes usually occurs on the athletic field in the absence of prior symptoms<sup>4</sup>.

The aetiology of SCD in athletes <35 years is mostly inherited and is due to structural heart diseases, mainly hypertrophic cardiomyopathy (HCM) and arrhythmogenic right ventricular dysplasia/cardiomyopathy (ARVD/C). In contrast, the vast majority of SCD in athletes >35 years is a consequence of acquired disease, in particular coronary artery disease (CAD).

A large number of congenital and often clinically silent cardiovascular diseases have been

Figure 2

These illustrations show differences in the mechanisms of cardiac adaption to endurance vs. strength sports.

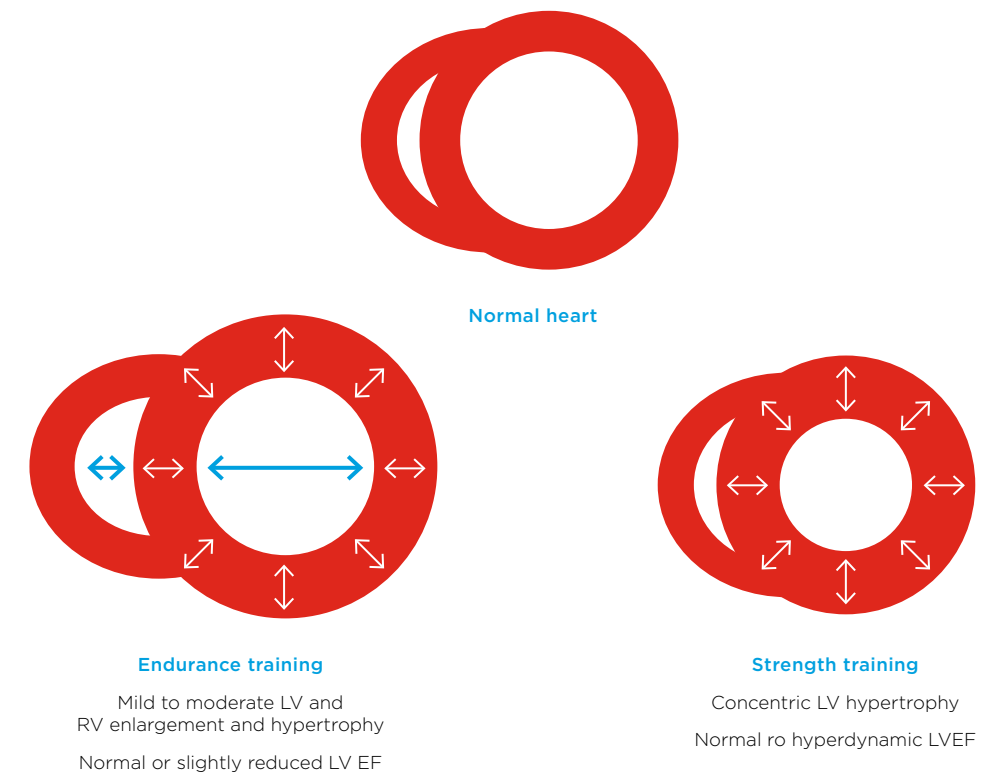


Figure 3

'Inter-arterial' malignant course of right coronary artery arising from the left sinus of Valsalva in a 16-year-old football player with recent syncope during intense training. Functional malignancy is attributable to the anomalous course of the vessel leading to arterial compression during the systolic phase, enhanced by the inotropic and chronotropic effect of intense physical activity.

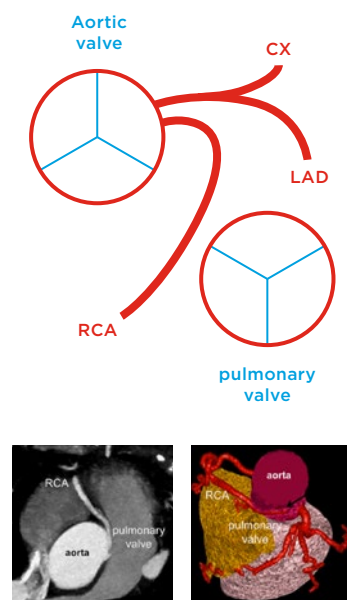


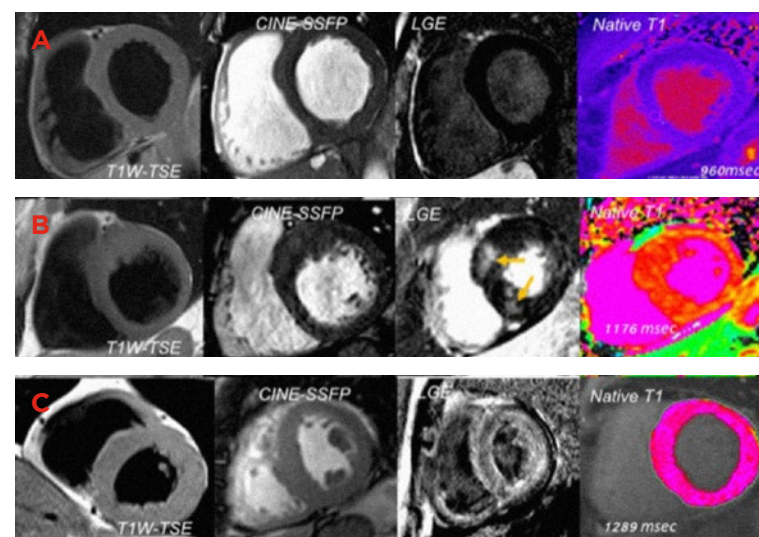
Figure 4

CMR comprehensive multiparametric approach in three different forms of left ventricular hypertrophy.

Top row (A) shows a case of physiological concentric hypertrophy observed in a 27-year-old professional rower (mean myocardial wall thickness 12–14mm). Increased wall thickness is not associated with pathological accumulation of gadolinium on LGE images nor with substantial changes of native T1 on mapping sequences (T1 normal value: 950–1000 msec).

In the middle row (B), an asymmetric form of hypertrophic cardiomyopathy is displayed occurring in a 26-year-old asymptomatic amateur tennis player. CMR images show a remarkable pathological asymmetric antero-septal hypertrophy (anterior-septal wall thickness: 16–21mm), matching with extensive myocardial damage consistent with the presence of multiple patchy areas of non-ischaemic LGE (see arrows) associated with remarkably increased values of native T1 (average of 1,176 msec).

Lower row (C) is a case of cardiac primary amyloidosis manifesting with a severe concentric biventricular hypertrophy in a 42-year-old marathon runner with occasional depiction of abnormal low voltage on limb leads at ECG. Parietal wall thickness is severely increased (ranging between 12–16mm in all segments), and is associated with a typical inhomogeneous appearance of the myocardium on LGE, depending on the extracellular deposition of amorphous amyloid material. Presence of extensive intra-cellular amyloid accumulation. Native T1 is also increased (average of 1,289 msec), reflecting the widespread and substantial extracellular infiltration of amyloid.



causally linked to SCD in young athletes at autopsy. In the United States, HCM has been consistently reported to be the single most common cardiovascular cause, accounting for approximately one third of the deaths. The second most frequent cause of these deaths in athletes is a congenital coronary artery anomaly of wrong sinus origin (most commonly, left main coronary artery origin from right sinus of Valsalva with inter-arterial course; Figure 3). Diagnosis requires a high index of suspicion in young athletes presenting with exertional chest pain and/or syncope, but symptoms are present in <50% of cases. Other conditions account for a much smaller proportion (5% to 8%) of the cardiovascular deaths in young athletes: they include myocarditis, valvular heart disease, ARVD/C and ion-channel disorders<sup>3</sup>.

An alternative demographic profile has emerged from the Veneto region of north-eastern Italy, in which ARVD/C is reported to be the most common cause of athletic field deaths. Such results, contrasting sharply with the results in the U.S., could be based on a unique regional genetic substrate.

A multi-modality imaging approach to athlete's heart aims to differentiate physiological changes due to intensive training from serious cardiac diseases with similar morphological features. A truly comprehensive assessment of the athlete's heart should begin with an exercise ECG and echocardiographic examination. Abnormal ECG patterns are present in ≈40% of trained athletes, occurring twice as often in men than women, and particularly in those participating in endurance sports. Therefore, most athletes have ECGs that are within normal limits or

that show only minimal alterations. Standard echocardiography has a pivotal role in morpho-functional assessment of athlete's heart, in differentiating physiological and pathological LV hypertrophy and in the identification of regional wall motion abnormalities. For inconclusive echocardiography or findings suspected for cardiomyopathies, the execution of cardiac magnetic resonance (CMR) is indicated.

CMR offers the advantage of a highly reproducible morpho-functional evaluation, a higher capability to detect regional wall motion abnormalities also of the right ventricle, and an undisputed advantage in tissue characterisation. The Late Gadolinium Enhancement (LGE) technique allows characterising the myocardium in relation to the presence of myocardial scars and definition of scars pattern, providing diagnostic information with high sensitivity and specificity. The detection, quantification and pattern analysis of fibrosis results are useful for the risk stratification, being directly correlated to major cardiac adverse events. Moreover, CMR is useful for the identification of reversible conditions due to the capability to detect myocardial oedema (Figure 4).

Hence, CMR may be a valuable support in the difficult differentiation of a physiologically adapted athlete's heart from subtle pathological conditions potentially underlined as a sport-related SCD. A particularly difficult differential diagnosis is between a physiological ventricular hypertrophy and the early stage of an HCM.

HCM is characterised by the presence of LV or biventricular pathological wall thickening



non-sustained by increased afterload. It causes reduction and obstruction of LV lumen and a high risk of SCD mainly related to life-threatening arrhythmias occurring on a scar substrate characterising the disease.

In the differentiation of an early HCM from a physiological hypertrophy, CMR may play a fundamental role, first of all with a detailed morpho-functional evaluation of both ventricles that may detect an unbalanced hypertrophy not compatible with a physiological adaptation to sport activities. Moreover, the CMR ability to detect myocardial scars with typical HCM pattern, visible on LGE images in about half of HCM (range 33–79%), is very useful. LGE has a high sensitivity (1 gram focal myocardial damage can be depicted) and strong correlation with histology, but the absence of LGE cannot be used to reliably exclude the possibility of an HCM. Novel CMR techniques may also provide useful information, first of all the native and post-contrast T1-mapping, which can assess the total extent of myocardial extracellular space, rather than the detection of regional dense scars identified by traditional LGE. T1-mapping may emerge as a reliable diagnostic imaging marker in differentiating pathologic from physiologic hypertrophy, but further investigations are needed to eventually define this role.

In athletes who present with unexplained chest pain or syncope, anomalous origin of the coronary arteries from the wrong sinus should be suspected. An anomalous course of either the right or left coronary from the opposite sinus with a course between the great vessels is associated with potentially

increased risk during intense activity. The majority of these patients have a normal 12-lead ECG, hence a high index of suspicion is often needed to prompt testing for diagnosis. In this regard, the role of CMR is limited, seeing as coronary MR angiography is not widely available. Otherwise, coronary computed tomography angiography makes non-invasive depicting of the coronary tree with a very low radiation exposure possible.

CMR is also a fundamental tool for the diagnosis of ARVD/C, being capable of providing an accurate evaluation of RV volumes/global function and a detailed assessment of RV wall regional motion abnormalities, associated with the unique possibility to detect fibrous/fatty replacement of the RV free wall. CMR can be particularly advantageous given the limitations inherent in assessing the RV on echocardiography. Moreover, the capability of myocardial characterisation offered by the CMR, although not included in the official diagnostic criteria, could be relevant in particular with athletes, since RV dilation is usually observed as part of the benign remodelling induced by training, while RV free wall fatty/fibrotic replacement is a finding not associated with athlete's heart.

Acute myocarditis is implicated in 5–22% of athletes' SCD in <35. Early symptoms may be very subtle. When diagnosis is verified, athletes are declared ineligible for competitive sport for at least 6 months. CMR is fundamental for the diagnosis allowing for the detection of oedema, hyperaemia and myocardial necrosis, typically localised in the midmyocardial or epicardial layer with a non-coronary distribution.

## PREVENTION OF SCD IN ADULT ATHLETES

The main cause of SCD in adult athletes is coronary artery disease (CAD). The relationship between intense exercise training and CAD is controversial. Although ischaemic heart disease is the final common manifestation, triggers are likely multifactorial being dependent on sympathetic activation, electrolyte and metabolic factors, activation of the haemostatic system, and haemodynamic effects on vulnerable coronary plaque. In particular, plaque rupture is considered to be an important mechanism of SCD in older athletes, that occurs among coronary lesions that bring about mild to moderate stenoses and is likely attributable due to the mechanical effect and parietal wall stress induced by the activity itself<sup>5</sup>.

Screening of individuals at risk should therefore necessarily include a combination of luminal and plaque assessment, not only to simply rule-out severe lesions but, most importantly, to identify high-risk plaques in a pre-clinical phase. In adult competitive athletes, timely detection of atherosclerotic lesions by coronary CT angiography (CCTA) has been proved to be superior to traditional non-invasive techniques.

Clear guidelines for screening athletes to CCTA are still lacking in the literature. This is due to the lack of prospective studies in large athlete populations. There is, however, a growing clinical utilisation of this technique in adult athletes in a series of clinical scenarios including screening after resuscitation, in asymptomatic competitive athletes with

positive ECG or in the presence of equivocal symptoms for ischaemic heart disease in competitive athletes with normal or near normal ECG.

The so-called 'sub-millisievert' new generation of CT scanner will certainly bring to a further expansion of the utilisation of CCTA also in this specific clinical setting, due to a substantial reduction of the procedural biological risk.

## CONCLUSION

Imaging plays a primary role in screening, diagnosis and follow-up of an athlete's heart, bringing new light into the so-called 'grey zone' between physiological adaptation of an athlete's heart and pathologic expression of cardiac diseases.

Wider availability and recent outstanding technical implementation of both CT and MR imaging have further enhanced our understanding of the complexity of an athlete's heart.

Advanced imaging techniques became a routine part of the comprehensive pre-participation eligibility screening which is performed in selected apparently healthy athletes and recommended by main international guidelines.

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### References

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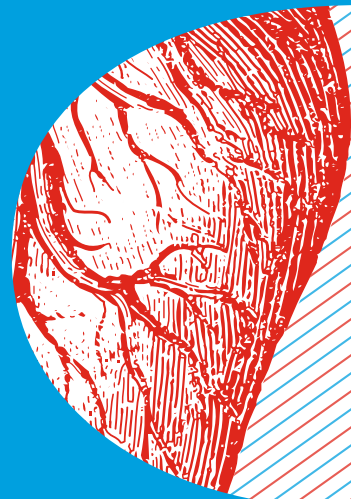
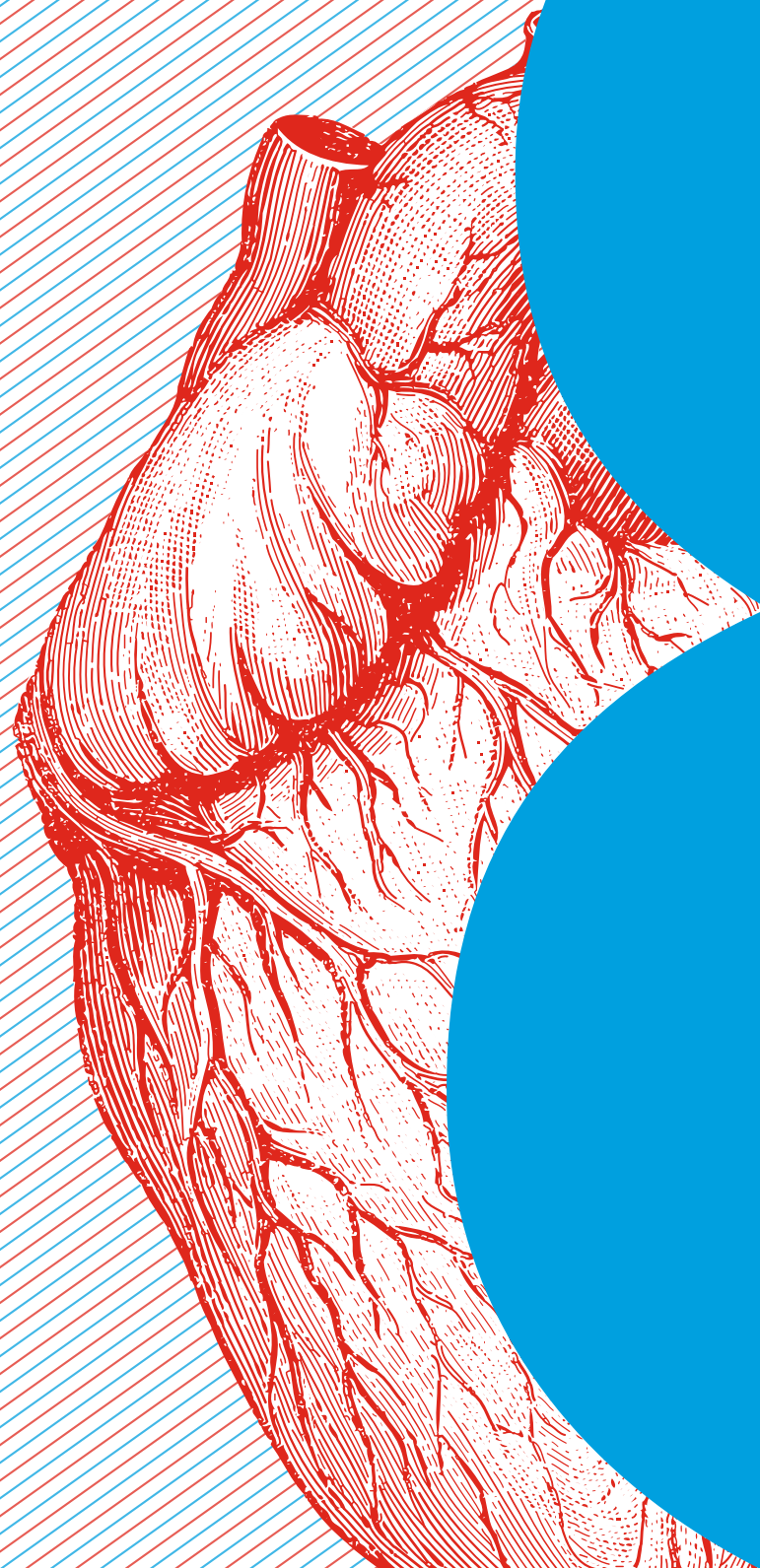
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8

# IMAGING OF CORONARY ARTERIES

# IMAGING OF THE CORONARY ARTERIES: FROM MORPHOLOGY TO FUNCTION AND BEYOND

BY FABIAN BAMBERG, CORINNA STORZ, ILIAS TSIFLIKAS, CHRISTOPH SCHABEL AND KONSTANTIN NIKOLAOU

## CLINICAL VALUE OF CORONARY CT ANGIOGRAPHY

Coronary artery disease (CAD) still is one of the leading causes of death worldwide and remains responsible for approximately 610,000 deaths per year in the United States<sup>1</sup>. Technical developments such as wide detectors, dual source configuration, low kV scanning and high-pitch acquisitions as well as iterative reconstruction algorithms have allowed coronary CT angiography (CCTA) to become established as an imaging modality that provides high temporal and spatial resolution at low radiation exposure, for motion-free cardiac imaging and detailed visualisation of coronary or myocardial pathology. Consequently, CCTA has emerged as a non-invasive, robust and well-established diagnostic tool for the assessment and evaluation of patients with known or suspected CAD. There is a large body of evidence, demonstrating a high diagnostic accuracy with a sensitivity ranging from 94–99% and a specificity of 64–83% for the detection of coronary stenosis<sup>2</sup>.

Clinically, with its high negative predictive value ranging from 97–99%, CCTA represents a reliable diagnostic imaging tool to rule out obstructive CAD, especially in low to intermediate risk settings<sup>2–5</sup>. As such, large-scale registries and prospective trials have shown that CCTA serves as a valuable alternative to invasive diagnostic testing in patients with stable angina<sup>6–8</sup> and low- to intermediate pre-test likelihood of CAD (e.g. asymptomatic, younger patients) and in those with less extensive coronary artery calcification, especially in patients who are unable to undergo stress testing for functional testing<sup>5,8</sup>. An example of a negative coronary CT angiography in a relatively

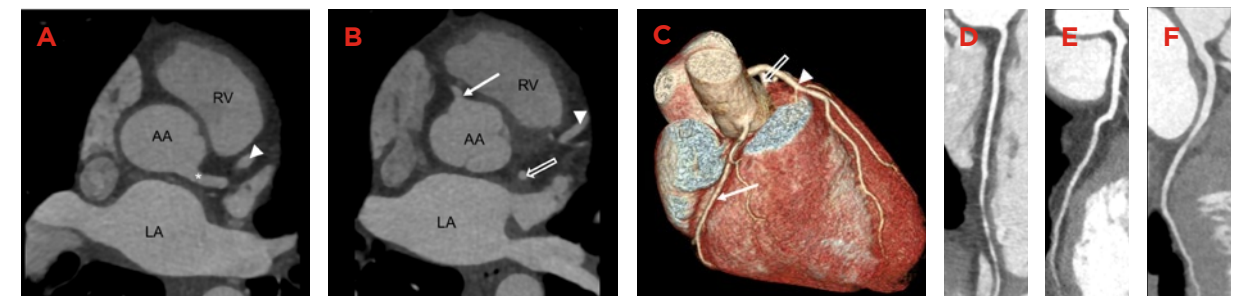
young female patient with suspected CAD is provided in Figure 1.

There is strong evidence that CCTA improves the efficiency of clinical decision making in the emergency department in the case of acute chest pain, resulting in a shorter length of hospitalisation and reduced costs<sup>9</sup>. Furthermore, CCTA is being used for the visualisation and assessment of coronary atherosclerotic plaque, three-dimensional vessel trajectories and anatomical features of the coronary vessel segments as well as detection of pathological coronary artery alterations such as calcifications or occlusions. CCTA is therefore rapidly gaining recognition as a reliable and highly

Figure 1

Coronary CT of a 48-year-old female with exertional atypical chest pain. The CT reveals the absence of coronary atherosclerotic plaque or stenosis. (A) Axial slice demonstrating the left main coronary artery (asterisk) and the left anterior descending coronary artery (arrowhead). (B) Origin of the right coronary artery (white arrow) and proximal segment of the left anterior descending coronary artery (arrowhead) and left circumflex coronary artery (open arrow). (C) Volume rendered three-dimensional reconstruction showing the left anterior descending coronary artery as well as the branch of the right coronary artery and the circumflex coronary artery. (D–F) Multiplanar curved reconstructions of the right coronary artery (D), the left anterior descending coronary artery (E) and the circumflex coronary artery (F) demonstrating the absence of coronary atherosclerotic plaque or coronary artery stenosis.

AA=ascending aorta, LA=left atrium, RV=right ventricle.



useful imaging tool in the pre-procedural planning of cardiovascular interventions, providing improved success rates for revascularisation and post-procedural outcome after percutaneous techniques<sup>10</sup>. Besides its diagnostic value, there is also an increasing role of CCTA to predict cardiovascular risk over time, as several follow-up studies report an excellent prognosis for patients negative in CCTA for any CAD or coronary atherosclerosis, whereas outcome in patients with obstructive and also non-obstructive CAD is substantially worse<sup>11, 12</sup>.

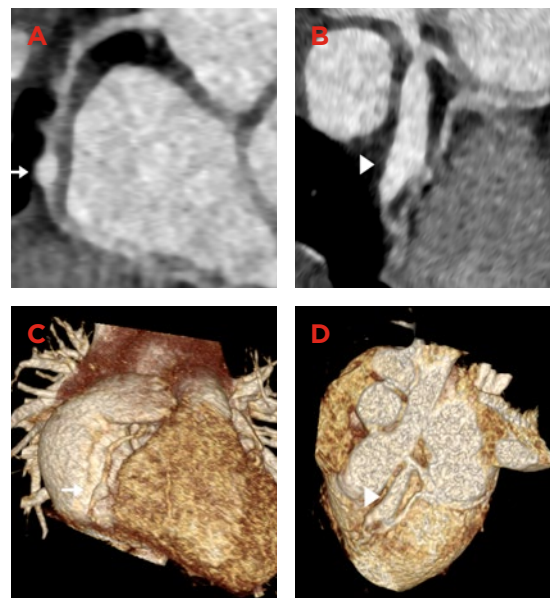
## LOW DOSE CORONARY CT ANGIOGRAPHY AND PAEDIATRIC IMAGING

Paediatric imaging has emerged as a particularly valuable setting for low dose CCTA

acquisitions, given that high anatomical resolution with short examination times can be combined with low radiation exposure. Specifically, high-pitch CT (pitch >3), low kV (as low as 70 kV), and iterative reconstruction algorithms have resulted in cardiovascular exams with radiation exposure of <1 mSv<sup>13</sup>. Nowadays, for a detailed visualisation of the cardiac anatomy, ECG-triggered protocols are recommended, although it has also been demonstrated that the detection of the coronary arteries even in a non-ECG-triggered spiral mode with high temporal resolution is possible<sup>14</sup>. Most paediatric cases will be scanned in a prospective ECG-triggered sequential scan ('step-and-shoot mode') or high-pitch scan whereas retrospective ECG-gating should be avoided due to high radiation exposure (see a low dose coronary CT angiography of a 6-month-old girl with Kawasaki Disease in Figure 2).

**Figure 2**

6-months-old girl with Kawasaki disease and suspected coronary artery aneurysms in echocardiography. Coronary CT scanned in ECG-gated high-pitch mode revealed aneurysms in the right coronary artery (RCA; white arrow) and the left anterior descending artery (LAD; white arrowhead). Note the good image quality despite an average heart rate of 154 beats per minute. Scan parameters: 70 kVp, 149 eff. mAs with automated dose-modulation leading to a DLP of 5.8 mGy\*cm resp. an effective dose of 0.5 mSv. (A) curved multi-planar reconstruction (MPR) of the RCA; (B) curved MPR of the LAD; (C) Volume rendering technique (VRT) of the heart with view on the RCA; (D) VRT of the heart with view on the LAD.



## MORPHOLOGIC ASSESSMENT OF ATHEROSCLEROTIC PLAQUE

Given its high spatial resolution, CCTA offers the unique potential to non-invasively visualise, characterise and quantify atherosclerotic plaque<sup>15</sup>. The notion of vulnerable plaques is a rather complex concept; however specific high-risk plaque features can be identified on standard CCTA datasets. Several adverse features associated with vulnerable plaques have already been identified and include the presence of positive remodelling, low-attenuation plaque, spotty calcifications and the napkin ring sign (see a typical low-attenuation plaque in Figure 3)<sup>16-19</sup>. In contrast, larger

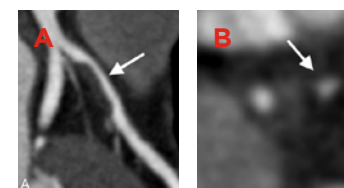
calcification is more likely to be found in stable coronary lesions. Although the evidence is still very limited, detailed assessment of plaque morphology for the presence of high-risk plaque features in patients presenting to the ED with acute chest pain but negative initial electrocardiogram and troponin provides incremental diagnostic value as the presence of high-risk plaque increases the likelihood of ACS, independent of significant CAD and clinical risk assessment, including age, sex, and number of cardiovascular risk factors<sup>20</sup>. Thus, identification of such high-risk plaques may improve risk estimates for the individual patient and may be of use in the selection of patients who could benefit from revascularisation.

## FUNCTIONAL ASSESSMENT OF ATHEROSCLEROSIS: FFR AND PERFUSION

Given its established value in morphologic imaging of CAD, much research efforts over the last years have focused on providing information beyond the assessment of coronary stenosis and plaque. To date, CCTA offers two different approaches to assess the functional relevance of a given stenosis: a) myocardial perfusion imaging and b) the calculation of a CT-based fractional flow reserve (CT-FFR). CT myocardial perfusion is based on the first-pass effect of iodinated contrast media through the myocardium during vasodilator stress (pharmacologically induced using regadenoson, adenosine, or dipyridamole). The study can either be performed by obtaining one single scan during maximum enhancement (also referred to as

**Figure 3**

Coronary CT of an atherosclerotic plaque in the LAD, demonstrating high-risk plaque features, including low-attenuation and positive remodelling in the proximal segment of the left anterior descending coronary artery. (A) curved multiplanar reformat and corresponding cross-section of the vessel (B).



'static' or 'snapshot/single-shot' perfusion imaging) or by acquiring multiple scans during contrast passage (i.e. 'dynamic' imaging of perfusion). The benefit of the 'snapshot' protocol is the reduction of radiation exposure, whereas the 'dynamic' protocol enables the quantification of absolute myocardial blood flow and volume. Perfusion defects as obtained by these techniques are identified as areas of hypo-attenuated myocardium compared to perfusion at baseline. While reversible malperfusion indicates ischaemic myocardium, persistent perfusion defects are considered to represent myocardial scar tissue<sup>21,22</sup>.

The calculation of the FFR using flow dynamics from coronary computed tomography angiography (CCTA) images is another non-invasive method for the

assessment of flow dynamics<sup>23</sup>. This novel approach allows lesion-specific flow analysis throughout the coronary tree without additional imaging or vasodilator stress. The currently most widely used technique (known as FFR-CT) uses a complex reconstruction algorithm to create a three-dimensional (3D) model of the coronary arteries and assess the left ventricular mass, which is directly proportional to the total blood flow at rest. By combining the information of branch diameter from the 3D model and resting blood flow, it is possible to specifically calculate the blood flow for each coronary segment (see an example in Figure 4). Freely available and simplified approaches using a one-dimensional (1D) analysis (cFFR) are currently being investigated<sup>24</sup>.

## CONCLUSION

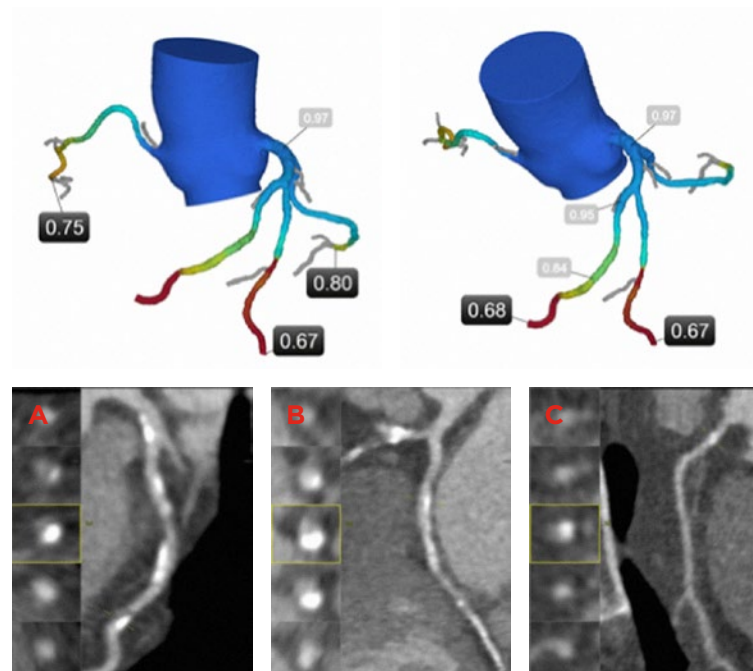
Cardiac CT imaging and coronary CT angiography have developed incredibly quickly over the past 10–15 years. Today, this technique is readily and widely available and has reached a point of great robustness and, together with the potential of low-dose acquisition at the same time, it will become ever more important in clinical routine management of cardiac patients. New insights into the functional assessment of coronary blood flow and myocardial perfusion are fascinating and will make this technique even more valuable in the future.

### References

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**Figure 4**

Example of a CT-based derivation of fractional flow reserve model (CT-FFR, upper bar) and source coronary CT datasets demonstrating diffuse calcified and non-calcified plaques with haemodynamically relevant coronary stenosis present in the distal left anterior descending coronary artery (also A) and a large diagonal branch (red colour-coding in the FFR model) whereas the right coronary artery and the left circumflex coronary artery (C and B, respectively) have diffuse coronary artery disease without haemodynamically-relevant coronary lesions.





