Heart muscle disease and cardiovascular magnetic resonance imaging

This article introduces the reader to the different types of heart muscle disease which are commonly encountered in clinical practice. It then discusses cardiovascular magnetic resonance and explains how it can help in the work up of these diverse conditions.

The myocardium of the human heart is made up of a complex structure of myocytes, blood vessels and extracellular matrix. Among other important properties, myocytes provide contractile function, while the extracellular matrix provides scaffolding and structure. The extracellular matrix is made up of a number of proteins including collagen (particularly type 1, which provides tensile strength) and glycoproteins (Eghbali and Weber, 1990). While myocytes can hypertrophy, there is little ability for them to be replenished once lost (Bostrom and Frisen, 2013). The extracellular matrix can be altered by exposure to physiological (such as intense training) or pathological insults (such as increased wall stress in hypertension or direct toxicity caused by some chemotherapeutic agents) (Sado et al, 2011). These disturb the extracellular matrix homeostasis by causing activation of inflammatory cells, mediators and cardiac fibroblasts. The latter produce increased amounts of collagen which, along with potentially reduced breakdown, results in fibrosis formation (Swynghedauw, 1999).

Heart muscle diseases can be inherited or acquired. Both can cause heart failure. The treatment depends on securing an accurate diagnosis and assessment of disease extent – the structural and functional changes present. Detailed cardiological work up should ideally aim to provide an underlying diagnosis and prognosis, determine the potential for inheritance by other family members, and suggest and then monitor therapy.

The imaging investigation of heart muscle disease

The primary imaging investigation is transthoracic echocardiography. This is relatively cheap, widely available, can be performed on any patient and demonstrates cardiac structure and ventricular size, function (systolic and diastolic) and wall thickness. It also allows evaluation of valves and intra-cardiac shunts. Diagnostic accuracy is highest with full blown disease but less robust for aetiology in both early and very advanced disease. There is also little capability for myocardial tissue characterization. For example, dilated, hypertrophic and ischaemic cardiomyopathy may all enter a final common pathway of apparent global dilatation and poor function with few residual clues to aetiology on single time point echocardiography alone.

Echocardiography image quality varies in a number of ways: either by disease (e.g. region of the left ventricle – the apex is not well seen), patient factors such as acoustic windows (reduced in up to a third of patients), with the operator (training/skill related variability), service related (equipment, availability of clinical information, old scans online for side-by-side comparison and the ability to review images in multidisciplinary meetings) and advanced capabilities (contrast availability, three-dimensional, other advanced echocardiography techniques) (Thavendiranathan et al, 2013).

All these factors may affect the overall performance of the modality and reduce accuracy and precision both for individual patients and groups (overall service performance or clinical trials where reproducibility determines power calculations) (Grothues et al, 2002). In clinical practice, measurements such as the ejection fraction, an important cardiac biomarker, may determine key treatment thresholds, for example UK guidelines for cardiac resynchronization require the patient, among other things, to have an ejection fraction <35% to be a candidate for device insertion (National Institute for Health and Care Excellence, 2007).

Introduction to cardiovascular magnetic resonance

Magnetic resonance imaging uses the abundance of hydrogen protons in the human body. At a basic level, when placed in a powerful magnetic field (1.5 or 3 Tesla in current clinical practice), each proton becomes a 'mini magnet' and aligns with the direction of the main magnetic field. Application of a radiofrequency pulse disturbs the proton alignment and provides them with energy and coherence. Once the pulse has been delivered, the protons return to their resting state in a manner described by the three rate constants T1, T2 and T2*. A receiver coil on the patient can pick up the energy released in this process and after advanced mathematical processing, a

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black and white image of the slice selected is produced for the operator to see. As the heart moves both with contraction and respiration, cardiac electrocardiogram gating and (typically) breath-holds are used. Most cardiovascular magnetic resonance views require 6–12 seconds of scanning and a patient is asked to hold his/her breath for that duration.

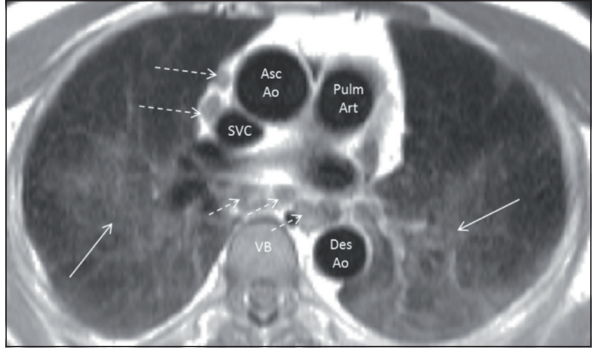
Cardiovascular magnetic resonance scans are highly codified and acquisitions stereotyped under international guidelines (Kramer et al, 2008). A typical normal study will provide information regarding thoracic and cardiac anatomy, ventricular mass, function and perfusion following adenosine infusion and lastly the presence of focal extracellular space expansion.

All studies begin with piloting and anatomical slices of the thorax for extracardiac pathology. These are particularly useful for looking at extracardiac anatomy – visualizing organs (lungs, liver, kidneys, lymph nodes and vasculature) (*Figure 1*) and some disease processes. For example, fluid overload as a result of cardiac decompensation, infiltration with sarcoidosis and congenital abnormalities can be seen.