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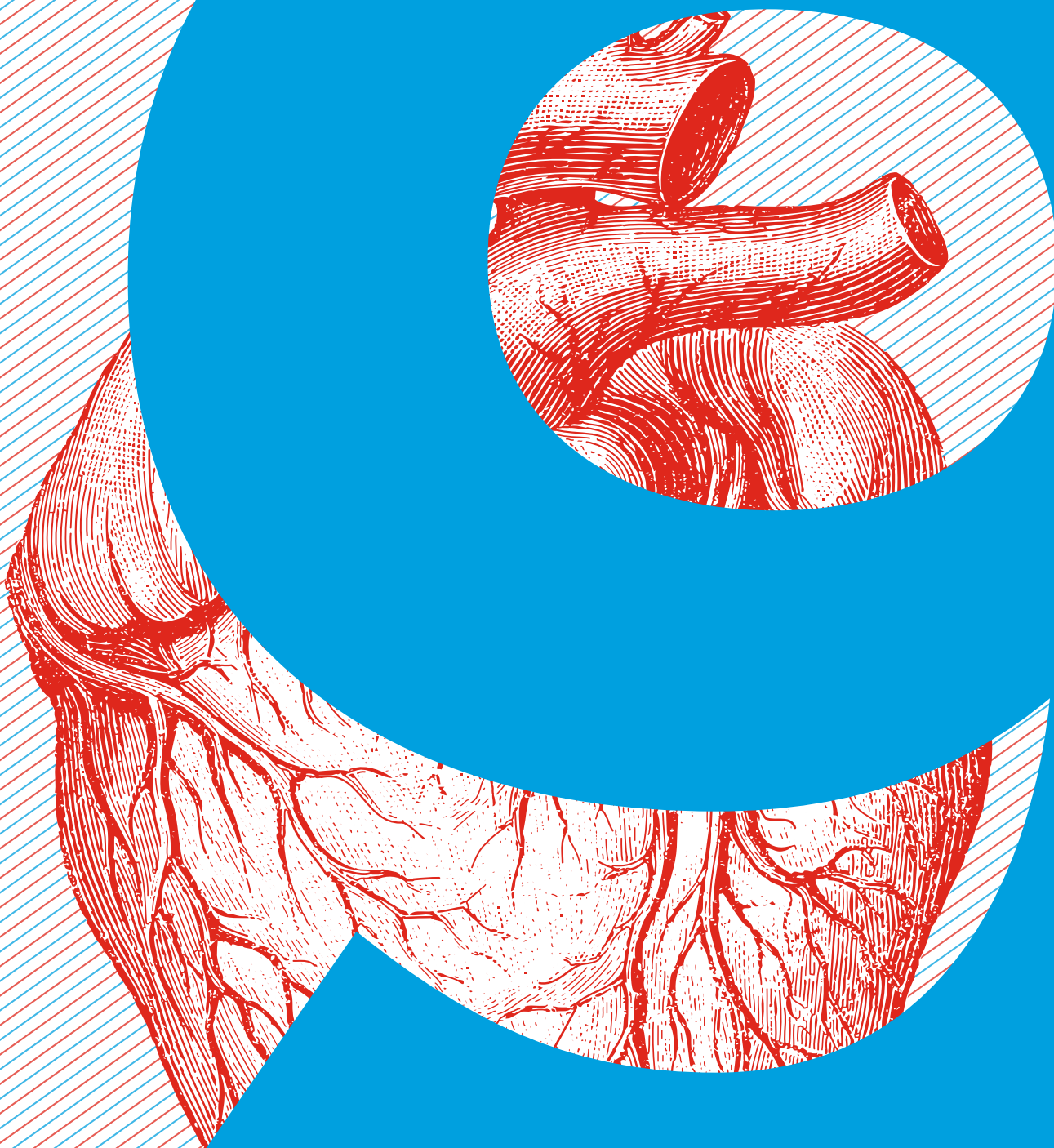
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9

NEW MR  
MYOCARDIUM  
MAPPING  
TECHNIQUES



# THE COLOURFUL HEART: NEW MAPPING TECHNIQUES HELP IN MYOCARDIAL TISSUE CHARACTERISATION

BY JENS BREMERICH

## INTRODUCTION

Parametric mapping is another dimension of cardiac MR beyond morphology and function. It enables quantitative characterisation of myocardial tissue. For more than a decade, T2\* mapping has been established as a clinical tool for quantification of iron deposition in the heart and to guide chelation therapy in patients with haemochromatosis or thalassaemia. Moreover, T2-mapping has been applied to distinguish acute from chronic diseases such as myocarditis. More recent developments are T1-mapping before and after contrast injection. Knowledge of T1 times before/after contrast and haematocrit enable the calculation of extracellular volumes (ECV). Expansion of ECV is found in interstitial accumulation of fluids in oedema, collagen in fibrosis, or amyloid in amyloidosis. Shrinking of ECV may occur in athlete's heart when myocytes are hypertrophied. This

chapter reviews established (see Table) and evolving clinical applications, limitations, and future developments of parametric mapping.

## PHYSIOLOGY AND MICROSTRUCTURE

Magnetic resonance probes density and magnetic microenvironment of water protons. Moreover, fluid-shifts between intra- and extracellular myocardial compartments are reflected in the biodistribution of standard extracellular contrast agents. Many cardiac pathologies are associated with alterations of intra- and extracellular structures and characteristic effects on magnetic parameters. The shortening of native T1 time is observed in glycosphingolipid deposition such as in Anderson-Fabry, the shortening of T2 and particularly T2\* are typical features of iron deposition such as in primary or secondary haemochromatosis. Parametric T2\* mapping is now accepted as a clinical tool to monitor iron deposition in thalassaemia and to

guide therapy (Figure 1). The prolongation of T2, on the other hand, is found in oedema as an indicator of acute disease (Figure 2). Extracellular volume expansion is found in interstitial amyloid deposition or replacement of infarcted myocardium by collagen also referred to as replacement fibrosis e.g. after infarction (Figure 3). Reactive or diffuse fibrosis may occur in oncologic patients during chemotherapy with cardiotoxic medication. Several studies support the notion that parametric mapping might be useful to identify myocardial damage before functional abnormalities occur. Early detection might reduce the burden of heart failure in patients cured of cancer.

## TECHNIQUES AND CONFOUNDERS

Longitudinal relaxation is the process of proton spins returning to equilibrium after excitation. This process is described by the T1 time. Long T1 times are found in

Table

Pathologies with typical parameter alterations

PARAMETER	DECREASE	MILD INCREASE	SEVERE INCREASE
T1 native	Anderson-Fabry, iron overload, fat, athlete's heart, haemorrhage	Diffuse fibrosis, scar, subacute/chronic inflammation	Acute infarct, acute inflammation, amyloidosis
ECV	Athlete's heart	Diffuse fibrosis	Scar, amyloidosis
T2	Iron overload, haemorrhage	Subacute inflammation	Acute inflammation, acute ischaemia, acute infarct
T2*	Iron overload, haemorrhage		

Figure 1

Short axis T2\*-maps from two different patients referred for assessment of iron overload. Relaxation times were measured in the septum to minimise confounding magnetic field inhomogeneities. In the patient with genetic haemochromatosis (A) T2\* was normal (39 ms). In the patient with myelodysplastic syndrome (B) T2\* was abnormal (9 ms), thus indicating a high risk of developing heart failure.

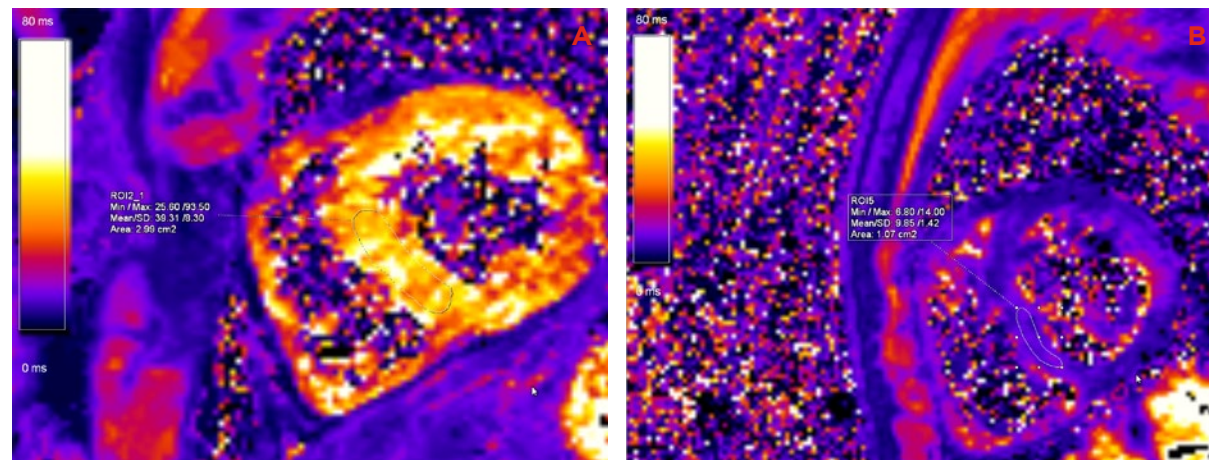
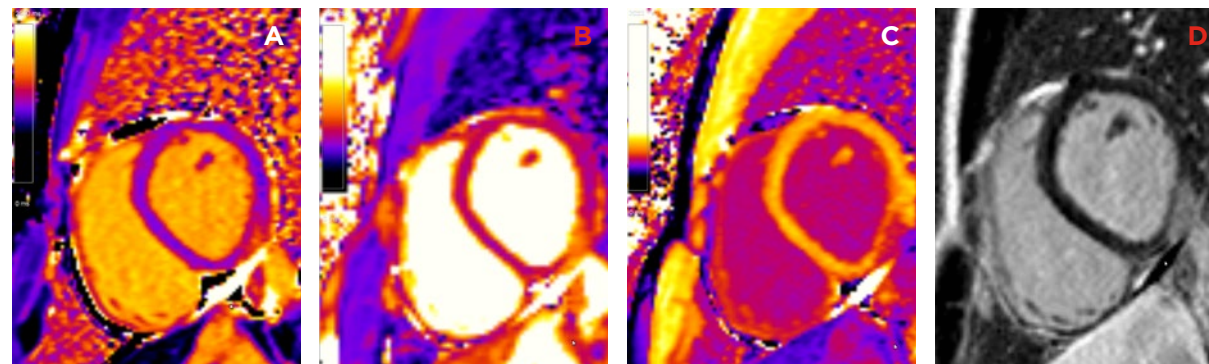


Figure 2

Short axis maps in a 17-year-old boy with acute myocarditis three weeks after gastroenteritis. Native T1 (A) and T2 (B) are prolonged indicating oedema in acute disease. Post-contrast T1 (C) is shortened and late Gadolinium enhanced image (D) show subepicardial late enhancement with non-ischaemic pattern.



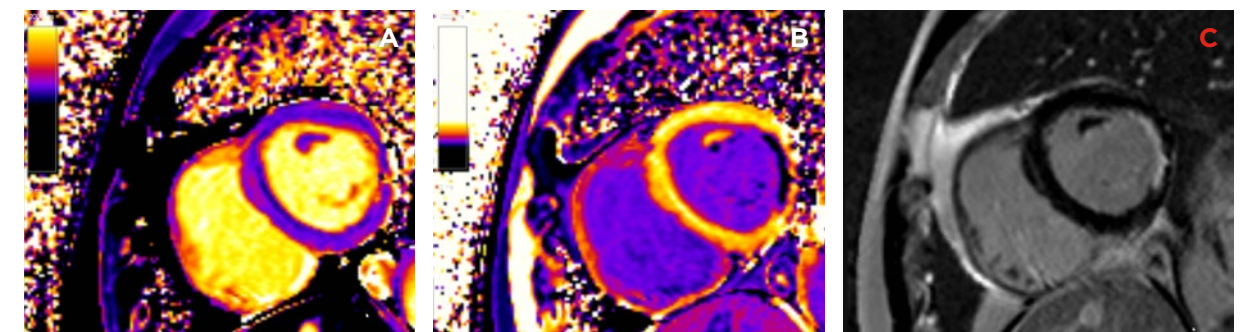
cerebrospinal fluid, short T1 times in fluids containing protein or Gadolinium. Longitudinal relaxation is probed by repeated measurements with inversion and/or saturation prepared sequences with variable delays between preparation and excitation pulses. Recovery values are subsequently fitted with an exponential curve to obtain T1 time. These repeated measurements are time-consuming and various pulse sequence schemes have been explored to shorten acquisition and enable breath-hold imaging. Please note that the choice of pulse sequence scheme has an effect on T1 times because of confounders such as longitudinal relaxation, magnetisation transfer, preparation pulse efficiency, flip angle, heart rate, and off-resonance effects. Extracellular volumes may be calculated based on pre- and post-contrast T1. This calculation, however, requires knowledge of haematocrit from blood samples. Techniques using a synthetic haematocrit based on MR

data without blood sampling are currently under investigation but still require validation. Transverse relaxation is the process of coherence loss of proton spins after excitation. Measurement of transverse relaxation time is based on acquisition with variable echo times and/or with T2 preparation pulses. The fitting of signal decay curves with an exponential fit provides T2 or T2\* times. Relevant confounders are susceptibility to off-resonance and T1 effects. Given these confounders for longitudinal and transverse relaxation, ranges of normal values shall be defined for every scanner/sequence combination for both, female and male healthy volunteers. A reasonable approach would be to scan 20–50 volunteers for each group and to define the range of normal values as the mean  $\pm$  of two standard deviations<sup>1</sup>.

Mapping T2\* is a robust clinical tool and typically based on multi-echo gradient recalled

Figure 3

Short axis maps in a 62-year-old man with infarct in the inferolateral wall. Native T1 (A) is prolonged, post-contrast T1 (B) is shortened and late gadolinium enhancement shows subendocardial injury with ischaemic pattern.



echo (GRE) sequences, which are now available for breath-hold acquisitions. This technique is recommended in clinical guidelines for management of iron overload. Unlike other parametric mapping parameters, T2\* values are not classified as normal versus abnormal, but rather stratified in a 3-tier risk model for developing heart failure (T2\* > 20 ms = low risk; 10–20 ms = intermediate risk; and < 10 ms = high risk).

## CLINICAL APPLICATIONS

Abnormally thickened myocardium may be a diagnostic challenge because it can have several causes. Parametric tissue mapping can help to specify the aetiology. Myocardial thickening is frequently associated with ECV expansion, which can occur in amyloidosis, hypertrophic cardiomyopathy, aortic stenosis, and hypertensive heart disease<sup>2</sup>. The role of ECV for diagnosis and its impact on therapeutic decisions, however, still needs to be clarified in more detail.

Among conditions with ECV expansion, amyloid disease is particularly remarkable, since expansion may be massive and may reflect different subtypes with different outcomes<sup>3</sup>. Expansion of ECV is also observed in acute myocarditis or in scarring such as after infarction. Moreover, ECV mapping has been shown to enable distinction of primary hypertrophic cardiomyopathy from hypertrophy secondary to arterial hypertension which has implications for treatment<sup>4</sup>.

Anderson-Fabry disease is characterised by native T1 shortening, reflecting

intramyocardial sphingolipid storage. Shortening of native T1 is found in few conditions only, thus raising the suspicion of this rare disease even in the absence of myocardial thickening<sup>5</sup>. In the same patient, areas with prolonged native T1 and T2 associated with LGE may be present. These findings may be interpreted as active inflammation and scar formation.

Iron overload is also among the few conditions presenting with the shortening of native T1. Unlike Anderson-Fabry, iron overload is associated with substantial T2\* shortening. This marker is well established to identify iron deposition after repeated blood transfusions such as in thalassaemia major or in increased intestinal iron absorption in hereditary haemochromatosis. Although potentially resulting in heart failure, these diseases can be treated efficiently when detected early. This underlines the importance of early diagnosis. Parametric T2\* mapping is recommended in clinical guidelines.

Diffuse myocardial fibrosis with excess collagen is another application, because parametric mapping may identify cardiac involvement before functional changes occur. Unlike replacement fibrosis after infarct, diffuse fibrosis may be related to chemotherapy with cardiotoxic agents that stimulate collagen proliferation. Early detection of cardiac damage is helpful to modify therapy and avoid an outcome of cured cancer but damaged heart. Diffuse fibrosis is suspected in prolonged native T1, expanded ECV and shortened T1 after contrast administration. Among these parameters, ECV expansion seems to be the most sensitive parameter. More clinical studies, however,

are required to introduce this application into clinical routine.

## EMERGING APPLICATIONS

Perfusion imaging based on native T1 mapping might be useful to distinguish normal from abnormal perfusion reserve. Response to adenosine stress native T1 times increases in normal myocardium but remains unchanged in ischaemic myocardium. The first results support the notion that native T1 mapping may be useful to detect ischaemia. Further clinical studies, however, are required to explore this interesting application.

## CONCLUSION

Parametric mapping adds another dimension to cardiac MR beyond function and morphology. Today T2\*-mapping is recommended in clinical guidelines, whereas T1-, T2- and ECV-mapping are not yet fully integrated in clinical workflows. Their clinical impact, however, appears very promising.

### References

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Currently, Professor Bremerich is president of the European Society of Cardiovascular Radiology. Professor Bremerich is a strong advocate of a fruitful cooperation between radiology, MR physics and clinical disciplines as is carried out at Basel University Hospital.



**10**

**TREATMENT  
OF AORTIC  
VALVE  
STENOSIS**

# NEW SOLUTIONS TO OLD PROBLEMS: AORTIC VALVE STENOSIS

BY RODRIGO SALGADO

## AORTIC VALVE STENOSIS

Aortic valve stenosis is the most common valvular heart disease in the Western world. This condition is especially significant considering the ageing Western population. The overall prevalence is estimated to be 5%, with 2%–3% of individuals over the age of 75 developing severe aortic valve stenosis, evolving from a non-symptomatic valve with thickened and calcified leaflets into an increasingly degenerative valve with extensive calcified and immobile leaflets. Concomitantly, symptoms progress from mild to severe, with increasing fatigue and shortness of breath being common complaints, eventually invariably leading to heart failure and death. The final symptomatic stage is short and rapidly progressive and is associated with a 2-year survival rate of 50% or less. By comparison, even some metastatic malignancies have a better prognosis at this point.

The final diagnosis is routinely made with Doppler echocardiography, providing a functional and morphological assessment of the aortic valve. Aortic valve stenosis is hereby defined as an obstruction of the left ventricular outflow tract at or near the level of the aortic valve, with an aortic stenosis jet velocity of over 4 m/sec, a mean gradient of over 40–50mm Hg, and an aortic valve area of less than 1.0 cm<sup>2</sup>. Critical aortic valve stenosis is reached when the valve area is less than 0.6 cm<sup>2</sup>.

## EVOLVING TREATMENT OPTIONS

Elective surgical valve replacement remains the standard of care for symptomatic aortic valve stenosis, replacing the diseased native valve with a new prosthetic heart valve. While this type of cardiothoracic surgery is nowadays a routinely performed procedure in specialised centres, it remains nevertheless an extensive operation with associated risks, and given the nature of the condition, often performed in patients of older age.

As such, some patients have a significantly elevated risk of surgery-related complications and death, making them unsuitable candidates for surgery. Until recently, no other curative therapies remained for these patients, leaving them only supportive palliative care.

Fortunately, recent developments in transcatheter-based therapies now offer an alternative therapeutic strategy for this nonsurgical patient population, as the native aortic valve can now be replaced by the deployment of a new bioprosthetic transcatheter heart valve (THV), brought in place via a nonsurgical endovascular, transaortic, or transapical pathway.

This procedure is known as transcatheter aortic valve replacement (TAVR) (also called transcatheter aortic valve implantation (TAVI) or percutaneous aortic valve replacement).

Despite such an increasing number of patients eligible for curative treatment, not every individual can receive such a THV. Several anatomic and technical criteria must be met in order to safely receive such a prosthetic device, including a suitable THV size (Figure 1).

In contrast to surgical valve replacement, valve selection and matching to the patient's anatomy is now not performed under direct surgical inspection but on the basis of pre-procedural imaging findings. Therefore, non-invasive imaging plays a crucial role in both patient selection and evaluation of the patient's anatomy in order to achieve maximum procedural success.

## UNDERSTANDING THE PROCEDURE

Basically, a TAVR procedure consists of deploying a THV in the aortic root after transporting the device from a chosen entry point.

Device transport can be in a retrograde fashion using the femoral or subclavian artery as an endovascular access point (the most commonly implemented and preferred approach), or anterograde through the apex of the left ventricle. Evidently, these transport pathways must be free of luminal narrowing or any other pathology that may obstruct the passage of the device. Also, even extensive tortuosity with kinking and coiling of the iliac arteries without narrowing, a phenomenon which can be seen in older patients with long-standing arterial hypertension, can pose significant problems during device transport.

Therefore, other access options also exist as new ways are explored to increase the number of eligible patients with inaccessible first-choice entry pathways. These including a suprasternal approach through the brachiocephalic trunk, an anterior approach through a minimal right anterior thoracotomy, or a

partial mini-sternotomy for transaortic placement through the ascending aorta.

Once the device is transported to the aortic root, it will be deployed using a device-specific method. All current clinically implemented THV fall into two categories: balloon-expandable or self-expandable valves. The two most used and most clinically implemented THV worldwide are currently the balloon-expandable Sapien series from Edwards Lifesciences (Irvine, California, USA) and the self-expandable Corevalve/Evolut range from Medtronic (Minneapolis, Minnesota, USA) (Figure 1).

During deployment, a balloon-expandable valve will expand using the radial strength of the accompanying balloon, and commonly force its circular design on the pre-existing oval-shaped annular morphology. Conversely, a self-expandable valve will deploy until it encounters the resistance of the annular wall, conforming itself to the mostly oval-shaped anatomy of the aortic annulus.

After deployment, the THV will have crushed the native valve against the aortic root wall, as such functionally replacing the diseased valve and restoring valve function.

Figure 1

Current available sizes of the two most commonly clinically implemented transcatheter heart valves, the Sapien series of Edward Lifesciences (A) and the Corevalve/Evolut series of Medtronic (B). The indicated size ranges correspond to the required aortic annulus diameter, assuming a circular morphology of this anatomic landmark. With the two models combined, a patient is currently able to receive this kind of prosthetic heart valve when the annular diameter lies in the range of 16–29 mm. The development of these devices is a continuous work in progress, and new models and sizes are already in the clinical test phase in order to accommodate to the largest number of patients and to minimise the risk of complications associated with first-generation devices.

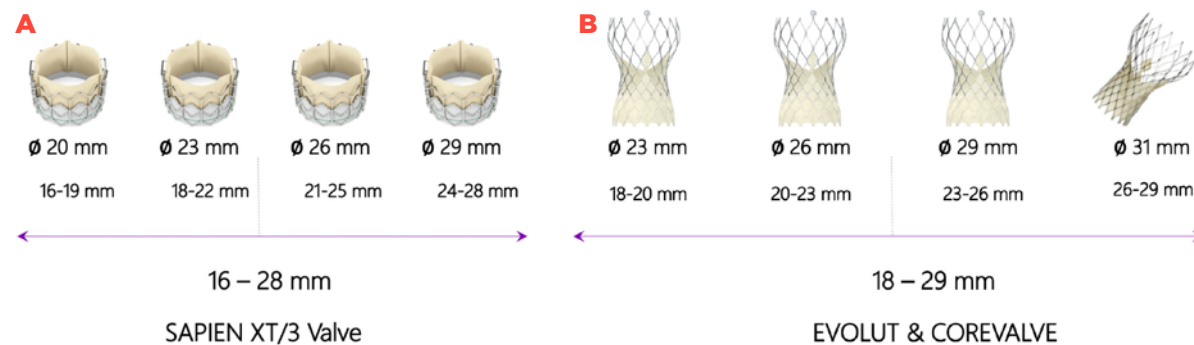


Figure 2

3D volume-rendered image of the heart illustrating the double-oblique orientation of the aortic root (asterisk). The horizontal line corresponds to a true axial image as acquired with CT. This figure clearly illustrates that, in order to correctly obtain critical measurements required to maximise procedural success, a re-orientation of the measurement plane in a double-oblique fashion along the axis of the aortic root is necessary. This is one of the reasons that currently CT is considered an essential imaging tool, improving pre-procedural planimetry of the annulus and aortic root over conventional ultrasound measurements.

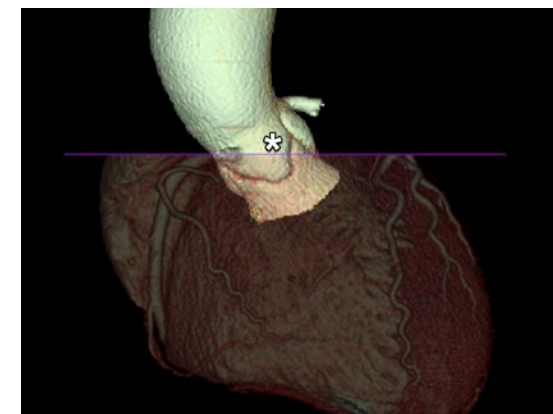
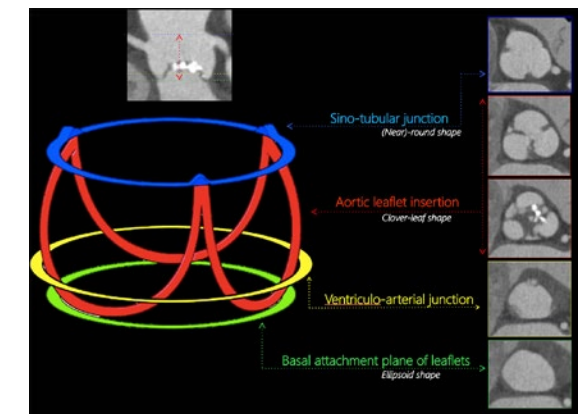


Figure 3

Composite image illustrating the crown-like configuration of the aortic valve leaflets within the aortic root, extending from the sino-tubular junction (blue) to the most basal attachment plane, hereby defining the so-called annular plane (green). The CT images on the right illustrate the varying cross-sectional morphology of the aortic root, being mostly circular at the level of the sino-tubular junction, but becoming more clover-leaf shaped at mid-level and usually ending in an ellipsoid or oval morphology at the annular level.



## PRE-PROCEDURAL CT IMAGING OF THE AORTIC ROOT

A true 3D imaging modality like computed tomography (CT) allows exquisite visualisation of the aortic root, providing all necessary anatomical information (Figures 2–5).

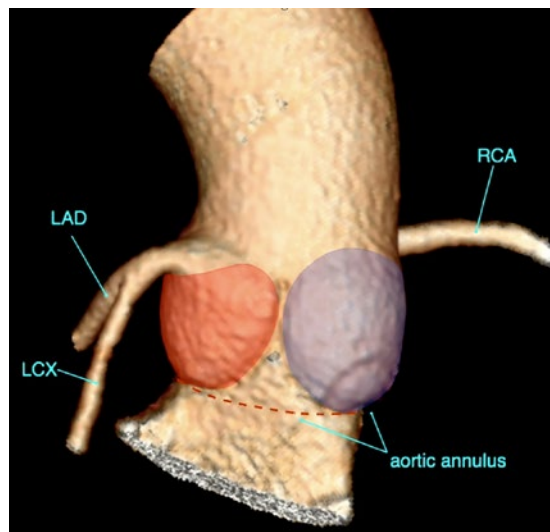
Firstly, in order to achieve the best possible outcome and avoid peri- and post-procedural complications, the new THV must of

course fit the native anatomy as closely as possible, avoiding the associated problems arising from over- or undersizing of the prosthetic valve. If the valve is too large, several complications can occur, including aortic rupture and device migration. Conversely, a valve that is too small can lead to leakage of blood between the THV and the aortic wall, the so-called paravalvular leakage. There is well-established evidence that this leakage may be related, at least in part, to preoperative undersizing of the aortic

annulus, with the subsequent choice of an undersized transcatheter valve and incorrect device positioning. Furthermore, other reports indicate that even mild leakage, which was previously generally considered to be of little clinical significance, is nevertheless an underappreciated contributor to late all-cause mortality. Finally, this leakage has been also associated with extensive native valve calcifications which may limit proper THV expansion when displaced during prosthetic valve deployment (Figure 6).

Figure 4

Volume-rendered CT image of the so-called annulus. The aortic annulus is a virtual structure, formed by connecting the nadirs of the basal insertion sites of the aortic leaflets (dashed red line). The sinuses of Valsalva are here coloured in red (left sinus) and purple (non-coronary sinus), with the different coronary arteries also labelled. LAD: left anterior descending artery; LCX: left circumflex artery; RCA: right coronary artery.

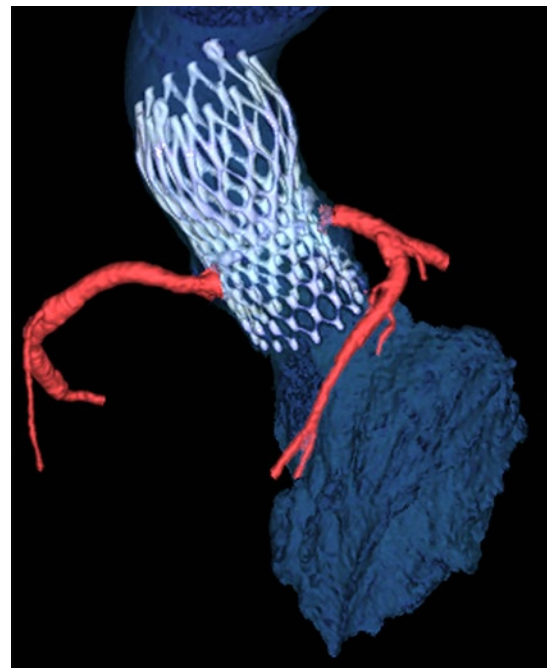


A correctly chosen valve size will therefore lead to the best functional recovery with the least complications.

Secondly, non-invasive CT imaging is essential to evaluate the patency of a safe transport path for the THV to the aortic root. Any obstruction along a specific pathway, e.g. a significant tortuosity or luminal narrowing of the iliac arteries (Figure 7), is clearly visualised, guiding the performing physician or surgeon to safer and more

Figure 5

Volume-rendered image of a Medtronic Corevalve transcatheter heart valve in place, extending from the annular plane in the ascending aorta. The coronary arteries are coloured in red.

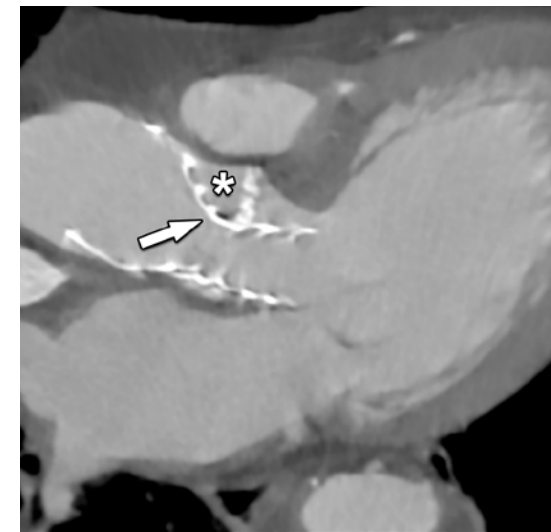


accessible access routes. A carefully chosen access route is therefore one of the key components of procedural eligibility and success, since in a given case, different pathways may be associated with potentially different risks for peri- and post-procedural vascular and embolic cerebrovascular complications.

Modern CT equipment allows the complete anatomical evaluation of a TAVI candidate in one examination, delivering with

Figure 6

Post-procedural image of a deployed Medtronic Corevalve in the aortic root. The deployment of this valve is here clearly compromised by extensive calcifications (asterisk) limiting expansion and deforming the valve (arrow). As such, extensive calcification may under certain conditions compromise valve deployment and diminish its functional effect, sometimes leading to paravalvular leakage between the incompletely deployed valve and the aortic wall.



only one intravenous contrast-medium injection all necessary pre-procedural information. As technology progresses, the latest CT-scanners allow this investigation with as little as 30-50 cc of contrast medium, as such minimising the impact on an often already depressed renal function. Furthermore, ECG-gated scan techniques allow evaluation of the aortic valve at different phases of the cardiac cycle, providing measurements in the preferred systolic phase.

Figure 7

Volume-rendered CT image of the abdominal aorta and iliac arteries. The prominent tortuosity of the left common iliac artery (arrow) forms an additional risk factor for safe device transport. Therefore, pre-procedural screening of the different access routes with CT is essential for procedural safety, indicating in this case that for this patient, the right iliac arteries provide a less hazardous route.



Finally, as this is an invariably older population, CT provides simultaneous evaluation of sometimes unsuspected but clinically relevant non-vascular incidental findings, with varying degrees of impact on the TAVI procedure and clinical outcome.

## RECENT DEVELOPMENTS AND FUTURE PERSPECTIVES

As our understanding of the pathophysiology of aortic valve stenosis evolves, a clear relation has been established between the amount of valve leaflet calcifications and the likelihood of having severe valve stenosis. This is important, as in certain conditions (e.g. patients with low left ventricular output) the clinically suspected diagnosis of valve stenosis cannot be confirmed using Doppler ultrasound, due to paradoxical results falsely indicating less severe stenosis (the so-called low-flow, low-gradient subpopulation). In these specific patients, recent investigations have shown that a simple quantification of leaflet calcification can provide diagnostic information in confirming the diagnosis of severe valve stenosis independently of the ultrasound results.

Finally, recent multicentre studies have indicated the at least non-inferiority of the TAVI procedure compared to surgical replacement in the population of only intermediate surgical risk. While at this stage it is still not common practice to use TAVI outside the patient population with high surgical risk, these results indicate that the potential population

which may benefit from TAVI may expand in the future, potentially leading to fewer open surgical procedures. Nevertheless, important questions remain to be solved, including still unknown data regarding the long-term durability of THV. This is a crucial point before applying this technique in younger patients.

## CONCLUSION

One cannot deny that the introduction of transcatheter valve replacement techniques has a significant impact on the treatment of aortic valve stenosis, providing a therapeutic option in patients who previously could only be offered palliative supportive care. While currently it is only indicated in high-risk patients, recent reports suggest a potential expansion of the applicable population in the future. Therefore, it is safe to state that the impact of TAVI on the treatment of valvular heart disease will only increase as more evidence and experience is gathered.

### References

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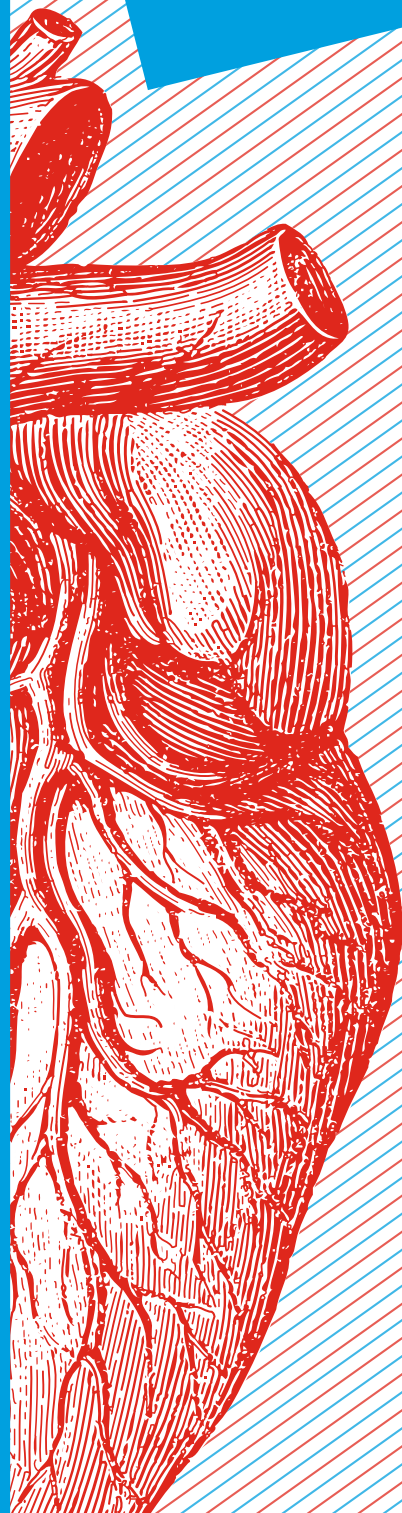
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*and the current president of the non-invasive cardiovascular imaging section of the Belgian Society of Radiology. He has special expertise in non-invasive cardiovascular imaging with CT and MR, with a focus on emerging CT/MR imaging technologies and non-invasive imaging evaluation of cardiovascular interventions. In this capacity, and also as an executive board member of the ESCR, he enjoys teaching and promoting non-invasive cardiovascular imaging to residents and other radiologists through lectures and workshops at national and international meetings.*

*He will be the future congress president of the annual ESCR meeting, to be held in Antwerp, Belgium, on October 24-26, 2019.*





11

# PROSTHETIC HEART VALVES

# A NEW VALVE: NON-INVASIVE IMAGING OF PROSTHETIC HEART VALVES

BY RICARDO P.J. BUDDE

## HEART VALVE REPLACEMENT

Hundreds of thousands of patients annually undergo heart valve replacement to replace a defective native heart valve. Traditionally, heart valve replacement required open heart surgery. After opening the sternum, the heart is exposed and opened to excise the defective native valve and subsequently implant a prosthetic valve. There are two main groups of surgical prosthetic heart valve types: biological and mechanical. Mechanical valves often have two semi-lunar discs that are mounted in a ring, whereas biological valves are made of porcine or bovine tissue. The mechanical valves are designed to last for decades but require lifelong anticoagulation with all its inherent risks. Biological valves do not require anticoagulation but degenerate and need to be replaced after approximately 15 years.

In the last decade, a minimally invasive alternative procedure was developed called transcatheter aortic valve implantation (TAVI, see also chapter 10). In TAVI, the native aortic valve is not excised but a new stent-mounted biological valve is placed within the diseased native valve. Since data on long-term valve durability are not yet available TAVI is currently limited to older and high-risk patients. However, with improvements in valve design, it will likely also be employed in younger and lower risk patients.

Although valve replacement is a very effective way to treat valve disease, it also presents the patient with artificial material in their heart with all

associated risks. Prosthetic heart valve dysfunction may occur and known mechanisms of dysfunction include thrombus formation on the valve, pannus tissue ingrowth underneath the valve causing obstruction, and structural valve failure. The gravest and most feared complication after prosthetic valve implantation is an infection of the prosthetic heart valve which is called endocarditis. The infection may lead to severe damage and destruction of the tissue surrounding the valve. Furthermore, vegetations may form on the valve that both can hamper valve leaflet motion as well as embolise to other parts of the body thereby causing abscesses in organs such as the brain or spleen. Unfortunately, prosthetic heart valve endocarditis is notoriously difficult to diagnose.

## PROSTHETIC HEART VALVE ASSESSMENT

Traditionally, echocardiography has been the technique of choice for valve assessment. It offers many advantages as it is non-invasive, readily available, non-expensive and provides not only anatomical but also functional information on valve function. However,

echocardiography has its limitations and the artefacts generated by the prosthetic heart valves may hamper assessment. Therefore, in case of (suspected) prosthetic valve dysfunction, echocardiography can often not determine the exact cause of dysfunction, or in case of endocarditis, detect perivalvular mycotic aneurysms or abscesses.

In the last decade, CT has emerged as a valuable tool for prosthetic heart valve assessment, providing detailed anatomical assessment as well as functional analysis of valve leaflet motion<sup>1</sup>. Most valve types generate limited artefacts and CT offers unparalleled detail of the (peri)valvular regions (Figure 1). CT has earned its reputation in the assessment of prosthetic heart valves and provides information on the cause of prosthetic valve dysfunction that is complementary to echocardiography, especially since reduced dose acquisition protocols are now available<sup>2</sup>. Furthermore, it can be used to monitor the effects of treatment as illustrated in Figure 2.

For endocarditis, CT is especially well suited to visualising mycotic aneurysms in the aortic root and to demonstrating their relation to the coronary arteries and extension towards other parts of the heart. Positron emission

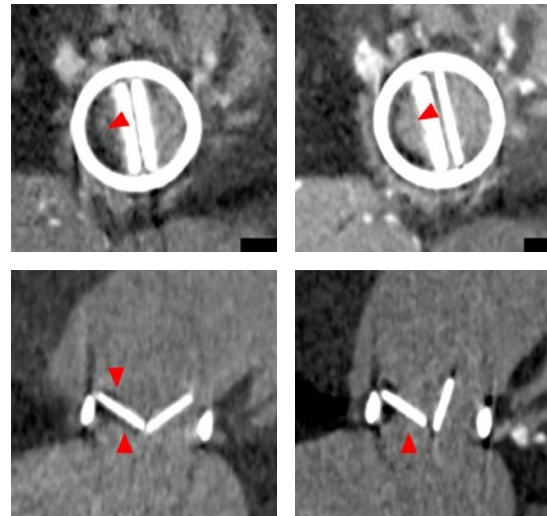


Figure 1

Three-dimensional volume-rendered CT image of two mechanical prosthetic heart valves. Note the detail of the valve that can be seen including the hinge points of the valve leaflets.

Figure 2

Thrombus formation on a mechanical heart valve prosthesis. In the left upper and lower hand panels, the valve is seen en face and perpendicular to the valve leaflets. Note that one of the two leaflets does not open at all due to thrombus formation (arrowheads) on the valve, whereas the other leaflet opens incompletely. After thrombolysis (right-hand images) there is complete opening of the right-hand valve leaflet. The left-hand leaflet is still stuck, but there is a reduction in the amount of thrombus on the valve leaflet (arrowheads) demonstrating the effects of the treatment.



tomography (PET) with CT (PET/CT) provides another dimension to a diagnosis of endocarditis<sup>3</sup> (Figure 3). Using labelled glucose which accumulates in infected tissue, endocarditis can now even be diagnosed before structural damage occurs.

## CONCLUSION

As outlined above, both CT and PET/CT have established their role for assessment of prosthetic heart valves in daily clinical practice. However, especially for endocarditis, the possibilities of PET/CT have only scratched the surface. With the development of new very specific tracers that bind to specific strains of bacteria, or even antibiotics, patient-tailored diagnosis, treatment monitoring and adaptations are on the horizon. Furthermore, a baseline CT scan in each patient who underwent prosthetic heart valve implantation may prove beneficial<sup>4</sup>. The future is bright for prosthetic heart valve assessment with CT and PET/CT.

Figure 3

Endocarditis PET/CT. PET/CT image of an infected aortic valve prosthesis. Note the avid tracer uptake around the valve indicative of active infection.



## References

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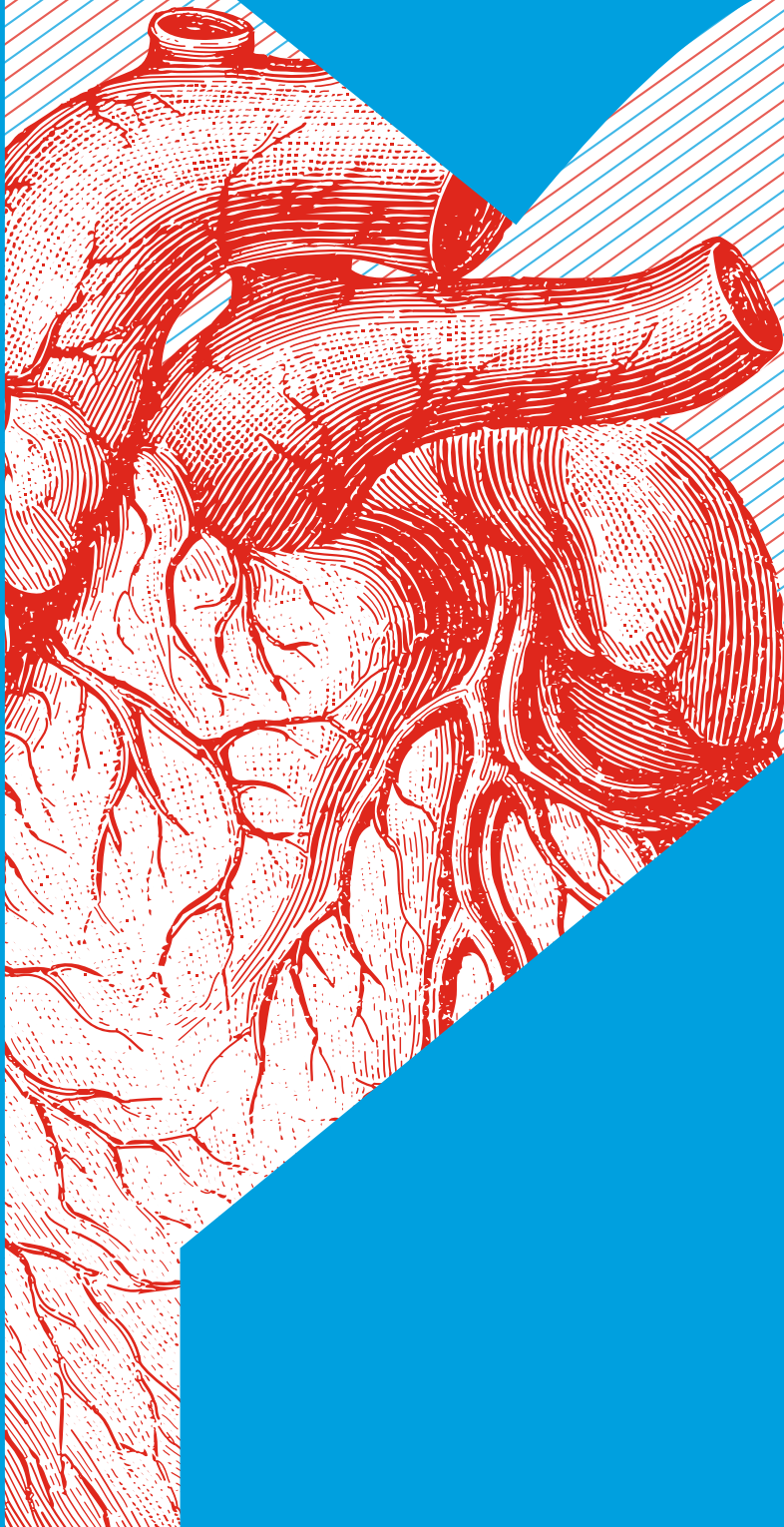
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He is actively involved in scientific research and has (co-)authored over 125 publications published in peer-reviewed journals, written several book chapters, has given many (invited) lectures at (inter)national meetings and serves as daily supervisor for multiple PhD students. His main research interests include imaging of (prosthetic) heart valves, aortic disease, endocarditis, imaging to optimise cardiac surgery and interventions as well as dose reduction techniques for CT imaging. The Dutch Heart Foundation has awarded him two large research grants as principle investigator including a prestigious Dekker grant.

Dr. Budde is an active member of the European Society of Cardiovascular Radiology as well as Fellow of the Society of Cardiovascular Computed Tomography. He is also co-director of the Hands-on Cardiac CT course at Erasmus MC ([www.skillslab.nl](http://www.skillslab.nl)).



12

HEART-  
BRAIN  
AXIS

# AN OFTEN-OVERLOOKED CONNECTION: THE HEART-BRAIN AXIS

BY BIRGITTA VELTHUIS

*“A good heart these days is hard to find”, sung by Feargal Sharkey in 1985, rings increasingly true in our ageing population.*

In addition, if you don't have a good heart, what are the chances that your brain will still function well at an advanced age? The two are more strongly connected than most people realise. With the older population growing, an increasing number of people will suffer from cardiovascular disease, myocardial and brain infarction, heart failure, atrial fibrillation, cognitive decline or eventually dementia. This combination of cardiac and brain disease is a growing global health burden with a large socio-economic impact<sup>1</sup>.

## ATHEROSCLEROSIS

Atherosclerosis is a systemic disease that develops over decades and forms a major component of multi-organ cardiovascular disease, morbidity and mortality. The initial phase of endothelial dysfunction starts in childhood. Autopsy studies have revealed that the fatty streaks, an early

substrate of atherosclerosis, are already seen in many children. It progresses throughout adult life and is activated by changes that trigger lipoprotein dysregulation and inflammatory response. The disease progresses in young adulthood (<40 years) with exposure to unhealthy modifiable lifestyle factors (sedentary lifestyle, unhealthy diet, obesity, smoking; see Figure 1) and other cardiovascular risk factors such as hypertension, diabetes, high cholesterol and dyslipidaemia. The PESA (Progression of Early Subclinical Atherosclerosis) study<sup>2</sup>, which evaluates the systemic extent of atherosclerosis in the carotid, coronary, abdominal aortic and iliofemoral arteries, showed that subclinical atherosclerosis was present in 63% of asymptomatic persons aged 40–54 years of age (Figure 2).

Atherosclerosis remains a subclinical process in most people, with clinical atherosclerosis only being the tip of the iceberg. Many people with atherosclerosis will not have

obvious clinical symptoms. More than half of the persons who die suddenly because of a heart attack do not have forewarning of their coronary heart disease. Only a minority of people who experience an ischaemic brain stroke have experienced earlier symptoms such as a transient ischaemic attack (TIA), a temporary neurological dysfunction caused by focal ischaemia but without acute infarction. As a consequence, we face an enormous challenge to know which asymptomatic persons are at risk and should be screened and receive appropriate lifestyle advice and possibly even medication. Although preventive strategies and improved treatment have reduced death rates of ischaemic heart and brain disease, they still remain in the top causes of death<sup>3</sup>.

Traditional risk scores are good at identifying people at high risk, but poor at differentiating intermediate and low risk. Imaging can help reclassify the traditional risk scores,

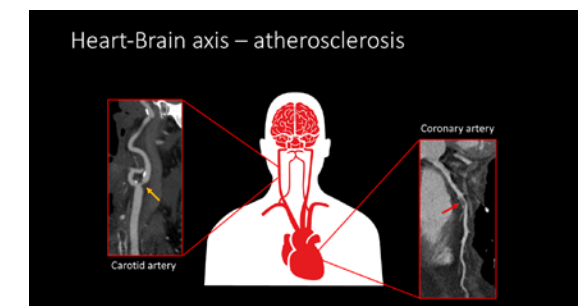
Figure 1

Atherosclerosis is a systemic disease which progresses during a lifespan with exposure to lifestyle factors such as smoking, obesity, and a sedentary lifestyle.



Figure 2

Cardiovascular diseases of the brain and heart are especially affected by atherosclerosis of the carotid (yellow arrow) and coronary (red arrow) arteries.



especially at young to middle age when one can still expect preventive measures to have the most effect. The European Society of Cardiology guidelines do not recommend routine screening with imaging modalities to predict future events in clinical practice. They consider imaging to be a risk modifier in cardiovascular risk assessment, i.e. it helps reclassify risk in individuals with calculated cardiovascular risks based on the major conventional risk factors around the decision-making thresholds<sup>4</sup>.

One of the earliest measures of vascular disease is increased arterial stiffness. This can be measured in various indirect ways but magnetic resonance imaging (MRI) is the most effective direct measurement. MRI measures of arterial stiffness are associated with future cardiovascular events according to the Dallas study<sup>5</sup>.

Atherosclerosis is best viewed using CT imaging when it is in an early phase. A non-contrast coronary artery calcium score is the most effective imaging tool to modify risk score calculation with only a minimal radiation dose. Additional contrast-enhanced CT angiography can depict the non-calcified plaque, and thereby the total atherosclerotic burden, and can also assess high-risk plaque characteristics associated with plaque rupture and luminal stenosis. Although additional coronary calcium scoring testing is only advocated for persons with intermediate risk, there is also benefit in populations with traditional low-risk classification<sup>6</sup>. 'Low-risk' subgroups that may benefit from a low dose calcium score are middle-aged women with a history of hypertensive pregnancy complications such as preeclampsia and middle-aged sportspersons engaged in high-level endurance sports<sup>7,8</sup>.

Figure 3

Atrial fibrillation is prevalent in the elderly, and thrombus formation in slow flowing parts of the heart such as the left atrial appendage (red arrow) is the most important source of cardioembolic brain stroke (yellow arrow).

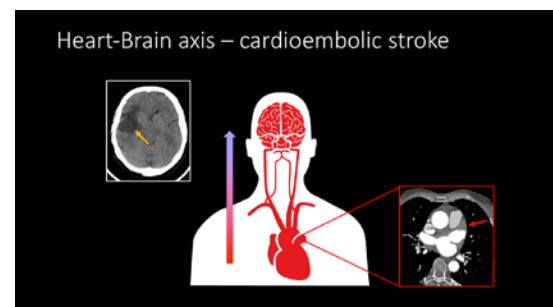
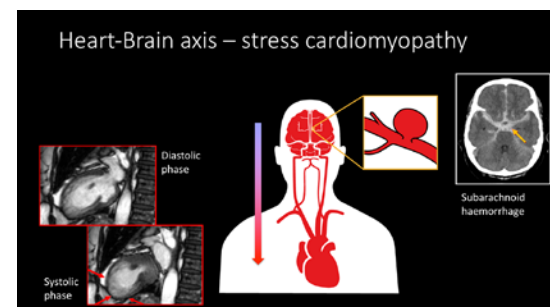


Figure 4

Acute stress, including a subarachnoid haemorrhage (yellow arrow) from a ruptured cerebral aneurysm, can cause temporary dysfunction of the heart (red arrows), a so-called stress cardiomyopathy.



## FROM HEART TO BRAIN

Emboli from the heart (cardioemboli) are one of the main causes (20–30%) of acute ischaemic brain stroke<sup>9</sup>. Atrial fibrillation is prevalent in the older population and is the main source of cardioemboli (Figure 3). Other causes include ventricular thrombi, often in patients with ischaemic or non-ischaemic heart failure, valve disease, and paroxysmal right-to-left venous emboli through an open connection between the right and left side of the heart (patent foramen ovale or atrial septal defect). Another source of ischaemic stroke is atherosclerotic plaque or dissection of the aorta or carotid/vertebral arteries.

Current CT scanners enable coverage of the heart to the brain in seconds using one contrast bolus. Imaging the heart, thoracic aorta, neck arteries and intracranial arteries in patients admitted with acute ischaemic brain stroke symptoms can not only demonstrate the site and extent of the occlusion, but also the possible causes of the stroke, which may assist short-term treatment decision-making.

## FROM BRAIN TO HEART

Stress is a well-known phenomenon that can affect the heart. Acute emotional and even physical stress can lead to a detrimental cascade of events, including release of catecholamines, which can result in a stress cardiomyopathy (Figure 4). Stress cardiomyopathy is also called Takotsubo cardiomyopathy, as the ventricle with apical hypokinesia and ballooning resembles a Japanese pot used to catch an octopus, or broken-heart syndrome

due to the association with acute emotional stress. This occurs most often in middle-aged women and is usually a self-limiting disease with a good prognosis.

An intracranial aneurysm is found in 3% of the population. Acute subarachnoid haemorrhage due to the rupture of an intracranial aneurysm is often associated with the worst headache a patient has ever experienced and an acute rise of intracranial pressure, and thereby acute stress. These patients often show a temporary cardiac dysfunction and rise in troponines, similar to other forms of stress cardiomyopathy. Although the cardiac dysfunction is temporary, those with signs of stress cardiomyopathy have perfusion deficits of the brain in the acute phase, a higher chance of delayed cerebral ischaemia, and a worse long-term prognosis<sup>10</sup>.

## CONCLUSION

In conclusion, the heart-brain axis is often overlooked, but remains essential in understanding the aetiology of cardiovascular disease, assessing systemic disease such as atherosclerosis, and improving diagnosis and prognosis both in the asymptomatic and symptomatic population. *“A good heart these days is hard to find, so please be gentle with this heart of mine.”*

### References

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*grew up in Malawi and Zimbabwe, Africa. She completed her medical and radiology training in Utrecht, the Netherlands. She obtained her PhD*

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*As professor in radiology of the heart-brain axis, she investigates the heart-brain connection in various diseases such as atherosclerosis, cardioembolic stroke and stress cardiomyopathy, as well as interaction with gender, ethnicity, genetic background and lifestyle. Furthermore, her neurovascular research concentrates on CT and MRI imaging in patients with ischaemic stroke, intracerebral haemorrhage, subarachnoid haemorrhage and cognitive decline. Her cardiovascular research focuses on imaging of cardiomyopathies, cardiac failure and sports cardiology.*



**13**

**EUROPEAN  
MR/CT  
REGISTRY**



# BUILDING THE FUTURE: THE EUROPEAN CARDIOVASCULAR MR/CT REGISTRY

BY MATTHIAS GUTBERLET

Can it help us to avoid unnecessary invasive catheterisation?

## BACKGROUND

Cardiovascular diseases and especially coronary artery disease (CAD) are still the most common diseases in industrialised countries and the number of people suffering from these diseases is still increasing. Early diagnosis and adequate treatment is crucial and has helped to reduce mortality over the last decades dramatically. The first invasive cardiac catheterisation was performed in 1929, almost 100 years ago, by Werner Forßmann, a surgeon in Berlin as a self-experiment. However, it took an additional 30 years before the first left heart catheterisation and the first selective coronary angiography were successfully performed by the paediatric cardiologist Mason Sones and the radiologist Melvin Judkins, respectively. Another almost 20 years were then needed before the first coronary angioplasty was successfully executed by Andreas Grüntzig in 1977. From that time on, the success story of minimal invasive treatment of heart diseases began and has certainly not come to an end with the minimal invasive catheter-based treatment of valve diseases.

However, according to the annual German Heart Report<sup>1</sup> from 2016, approximately 1 million invasive cardiac catheterisations were performed in 2014 in Germany, but percutaneous coronary interventions (PCIs) followed only in 40%.

### Note

This means that up to 60% of invasive cardiac catheterisations would not have been necessary if alternative methods for diagnosing coronary artery disease or other heart diseases could do the job just as well.

## NON-INVASIVE ALTERNATIVES TO CARDIAC CATHETERISATION

Despite the fact that nowadays diagnostic cardiac catheterisation is a 'low-risk' procedure in experienced hands, the risk is not 'zero'. Therefore it is desirable to reduce the burden on both the patient and on the health system. This describes not only the situation in Germany, but also in almost the entire European Union. The goal is to decrease invasive procedures in favour of non-invasive diagnostic testing, without jeopardising diagnostic and therapeutic safety. The latter has already been proven in the last decade for almost all other non-invasive imaging tests like the functional techniques stress echocardiography, myocardial perfusion SPECT, and in recent years also for stress perfusion or dobutamine stress magnetic resonance imaging (MRI), without the need for radiation exposure. But in recent years also the morphological technique cardiac computed tomography (CCT) has rapidly developed in terms of speed, spatial

resolution and radiation dose reduction and is therefore nowadays the main direct competitor of invasive coronary angiography (ICA). Like in ICA, direct visualisation of the coronary arteries is possible with CCT without the use of an invasive procedure and with lower or at least comparable radiation exposure.

## WHY HAVEN'T ALTERNATIVE NON-INVASIVE METHODS REPLACED INVASIVE DIAGNOSTIC CATHETERISATION YET?

To replace ICA, the following prerequisites have to be fulfilled:

- Widespread use and availability of the alternative techniques in clinical routine
- High-quality services provided by the radiologist
- Important results not only in academic centres
- Full coverage by health insurance companies, in particular by compulsory health insurance

## FOUNDING OF THE ESCR CARDIAC MR/CT REGISTRY IN 2012

In September 2012, the European Society of Cardiovascular Radiology (ESCR) launched

the MR/CT Registry in which a representative sample of cardiac magnetic resonance imaging (CMR) studies as well as cardiac computed tomography (CCT) examinations from all over Europe could be documented (<https://www.mrct-registry.org>). The submission of data is now a pre-requisite for the accreditation and certification process in Germany. It also serves as a tool for quality control in cardiovascular radiology (Figure 1) and may help to establish a database for big data analysis, deep learning and the use of artificial intelligence to improve diagnosis.

## A SUCCESS STORY!

Almost six years after the start of the ESCR Cardiac MR/CT Registry, more than 220,000 cardiac MRI and cardiac CT studies from all over Europe have been submitted. A slight imbalance in favour of cardiac magnetic resonance imaging (CMR) has developed

over the recent years with approximately 118,000 CMRs and 93,000 submitted CCTs. The majority of participating institutes and contributing users are from Germany. However, the 300 contributing institutes come from 33 different European countries. The majority of centres are not academic centres anymore, but larger community hospitals, and also radiologists in private practice; meaning that a widespread use and availability of these new and fascinating non-invasive techniques is accomplished in clinical routine already in most European countries. According to the MR/CT Registry only 2% of CMRs and as few as 0.3% of CCTs are performed in clinical trials, all other examinations were performed due to a real clinical indication and a real clinical need.

To maintain a high image quality besides well-trained radiologists (i.e. ESCR Diploma holders – members of the European Board of Cardiovascular Radiology – EBCR) adequate equipment is needed. A 1.5T scanner

Figure 1

Cover page of the recent ESCR Cardiac MR/CT Registry booklet, which can be downloaded for free via the following URL: [https://www.mrct-registry.org/images/ESCR\\_2018\\_CardiacMRCT-booklet.pdf](https://www.mrct-registry.org/images/ESCR_2018_CardiacMRCT-booklet.pdf)



for CMR and for CCT at least a 64-row CT is recommended. Fortunately, this prerequisite is already fulfilled according to the ESCR MR/CT Registry data. Almost 80% of contributing users used a 1.5T system and approximately 20% even a 3.0T system. On the CT side approximately 99% of the users are using a 64-row CT or higher.

## MAIN INDICATIONS

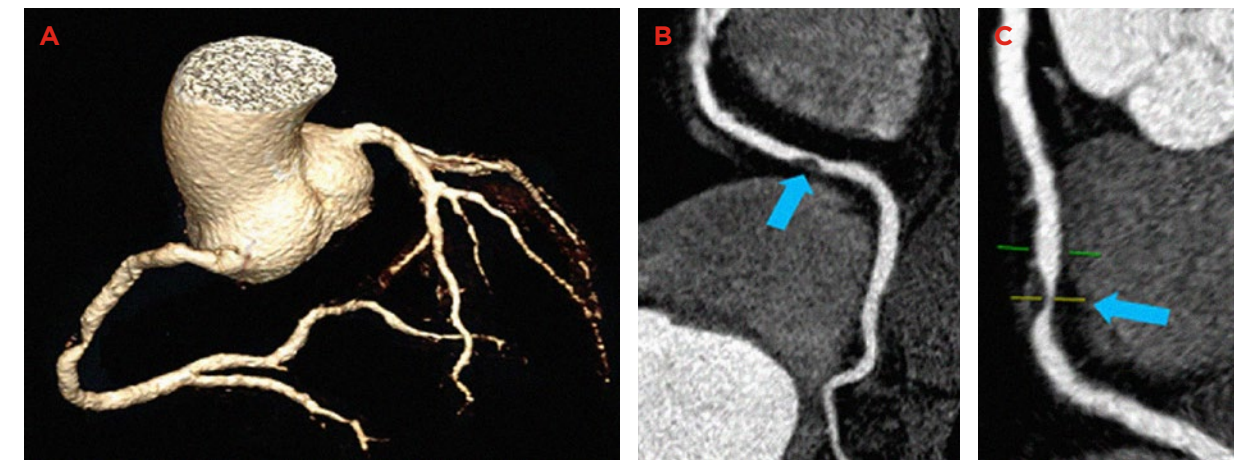
As the direct competitor of ICA, it is unsurprising that CCT is mainly performed in

known or suspected coronary artery disease (CAD) and accounts for more than 2/3 of all cardiac CT examinations, followed by valve and aortic diseases, mainly to plan interventional or surgical procedures. Actually, CCT has the potential to evaluate CAD even better than ICA, because it cannot only visualise the vessel lumen, but also the vessel wall (Figure 2).

The main indications for CMR are the evaluation or differential diagnosis of cardiomyopathies and myocarditis, closely followed by the evaluation of known or suspected CAD. Both account for more

Figure 2

Non-invasive imaging by coronary computed tomography angiography (CCTA) in a male patient with a high-degree stenosis (narrowing of the vessel) of the middle section of the right coronary artery (RCA) using a 3D-visualisation method, that shows only the inner lumen of the three coronary vessels ('coronary vessel tree') and the aortic root (A) and the corresponding 'curved multiplanar reformats' (CPRs) in (B, C) from different views, which also allows assessing the vessel wall two-dimensionally. Here you can see that the high degree stenosis (blue arrow) is caused by a non-calcified, so-called 'low-attenuation' plaque, which has a worse prognosis than calcified plaques. A direct visualisation of the vessel wall is not possible with ICA.



than 80% of all indications. Around 20% of indications are equally distributed between congenital heart disease and valve disease. Therefore, the strength of CMR is the differential diagnosis and the strength of Cardiac CT the fast and reliable rule out of CAD, especially in patients with a low intermediate pre-test probability (PTP)<sup>1</sup>.

An estimate of the PTP can be achieved only by taking the age, gender and symptoms into account (Table 1). According to the current guidelines for the management of patients with suspected stable CAD, only patients with an intermediate

pre-test probability between 15–85% should be referred to a non-invasive imaging test, patients with a high PTP > 85% of CAD should be referred directly to ICA and in patients with a low PTP < 15% other causes of chest pain should be evaluated first<sup>1,2</sup>.

### MAJOR COMPLICATIONS IN CMR/CCT

CCT and CMR are very safe methods. According to the documented cases in the ESCR Cardiac MR/CT Registry, the overall

adverse event rate in CCT was as low as 0.44% and in CMR slightly higher with 0.5%, because it includes stress MRI with a pharmacological stressor like adenosine in 91%, regadenoson in 7% or dobutamine in 2% (Figure 3) to evaluate myocardial perfusion in suspected or known CAD with an intrinsically higher risk<sup>3</sup>. However, severe adverse events such as an allergic shock or resuscitation occurred only in 1:10,000 patients.

### CLINICAL CONSEQUENCES

One of the major goals of using different non-invasive imaging methods is to avoid unnecessary ICAs, which could be achieved in approximately 1/3 of CMR examinations and approximately 37% of CCTs. 22% of all CCTs and 6% of CMRs had a direct impact on interventional procedures. A direct referral to the cath

lab was only necessary in 2.5–4.9%. All other patients could be discharged or only required a change of drug regime (Table 2).

### RADIATION EXPOSURE

In clinical trials, CCT can be performed under certain circumstances (low and stable heart rate, latest CT equipment etc.) with a radiation exposure as low as < 1 mSv. However, in a clinical standard scenario this can't be always achieved, especially if not only the heart, but also the aorta, i.e. pre-interventionally before transcatheter aortic valve implantation (TAVI), has to be assessed. Nevertheless, the results of the ESCR Cardiac MR/CT Registry revealed that even in a clinical scenario dose reduction protocols, like 'step-and-shoot' or the so-called 'flash-mode' are used in more than 50% of all patients, resulting in a

Table 1

Pre-test probability of obstructive CHD in patients with stable chest pain to estimate the need for further diagnostic tests on the cardiology care level

Age* [years]	TYPICAL ANGINA PECTORIS		ATYPICAL ANGINA PECTORIS		NON-ANGINAL CHEST PAIN	
	Men	Women	Men	Women	Men	Women
30–39	59%	28%	29%	10%	18%	5%
40–49	69%	37%	38%	14%	25%	8%
50–59	77%	47%	49%	20%	34%	12%
60–69	84%	58%	59%	28%	44%	17%
70–79	89%	68%	69%	37%	54%	24%
>80	93%	76%	78%	47%	65%	32%

This data is based on the following definition of anginal symptoms: (A) squeezing pain located either retrosternally or in neck, shoulder, jaw or arm, (B) aggravated by physical exertion or emotional stress, (C) improved with rest and/or nitro-glycerine within 5 minutes. The combined presence of the following features define typical angina pectoris if three of the features are present and atypical angina pectoris if two are present, while one or none of the features defines non-cardiac chest pain.

\* The calculated probabilities for the age groups represent the estimates for patients aged 35, 45, 55, 65, 75, and 85 years, respectively (modified from reference 1).

Figure 3

Distribution of the different pharmacological substances used in stress-MRI according to the documented cases in the ESCR MR/CT Registry. Figure from the MR/CT Registry booklet 2018.

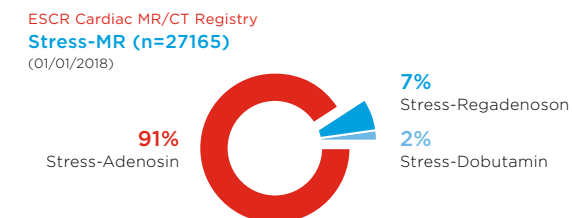


Table 2

CLINICAL CONSEQUENCES	CARDIAC MR	CARDIAC CT
No further invasive diagnostics	32.5%	36.6%
Impact on interventional procedure	6%	21.7%
Direct referral to catheter laboratory	2.5%	4.9%
Patient discharge	4.4%	3.3%
Change of drug regime	5.6%	2.4%

Multiple clinical consequences for one imaging study possible

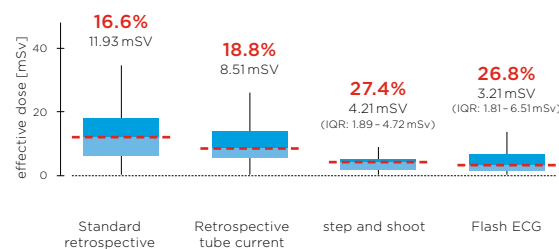
median radiation exposure of 4.21 mSv and lower (Figure 4), which is within the range of a median radiation exposure with ICA.

### WHO IS PERFORMING AND REPORTING IT?

Most CMRs and CCTs are performed and reported on by radiologists (Figure 5) according to the ESCR MR/CT Registry data. But up to 1/3 of the examinations are reported on together, in consensus reading between cardiologists and radiologists, which might be a very good way to keep high-quality standards in less experienced or not yet certified imaging centres.

Figure 4

'Box-plots' of the mean effective dose for the most commonly used four acquisition techniques in cardiac computed tomography (CCT). It demonstrates that even in a clinical scenario, dose reduction protocols, like 'step-and-shoot' or the so-called 'flash-mode' are used in more than 50% of all patients, resulting in a median radiation exposure of 4.21 mSv or lower, which is within the range of a median radiation exposure with invasive coronary angiography (ICA).

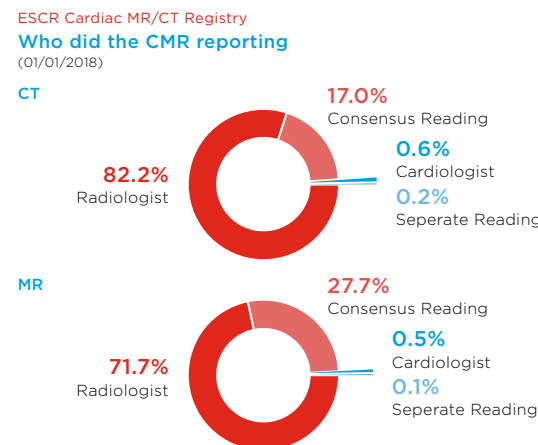


### WILL MY INSURANCE COMPANY PAY FOR CARDIAC MR AND/OR CARDIAC CT?

Despite the proven value and support by national and international guidelines to perform non-invasive imaging techniques in diagnosing cardiovascular disease rather than using invasive procedures like ICA, the reimbursement policy of health insurance systems and companies varies substantially throughout Europe. The most progressive approach was introduced in the UK in 2016 by the National Institute for Health and Care Excellence (NICE). On the one hand the NICE-Guidelines recommend using coronary computed

Figure 5

Pie charts of the distribution of radiologists reporting on cardiac CT and cardiac MRI and consensus reading together with cardiologists according to the ESCR Cardiac MR/CT Registry (from the 2018 Booklet).



tomography angiography (CCTA) as the first line method in suspected stable coronary artery disease, which is therefore also covered by the National Health Service (NHS). On the other hand, unlike the NHS, CMR and CCT is not covered by the compulsory health insurance in Germany and an affected patient has to apply for health insurance coverage individually. Therefore, these valuable methods can be provided in Germany and other European countries mainly in inpatients during their hospital treatment, and during their ambulatory treatment only if privately insured or as a self-paying patient.

### CONCLUSION

According to the results of the ESCR Cardiac MR/CT Registry, non-invasive imaging techniques, especially CMR and CCT have the potential to replace unnecessary invasive catheterisation for diagnosing cardiovascular diseases. Invasive cardiac catheterisation should only be used to guide and perform cardiovascular interventions in the near future. The non-invasive methods CMR and CCT have proven their widespread use in clinical routine by radiologists alone or together with cardiologists and its benefits for our patients. Especially cardiovascular CT helped up to 2/3 of the patients to avoid invasive cardiac catheterisation. The ESCR cardiovascular MR/CT Registry is one example of how carefully collected and documented medical data provides evidence that new radiological techniques help to improve medical care and especially to ensure optimal patient care and maybe

replace other less cost-effective and less gentle methods in the near future.

Furthermore, the documentation and being a pre-requisite for accreditation and certification of medical personnel and institutions help to maintain certain quality standards in performing these new diagnostic tools. We hope that these new and very beneficial methods for the patients will be reimbursed by more and more health services throughout Europe in the near future.

The ESCR Cardiac MR/CT Registry may also serve us to build the future by establishing a database for big data analysis, deep learning and the use of artificial intelligence to improve diagnosis.

#### References

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EBCR**

*is Professor of Radiology and Chairman of the Department of Diagnostic and Interventional Radiology at the Heart*

*Center Leipzig - University Leipzig since 2007.*

*He started his career in cardiology at the German Heart Center and at the Department of Radiology and Nuclear Medicine at the Charité, Berlin in 1995. He is an internationally renowned expert in cardiovascular imaging.*

*His main research interests are non-invasive cardiovascular imaging with a multimodality approach (MRI, MDCT, SPECT, PET and MR/PET), especially for coronary heart disease, cardiomyopathies/myocarditis and congenital heart disease, as well as image-guided therapy.*

*He has authored or co-authored more than 200 peer-reviewed publications, a textbook on Imaging in Congenital Heart Disease and Image-guided Therapy and has given numerous invited lectures, tutorials and refresher courses at national and international meetings. He has also been the organiser of the annual interdisciplinary cardiovascular imaging meeting in Leipzig 'Deutsche Kardiodiagnostiktage' since 2013.*

*From 2014 to 2016, Professor Gutberlet was chairman of the board of the cardiovascular imaging group of the German Radiological Society (DRG) and from 2014–2017 also the president of the European Society of Cardiovascular Radiology (ESCR). He is currently*

*Chair of the ESCR Steering Committee for the Cardiac MR/CT Registry and a member of the current writing committee for the National Care Guidelines (Nationale Versorgungs Leitlinie - NVL) for stable coronary artery disease in Germany.*



**14**

**CERTIFICATE OF  
EXCELLENCE  
EBCR**

# CERTIFICATE OF EXCELLENCE: THE EUROPEAN DIPLOMA IN CARDIOVASCULAR RADIOLOGY

BY **KARL-FRIEDRICH KREITNER**

## INTRODUCTION

The European Society of Cardiovascular Radiology (ESCR) introduced the European Board of Cardiac Radiology Diploma in 2011 in Amsterdam. The aim of this initiative was to standardise training and expertise in cardiac radiology across Europe. Therefore, the level of knowledge requested for the diploma corresponds to the curricular content for full subspecialisation in the field of radiology provided by the European Society of Radiology (ESR) *European Training Curriculum for Subspecialisation in Radiology (Level III)*<sup>1</sup>. As this training curriculum also includes the part of vascular radiology, the society changed the name of the diploma to the European Board of Cardiovascular Radiology (EBCR) Diploma.

## AIMS

The EBCR Diploma is a common European qualification in cardiac radiology and confirms specific competence of radiologists to perform,

interpret and report cardiac CT and MR examinations independently. The EBCR Diploma represents a recognised qualification in cardiovascular radiology (CR). The EBCR Diploma will assist cardiovascular radiologists in the promotion of their skills and experience in CR when dealing with other clinical colleagues and with the general public. Since its conception in 2011, the EBCR Diploma has officially been endorsed by the European Society of Radiology (ESR)<sup>2</sup>.

## REQUIREMENTS

According to the ESR criteria for subspecialty diploma endorsement, candidates for the EBCR diploma should be board certified radiologists with a radiology residency which preferably lasts no less than five years. After that time, a subspecialty training of at least two years is necessary. This provides the candidates with an in-depth training and experience in cardiovascular radiology.

## EVIDENCE OF TRAINING IN CARDIOVASCULAR RADIOLOGY

The evidence of training in cardiovascular radiology is as follows: all candidates present a documentation or logbook with a total record of their experience in cardiovascular CT and MR examinations. This documentation can be done in three ways, either by a RIS statistic printout of cardiovascular MR and CT cases or a logbook self-declaration with names of patients (initials) and nature of

examination or an active participation in the CT/MR Registry of the ESCR (for details on this registry see chapter 13). The minimum qualifications required for entry to the examination are the following:

The candidate should have experience in

- At least 150/300 (life-cases/data-base-cases) cardiac CT studies; at least 100 of the CT life-cases should be contrast enhanced scans
- At least 100/300 (life-cases/data-base-cases) cardiac MR studies
- At least 100 non-coronary vascular CT cases
- At least 50 vascular MR cases

The curriculum vitae should include the records of training posts in cardiovascular radiology, scientific and educational activities in particular. A letter of support is also needed from the candidate's cardiovascular radiology programme director or head of the department, confirming the candidate's training, especially after their board certification.

## EVIDENCE OF EDUCATION IN CARDIOVASCULAR RADIOLOGY

The evidence of education in cardiovascular radiology consists of various activities: 50 CME credits category 1 in cardiovascular imaging with various modalities (e.g. 50% CT and 50% MR) are required. Furthermore,

the candidates should take part in the ESCR Educational Programme that includes educational webinars, educational workshops and ESCR Educational Courses:

- ESCR offers online webinars on a monthly basis, about 50% of them are dedicated to education. From 2019, the education webinars will each concern a main topic.
- ESCR is offering a growing number of educational hands-on workshops for small groups. There are workshops provided as pre-conference workshops prior to the Annual Meetings as well as prior to the European Congress of Radiology (ECR). Additionally, there are further workshops on different occasions in preparation. Details of these workshops can be checked on the ESCR website for continuous updates on endorsed or ESCR-organised workshops.
- The main ESCR educational course is integrated into the annual meeting of the ESCR with a multiple choice examination (Cardiovascular Imaging – CI Examination) at the end. Additionally, the ESCR will endorse educational courses as organised by other ESCR members and ESCR member societies, and may organise additional educational events to prepare for the diploma.
- The Cardiovascular Imaging Examination was introduced by the ESCR during the Annual Scientific Meeting 2009 in Leipzig as a written multiple choice examination. In 2010, on occasion of the Annual Congress in Prague, the examination was offered on a computer-based system,

using the online self assessment tool by the ESR. The examination is offered on a regular basis at the ESCR Annual Scientific Meetings every year. The CI Examination is a web-based test; candidates are asked 24 multiple choice questions (MCQ). Questions are related to the topics covered by educational sessions during the respective congress. Some general/basic questions, not related to the educational sessions, may also be included.

## DIPLOMA EXAMINATION

If all of the above-mentioned requirements are fulfilled, the applicant may undergo the written and oral examinations for the European Diploma in Cardiovascular Radiology that are offered at the annual meeting of the ESCR as well as during ECR.

Only a limited number of candidates can be accepted for these exams at each meeting. Therefore, applications will be accepted on a first come, first served basis depending on the date of receipt of the appropriate application form. Early application is therefore recommended.

The written examination consists of 30 multiple choice questions and lasts 45 minutes. Candidates will be tested in all aspects relevant to cardiovascular radiology such as anatomy, physiology, embryology, clinical practice, pathology, and cardiovascular CT and MR. The oral exam consists of a 20-minute oral examination by ESCR representatives in English. The examiners will show

each candidate a series of – at least two – cases, where the examiners will test the candidate's knowledge of all aspects of the cases under discussion – indication, clinical background, diagnosis, differential diagnosis, technical parameters, limitation, etc.

After the written and oral examination, an examiners meeting will be held. At this meeting, the results of both components of the exam will be added together to produce a total score for the examination for each candidate. The scores for each candidate will be reviewed and potential fail candidates will be discussed. At the end of the meeting, a list of pass and fail candidates will be produced and candidates informed accordingly by email. There will be no publication of the scores, but just of 'passed' or 'failed'.

Successful candidates will be awarded the EBCR Diploma and may add EBCR (European Board of Cardiovascular Radiology) to their name. The diploma is granted for a period of five years. After five years, renewal is requested after proof of continuous activity in cardiovascular radiology. The examination itself does not need to be retaken after five years.

## CONCLUSION

The European Diploma in Cardiovascular Radiology is undoubtedly a certificate of excellence and helps to improve the standard of cardiac imaging in Europe. The aim must be that the number of diploma holders is sufficiently high in every European

country in order to guarantee a nationwide supply of high expertise in this important field of radiology.

Since the start of the Diploma on the occasion of the Annual ESCR Meeting in Amsterdam in 2011, there have been 179 colleagues that successfully passed the examination. Only one candidate failed up to now. Per year, between 20 and 25 colleagues apply for the diploma. Currently, there are 159 diploma holders who have a valid certificate and there are 20 colleagues who need to renew their diploma.

We are on the right path to achieving our aims, but nevertheless, this requires the enthusiasm and continuous support of all persons who are engaged in the field of cardiovascular radiology.

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### References

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ARTIFICIAL  
INTELLIGENCE  
AND  
CARDIO-  
VASCULAR  
DISEASE

# ARTIFICIAL INTELLIGENCE AND CARDIOVASCULAR DISEASE - FRIEND OR FOE?

BY TIM LEINER, JELMER M. WOLTERINK AND IVANA IŠGUM

Every medical conference these days has sessions and keynote lectures on 'artificial intelligence' (AI), 'machine learning' and/or 'deep learning'. The tremendous impact of these technologies in many domains of life from searching the internet to language translation and discovery of the Higgs boson is undeniable and it is certain that they will also change the medical profession substantially.

Disciplines such as radiology and pathology are especially well-suited for the application of AI because these specialists now almost exclusively work with digital images which lend themselves very well to

computerised analysis. In this chapter, we will try to outline some basic concepts and what we think will be the impact of these developments in cardiovascular radiology.

## WHAT IS AI? - SOME BASIC CONCEPTS

Artificial intelligence can be defined as computer systems that can perform tasks that normally require human intelligence. Machine learning (ML) refers to a branch of AI in which computers are trained to make a decision based on data without being programmed with explicit rules. In other words, it is not necessary to define all the relevant features associated with a certain condition or disease in the computer programme, the computer learns these from examples. In order to better understand the way ML works it is important to briefly review the key differences in the way ML algorithms are trained.

ML algorithms can be trained in a number of ways, depending on the availability of labelled data. *Supervised learning* refers to training an algorithm based on a large number of examples with labels, for instance the presence or absence of coronary stenosis in a coronary computed tomography (CT) dataset. Based on the training dataset a model or classifier is built that can process new, unseen coronary CT data and generate an output that states whether or not a stenosis is present. Conversely, *unsupervised learning* does not rely on labelled data but seeks to find patterns in the data. Based on these observed patterns, groups or clusters can

be identified that are similar and separable from other groups. Subsequently, a model can be built that can assign group or cluster membership to new, unseen data. There is a range of learning paradigms between supervised and unsupervised learning. In some cases, labels may be available on for instance the patient level but not on a vessel level. Finding a vessel with stenosis categorises then as *weakly supervised learning*. In other cases, labels may be available for a subset of training data that may not be sufficient for accurate classification. This is also known as *semi-supervised learning*.

Modern ML techniques differ in the way that information is extracted from the input. Radiomics is a process typically referring to supervised ML learning that consists of extracting a large number of quantitative features from radiology images and subsequent classification using an ML classifier to determine diagnosis or perform prediction. An important issue with radiomics is that many of the extracted features may be redundant or suboptimal for the task at hand. In contrast, *deep learning* (DL) techniques extract descriptive features from data at increasing levels of abstraction and immediately use these for the given classification task. The most popular DL techniques are based on artificial convolutional neural networks (CNNs) with multiple (also known as 'hidden') layers between the input and output layers (Figure 1). Over the past years, it has become clear that DL is very well suited for many relevant tasks in radiology such as detecting abnormalities in images, delineating anatomical structures or classifying findings.

## AI AND CARDIOVASCULAR IMAGING

AI has many potential uses in cardiovascular imaging. Although detection of abnormalities and image interpretation are the first applications that may come to mind, the impact will be much broader. Virtually all steps of the radiological workflow, from decision support with regard to the indication to perform an imaging test to predicting prognosis from the resulting images, can be improved by using ML. Below we briefly review how ML is and potentially can be used in clinical practice.

### Decision support

Cardiovascular medicine is increasingly guideline driven. Many professional societies have issued guidelines with the aim of providing standardised and evidence-based care to patients with suspected or known

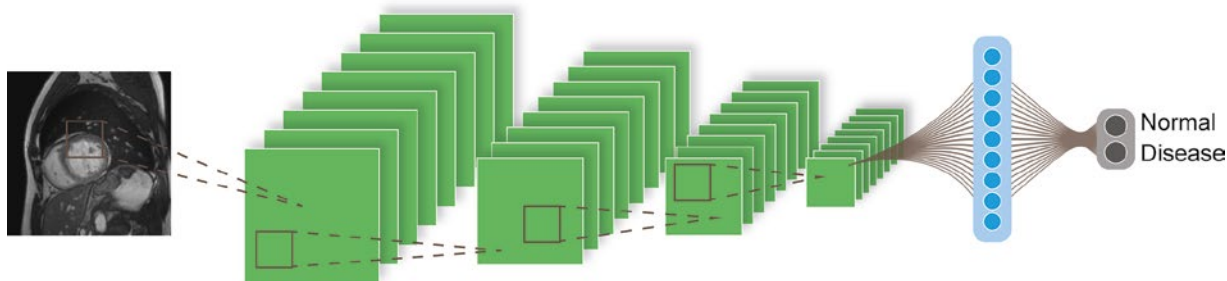
cardiovascular disease. Using this information in clinical practice can be a daunting task. The European Society of Cardiology currently lists 49 categories of guidelines for example. It is self-evident that no single person can master the intricacies of all these guidelines on a day to day basis. It is expected that ML-based decision support systems can help the clinician and radiologist select the best imaging tests in individual patients.

### Image acquisition

Hardware vendors are now selling the first AI-based commercial products that help the technologist select the optimal imaging protocol in individual patients, including the selection of the precise location and extent of image acquisition. Automated identification of the heart and prescription of scan planes is now possible. This may be

Figure 1

Neural networks consist of input layers to which input signals are clamped, and hidden and output layers containing processing elements that transform input from the previous layer using non-linear activation functions. This way, the input is transformed into the desired output, such as a classification label.



especially advantageous for less-experienced radiographers, for follow-up imaging as well as complex cases.

### Image reconstruction and improvement of image quality

Machine learning has great promise in CT and MR image reconstruction. Deep learning with CNNs has been successfully applied for very fast reconstruction of highly accelerated cardiac MR acquisitions as an alternative to much slower current state of the art methods such as compressed sensing. Conversely, DL has been applied in CT image reconstruction as well. Several research groups have shown that high-quality CT images of the heart can be reconstructed from low-dose acquisitions

with an up to 80% lower radiation dose (Figure 2).

### Post-processing and image analysis

One of the most obvious applications of ML and DL in cardiovascular imaging is image post-processing and analysis. One of the most important and also labour-intensive tasks in cardiac MR is contouring of the left and right ventricles at end-systole and end-diastole in order to obtain cardiac ejection fractions and myocardial mass (Figure 3). Many research groups have now shown that this process can be fully-automated with highly reliable results using ML algorithms and several commercial software packages have already incorporated this technology. Another application in cardiovascular

Figure 2

Deep learning methods can be used to transform a CT image acquired at an extremely low dose (20% of routine dose) into a high-quality image resembling an image of the same patient acquired at a routine dose.

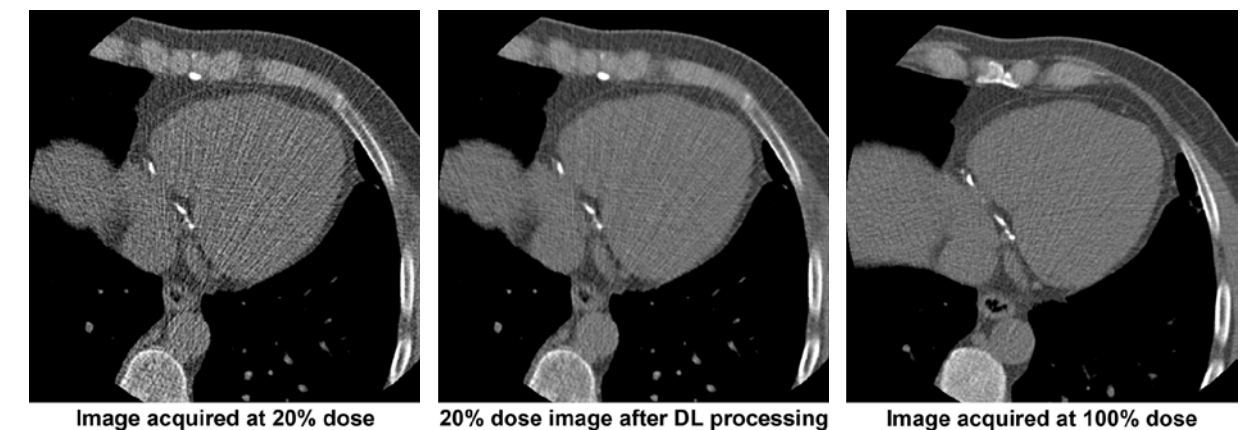
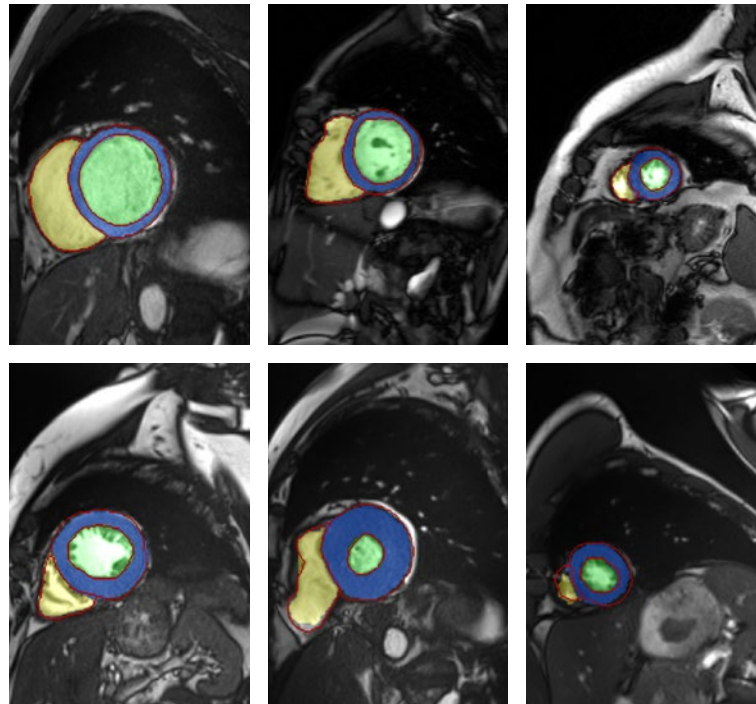


Figure 3

Results of fully automatic segmentation of the left ventricular cavity (green), left ventricular myocardium (blue) and right ventricular cavity (yellow) in cardiac cine MR. Manual reference annotations are shown in red.



imaging that comes to mind is automated determination of aortic volumes to determine the degree of expansion due to pumping action of the heart or to assess volume and rate of growth of an abnormally enlarged or aneurysmal aorta.

### Interpretation and diagnosis

Researchers are now attempting to generate complete radiology reports from images only. DL algorithms are being trained to do this by showing them large datasets of hundreds of thousands to millions of combinations of imaging and the corresponding radiology reports. Although this has not been attempted specifically in cardiovascular radiology, it is expected that this will happen in the future. However, in many patients, information obtained with

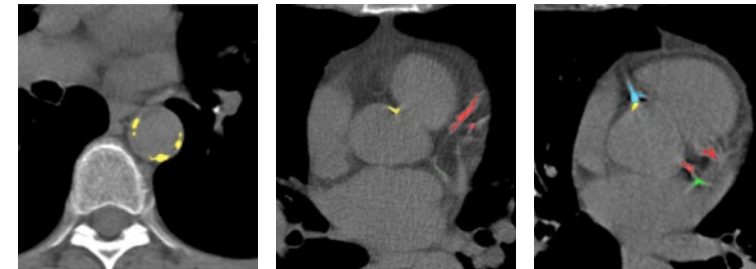
cardiac imaging tests is just one part of the total clinical picture.

### Opportunistic screening and prognosis

One of the most promising applications of AI and ML in cardiovascular imaging is fully automated detection, quantification and reporting of relevant prognostic information. This may be more detailed information relevant to the clinical problem for which imaging was requested, but also information visible in the images outside of the organ of interest. For instance, more detailed analysis of cardiac motion patterns in patients with pulmonary hypertension has been shown to have a better predictive value for adverse outcomes compared to right ventricular ejection

Figure 4

Fully automatically identified calcifications in the thoracic aorta and coronary arteries in chest CT.



YELLOW: Thoracic aorta, RED: Left anterior descending artery, GREEN: Left circumflex artery, BLUE: Right coronary artery

fraction, which is currently used for this purpose. Another example is fully automated identification of vascular calcifications in lung cancer screening CT scans (Figure 4).

### Combining imaging with other data sources

A final area where AI can be of high value in the future is by combining the results from imaging examinations with other data such as information in electronic health records, laboratory data, genetic analyses and medication use. Combining these data will for instance yield new insights into which combinations of clinical variables are associated with certain imaging findings or effectiveness and side effects of new cardiovascular drugs.

### AI – FRIEND OR FOE?

The way radiology is being practised will fundamentally change over the next years as ML and DL algorithms make their way

into clinical practice. There is no doubt that some tasks that are now performed by radiologists or radiographers will be performed by computers in the near future. We strongly believe, however, that AI offers an opportunity to make radiologists more accurate, more productive and to deliver better care precisely tailored to individual patients. AI will quickly become one of our best friends.

### References

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Professor Leiner has served as faculty member and member of the organising committees at the annual meetings of the European Society for Magnetic Resonance in Medicine and Biology (ESMRMB), International Society for Magnetic Resonance in Medicine (ISMRM), Society for Cardiovascular Magnetic Resonance (SCMR), European Society of Radiology (ESR), Radiological Society of North America (RSNA), and at annual meetings of the Dutch Radiological Society. He chaired the Scientific Programme Committee of the ESMRMB in 2017.

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She has been a member of the programme committees of the major image analysis conferences, programme co-chair of the 1<sup>st</sup> International Conference on Medical Imaging with Deep Learning and co-organiser of several image analysis challenges and workshops. She has co-authored more than 70 peer-reviewed journal publications and more than 35 conference papers.



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**SUDDEN  
CARDIAC  
DEATH**

# PREDICTING THE FUTURE: SCREENING FOR SUDDEN DEATH

BY **LUIGI NATALE** AND **VERONICA BORDONARO**

## DEFINITION AND EPIDEMIOLOGY

Sudden cardiac death (SCD) / sudden cardiac arrest (SCA) refers to an unexpected death or arrest from a cardiovascular cause that occurs rapidly outside of the hospital or the emergency room.

More precisely, according to the 2015 ESC guidelines, “the term SCD is used when: (1) a congenital, or acquired, potentially fatal cardiac condition was known to be present during life, (2) autopsy has identified a cardiac or vascular anomaly as the probable cause of the event, (3) no obvious extra-cardiac causes have been identified by post-mortem examination and therefore an arrhythmic event is a likely cause of death”.

SCD represents a devastating public health problem that is responsible for 15%–20% of all deaths and, although resuscitation rates are generally improving, the majority of individuals who experience a sudden cardiac arrest will not survive.

The majority of SCDs occurs in the adult population, with the absolute rate increasing with age, while 1% occurs in people who are under 35 years old. There are also recognised differences in SCD incidences in certain population groups: the risk of SCD is higher in men than in women and it is also increased among people of colour.

Cardiac diseases associated with SCD differ between young and older individuals: in young subjects, and particularly in athletes, there is a

prevalence of cardiomyopathies and channelopathies, myocarditis and substance abuse, while in older populations, chronic degenerative diseases like coronary artery disease (CAD), valvular heart diseases and heart failure (HF) predominate.

Attempts to predict SCD and to provide reliable markers of SCD represent one of the most active areas of investigation in cardiology during recent years.

The complex pathophysiology of SCD is based on the presence of a specific abnormal, structural or electrophysiological substrate that interacts with a functional trigger, resulting in acute haemodynamic collapse, which can differ widely based on the underlying cause.

SCD primary prevention involves the implantation of ICDs (implantable cardioverter defibrillators); however, the difficulties in understanding the direct pathophysiologic markers of arrhythmic substrate of SCD make precise and individualised preventive therapies an enormous challenge.

Current practice guidelines for selecting candidates for ICD therapy rely on left ventricular (LV) ejection fraction (EF) <35% as the criterion to determine candidacy. EF, however, is an inadequate surrogate of the underlying myocardial substrate predisposing to SCD and thus is neither sensitive nor specific. Moreover, in the vast majority of patients who receive ICD, the device may never be utilised for the treatment of spontaneous ventricular arrhythmias. Moreover, an inappropriate ICD implantation could result in a very low quality of life.

Therefore, new diagnostic tools for better risk stratification are necessary, and they should aim to reveal the direct markers of arrhythmogenic substrates, by recognising structural heart disease (SHD).

## IMAGING TECHNIQUES

In clinical settings, echocardiography is the first imaging modality of choice as it is inexpensive and non-invasive. It is also easily accessible and it is routinely used in the assessment of patients with suspected SHD, allowing for the evaluation of regional and global ventricular function, myocardial wall thickness and thickening and chambers diameters.

However, in patients with a structurally normal heart and potentially increased SCD risk, CMR and CT are advisable as they can significantly improve diagnostic accuracy. For example, in SHD such as arrhythmogenic right ventricular dysplasia (ARVD) or anomalous origin of coronary arteries, CMR or CT can be of particular value.

Cardiac magnetic resonance (CMR) represents a non-invasive technique to characterise myocardial tissue and provide important details about myocardial structure and composition, abnormalities of which define the direct pathophysiologic substrate for SCD.

The presence and extent of myocardial tissue heterogeneity with regions of scar and interstitial fibrosis provide



a substrate for ventricular arrhythmias, both in ischaemic and non-ischaemic cardiomyopathies.

Furthermore, the extent and architecture of fibrosis, even in the absence of contractile dysfunction, leads to electrophysiological derangements that increase the risk of scar-related re-entry ventricular arrhythmias and of SCD.

CMR allows the visualisation of myocardial scars with the late gadolinium enhancement (LGE) technique, with proven histopathological correlation. Furthermore, the geographic distribution of LGE helps distinguish among different types of cardiomyopathies.

Because of its high spatial resolution, CMR can differentiate different scar patterns and detects areas with interstitial fibrosis or oedema with T1- and T2-mapping techniques.

## SCD AND CORONARY ARTERY DISEASE (CAD)

### Atherosclerotic CAD

About 75–80% of SCD in patients over 40 years of age is caused by atherosclerotic CAD; SCD in these individuals is often the consequence of cardiac arrhythmia, induced by an abrupt condition of thrombosis and acute myocardial event, caused by coronary artery plaque rupture, fissuring or haemorrhage.

The risk of SCD is increased in the presence of lipid-rich vulnerable plaques with positive remodelling, multivessel involvement or in the case of abrupt proximal obstruction rather than progressive diffuse stenosis with collateral vessels formation.

In this setting, coronary CT angiography (CCTA) does not only provide information about the anatomy of the coronary

arteries but it also represents a non-invasive technique which allows for the quantification of stenosis and which provides information about characteristics of plaques and their vulnerability (Figure 1).

CMR in ischaemic cardiomyopathy (ICM) can accurately quantify left ventricular EF and mass, which are strong predictors of ventricular arrhythmias. Also, the presence and extent of LGE correlates with outcomes. The myocardial scar extent, assessed by CMR-LGE, correlates closely with pathological quantification of irreversible myocardial injury at all stages of infarct evolution beyond the acute event period (Figures 2 and 3).

The infarcted myocardium can be divided into 1) core infarct zone; 2) grey or peri-infarct zone; and 3) total infarct core peri-infarct zones. Recent evidence suggests that the heterogeneity in scar tissue can create electrical dispersion and areas of slow conduction that are a substrate for electrical re-entry and malignant arrhythmia (Figure 4).

This leads to an increasing use of CMR not only for risk stratification but also to guide ICD implantation or ablation therapy.

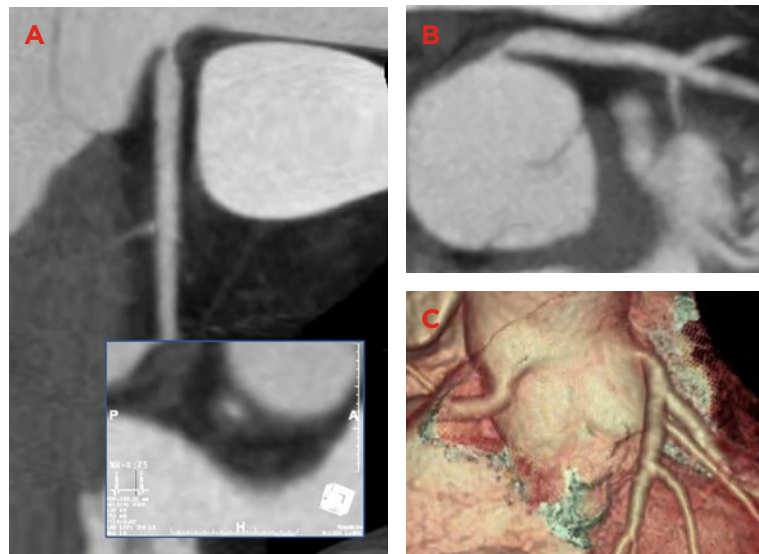
### Non-atherosclerotic CAD

Many non-atherosclerotic CADs, including anomalous origin of coronary arteries, acute dissection, myocardial bridging, vasculitis and coronary artery spasm, can be the pathophysiologic substrate for SCD, especially in young people and particularly in athletes.

More specifically, coronary artery anomalies can be divided into haemodynamically significant anomalies, which may be associated with shunting, ischaemia, or sudden cardiac death, and anomalies that are usually not haemodynamically significant.

Haemodynamically significant anomalies include:

- Coronary artery atresia, which is a rare condition with only a handful of cases recorded in the literature (Figure 5)
- Anomalous origin from the pulmonary artery, also known as ALCAPA/ARCAPA (anomalous origin of the left/right coronary artery from the pulmonary artery), in which the development of a collateral circulation from the right pulmonary artery to the anomalous left coronary circulation and the decrease of pulmonary vascular resistance result in the steal of blood flow from the myocardium to the pulmonary trunk (Figure 6)
- Interarterial course, in which a coronary artery arises off a contralateral sinus of Valsalva, with a course between the aortic root and pulmonary artery. This is the coronary anomaly more commonly associated with SCD, leading to it being described as ‘malignant’ (Figure 7). Several reasons have been suggested for the association between this coronary anomaly and SCD, but the most important include the associated presence of a slit-like orifice or otherwise stenotic ostium, an acute angle between the anomalous coronary artery and the aorta and an intramural aortic segment



**Figure 1**

Case of a 51-year-old male with effort-induced chest pain. Coronary CT angiography shows a significant stenosis of the left main trunk due to a non-calcified eccentric plaque with positive remodelling (vulnerable plaque). An angled appearance of the vessel at the level of its origin from the cusp is also evident.

Figure 2

Case of a 72-year-old patient with acute myocardial infarct (AMI). CMR images of (A) short axis T2 short tau inversion recovery (STIR), (B) resting first-pass perfusion sequence, (C) short axis LGE image, all acquired at the mid-left ventricular level, and (D) three-chamber LGE sequence, show a large area of oedema with microvascular obstruction and transmural necrosis in the septum and the anterolateral LV wall.

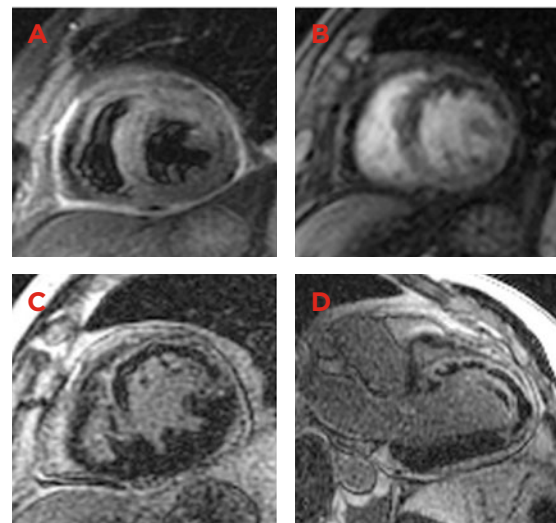


Figure 3

CMR-LGE views in a 69-year-old patient with CAD show a large transmural ischaemic scar in the territory of the left anterior descending coronary artery.



Figure 4

Case of a 67-year-old female with AMI; the so-called 'doughnut' pattern is visible both in the LGE short axis image and STIR short axis image, representing a core of microvascular obstruction and haemorrhage within the transmural infarcted area.

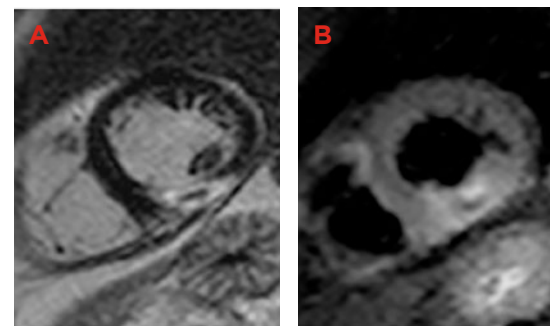
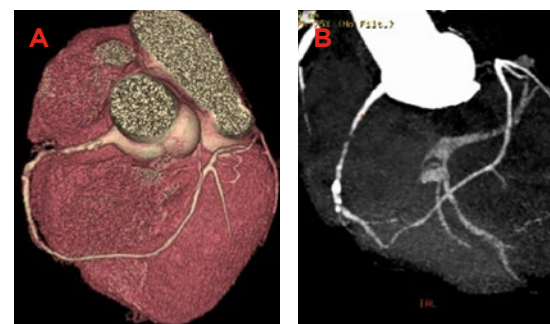


Figure 5

Volume rendered (A) and maximum intensity projection (B) images of a CCTA show the atresia of a left main coronary artery in adult patients with a positive stress test. The left anterior descending (LAD) coronary artery and left circumflex (LCX) coronary artery are diminutive relative to the right coronary artery (RCA), with right to left collateral (acute marginal branch).

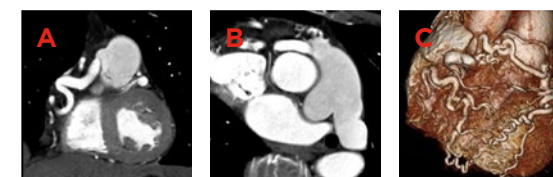


- Congenital fistula, an uncommon anomaly characterised by an abnormal communication between the coronary artery and a cardiac chamber or a great vessel, resulting in arterial blood bypassing the normal myocardial capillary network

Coronary CT angiography has emerged as the standard of reference for the evaluation of coronary artery anomalies and several studies have confirmed its superiority to conventional angiography in this field, allowing non-invasive depiction of the coronary arteries anatomy, as well as their course and relationships with other mediastinal vascular structures. It may lead to a potential use of this imaging technique in the context of

Figure 6

ARCAPA syndrome in a 67-year-old female. Coronal (A) and oblique axial (B) CT images show a right coronary artery which abnormally arises from the anterolateral wall of the pulmonary artery; several coronary-coronary collateral arteries are also present. A volume-rendered image (C) shows an entire coronary arterial system markedly enlarged and tortuous, as a result of increased flow.



screening for sudden cardiac death, especially in young individuals.

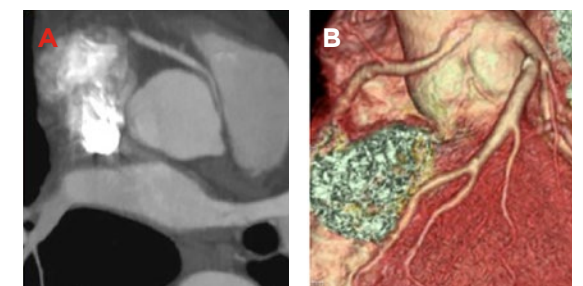
There is also a growing role for cardiac magnetic resonance (MR) imaging in the demonstration of the coronary arteries; however, coronary MR imaging is not yet widely used in clinical settings.

## SCD AND NON-ISCHAEMIC CARDIOMYOPATHIES

Non-ischaemic cardiomyopathies (NICM) are myocardial disorders defined by structural and functional abnormalities of the

Figure 7

Interarterial coronary artery in a 48-year-old man with atypical chest pain. Axial maximum intensity projection CT image (A) and volume-rendered image (B) show an interarterial RCA artery coursing between the aorta and pulmonary artery. An apparent narrowing is present at the origin of the RCA, which has a separate ostium off the left coronary cusp. The RCA has a slit-like orifice, which may be seen in interarterial coronary arteries and has been associated with a higher risk of SCD.



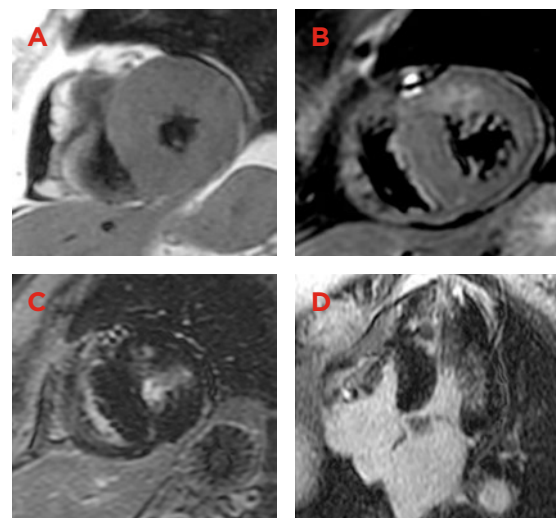
ventricular myocardium that are not solely explained by flow-limiting coronary artery stenosis or abnormal loading condition.

Nearly all NICM can be associated with an increased risk of SCD that varies with the aetiology and the severity of the disease and they have been consistently implicated as the primary cause of sport-related cardiac arrest in young competitive athletes.

Hypertrophic cardiomyopathy (HCM) is an inherited autosomal dominant condition

**Figure 8**

CMR in a symptomatic patient with HCM. Short axis T1 weighted image (A) shows a concentrically hypertrophied LV myocardial wall with tissue oedema in the mid-myocardial anterior LV wall on T2 short tau inversion recovery (STIR) short axis image (B); short axis (C) and 4 chamber (D) LGE images show focal fibrosis in the same segment as well as in the anteroseptal wall.

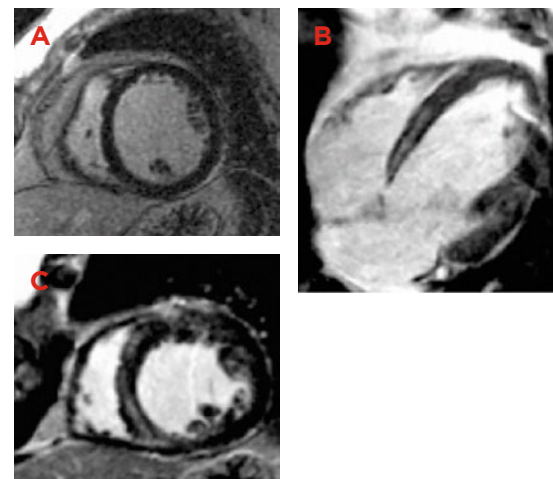


characterised by an unexplained diffuse or segmental increased LV wall thickness (>12–15mm), with an absence of any detectable cardiac or systemic cause of abnormal LV loading conditions.

This entity represents one of the most common causes of SCD in young adults and the pathophysiological mechanism in these cases may include a malignant arrhythmia, syncope from the abrupt haemodynamic deterioration of the LV outflow tract gradient, and ischaemia.

**Figure 9**

CMR images of DCM. The left ventricle is significantly dilated in these three patients, with globally reduced systolic function. Delayed contrast-enhancement sequences are able to characterise the myocardium and differentiate DCM from LV dysfunction related to other causes. The three different LGE patterns include non-enhancement (A), patchy enhancement (B) and longitudinal striae of mid-wall enhancement in non-coronary territories (C).



Histologically, HCM is characterised by abnormalities in small arteries, myocardial fibres disarray and interstitial fibrosis; increased LV wall thickness is accompanied by an increased percentage of fibrosis and a subsequent decrease in LV function.

The amount of LV myocardial fibrosis assessed by pathology and in vivo by CMR is an important outcome predictor in HCM because it is closely related to the primary arrhythmogenic substrate of SCD. LGE pattern in HCM is heterogeneously distributed but most commonly occurs in regions of hypertrophy and tends not to follow a coronary artery territory (Figure 8). Furthermore, pre- and/or post-contrast T1 values (myocardial T1 mapping) can allow a quantitative assessment of the amount of fibrosis and can be useful for risk stratification.

Recent studies showed that the extent of LGE was independently associated with increased risk for SCD even after controlling for traditional risk factors (family history, syncope, multiple repetitive episodes of non-sustained ventricular tachycardia, blood pressure drop during exercise, massive hypertrophy): it has a clinical importance when making a decision about implanting an ICD in patients who would be falsely labelled as lower risk on the basis of clinical features alone. By contrast, the absence of LGE in clinical intermediate risk patients was associated with a low likelihood of adverse events and the decision to implant an ICD might be deferred in this group.

Cardiac CT can be used in these patients as a screening for detecting LV crypts, which seem to be an early finding in preclinical HCM.

Dilated cardiomyopathy (DCM) is defined as LV dilation and systolic dysfunction in the absence of abnormal loading conditions or CAD sufficient to cause global systolic impairment.

Histologically, it is characterised by the loss of myocytes and their replacement by interstitial fibrosis.

The first manifestation of DCM can be the SCD, probably with the onset of non-sustained ventricular tachyarrhythmia caused by bundle-branch re-entry.

For these reasons, a routine diagnostic workup with CMR in suspected DCM is needed. In particular, cine imaging can give an assessment of biventricular volumes, wall thinning and LV function while LGE can reveal myocardial fibrosis, often located in the middle layer of the myocardium with a patchy or longitudinal pattern. This finding can help in the differentiation from a CAD-related dilation, in which LGE is typically subendocardial or transmural (Figure 9).

Similar to HCM, myocardial mapping is proving a promising tool in the quantification of diffuse myocardial fibrosis that is often missed by LGE.

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is a progressive heart muscle disorder characterised by the replacement of cardiomyocytes by adipose and fibrous tissue. Clinically, ARVC is defined by structural and functional abnormalities of the right ventricle (RV), but LV involvement occurs in over half of patients. In most cases, ARVC is inherited as an autosomal dominant genetic

trait caused by mutations in genes encoding for desmosomal proteins.

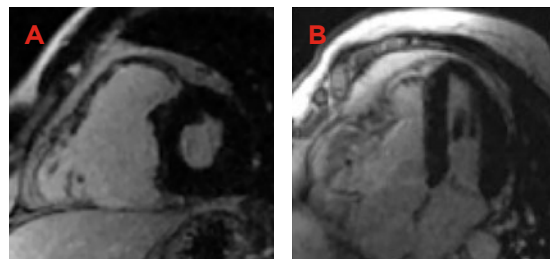
Generally, patients with ARVC are asymptomatic and unexplained syncope or SCD can be the first clinical manifestation.

The diagnosis of ARVC is based on the combination of multiple parameters, including (1) global or regional dysfunction and structural alteration of the RV demonstrated on imaging; (2) tissue characterisation by endomyocardial biopsy (EMB); (3) repolarisation and (4) depolarisation electrocardiographic (ECG) abnormalities; (5) arrhythmias; (6) familial history of SCD or SCA.

CMR plays an important role in the diagnosis of ARVC and it has been included in the 2010 Revised Task Force Criteria, for the

**Figure 10**

A 26-year-old male with a history of dyspnoea, exercise intolerance and left bundle branch block at ECG. No abnormal enhancement is present. Short axis (A) and 4 chamber (B) CMR-LGE images show a huge right ventricular dilation with multiple aneurysms in the free wall and diffuse contrast enhancement.



qualitative assessment of abnormalities on cine images (RV regional akinesia, dyskinesia, dyssynchrony), combined with specific quantitative cut-off values of RV dilatation/dysfunction.

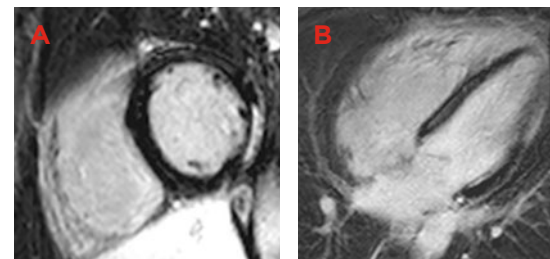
Furthermore, the presence of LGE is a marker of inducible ventricular tachyarrhythmia in 75% of patients, whereas its absence is associated with a lower incidence of inducible arrhythmia (Figure 10).

## SCD AND MYOCARDITIS

Acute myocarditis may account for a large proportion of SCD in young people. Myocarditis is an acute or chronic

**Figure 11**

Case of a 45-year-old female with acute myocarditis who presented with acute chest pain and mildly increased troponin-I. Short axis (A) and 4-chamber (B) CMR-LGE images show a sub-epicardial enhancement at the infero-lateral wall with endocardial sparing.



inflammatory disease of the myocardium triggered by an infectious agent (enteroviruses such as Coxsackie B, adenoviruses, parvovirus B19 and human herpesvirus type 6) but also by many other causes, for example opportunistic infections, autoimmune response or drug-related cardiac toxicity. In the initial phase of viral infection, active viral replication leads to direct injury and lysis accompanied by innate immune activation. In some patients, disease activity persists and triggers an adaptive autoimmune response with profound myocardial inflammation, causing HF and arrhythmias. Acutely, active myocardial inflammation is arrhythmogenic, caused by triggered activity and abnormal automaticity, leading to a refractory malignant ventricular tachyarrhythmia in the context of severe acute HF.

In chronic myocarditis, myocardial replacement fibrosis promotes re-entrant arrhythmic mechanisms, resulting in a high risk of SCD similar to that for DCM.

In patients with suspected myocarditis, CMR can visualise necrosis or scar on LGE (frequently located in sub-epicardial or intramural regions, with a non-ischaemic distribution pattern) and tissue oedema in the acute phase with T2-STIR or the T2-mapping technique (Figure 11). Furthermore, CMR allows a reliable quantification of LV dysfunction in order to appropriately choose the treatment strategy (anti-arrhythmic drugs, pacemaker or ICD implantation, radiofrequency catheter ablation etc.), improving the SCD risk stratification.

## CONCLUSION

The role of imaging, namely non-invasive imaging, is pivotal in SCD/SCA prevention; in young subjects, particularly professional and non-professional athletes, pre-participation screening is mandatory (as for example in Italy) and, if needed, imaging should be widely used for prevention. In subjects who are over 35 years old, the information that can be obtained by echo, CT, MR and nuclear techniques have already gained a clinical role, both for diagnosis and for prognosis; consequently, imaging can be used as an effective gate-keeper for personalised treatment approaches and appropriate ICD implantation.

### References

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IMAGING  
AFTER ACUTE  
CORONARY  
SYNDROME

# WHEN THE ACTION IS OVER: IMAGING AFTER ACUTE CORONARY SYNDROME

BY CHRISTIAN LOEWE

While cardiovascular imaging by means of cardiac CT and cardiac MR plays almost no role in the diagnosis of acute coronary syndromes (ACS), the importance of cardiac MR in the management of patients after treatment of an ACS is continuously increasing.

The probability of early complications, of delayed or missing recovery and risk of secondary events could be estimated and predicted by cardiac MR derived biomarkers, underlining the outstanding potential of cardiac MR in the management of this rather vulnerable patient population. With further evidence, the guidelines for patient management after treatment of an ACS could be changed to include cardiac MR in the near future.

## IMAGING IN ACUTE CORONARY SYNDROME

The basic aim in the treatment of acute myocardial infarction is the revascularisation of the culprit artery to restore the myocardial blood flow. Strong evidence exists that early revascularisation is an important factor for a good clinical outcome and for prevention of ischaemic heart failure. Thus, after the – usually preclinically established – diagnosis of ACS, patients are directly sent to the cath lab for revascularisation, and no additional imaging tests are carried out so as not to lose any time.

However, in up to 30% of patients with myocardial infarction, functional myocardial recovery is not reached despite good primary technical success at acute percutaneous coronary intervention (PCI). Possible reasons for this unfavourable result of acute revascularisation are manifold: the time between coronary artery occlusion and technical successful revascularisation could have been too long, which could lead to early myocardial necrosis in combination with lack of collateral vessels. Another possible reason could be the persistent occlusion of microvasculature regardless the restored perfusion within the main epicardial vessels. The reperfusion can also lead to additional myocardial damage, and in 30%

of the patients the revascularisation is not complete. Furthermore, in case of multivessel disease and multiple coronary lesions, the usual attempt at the revascularisation of only the culprit artery might have been insufficient for full recovery of myocardial function.

The lack of functional recovery after successful revascularisation is known to be a predicting factor for dismal outcomes like heart failure and for a high probability of recurring major cardiovascular events, especially of re-infarctions. Therefore, the early identification of patients with limited or lack of functional recovery is important to improve the clinical situation, and to prevent complications and further cardiovascular events.

## WHEN THE ACTION IS OVER – IMAGING AFTER ACUTE CORONARY SYNDROME

Several studies have been published during the last decade demonstrating the outstanding potential of cardiac MR derived biomarkers in the risk stratification and management of patients after technically successful treatment of ACS. The aim of using cardiac MR in this patient population is to assess the

Figure 1

LGE thickness: 57-year-old man. MR performed on day 4 after STEMI (acute occlusion of LAD). LGE imaging obtained 15 min after administration of 0.2 mmol/kg body weight Gadovist® shows non-transmural subendocardial. Functional recovery of this area is very likely.

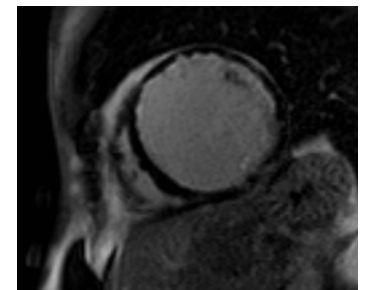
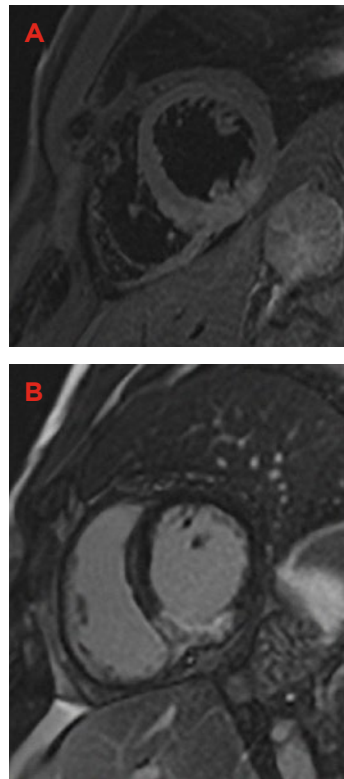


Figure 2

LGE transmural and MSI:  
54-year-old man. MR performed on day 5 after STEMI (acute occlusion of RCA). (A) T2-STIR shows extensive myocardial oedema in the posterior wall. (B) LGE imaging obtained 15 min after administration of 0.2 mmol/kg body weight Gadovist\* shows transmural LGE indicating transmural scar at the posterior wall. However, the area of scar is smaller as compared to the oedema.



treatment success, to predict the outcome, to indicate the early need for further treatment and to assess treatment or event related complications.

### The calculation of the myocardial salvage index

Cardiac MR is able to directly visualise the myocardial necrosis. The extent of late gadolinium enhancement (LGE) in the ischaemic myocardial territory represents an important predictor of the functional recovery of the ischaemic myocardium. Although it has been shown recently that MR-LGE overestimates the 'real' necrosis in the acute setting within few days after the ACS and revascularisation due to additional inflammatory processes and haemorrhage, LGE is one of the most powerful biomarkers for the assessment of treatment success and prediction of functional recovery.

However, in patients with recurrent events, the differentiation between acute and pre-existing necrotic changes can be challenging. Despite this, it is of major importance for outcome prediction. For this differentiation, oedema imaging has to be added to the LGE. Traditionally, oedema imaging was performed using T2-STIR sequences, but it has been shown that T2-STIR is vulnerable to artefacts and inhomogeneities in the signal intensity. Therefore, T2 mapping was introduced as a powerful alternative and is currently under investigation for this application. Additionally, diffusion-weighted techniques are under evaluation as well for accurate diagnosis of myocardial oedema.

To sensitively assess the treatment success of an acute revascularisation for ACS, the myocardial salvage index (MSI) was introduced

and established. It is an index calculated by the relation between the myocardial tissue at risk (as assessed by using T2 STIR) and the 'really' necrotic tissue (as identified by means of LGE). The higher the MSI, the more myocardial tissue was 'saved' by the early revascularisation, and the better the prognosis will be with regard to re-infarctions and functional recovery. However, despite rather good evidence about the correlation between MSI and outcome, the technique itself is still under major discussion: first, the extent of oedema after revascularisation is dependent on time; it makes a difference if the post-ACS MR scan is performed on day 2 or on day 6. Second, cooling of the patients, as used for brain ischaemia for years, is applied at least in several studies to ACS patients as well, and reduction of body temperature will reduce the oedema (and possibly the tissue at risk) leading to a virtual decrease of the MSI. Third, as mentioned previously, the technique of oedema quantification is not finally optimised and established and is still a matter of investigation.

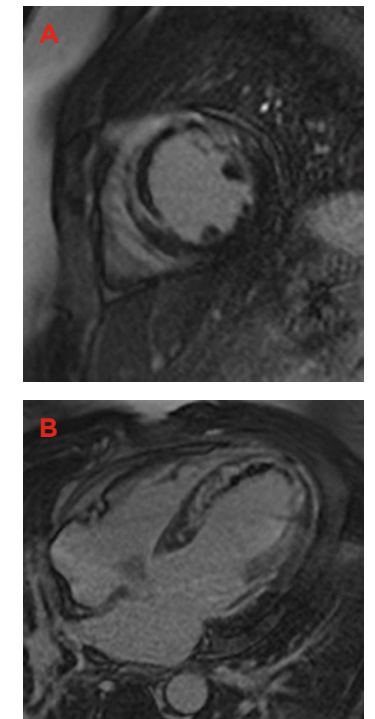
Regardless all these known limitations and pending questions about optimal imaging technique, the MSI is a very accurate and clinically useful test to prove the success of the revascularisation and to foresee dismal clinical outcome providing the possibility for early adaption of the individual patient's treatment plan.

### LGE transmural

Whereas the MSI is a main indicator for the success of the revascularisation procedure itself, the LGE transmural is an indicator for the severity of the ACS and the extent of the myocardial death. A transmural LGE, as well as an LGE involving four connected myocardial

Figure 3

LGE and MVO: 47-year-old man.  
MR performed on day 4 after STEMI (acute occlusion of LAD). (A, B) LGE imaging obtained 15 min after administration of 0.2 mmol/kg body weight Gadovist\* (short axis). There is extensive LGE in the anterior septum as well as the anterior wall. However, there is a huge 'black' area within the LGE indicating extensive MVO.





segments, represent a clear predictor for lack of future functional recovery. Consequently, these patients are at high risk for a reverse remodelling of the left ventricle and the generation of a left ventricular aneurysm. These patients are in need of very special follow up care to quickly adapt their medication (including anti thrombotic medication!) to the unfavourable myocardial situation and to give early indication regarding cardiac surgery if required. Additionally, the proof of lacking transmural by means of MR LGE can be the basis for decision making of further revascularisation.

### Visualisation of microvascular obstructions

After a successful revascularisation of the culprit artery by means of acute PCI, so-called microvascular obstruction (MVO) might occur in the region of the re-perfused myocardium due to microemboli of plaque material during PCI. Although the exact pathogenesis of MVO is not fully understood yet and although it is not clear if it is really caused by the reperfusion or by microemboli during the initial rupture of the culprit plaque, it is well known that the presence of MVO is a predictor for unfavourable outcomes. Patients with MVO have a higher likelihood of early complications, show a higher incidence of reverse LV remodelling and even a higher mortality. Cardiac MR allows the direct visualisation of areas with MVO, which can easily be identified as non-enhanced areas within the ischaemic LGE. There is an excellent correlation between the presence of MVO and TIMI flow graduation at invasive angiography. The presence and extent of MVO is not only dependent upon the initial situation (duration of occlusion and size of infarction) but also from the timing of the imaging after

the procedure and will continuously decrease during the first weeks. To accurately assess the MVO and to use it accordingly to predict risk of complications and outcome, the MR study should be performed between day 2 and day 7, underlining again the value of an early cardiac MR after acute PCI for ACS.

### Evaluation of complications

The early MR after acute PCI for ACS should also be used to identify possible treatment-related complications early. These possible complications include papillary necrosis, mitral regurgitation, aneurysms and pseudo-aneurysms. All of these complications have the potential to deteriorate the clinical situation of the patients and to negatively affect the clinical outcome. Early identification allows for early secondary intervention, intensified follow up and/or medical intervention.

## CONCLUSION

Whereas MR imaging does not play any role prior to acute PCI in ACS, a lot of substantial information about treatment success, the presence of complications and expected outcome and recurrent events can be gained by means of cardiac MR after the treatment of ACS. LGE transmural, the myocardial salvage index and detection of microvascular obstruction are the most powerful MR derived biomarkers. Based on the already existing evidence, cardiac MR should become a standard procedure after technically successful PCI for ACS.

### References

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### PROF. CHRISTIAN LOEWE

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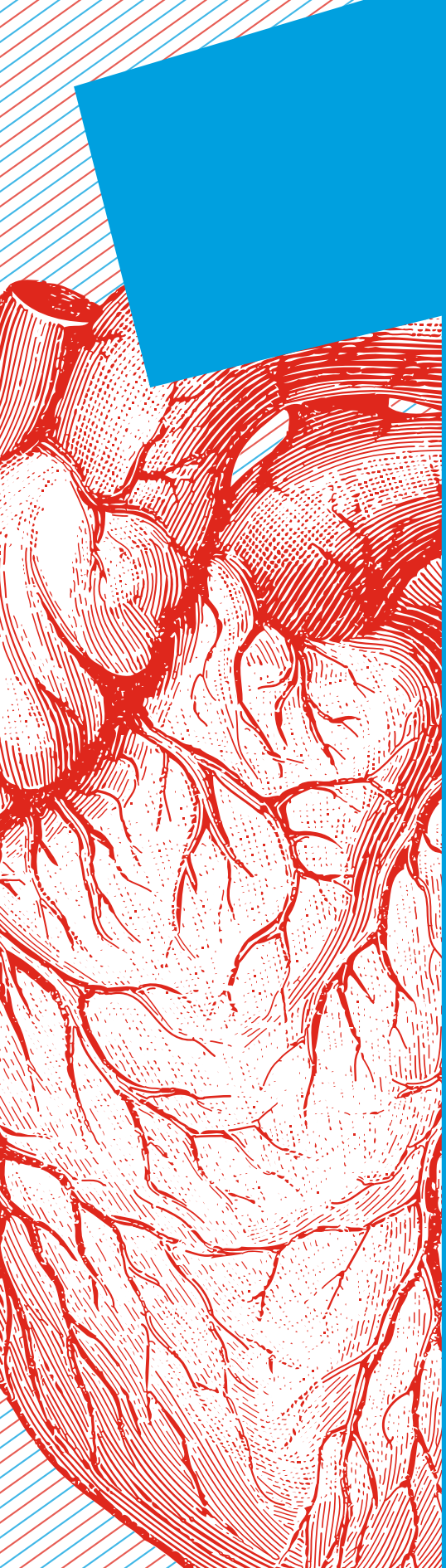
Image-Guided Therapy at the Medical University of Vienna, Austria.

He is highly interested and active in radiological education, exemplified by a couple of functions and activities: He is actively involved within the Austrian Roentgen Society and has been responsible for the Austrian Board examination for years. Furthermore, he has been a member of the Executive Committee of the European Society of Cardiovascular Radiology (ESCR) for the past five years and Chairman of the Educational Committee and the European Board of Cardiovascular Radiology (EBCR) within the ESCR. He is a member of the Programme Planning Committee of ECR 2018, 2019 and 2020 and he is a member of the Steering Committee of the European School of Radiology. He founded Vienna Heart, a successful teaching initiative to train radiologists in modern cardiac imaging. He is also chairman of the Accreditation Council in Imaging (ACI) responsible for the accreditation of radiological events on behalf of the UEMS.

Professor Loewe served as member of the Editorial Board for European Radiology for ten years and served for two periods as Associate Editor for Radiology. He has published more than 100 scientific articles in peer-reviewed

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His main focus is cardiac imaging, imaging peripheral arteries, diagnosis and treatment of aortic diseases, as well as minimally invasive treatment of oncological diseases.



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**RADIATION  
EXPOSURE**

# INFLUENCE OF PROTOCOL OPTIMISATION ON RADIATION EXPOSURE IN CARDIAC IMAGING

BY VALENTIN SINITSYN AND MARIA GLAZKOVA,  
ON BEHALF OF EUROS SAFE IMAGING

## We are living in the era of low-dose cardiac and coronary CT

Coronary and cardiac computed tomography angiography (CCTA) is a non-invasive modality that is used more and more frequently in modern healthcare as a valid alternative to invasive coronary angiography for assessment of coronary atherosclerosis and many other cardiac diseases, as well as targeted indications like left atrium and pulmonary vein assessment or cardiac and aorta imaging before transcatheter aortic valve replacement (TAVI). There is a general trend towards increased use of CCTA for diagnostic imaging of the heart and coronary arteries (CA). CCTA has been included in different national and international cardiac referral guidelines. However, wider use of this modality has been criticised by some experts because of the relatively high levels of radiation to which patients are exposed. Yet the situation with regards to radiation exposure associated with CCTA has changed dramatically: we have entered the era of low-dose CCTA, and it is important that radiologists be aware of how to perform low-dose cardiac and coronary CT.

The dose delivered by CCTA can vary substantially depending on patient characteristics and the settings of multiple scanner operating parameters. The major configurable CCTA settings that can affect the dose are: tube voltage (kV), tube current (mA), and various other parameters of the scan protocol, such as type of ECG-gating, pitch, slice thickness, scan length, and the type of image reconstruction (standard or iterative).

## STRATEGIES TO REDUCE RADIATION DOSES IN CCTA

Today CCTA should be carried out with low-dose protocols whenever possible. There are a number of different strategies to reduce or minimise the radiation exposure to a patient during CCTA.

The most important ones are as follows:

- Prospective ECG-gating
- Reduction of tube voltage (kV) and tube current (mA) in combination with iterative image reconstruction
- Tube current modulation (in case of retrospective gating)
- Adjustment of pitch settings
- Tailoring of the scan length to the necessary parameters (avoidance of overscanning)
- Faster data acquisition (high-pitch scanning)

In the case of CCTA, radiologists have to find an optimal balance between image quality, good contrast to noise ratio, and acceptable low radiation dose.

### Prospective ECG-gating

In the case of CCTA, ECG-gating is obligatory in order to get movement-free diagnostic datasets of the heart and vessels. Coronary CTA can be performed with retrospective and prospective ECG-gating (Figure 1). CCTA with retrospective ECG-gating allows for data reconstruction of the whole scan volume at any time point within the cardiac cycle. But employing this technique makes high radiation doses (range 8–16 mSv) unavoidable, unless special measures to decrease radiation are taken. In the case of CCTA with prospective ECG-gating, the images are obtained only in predetermined, fixed R-R intervals (usually 60–70%). With this approach, it becomes impossible to obtain reconstructions in all the phases of the cardiac cycle, but radiation doses can be reduced significantly. CTA performed with a prospective ECG-gating (as opposed to a retrospective one) provides a substantial (3–6 fold) decrease in the effective radiation dose without compromising on image quality. Prospective-gated CCTA works very well in patients with low heart rate (HR) (60–65 beats per minute); though, in cases of high HR, the use of prospective ECG-gating can lead to non-diagnostic images due to motion artefacts. Low dose CCTA with prospective gating has become a new standard for diagnostic evaluation of CA and the heart chambers' morphology when there is no need for functional information. It is suitable even for static (single-shot) studies of myocardial perfusion at stress and rest. CCTA with

Figure 1

Coronary CTA with prospective (A) and retrospective (B) gating. In the case of (A), the centre of the triggering window was set at 70–80% of the RR interval. For (B), images could be reconstructed in every phase of the cardiac cycle without any corresponding increase of radiation exposure.

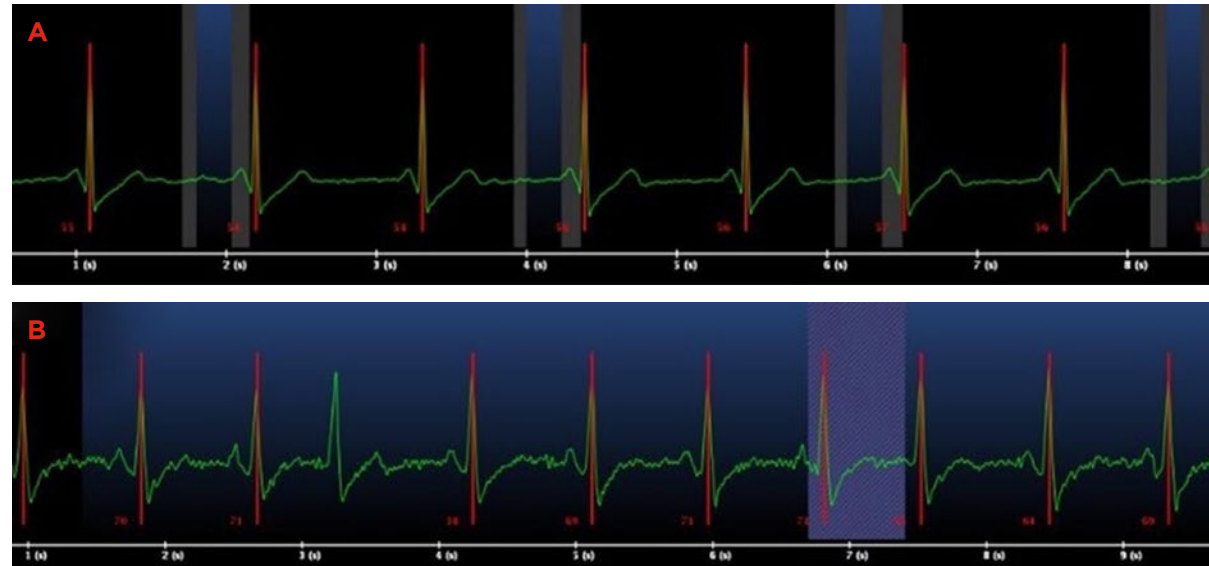
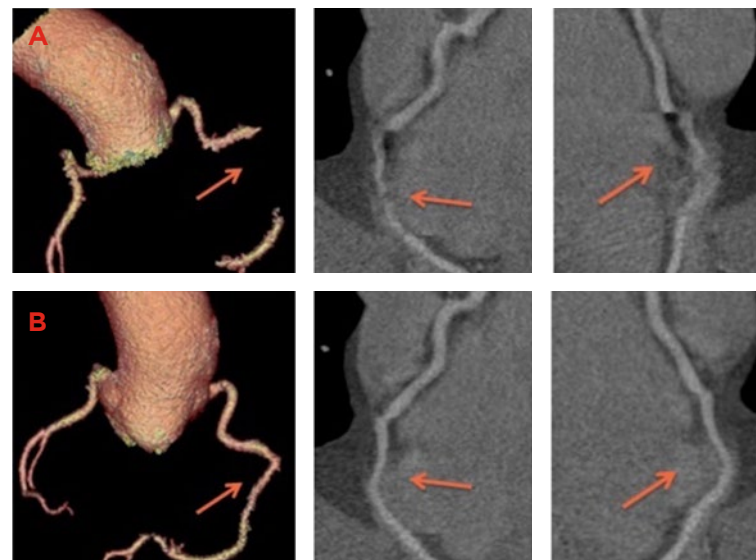


Figure 2

65-year-old male patient with an average HR >65 bpm. The VR and MPR made with standard prospective-gated CCTA show motion artefact in the middle segment of RCA (A). In the case in which the MC algorithm was applied (B), no artefacts are seen. Radiation dose 3.8 mSv.



retrospective gating is used when one needs information about the function of heart chambers and valves or in patients with arrhythmias. Recently, novel motion-correction (MC) algorithms have been developed by several manufacturers. These MC algorithms use information from adjacent cardiac phases obtained with prospectively gated CCTA within a single cardiac cycle. Such an approach minimises the artefacts related to CA motion. These MC algorithms can improve the image quality of prospectively gated low-dose CCTA even in patients with higher HR (Figure 2).

### Reduction of tube voltage and current combined with the iterative reconstruction

Reduction of tube voltage (kV) decreases radiation dose roughly proportionally to the square of the voltage settings. Thus, decreasing the tube voltage from 120 to 100 kV reduces the radiation dose by almost 40% whilst decreasing it from 120 to 80 kV reduces the dose by 60–70% (if the tube current remains constant). The kV settings are predefined or selected by the operator according to the subject's body mass index (BMI) and indications of the study. There are some simple rough recommendations for selecting the optimal tube voltage for CCTA: 120 kV for patients with a BMI of more than 30 kg/m<sup>2</sup>, 100 kV for a BMI from 21 to 29 kg/m<sup>2</sup>, and 80 kV for a BMI of less than 21 kg/m<sup>2</sup>. Consequently, the selection of tube voltage settings is in some way a trade-off between image noise and radiation dose. Modern CT scanners with iterative image reconstruction CCTA can, in most cases, be performed with a low tube voltage without any loss in image

quality. It is well known that low tube current/voltage leads to reduced exposure to radiation for patients, but also to increased image noise. Due to the introduction of iterative image reconstruction, the radiation dose can be substantially reduced (by 30–70% in comparison to traditional filter back projection) without any losses of fine details on images (Figure 3). Combined application of prospective ECG-gating, low tube current voltage and iterative reconstruction allows for significant reductions in radiation dose – to below 1–2 mSv (Figure 4).

### Tube current modulation

Tube current modulation is an important tool for decreasing the radiation dose in cases where retrospective cardiac gating is necessary – for example, when the evaluation of cardiac chambers, valve function, or dynamic myocardial perfusion studies are needed. The tube current is selected and modified based upon patient weight and/or BMI, thoracic diameter or noise measurement. Most modern scanners offer tube current modulation based upon the thickness of the body estimated from the topogram. For CCTA with retrospective ECG-gating, the tube current can be modulated at different phases of the cardiac cycle, for example, full tube current can be applied at the end- or mid-diastolic phases used for imaging of CA and decreased tube current can be used in other phases for heart chamber visualisation where lower image quality is acceptable. ECG-tube current modulation can reduce the radiation dose of coronary CTA by up to 60% in comparison to scans with fixed tube current settings.

Figure 3

Low-dose CCTA with prospective ECG-gating and low tube voltage (100 kV) in a patient with a BMI of 30.5 kg/m<sup>2</sup>. Iterative reconstruction allows the study to be performed with low radiation exposure without any loss of image quality due to the use of iterative image reconstruction. Radiation dose 1.59 mSv.

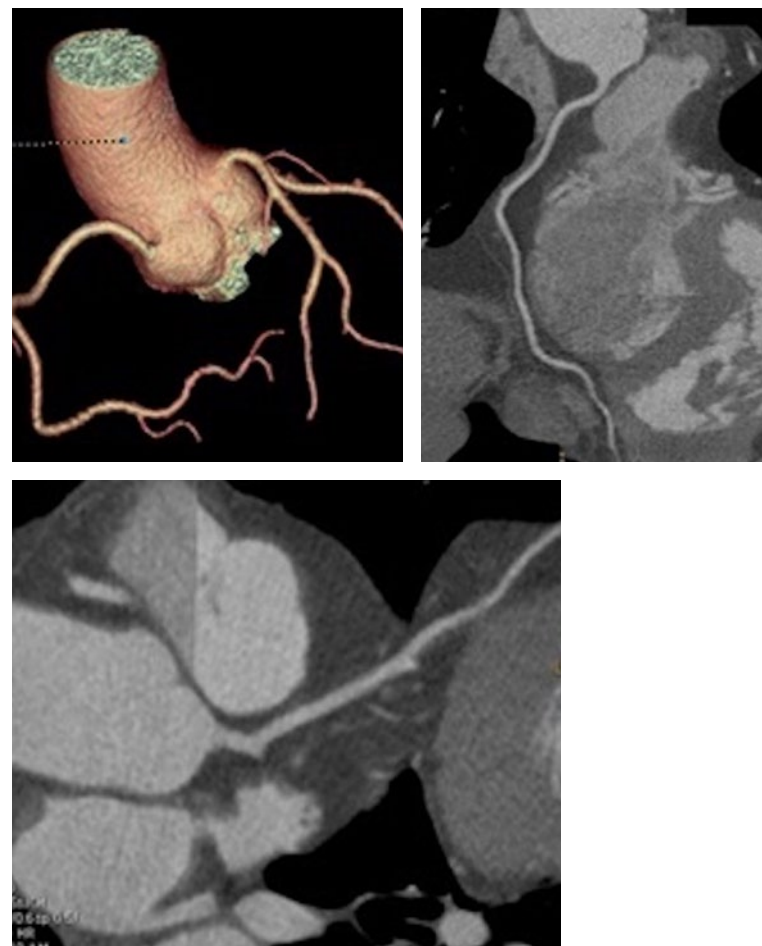
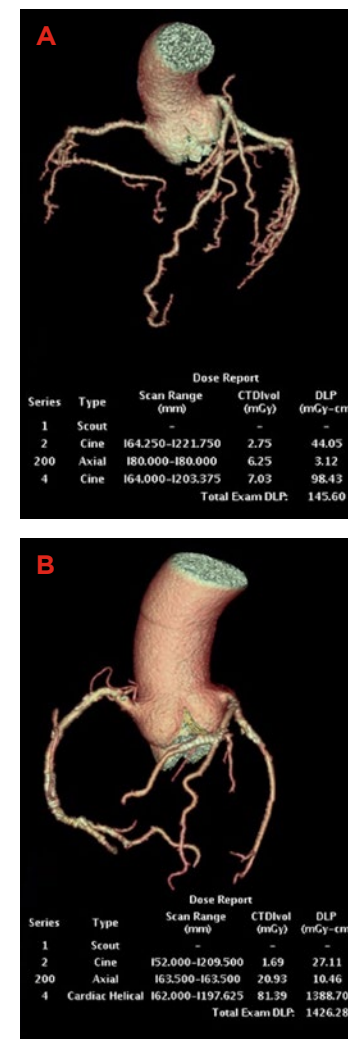


Figure 4

Coronary CTA with prospective (A) and retrospective (B) ECG-gating. The radiation dose was decreased from 19.4 to 1.37 mSv thanks to prospective ECG-gating and low tube voltage without any loss in image quality.



### Adjustment of pitch value

Distance travelled by the CT table divided by x-ray beam width denotes pitch. Radiation exposure for helical scanning at a pitch of 1 is comparable to that obtained during axial scanning. Scanning with pitch settings >1 is associated with a decrease of radiation exposure. A specialised form of helical scanning ('high pitch' or 'super-helical') has been developed for use in new 'fast' CT systems like the latest generation of dual-source CT (DSCT), or wide-detector, systems. According to different studies, the mean dose during high pitch scanning is very low (it could be in sub-millisievert range) without any associated decrease in image quality. High pitch scanning is particularly beneficial in diagnosis of CA anomalies and cardiac anatomy assessment of congenital heart diseases in children and young patients. So far, the main limitation of this technique is its dependence on low HR (typically less than 65 bpm), but this disadvantage may disappear with further improvements in CT techniques.

## CONCLUSION

Just ten years ago, CCTA was associated with relatively high radiation exposure. According to the data from the ACC/HRS/NASCI/SCAI/SCCT Expert Consensus Document on Optimal Use of Ionising Radiation in Cardiovascular Imaging (2018)<sup>1</sup>, the radiation dose during cardiac CTA can range from 0.5 to 30 mSv (Table). However, in most cases of CCTA, this is no longer a big problem.

In summary, we would like to stress the most effective ways to decrease radiation exposure in coronary and cardiac imaging<sup>2,3</sup>:

1. Selection of the right indications for the examination (e.g. use iGuide4 from ESR)
2. Details such as the patient's age, sex, weight, and height must be taken into consideration
3. Scan length should be tailored according to the aim of the study
4. Prospective ECG-gated CTA should be used in most cases when sufficient image quality can be expected
5. Retrospective ECG-gated CCTA should be done with tube current modulation

Table

Typical effective doses for different CCTA scanning protocols

SCANNING PROTOCOL	RANGE OF EFFECTIVE DOSES (MSV)
CCTA, retrospective gating, no tube current modulation	8-30
CCTA, retrospective gating, with current modulation	6-18
CCTA, prospective triggering	0.5-7
CCT, high-pitch helical	<0.5-3
CTA, pre-TAVR: coronary (multiphase) and chest/abdomen/pelvis	5-50
Calcium score	<0.5-3

6. Iterative image reconstruction (combined with appropriate decreases of tube voltage and current) is recommended for CCTA in all examinations (if the scanner has this option)
7. New technical features (e.g. high-pitch scanning, motion correction algorithms) should be used when possible and appropriate

## ABOUT EUROSAFE IMAGING

EuroSafe Imaging is the European Society of Radiology's flagship campaign to promote quality and safety in medical imaging. The mission of EuroSafe Imaging is to support and strengthen medical radiation protection across Europe following a holistic, inclusive approach. Radiation protection focuses on three cornerstones, namely justification of any medical exposure, optimisation of the imaging task to keep the exposure as low as reasonably achievable, as well as dose limits. EuroSafe Imaging has launched its Call for Action 2018 to guide all activities, which build upon these principles. The ESR's EuroSafe Imaging campaign is pleased to present this article focusing on protocol optimisation in cardiac imaging.

### References

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**CARDIAC MRI:  
THE RADIO-  
GRAPHERS'  
PERSPECTIVE**

# CURRENT AND FUTURE DIRECTION IN CARDIAC MRI: THE RADIOGRAPHERS' PERSPECTIVE

BY AIDEEN FALLON, ALISON FLETCHER AND VASILIS SYRGIAMIOTIS

## INTRODUCTION

Cardiac magnetic resonance imaging (CMR) is a rapidly growing area of cardiac imaging throughout the world. Rapid technological advances and developments have seen it provide unique imaging capabilities and accuracy. It provides high spatial and temporal resolution imaging which is non-invasive and which produces no ionising radiation. CMR uses different pulse sequences to visualise the myocardium, valves and great vessels. In a single scan, ventricular volumes and function can be assessed together with evaluation of myocardial fibrosis, iron loading, flow quantification, tissue characterisation and myocardial perfusion.

## TECHNIQUES UTILISED

Cine imaging can be acquired in any plane, provides highly reproducible imaging of cardiac morphology and function as well as myocardial mass

and wall motion abnormalities, and is the gold standard for evaluating ventricular function and volume in both left and right ventricles, making it an ideal imaging modality for serial monitoring (Figure 1).

Non-contrast tissue characterisation utilises T1 black-blood imaging to show fatty infiltration or deposition (Figure 2) and T2 black-blood imaging for oedema from acute myocardial infarct (MI) (Figure 3A) or myocarditis (Figure 3B). These techniques are also useful in soft tissue differentiation for assessing myocardial and extra-cardiac structures and masses (Figure 4). T2\* imaging can be used to demonstrate iron deposition in patients with haemochromatosis or thalassaemia.

Myocardial fibrosis or infiltration can be assessed after the administration of a gadolinium-based contrast agent. It is possible to assess three phases – first pass (which can be

acquired at stress using a pharmacological stress agent), early enhancement and late enhancement. Late gadolinium enhancement (LGE) imaging is acquired 5–10 minutes after the administration of a contrast agent. The LGE technique allows for the differentiation between ischaemic and non-ischaemic cardiomyopathies depending on the specific patterns of focal fibrosis (Figure 5) and provides valuable information on the aetiology of pathology to help guide treatment and predict adverse outcomes.

## FUTURE DIRECTIONS

T1-mapping is a technique for parametric mapping of myocardial relaxation times in CMR. It is used for imaging focal and diffuse fibrosis and, in combination with contrast-enhanced T1-mapping and

Figure 1

Cine images showing (A) asymmetrical myocardial hypertrophy in the basal septum due to hypertrophic cardiomyopathy (B) thinned anterior wall due to previous left anterior descending infarct (C) double inlet right ventricle.

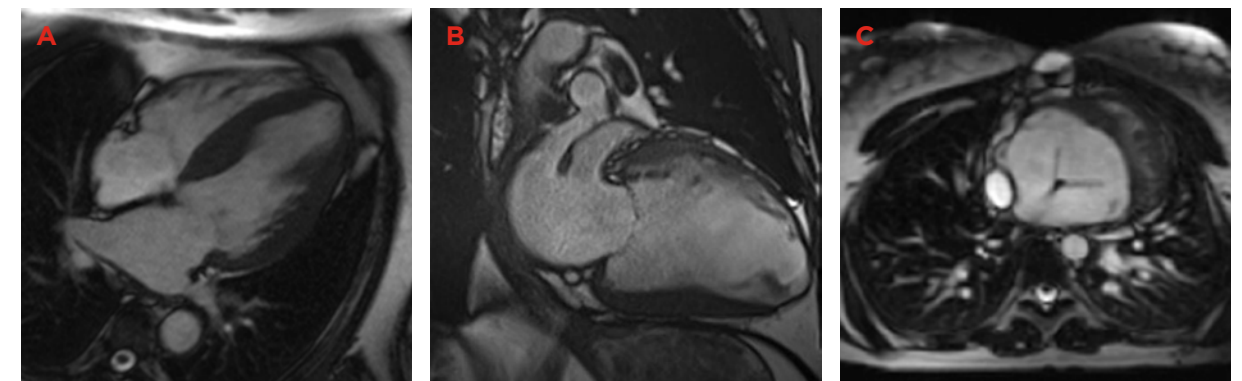




Figure 2

T1 axial image showing fatty fibrosis of right ventricular free wall in arrhythmogenic right ventricular cardiomyopathy.

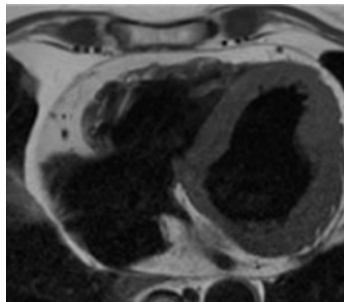


Figure 3

T2 short axis images showing (A) oedema in right coronary artery territory (inferior wall) due to late presentation myocardial infarct, with microvascular obstruction, (B) oedema in non-coronary artery territories in acute myocarditis.

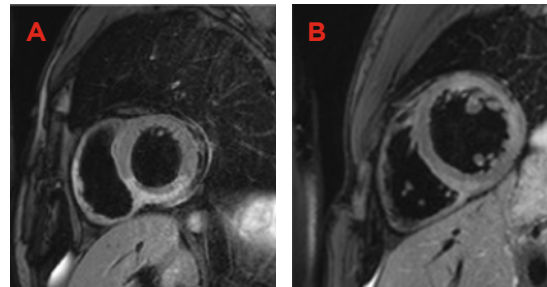
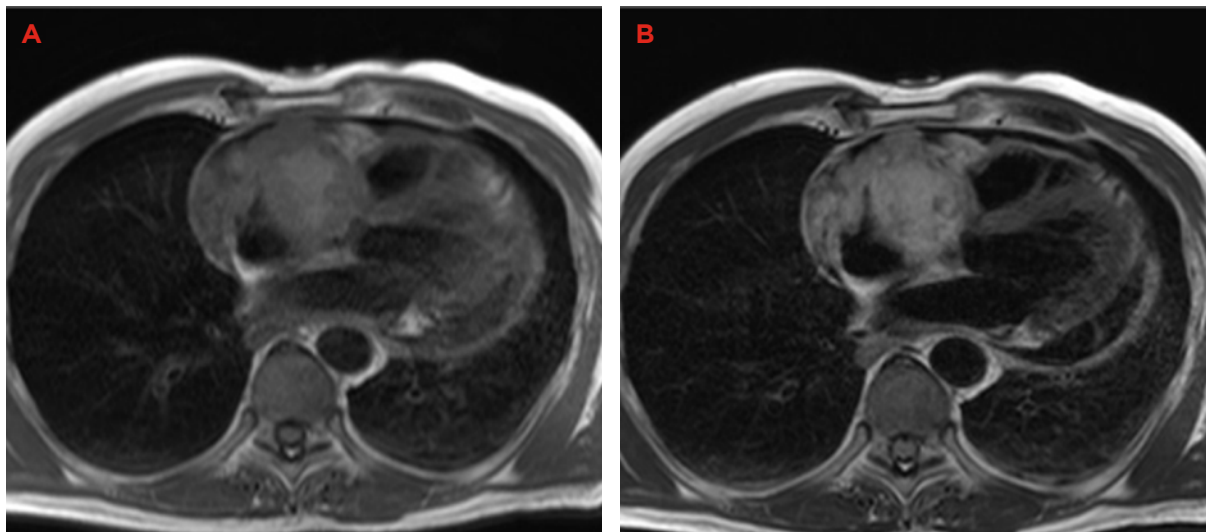


Figure 4

Axial image of cardiac mass with (A) T1 weighting and (B) T2 weighting.



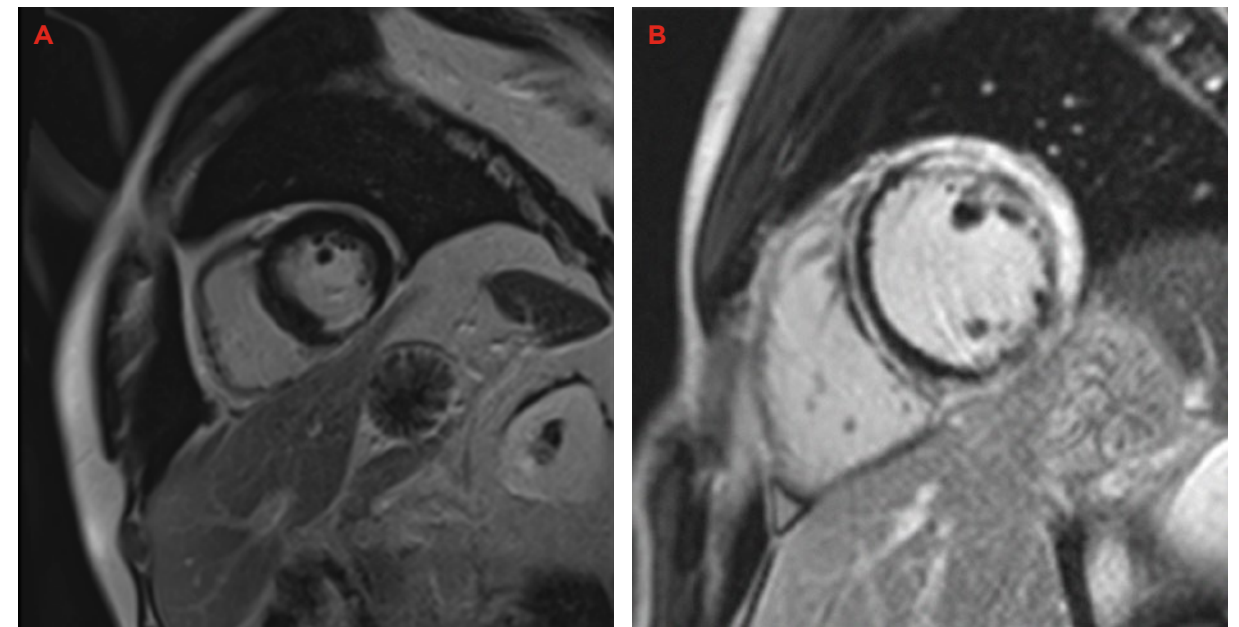
blood haematocrit, calculating the extra-cellular volume (ECV) fraction. Oedema, from inflammation or acute infarction, and increased interstitial space from fibrosis or amyloid deposition are the two most important reasons for an increased native (non-contrast) T1. Lipid or iron overload are the two most important for decreased native T1. Native T1-mapping is possible in patients where poor renal function is a contraindication to contrast administration and so LGE cannot be performed. ECV is a marker of tissue remodelling and an increased ECV is most often due to excessive collagen deposition<sup>1</sup>.

Blood flow in the heart and great vessels is multidirectional and pulsatile and 4D phase contrast CMR has enabled visualisation of multi-directional flow features. In the aorta, areas of high-velocity flow close to vessel walls may indicate altered fluid mechanical effects on the vessel wall, and in complex congenital heart disease studies using 4D flow, imaging is showing potential applications<sup>2</sup>.

CMR has also become an important component of risk stratification and procedural planning in congenital and paediatric heart diseases. Innovative approaches to image acquisition and reconstruction are leading

Figure 5

Late gadolinium enhancement images showing (A) subendocardial LGE due to myocardial infarct in right coronary artery territory and (B) epicardial LGE in acute myocarditis.



the way toward fast, high-resolution, 3- and 4-dimensional datasets for delineation of cardiac anatomy, function, and flow. Moreover, techniques for assessing the composition of the myocardium may help clarify the pathophysiology of late complications, identify patients at risk of heart failure and assist in the evaluation of therapeutic strategies. Traditional techniques account for cardiac motion due to respiration by tracking the diaphragm, but newer techniques, such as self-navigated 3D whole heart imaging, track the cardiac position itself and provide robust 3D clinical datasets in patients with congenital heart disease.

Improvements in reconstruction algorithms allow for accelerated, time-resolved, 3D velocity-encoded flow imaging whilst maintaining spatial and temporal resolution. These novel techniques, along with the use of newer contrast agents that afford better signal to noise ratio, may eventually allow for the fusion of anatomic and flow data into a single, comprehensive dynamic 3D dataset that can be reformatted in order to analyse cardiac structure, function, and blood flow. The CMR guided cardiac catheterisation in congenital heart disease may eventually allow for simultaneous measurements of pressure and flow, providing insights into chamber compliance, vascular impedance, and myocardial contractility. As spatial resolution improves, foetal CMR may produce valuable information on the link between foetal blood flow derangements in congenital heart disease and neurodevelopmental outcomes. CMR based feature tracking may yield new knowledge on regional and global myocardial function and deformation, allowing for a further refinement of patient-specific risk of adverse outcomes.

New developments in hardware include respiratory detection through the scanner table and receiver coil developments to allow for detection of a vectorcardiogram, eliminating the need for respiratory bellows, navigator bands or an ECG. The combined development of rapid, real-time MRI sequences, together with MR compatible catheters and guidewires, show promising potential for MR guided catheter-based interventions.

## THE ROLE OF THE MR RADIOGRAPHER

The advent of CMR has changed the work-up of patients with suspected cardiac and cardiac-related pathologies, aiding diagnosis and assisting in determining appropriate treatment paths, therapeutic response and risk stratification. The CMR exam is tailored to the patient presentation and pathology and produces many challenges that the MR radiographer must overcome.

The MR radiographer must have a deep understanding and knowledge of the principles of MRI, MRI sequences and dedicated CMR sequences, and detailed anatomical knowledge of the cardiovascular system. This information must build upon the knowledge already gained in undergraduate education and experience, through higher education and training. The high magnetic field strengths used in MRI present significant safety considerations and radiographers must have extensive knowledge and understanding related to MRI safety in order to ensure patient and staff safety.

The process of undergoing a CMR examination may be a daunting experience for patients. The CMR radiographer must have the necessary skill set to effectively communicate with patients in order to both allay anxiety of undergoing the examination and in relation to the potential outcomes of the examination. This soft skills set is vital in order to maximise patient compliance, which is essential for the examination. Patients must be able to cooperate with the process by remaining still and repeatedly holding their breath. The MR radiographer plays a crucial role in preparing the patient for this by explaining the MR procedure and educating and reassuring them regarding the different aspects of it, for example, the effects of pharmacological stress agents, to a level that is appropriate for each individual patient regardless of age. Whilst advances in technology have reduced scan times or negated the need to breath-hold entirely, patient compliance is still essential.

In order to tailor the examination to the patient presentation and pathology, the radiographer must have knowledge of pathological processes – the presentation of conditions and also CMR imaging appearances. In conjunction with this, the radiographer must also have knowledge and understanding of contrast agents used in MRI, and pharmacological stress agents which may be used within the CMR department. In order to optimise the examination, the radiographer must tailor the image acquisition parameters to the patient's physiology e.g. the use of differing ECG gating and triggering techniques when arrhythmias are present, and adjustment of parameters to alter sequence acquisition times for the patient's breath-holding capability, whilst still maintaining image quality. In order to ensure

accurate measurements and flow quantification, the CMR radiographer must acquire imaging in correct and appropriate planes, and where serial monitoring is required it is essential that the images be reproducible.

In some CMR centres, it is the radiographer who supervises particular CMR scan lists, including vasodilator stress CMR, so advanced knowledge is needed for decision making and safe practice.

Whilst carrying out this role the radiographer must also make sure that all hardware and software is operating appropriately. As such the radiographer has an important role to play, in conjunction with other professions in the quality assurance programme of the CMR department. An appropriate and timely quality assurance programme is necessary and indeed required for some newer CMR techniques, such as parametric mapping<sup>3</sup>.

## CONCLUSION

The rapid advances and continued developments in CMR now see it provide unique imaging capabilities and accuracy. It has changed the work-up of patients, aids diagnosis and assists in determining appropriate treatment paths, therapeutic response and risk stratification. The MR radiographer plays a crucial and vital role in this, ensuring patient safety and compliance when undergoing the examination and undertaking the examination with a high level of skill and technical expertise. They must also provide accurate and reproducible images, tailor the examination to the patient's needs, and

also fully image any pathology that may be present, all in a single scan sitting. By using this skill and expertise, and through a combination of the sequences available, CMR is an ideal imaging modality for both adults and paediatrics. In addition, the implementation of radiographers core skills enables new and advanced techniques to be implemented effectively and efficiently for improved patient outcomes.

#### References

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*Ms. Fallon was invited to co-author this chapter on behalf of the European Federation of Radiographer Societies (EFRS). Through its member organisations, the EFRS represents more than 100,000 radiographers and 8,000 radiography students in Europe.*



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*Ms. Fletcher was invited to co-author this chapter on behalf of the European Federation of Radiographer Societies (EFRS).*



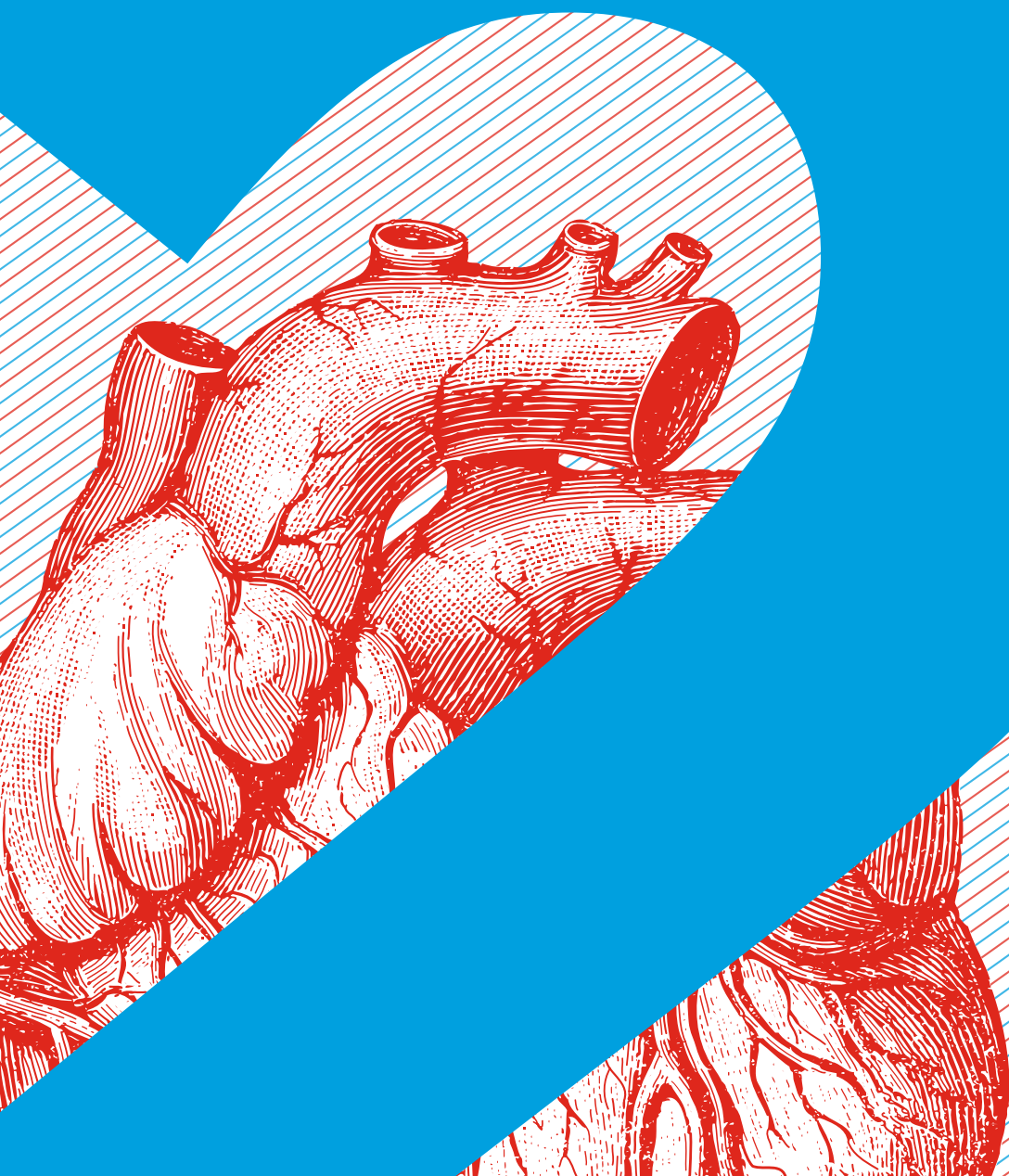
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*Mr. Syrgiamiotis is a European Federation of Radiographer Societies (EFRS) Board member and was invited to co-author this chapter for the EFRS.*



**20**

**CARDIAC CT:  
THE RADIO-  
GRAPHERS'  
PERSPECTIVE**

# CURRENT AND FUTURE DIRECTIONS IN CARDIAC CT: THE RADIOGRAPHERS' PERSPECTIVE

BY KONSTANTINOS MICHALOS AND HELLE PRECHT

## TECHNOLOGY EVOLUTION AND CORONARY COMPUTED TOMOGRAPHY ANGIOGRAPHY

The vast technological advancement over the past decades has helped with the evolution of medical imaging. Especially in the field of computed tomography (CT), fast rotation time, larger and more sensitive detectors, newly developed x-ray tubes and more advanced processing software have been established for more precise CT images. To use the full extent of the CT scanner and focus on the individual patient, the radiographer's work has become more diverse and complex according to the technological development.

This technological evolution has been of great importance to the field of coronary artery disease (CAD). Contemporary lifestyle, consumption habits (non-healthy food, smoking, etc.) and mostly stress are some of the elements that have led to a noteworthy increase in the number of cardiovascular patients. One very reliable choice for

imaging the coronary arteries is the use of CT. CT has accomplished something very important; the ability to capture the moving heart without motion in a non-interventional procedure.

## EXAMINATION PROCESS

The coronary CT angiography (CCTA) is a method that first appeared in the year 2000, with a 4-slice CT system and later in 2002 with a 16-multidetector (MD) CT. Next generation CT scanners with 64-detector rows were implemented in 2004. These CT scanners integrated new and improved manufacturing features that introduced a better temporal resolution by decreasing the rotation time, improving the spatial resolution that offered a more accurate imaging of the heart. The introduction of isometric voxel increased the image quality by making it possible to have the same spatial resolution in every plan. In 2016 the 320-detector CT scanner was implemented with new possibilities to scan the entire heart in one rotation, increasing spatial and temporal resolution as lowering artefacts.

As CCTA is a non-invasive imaging method, the patient does not need any medical observation, nor hospitalisation, after its completion. The diagnostic efficacy of CCTA keeps improving, but CCTA still has limitations, even if all the new technical developments are used. In case of no findings, CCTA is 100% accurate, whereas in case of any stenosis, the degree of stenosis is usually overestimated due to the method's barriers. Therefore, other modalities such as digital subtraction

angiography, magnetic resonance imaging, optical coherence tomography or intravascular ultrasound could be taken into consideration in order to compare findings.

The examination of CCTA consists of three main parts:

### 1. Patient preparation:

The patients' blood pressure and heart rate are measured and a venflon (18G) is placed in a vein in the preparation room. To obtain the best image quality, the heart rate should be below 65-75 BPM, depending on the individual CT scanner. If the heart rate is too high, beta-blockers are administered (in absence of contra-indications). These low heart rates are maintained for the whole procedure, to avoid motion artefacts. In the newer CT scanners, however, it is possible to scan the patient with a higher heart rate, but then the scan is reconstructed in two phases (40 and 75%) to ensure diagnostic quality without motion artefacts.

At this preparation stage, specific breath-hold instructions or extended breath hold exercises are given to the patient. A clear communication and close cooperation between the patient and the radiographer is made to obtain a stable and low heart rhythm. The patient is correctly centred in all three plans with arms above the head. If preferred, nitro-glycerine could be given just before the examination to enhance the visibility of the coronary arteries (Figures 1, 2).

Figure 1

Placement of the ECG electrodes on the patient placed on the scanner bed.

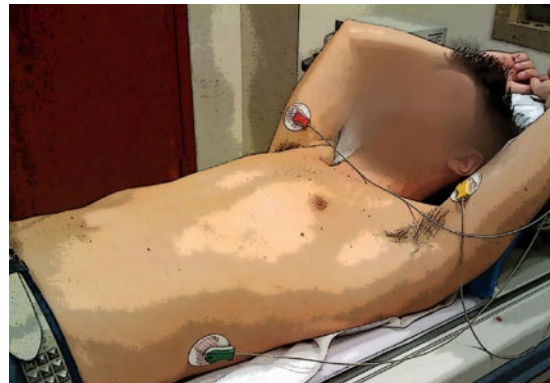


Figure 2

Heart rate planning prospective ECG triggering, scanning in the 75% phase of the cardiac cycle and R-R interval.

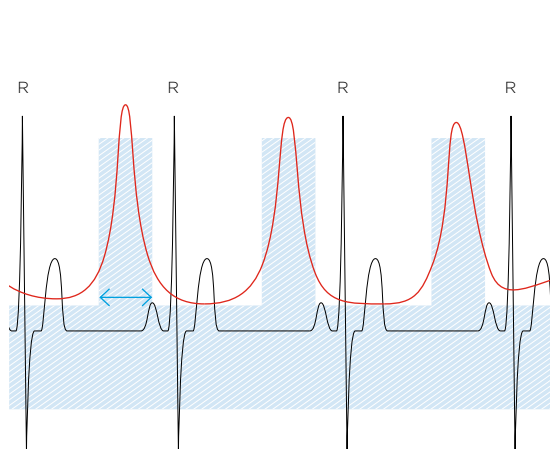


Figure 3

CCTA acquisition planning showing the field of view (FOV).

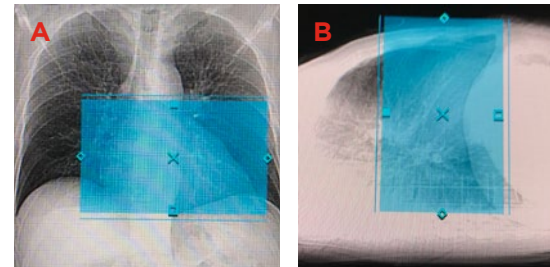
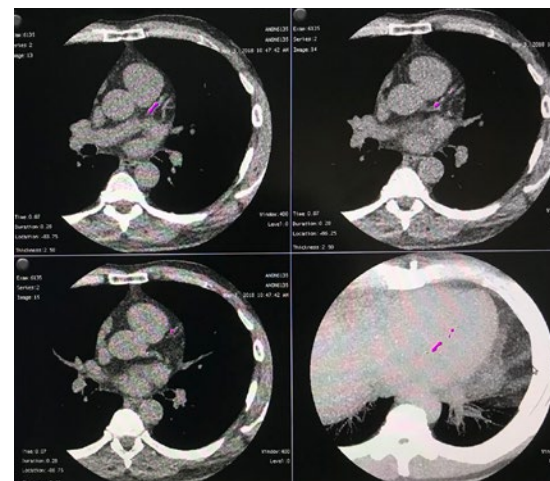


Figure 4

Non-iodine-contrast calcium scoring with the calcium marked in the coronary arteries.



## 2. Main examination (acquisition):

This part of the examination consists of the calcium scoring scan (CS) and the main CCTA (Figure 3). During CS, plain non-contrast images from the heart are made (Figure 4). The calcium score scan shows and allows calculation of the amount of calcification in the coronary artery wall. The CS images are used to plan the main CCTA protocol that takes place right after the CS acquisition. For the main CCTA, the heart-beat-triggering images are acquired, with simultaneous intravenous contrast medium administration. See Table for specific

technical CCTA and iodine contrast information.

## 3. Post-processing:

The acquired image data undertake further post-processing techniques to achieve the best possible diagnostic images for the individual patient. These include iterative reconstructions in order to form a series of images of the coronaries arteries' multi-planar reconstruction (MPR, Figure 5) and vessel tracking is used and combined with 3D rendering, fly-through and other types of vessel presentation images (Figure 6).

## Table

Protocol examples used in clinical CCTA for an average 60-year-old cardiac patient (175cm and 90kg)

### INDICATIVE TECHNICAL PROTOCOLS FOR CCTA

CT technique	Greece	Denmark
CT scanner	Toshiba Aquilion Prime	Revolution CT from GE Healthcare
Detectors	80	256 Gemstone (GSI)
kV	Auto-kV	100
mA	Auto-mA	412
Collimation	80 x 0.5mm	256 x 0.625mm
Slice thickness	0.5mm	0.625mm
Rotation time	Auto, according to pitch selection from breath exercise prior to CCTA (-0.35 sec)	0.28 sec
Pitch	Auto adjusted from breath exercise	Axial
Scan length	120mm	140mm
Scanning time	4 sec	0.28 sec
Effective dose	2-4 mSv (according to heart rate)	1-1.3 mSv
Iodine contrast protocol flow	5-6 mL/sec (according to heart rate)	6 ml/sec
Iodine contrast	According to BMI Approx. 90mL iodine contrast / 50 mL saline flash	60 ml iodine contrast / 50 ml salty water
Iodine contrast timing	Bolus tracking	Scan in smart prep mode, contrast tracked manually and scan started

Figure 5

Curved multiplanar reconstruction (MPR) of the left coronary artery.

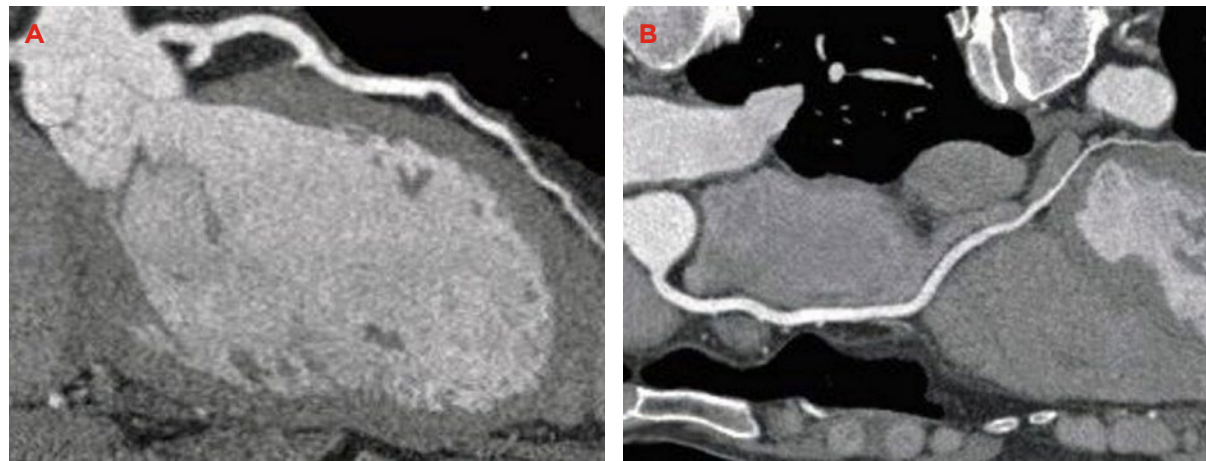
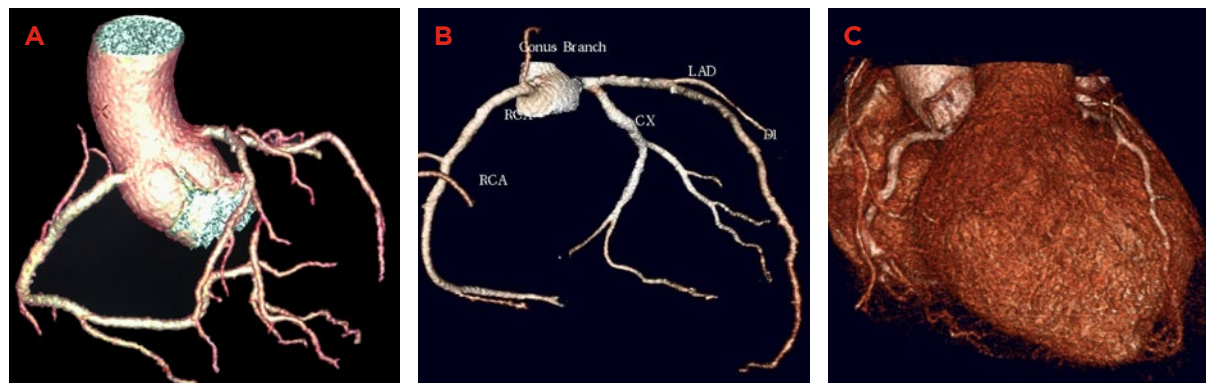


Figure 6

Volume rendering technique (VRT) images showing the coronary tree with and without the myocardium.



## FUTURE DEVELOPMENTS

The latest MDCT scanners provide an extended range of both hardware and software advances, as the processing power of computers has reached an extremely high level. The great speed of computing processing has allowed vendors to produce model-based iterative reconstruction algorithms for image processing. The radiographer can hereby maximise image quality in order to make a more accurate diagnosis possible by increasing the spatial resolution, while at the same time maintaining radiation dose at a minimum level.

Another very useful feature is the automatic tube voltage adaptation and the organ-based tube current modulation. This allows system software to select a kV according to patient size and to reduce the mA in the anterior-posterior position. These two features can reduce the radiation dose and still keep the image quality high. In other words, a full volumetric calculation of the scanning anatomic region takes place in real time, with the goal being to protect the patient from radiation. In accordance with the latest developments of the improved and more sensitive material used for the detectors, highest image quality is achieved in combination with the necessary radioprotective techniques.

Recent technical advances can assess dynamic myocardial perfusion by scanning the heart multiple times over the same area. Hereby CCTA does include haemodynamic information on ischaemia and infarction. This gives physiology information based on the dynamic procedure in the imaging

technique but does result in a higher radiation dose to the patient. An additional new technical feature is dual energy (DE) technique. DE CCTA exploits the fact that tissues in the human body and the intravascular iodine-based contrast media have unique spectral characteristics when penetrated by different x-ray energy levels. This property could enable the mapping of the iodine (and thus blood) distribution within the myocardium at a lower radiation dose but without dynamic information of the myocardium. Another development is fractional flow reserve (FFR) C. This enables the calculation of rest and hyperaemic pressure fields in coronary arteries without additional imaging and modification of CT acquisition protocols. The FFR is a physiologic measure of coronary stenosis expressing the amount of coronary flow still attainable despite the presence of a stenosis and could potentially identify ischaemia in CAD patients.

## THE RADIOGRAPHER'S ROLE

It would be no exaggeration to mention that cutting-edge technology needs to be handled by specially trained personnel. The radiographer's role involves special education and skills in order to provide patients with high-quality healthcare services. They aim to reach a quick and accurate diagnosis, with a minimum of radiation dose.

A CCTA is a quite demanding examination, requiring the radiographer's active participation. CCTA is by no means a routine exam. Thus, as they are participating in a

special examination, the radiographer is required to show certain communication skills, to make the patient feel comfortable in the examination room and successfully cooperate for the breath-holding involved, so that motion-free images are produced for an accurate diagnosis. The radiographer also has to demonstrate adequate comprehension of the patient's ECG, iodine contrast protocol and knowledge of how the differentiation of the heart rate during the scan can affect image quality, especially in previous CT systems (e.g. 64-MDCT) where more than one heart cycle is needed for reconstruction.

Furthermore, the radiographer needs to be fully aware of the CT system's capabilities. They should continuously be technically informed of the CT scanner's hardware and software applications, to combine all technical parameter with the best processing software to provide cardiologists and radiologists with the highest possible CCTA image quality. Therefore a patient-centred healthcare system should always be the radiographer's priority.

## THE EFRS'S CONTRIBUTION TO THE SPECIALISED CT RADIOGRAPHER

The European Federation of Radiographer Societies (EFRS) has always supported this expanding role of radiographers since its foundation. The annual general meetings and the annual European congress of the EFRS during each year's European Congress of

Radiology (ECR) are only some of the EFRS's acts to keep the professionals up-to-date.

A very important accomplishment of the EFRS has been the benchmarking of the standards a radiographer should meet in their department, establishing the criteria, knowledge and skills to have for a successful practice of the profession. Additionally, the EFRS official journal Radiography keeps radiographers informed about the latest scientific research of the profession worldwide. On top of the broadened research network that the EFRS maintains, where any registered radiographer is able to actively participate, annual events also take place, where radiographers obtain continual professional education (CPD) to keep up-to-date with the current trends and learn new imaging protocols and therapies.

## CONCLUSION

A CCTA is a quite demanding examination regarding anatomy, physiology and new technical developments, requiring the radiographer to have in-depth knowledge and experience to produce optimised images for diagnosis.



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*Mr. Michalos has co-authored the technical chapters of the CCTA examination of the first publication about it in Greece. He has co-authored two more books regarding radiation protection and many publications in the Greek official journal of radiographers. He has also given many lectures and has participated in numerous electronic posters in national meetings and congresses. Since 2009, he has been a member of the board of the Greek Society of Radiographers (STRAEPT) and for the last two years, he has been one of its two representatives to the European Federation of Radiographer Societies (EFRS).*

*Currently, he is an undergraduate student at the Hellenic Open University, in the Department of Computer Science, combining his prior medical field studies with the tools, innovation and general knowledge that computing technology offers to radiology.*



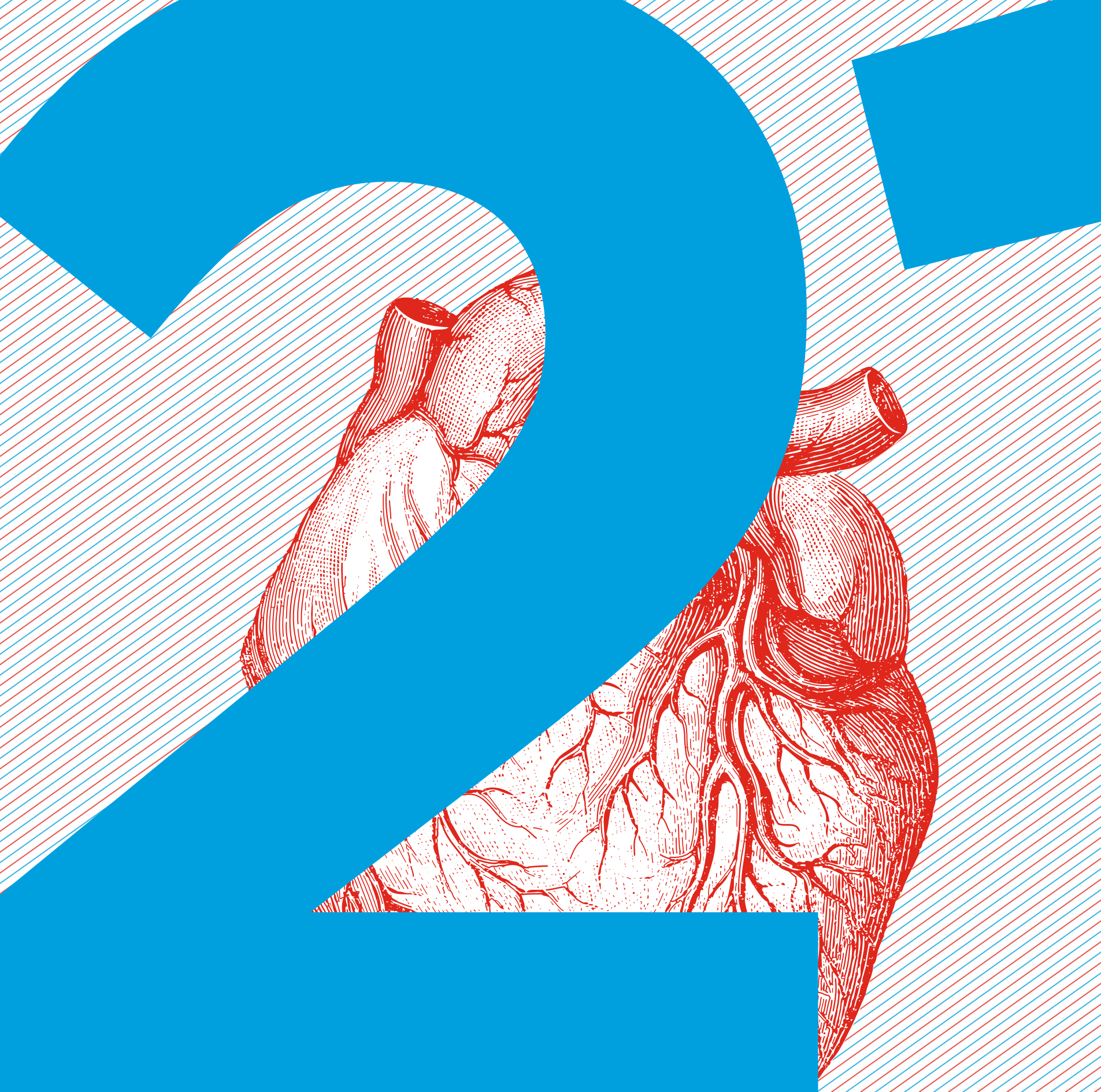
### HELLE PRECHT

*completed training as a radiographer in 2003 and was a clinical radiographer until 2006. Previously she was an application specialist on Canon Digital Radiography*

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*Since 2012 she has been dedicated to research involving CCTA and optimisation of image quality and radiation dose. This is shown in multiple scientific publications, a great research cooperation network all over Europe and active participation in a number of congresses. Currently, Ms. Precht is employed at OUH, Medical Research Department, Svendborg focusing on optimisation within CCTA testing new technical possibilities, employed as a researcher at the University of Southern Denmark and associate professor at University College Lillebælt, Odense with a broad spectrum of research projects both nationally and internationally.*





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**RADIO-  
GRAPHERS  
IN OTHER  
CARDIAC  
IMAGING  
AREAS**

# THE ROLE OF RADIOGRAPHERS IN OTHER AREAS OF CARDIAC IMAGING

BY CHRISTOPHER STEELMAN AND DIEGO CATANIA

## INTRODUCTION

The cardiac catheterisation laboratory is one of the most unique medical environments in existence today. Also known as the 'cath lab', it is where a multidisciplinary team diagnoses and treats congenital and acquired heart disease. Since the emergence of the cath lab in the 1980s, the use of percutaneous intervention, a minimally invasive procedure that uses only small incisions to access the heart, has grown exponentially. With rapidly evolving technology and expanding indications, percutaneous transluminal coronary angioplasty (PTCA) has grown to equal stature with coronary artery bypass grafting as the number of annual PTCA procedures grew to 300,000 in 1990<sup>1</sup>. Today, coronary angioplasty is performed on more than 2 million patients in the world annually<sup>2</sup>. And from the beginning, the radiographer has played a fundamental role in the multi-professional teams who treat patients with life and limb threatening diseases. Contributing far more than an expertise in imaging, today's cath lab radiographer has accepted the challenge of rapidly developing technology and the incredible procedures they enable.

## HISTORY

The cath lab has come a long way since 1929 when Nobel Prize winner Werner Forssmann performed the first cardiac catheterisation on himself. Under local anaesthesia, Forssmann inserted a catheter into a vein in his arm. Not knowing if the catheter might pierce a vein, he walked downstairs to the x-ray department where, under the guidance of a fluoroscope, he advanced the catheter 65cm into his right ventricular cavity<sup>3</sup>. Medical imaging and invasive cardiology have been inseparable ever since.

## CATH LAB RADIOGRAPHER

Radiographers specialising in the cath lab possess a broad knowledge base and refined psychomotor skills. However, the cath lab radiographer's responsibilities are unique and extend far beyond that of medical imaging. A cath lab radiographer is a multi-talented professional who literally works side-by-side with cardiologists. Radiographers share the knowledge and skills necessary to assist in a collection of increasingly sophisticated procedures. Lifesaving procedures often create an environment of high stress and emotion, and the cath lab radiographer demonstrates poise and a level of composure not common among other medical imaging professionals. The anxiety of the patient during these life-changing procedures is well documented<sup>4,5</sup> and is associated with worse outcomes in coronary artery disease patients. Fortunately, the European Federation of Radiographer Societies (EFRS) Level

6 radiographer is well prepared to "appraise the needs of patients and exercise sound clinical reasoning skills in order to provide appropriate, holistic and context-specific care in a broad range of situations within the clinical setting"<sup>6</sup>.

Working under the guidance of a licensed physician, the cath lab radiographer:

- performs or reviews a baseline patient assessment
- evaluates patient response to diagnostic or interventional manoeuvres and medications
- provides patient care and often drug administration commonly used in the cardiac catheterisation laboratory
- provides procedural (scrub) assistance
- operates all imaging technology
- performs physiologic monitoring and case documentation
- performs pre-cardiac and post-cardiac patient care activities and procedures
- contributes to the cath lab team's efforts to provide emotional support prior to, during and after the procedure

The radiographer also coordinates access to supporting imaging such as computed tomography and ensures the availability of a wide range of equipment ensuring diagnostic and interventional procedures are carried out with optimum efficiency.

The modern cath lab employs an array of imaging technology, all of which must be mastered by the radiographer. Intravascular ultrasound (IVUS) and optical coherence tomography (OCT) provide detailed images and critical information necessary for accurate vascular assessment. As a procedural assistant, the radiographer displays an exceptional knowledge of the preparation and use of wires, balloon catheters, stents and a myriad of other devices. The radiographer employs not only their knowledge but also their skills to ensure optimum outcomes. In addition to the cardiac cath lab, you will also find radiographers assisting with procedures in interventional radiology, paediatrics, neurology and electrophysiology.

## MULTIDISCIPLINARY PRACTICE

The increasingly complex procedures of the cath lab require highly coordinated multidisciplinary teams. Recent developments in cardiac surgery and interventional cardiology and new percutaneous alternatives have led to the creation of integrated, hybrid cath lab/operating rooms that enable both surgical and intravascular procedures. The radiographer works with a team of professionals including cardiologists, cardiac surgeons, sonographers, vascular surgeons, anaesthesiologists, engineers and nurses. There is mutual trust in the cath lab and an expectation that each member excels in their area of expertise for the benefit of the patient. The cath lab team performs

their tasks with efficiency and precision, moving about the cath lab in a well-choreographed routine. And although the radiographer is associated mainly with their expertise in medical imaging skills, they are a vital member of the cath lab team and contribute to all phases of patient care.

## CATH LAB PROCEDURES

The minimally invasive treatment that continues to define the cardiac cath lab is angioplasty and the use of coronary stents. Arteries once thought to be forever occluded are now being restored with sophisticated techniques enabled by novel technology. For a great number of patients, a procedure in the cath lab is a welcome alternative to coronary artery bypass surgery. However, in recent years there have been striking advancements in the number of procedures that the cath lab offers as an alternative to surgery. It has been predicted that 50% of the financial return from cardiac cath labs will be from non-coronary procedures by 2020<sup>7</sup>. Heart valve repairs and replacements, left atrial appendage (LAA) occlusions, heart failure interventional device therapies, closures of atrial septal defects (ASDs) and ventricular septal defects (VSDs) and patent foramen ovale (PFOs) can all be treated in the cath lab.

There are many new interventional technologies on the horizon. However, these procedures are only possible with the application of ionising radiation. Radiation dose has been associated with an additional risk

of developing radiation-induced cancer and cataracts for medical staff, and there is the potential for cancer and tissue reactions (erythema, dermal atrophy, and ulcers) for patients. Although increasingly complex procedures demand longer fluoroscopy time, cineradiography time or both<sup>8</sup>, innovative technologic advancements and diligent adherence to best practices have greatly reduced the radiation dose to patients and operators. The radiographer plays a central role in ensuring the proper use of radiation protection tools and techniques ensure that the radiation doses to patients and staff are as low as possible.

## RADIATION SAFETY ADVOCATE

Radiographers are specifically trained to operate medical imaging equipment in a manner that optimises image quality and minimises patient and clinical personnel exposure. ALARA stands for 'as low as reasonably achievable'. This fundamental principle of radiation protection is taught to radiographers on their first day. It is the primary goal of all radiographers, but there are few places where this principle is more important than the cath lab. Radiation exposure to patients in diagnostic and interventional procedures has been estimated to be hundreds to a thousand times more than a chest radiograph<sup>9</sup>. It is the radiographer who is educationally prepared and clinically competent to ensure that not only the patient's but the entire cath lab team's exposure is 'as low as reasonably achievable'.

## CATH LAB RADIOGRAPHER TRAINING

It takes many years for a radiographer to become astute in this clinically complex environment. Radiographers who perform medical imaging examinations have met stringent educational and credentialing standards. The Education Qualifications Framework Level 6 published by the EFRS and the International Society of Radiographers and Radiological Technologists (ISRRT) defines the core knowledge, skills, and competences that enable the radiographer to contribute to the care of the patient<sup>6</sup>. Today's cath lab radiographer is equipped with knowledge of radiation physics, radiation biology, x-ray image formation, and the operation of an x-ray cinefluorographic unit.

The radiographer is responsible for understanding each level of complexity relative to radiation safety, cardiac anatomy, physiology, and haemodynamics, and the technical aspects of all the equipment utilised during any cardiac or vascular procedure. They are masters of the delicate interplay of technology and anatomy that is required to achieve optimum outcomes. The competent radiological technologist is informed about current modifications and advances in procedures, as well as developments in the industry itself.

To keep pace with new and increasingly sophisticated procedures, the cath lab radiographer commits to a career-long continuing educational process. The EFRS recommends lifelong learning for all radiographers to support service and personal development. Continuous Professional Development (CPD) is defined as "the continuous learning

process required to maintain, develop and improve one's knowledge, skills and competences to work effectively and safely"<sup>10</sup>.

Credentialing in this healthcare setting has grown proportionally to the new forms of treatment that are enabled by advancing technologies. Many of these specialties and subspecialties have national and international exams which healthcare workers can pursue. This is also true in the cath lab. The Registered Cardiovascular Invasive Specialist<sup>11</sup> is one example of a credential earned by cath lab radiographers around the world. In addition to their radiography training, the cath lab radiographer often seeks credentials in sonography, electrophysiology and a growing list of other areas. The cath lab radiographer who earns these secondary credentials demonstrates not only fundamental knowledge but also a dedication to their professional development.

## THE FUTURE

Mortality from myocardial infarction has dropped dramatically – by 80% since the 1950s – due to technological advancements, and the cath lab has contributed to that success<sup>12</sup>. Future technology capability will enable more sophisticated procedures, improving patient and operator safety, and expand the use of minimally invasive cardiovascular procedures into areas that were previously only the domain of surgeons. The fusion of x-ray and MRI/CTA are already changing the way catheterisations are performed on patients with cardiovascular disease. Radiographers will soon be

performing advanced 3-D imaging to facilitate more accurate navigation inside vessels and device placement. Advanced visualisation will include free-floating and 3-D holographic images, and robotic systems for peripheral, coronary and electrophysiology procedures will soon become standard practice in the cath lab. Ionising radiation could soon be eliminated from the cath lab as the use of MRI image guidance replaces x-ray based imaging. The ability to visualise all the patient's anatomy, not just an x-ray of unblocked coronary artery lumens, holds tremendous potential.

From the first cardiac catheterisation, when Werner Forssmann walked to the x-ray department to confirm the placement of a catheter in his arm, to the use of sophisticated three-dimensional imaging to replace valves in a heart, the radiographer has contributed to the diagnosis and treatment of millions of patients.

## CONCLUSION

This chapter attempts to demonstrate the rapidly evolving role of the radiographer. Although the challenges are many, with the support and guidance of the EFRS and ISRRT and an unwavering dedication to patient care, the radiographer will continue to make significant contributions to the cardiovascular care team.

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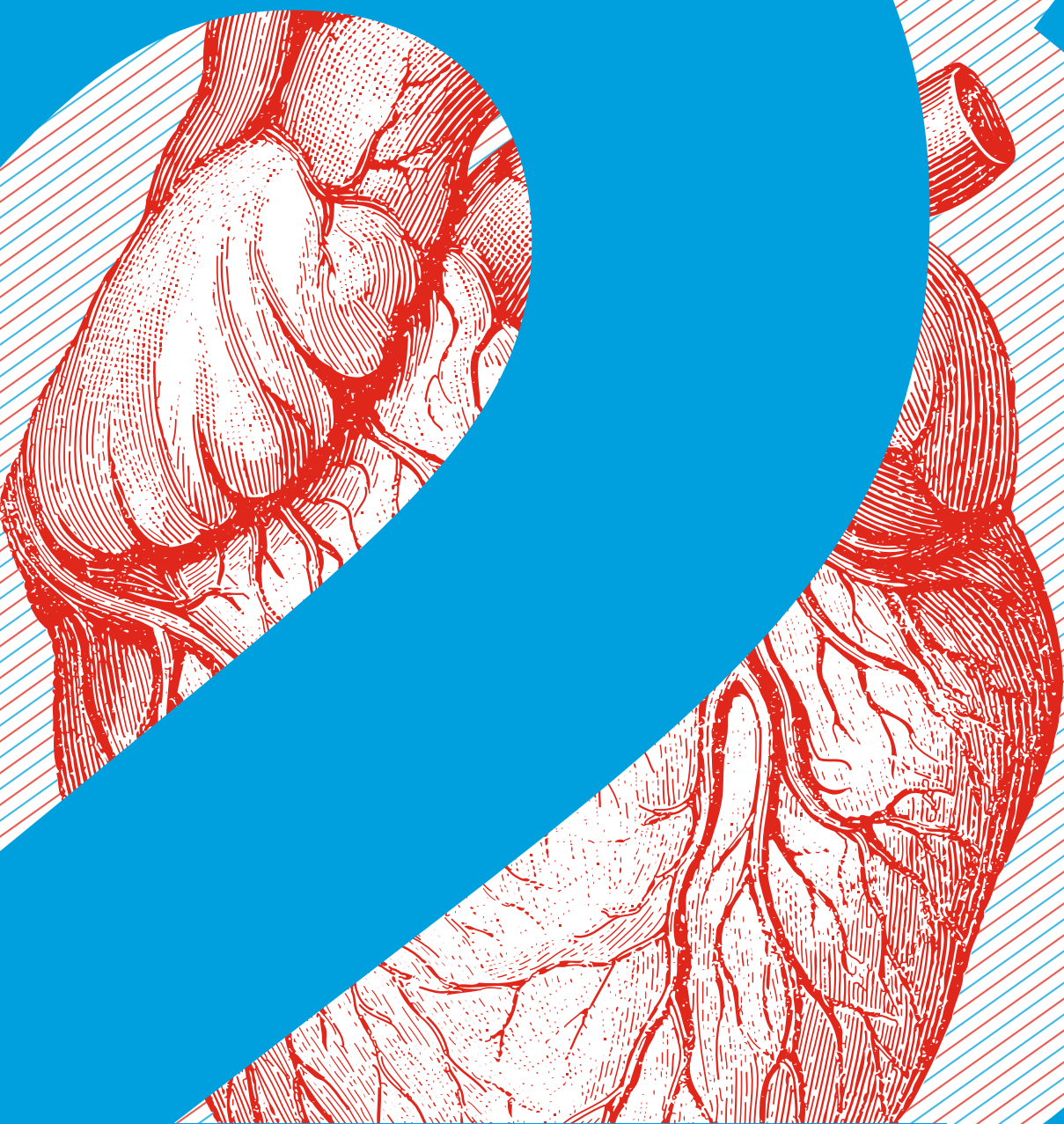
Mr. Catania is founder and CEO of A.I.T.R.I., the Italian Association of Interventional Radiographers, a national scientific association accredited by the Italian Ministry of Health. He conducts research and training programmes aimed at all health professionals. Since its foundation, he has worked with the purpose to increase and improve the teaching and research in diagnostic disciplines especially in the area of interventional radiology, through the organisation of national and international conferences. He was given an award by the National Federation of Colleges TSRM (radiographers' professional body). He has developed the 'Guidelines and Operational Standards for Radiographers and Medical Radiology Technicians in Radiology and Interventional Cardiology' and is Study Group member for Quality Assurance in Interventional Radiology at the Italian National Institute of Health.

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CARDIAC  
IMAGING IN  
RADIOLOGY -  
THE EFOMP  
PERSPECTIVE

# CARDIAC IMAGING IN RADIOLOGY – THE EFOMP PERSPECTIVE

BY MIKA KORTESNIEMI AND TOUKO KAASALAINEN

## INTRODUCTION

Medical imaging of the heart involves high temporal and spatial resolution<sup>1</sup>. It also affects patient populations in modern society with a higher prevalence of cardiac diseases. This in turn has an effect on the overall economy and quality of life. Coronary artery disease (CAD) causes more than 17 million deaths per year and is the leading cause of mortality globally<sup>2</sup>. Therefore, the technical, clinical, and socio-economical stakes are high when we consider cardiac imaging. Along with the technical development and demands of cost-efficiency in healthcare services, there is a continuous pressure to improve competence and patient safety, as well as the specialisation and efficiency of the diagnostic process. This also affects medical physicists<sup>3</sup>. The optimal usage of equipment described by patient flow, the optimal utilisation of equipment features indicated by specialised diagnostic protocols and radiological optimisation (for radiation protection) are all relevant topics in which medical physicists must be competent.

The requirements for sufficient competence for medical physicists and a definition of their professional responsibility are also laid down by the European Union Council Directive 2013/59/Euratom. Here the basic safety standards for protection against dangers arising from exposure

to ionising radiation are described<sup>4</sup>. Medical physicists are responsible for the standardisation and calibration of medical equipment, so as to further ensure the accuracy and safety of the applications and physical methods used in clinical settings<sup>3</sup>. Emphasised by the on-going technological development of healthcare equipment and applications, the successful execution of tasks fulfilled by medical physicists builds increasingly upon clinically relevant parameters and multiprofessional collaboration. The need to increase multiprofessional working also extends to other healthcare professions. Cardiac radiology is a good example of a field where these high technical and professional demands must be fulfilled consistently.

## EVOLVING MODALITIES FOR RADIOLOGICAL CARDIAC IMAGING

In CAD, catheterisation angiography has been the gold standard for a long time. However, there is a small but real risk of complications arising from invasive coronary angiography and because of that, non-invasive imaging examinations have been developed for the diagnostics and treatment chain of more stable and medically treatable states of diseases<sup>1,2,5</sup>. Luckily, imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), gated single photon computed tomography (GSPECT), positron emission tomography (PET) and ultrasound have evolved significantly over the past couple of decades and can provide what is needed for non-invasive and reliable imaging of the

heart<sup>6-12</sup>. In this chapter, we will refrain from going into extensive technical details regarding cardiac imaging technology. Instead, we will only briefly review the aspects of CT and MRI relevant for the considerations of medical physicists when they purchase new scanners and optimise their applications.

## COMPUTED TOMOGRAPHY (CT)

The evolution of CT technology has moved quickly in various directions among CT vendors. Generally, cardiac applications with CT were boosted over a decade ago by scanners with 64 slices and above<sup>9,13</sup>. In recent years, CT gantry rotation times have been reduced to less than 0.3 seconds, reaching 0.25–0.27 seconds in several scanner models, and a new goal of a 0.2 second rotation time is currently being pursued<sup>14</sup>. Rotation time has a clear impact on cardiac CT imaging because it directly affects the temporal resolution, which is an essential factor in image quality and relates to the clinical range of cardiac pulse rates.

In addition to the reduced rotation times, dual-source scanners, wider detector coverage, iterative reconstructions and motion-artefact corrections have made improvements to cardiac CT image quality and coverage of the whole heart in one fast axial or helical scan possible<sup>7,14</sup>. Examples of 3D coronary CT images obtained with dual-source scanner are shown in Figure 1.

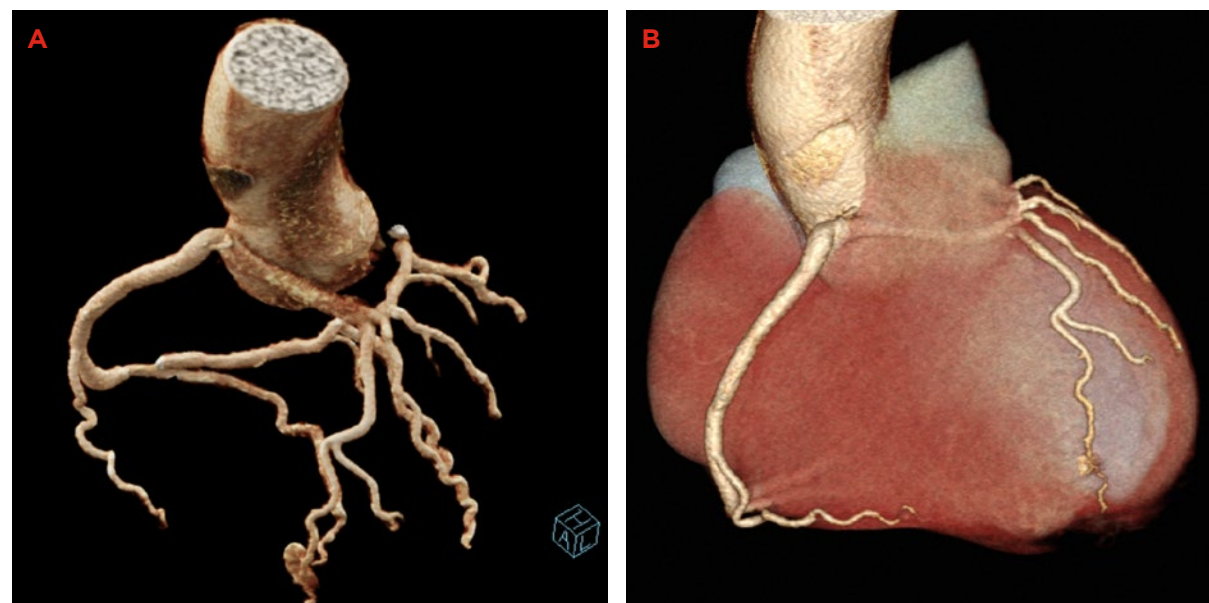
In order to acquire a comprehensive set of image data from all cardiac cycle

phases for left ventricle function and wall motion evaluation, continuous exposure and scanning is required. This involves a higher radiation exposure for the patient. However, if the image data is only required from a certain cardiac phase, the ECG-gated scan may reduce radiation dose considerably, because the exposure is given only for a fraction of the overall scan time<sup>5</sup>. These dose saving features are included in all modern cardiac CT scanner configurations.

Contrast-enhanced CT provides anatomical data and it may extend to cardiac CT perfusion studies (CCTP) with functional stenosis assessment during vasodilation stress typically induced with adenosine<sup>15,16</sup>. Dual-energy CT cardiac perfusion scans may further improve diagnostic quality by providing iodine maps and by decreasing the beam hardening artefacts in the images<sup>17-19</sup>. The more recent cardiac imaging applications also include CT fractional flow reserve imaging (CT-FFR) using computational flow

Figure 1

Volume renderings of the cardiac CT data showing an anomaly where all coronary arteries begin from the right coronary cusp and the left main branch follows the interarterial route between the pulmonary branch and the aorta. Accurate 3D representation during the CT examination facilitates the interpretation of the complex cardiac anatomy for the clinicians. The cardiac CT scan was performed with a dual-source CT scanner (120 kVp, CTDIvol 11 mGy, DLP 190 mGycm, effective dose 3 mSv, 75 ms temporal resolution, 55 bpm pulse rate). Images courtesy of Dr. Sari Kivistö, HUS Medical Imaging Center, Finland.



dynamics to determine the blood flow for all segments of the coronary circulation non-invasively and to depict lesion specific ischaemia<sup>20, 21</sup>.

## MAGNETIC RESONANCE IMAGING (MRI)

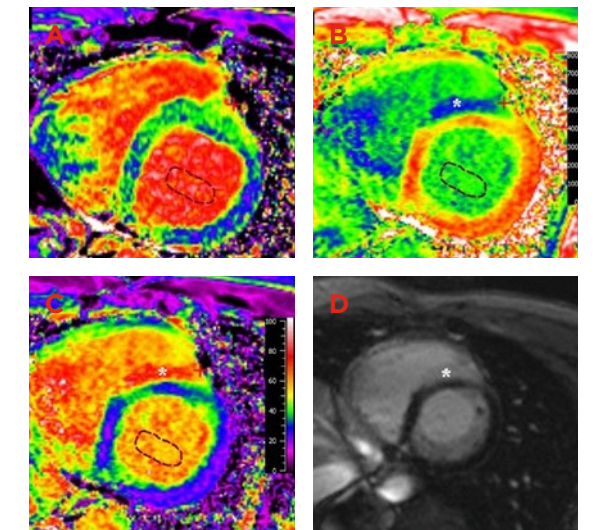
Cardiovascular magnetic resonance (CMR) imaging has become a routinely used imaging modality in the diagnosis of cardiovascular diseases without exposing the patient to ionising radiation<sup>22</sup>. CMR does not only make accurate assessment of myocardial morphology and function possible, but also shows focal fibrosis and infiltration. Late gadolinium-enhancement (LGE) imaging is one of the most important applications of CMR. It is widely used in predicting adverse cardiovascular outcomes e.g. in ischaemic and non-ischaemic heart diseases as LGE has proved to be associated with increased risk of all-cause

mortality and sudden cardiac deaths<sup>23</sup>. Thus, LGE imaging is used to guide risk stratification and patient management.

Improvements in MRI technology and the introduction of novel MRI sequences have enabled more reliable quantitative myocardial tissue characterisation. For example, pre- and post-contrast pixel-wise T1 mapping has become a promising technique for non-invasive evaluation of diffuse myocardial fibrosis and inflammation, whereas T2 mapping and T2\* mapping are used for oedema imaging and iron deposition determinations respectively<sup>24-27</sup>. The T1 relaxation time (a measure of how fast the nuclear spin magnetisation recovers back to its equilibrium state after a radiofrequency pulse) of myocardium is becoming an essential biomarker for a variety of pathological conditions<sup>24</sup>. By using both pre- and post-contrast T1 mapping and patient haematocrit, it is possible to determine extracellular volume (ECV), which in turn aims to quantify the relative expansion

Figure 2

A pre-contrast T1 map (A), post-contrast T1 map (B), calculated ECV map (C) and LGE image (D) of a patient with suspected sarcoidosis. 3T CMR examination revealed hypertrophy in the anterior septum, and in the same area, a large enhancement in LGE image was seen (marked with \*). The post-contrast T1 map showed significantly decreased T1 relaxation time (~220 ms) in this area of the myocardium compared to the normal myocardium (~520 ms). The corresponding ECV was increased up to a value of 75, whereas ECV was less than 30% in the normal myocardium. Patient haematocrit was 42%. Images were acquired in HUS Medical Imaging Center, Finland.





of the extracellular matrix as a result of diffuse fibrosis (Figure 2). CMR can also be used for myocardial perfusion imaging in diagnosing CAD.

Traditionally, clinical CMR studies have been performed at 1.5T due to artefact-free images. However, recent developments in MRI technology (e.g. multi-transmit parallel radiofrequency transmission technology) have shifted clinical studies more and more towards 3T, as higher magnetic field strength is known to improve signal-to-noise and contrast-to-noise ratios. Regardless of the benefits and developments in MRI technology, 3T CMR may still suffer from the presence of image artefacts due to B1 inhomogeneity and also because of problems in ECG-gating.

## MEDICAL PHYSICIST ROLE IN CARDIAC RADIOLOGY

In radiology, medical physicists are mainly involved in quality assurance, dosimetry and optimisation<sup>3</sup>. Optimisation is a comprehensive task and is a cornerstone of the responsibilities of a medical physicist. In any radiological examination there should be a joint effort to bind the knowledge of radiologists, cardiologists, technologists and medical physicists together in order to reach optimal image quality compared to cost or risk parameters. Cardiac imaging forms a specific sub-field of radiology, which also includes implementation of new imaging methods and clinical applications. Optimisation of imaging parameters is a common and highly demanding challenge

in CT protocols as well as in MRI sequences. Depending on the indication, appropriate cardiac cycle specific gating of raw data acquisition affects both image quality through motion artefacts, and radiation exposure in CT due to the effective cumulative scan time. Selection of the optimal temporal scan window is not a straightforward task in CT because the most static phase of the cardiac cycle may occur in the phase of diastole, usually in stable and lower <70 bpm pulse frequencies – or during the end-systolic phase with faster and more irregular beat patterns<sup>28, 29</sup>. Therefore, in-depth knowledge of the scanner features and clinical process is needed in order to handle the overall patient flow and to maintain consistent image quality with various individual patients.

In CMR, image quality may also be lower than ideal due to heart and respiratory motion, not forgetting the impacts of implants and prosthesis on image quality. For example, CMR examinations in patients with cardiac pacing devices may require the presence of a medical physicist to optimise pulse sequences. Cardiac imaging in radiology may also involve methods where standard quality assurance does not provide full coverage through standard metrics, e.g. in iodine maps in dual-energy CT, dynamic ECG-triggering or gating for motion compensation, blood flow and volume quantification, and also spectroscopic and metabolic imaging extending to specifics such as iron loading levels. Therefore, more elaborate quality assurance methods relating to cardiac imaging require specific equipment such as dynamic motion, flow-controlled, or material specific phantoms, which are

optimally connected to an ECG-signal source for clinically relevant testing<sup>30, 31</sup>.

The dosimetry for the determination of radiation exposure in x-ray cardiac imaging may also require the use of more developed methods, especially when dosimetry results are used for the optimisation of clinical scans. Patient-specific dosimetry goes beyond the standard methods by definition. All these aspects indicate that medical physicists need to have sufficient training and knowledge to make an effective contribution to the multi-professional imaging team.

This also calls for appropriate continual professional development of the medical physicists currently working in radiology and cardiology departments, so as to update and maintain their knowledge<sup>32</sup>. This knowledge must be paralleled by technical developments in cardiac imaging modalities, covering angiography equipment, CT, MRI, and ultrasound systems – and should extend to hybrid devices used in the middle ground between radiology, cardiology, and nuclear medicine. Such a unique level of multidisciplinary and multi-professionalism also makes for excellent research topics (e.g. Euramet 15HLT05 Empir project<sup>33</sup>), and further down the line, may demonstrate the increasing value of modern diagnostics to healthcare.

## CONCLUSION

Cardiac imaging in radiology is highly demanding both technically and professionally. The medical physicists' professional role in cardiac imaging mainly involves quality

assurance, dosimetry and optimisation. Optimisation of cardiac imaging technique should be a multiprofessional effort with adequate combined knowledge and competence, so as to utilise the advanced features of modern diagnostic modalities, which in turn emphasise the benefits of latest CT and MRI applications.

## ACKNOWLEDGEMENTS

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## Chapter 6:

**THE HEART CAUGHT A COLD:  
CARDIAC MRI IN MYOCARDITIS**

By Charles Peebles

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TO FUNCTION AND BEYOND**

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By Jens Bremerich

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By Matthias Gutberlet

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#### Chapter 14:

##### **CERTIFICATE OF EXCELLENCE: THE EUROPEAN DIPLOMA IN CARDIOVASCULAR RADIOLOGY**

By Karl-Friedrich Kreitner

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- 2 European Diploma in Cardiovascular Imaging: <http://www.escr.org/cms/website.php?id=en/education/diploma.htm>

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##### **ARTIFICIAL INTELLIGENCE AND CARDIOVASCULAR DISEASE – FRIEND OR FOE?**

By Tim Leiner, Jelmer M. Wolterink and Ivana Išgum

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By Luigi Natale and Veronica Bordonaro

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By Christian Loewe

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##### **INFLUENCE OF PROTOCOL OPTIMISATION ON RADIATION EXPOSURE IN CARDIAC IMAGING**

By Valentin Sinityn and Maria Glazkova, on behalf of EuroSafe Imaging

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#### Further reading

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