Following this, cine imaging is performed in the long and short axis planes. These allow appreciation of cardiac anatomy and ventricular volumes, ejection fraction and mass. The images obtained are of high spatial resolution and can always be piloted in the correct heart axis, resulting in excellent reproducibility of ventricular measurements of size, function and mass (*Figure 2*). Compared to echocardiography, this may translate into large reductions in sample size in clinical trials (Grothues et al, 2002).

Following cine imaging, for ischaemic cardiomyopathy, perfusion following intravenous adenosine infusion is often performed. For heart muscle diseases, tissue characterization techniques without contrast typically follow: T2 assessment will show areas of myocardial oedema in myocarditis (Eitel and Friedrich, 2011), T2* will show iron overloading (Anderson et al, 2001), T1 will show fat (Sado et al, 2013), fibrosis (Dass et al, 2012), amyloid

Figure 1. A transverse mid-thoracic anatomical image of a patient with sarcoidosis. There is diffuse lung parenchymal disease (arrows). There is also widespread lymphadenopathy (dotted arrows). Asc Ao = ascending aorta; Des Ao = descending aorta; Pulm Art = pulmonary artery; SVC = superior vena cava; VB = vertebral body.



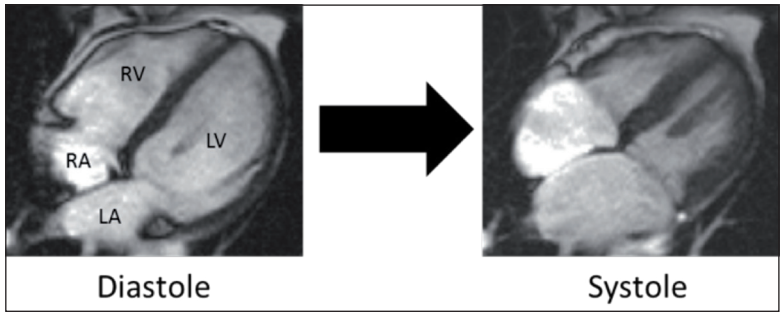


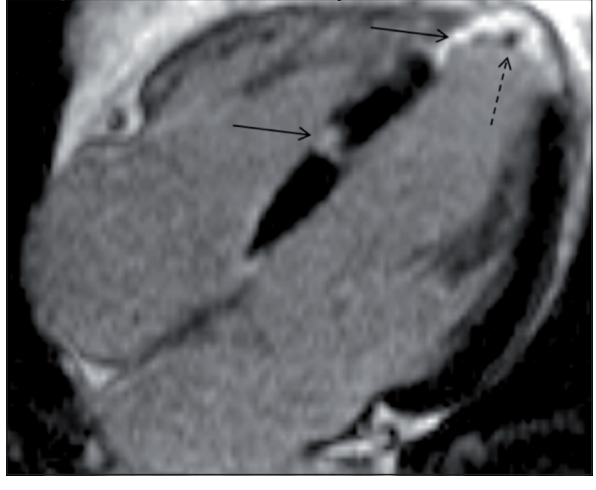
Figure 2. End diastolic and end systolic stills taken from a cine 4-chamber sequence in a healthy volunteer. All ventricular segments are seen to have contracted normally. LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle.

infiltration (Karamitsos et al, 2013) and oedema (Ferreira et al, 2012). Other techniques may include flow sequences allow assessment of shunts, stenotic or regurgitant valvular disease. Following this, a gadolinium-based contrast agent is administered intravenously. These are extracellular markers and accumulate passively in areas of interstitial, extracellular volume expansion from fibrosis, oedema or infiltration with amyloidosis. The late gadolinium enhancement technique (*Figure 3*), detects such focal accumulations – scar or oedema imaging – a major benefit of cardiovascular magnetic resonance; while newer techniques (T1 mapping for extracellular volume) may also detect global myocardial changes.

Limitations of cardiovascular magnetic resonance

The main limitations of cardiovascular magnetic resonance from a patient perspective are claustrophobia

Figure 3. An late gadolinium enhancement image from a patient who presented with an ST elevation myocardial infarction 6 weeks before the cardiovascular magnetic resonance. A stent was deployed in the mid portion of the left anterior descending artery. There is a transmural left ventricular apical scar with a second scar in the mid septum (arrowed). The latter may well be from a jailed septal branch from the stent. Of note, a small thrombus (seen as black on this image as the thrombus is avascular and so does not take up contrast) is also seen at the apex (dotted arrow).



(around 10% of patients will be claustrophobic, with around 2% unable to complete the study as a result) (Francis and Pennell, 2000) and the requirement for the patient to be able to lie flat for the duration of the study (hence patients with severe decompensated heart failure should undergo treatment to improve their symptoms before cardiovascular magnetic resonance is considered). Other potential limitations include patients with renal failure if the estimated glomerular filtration rate <30 ml/min as this conveys a risk of developing nephrogenic systemic fibrosis. This risk appears to be less with cyclic agents at low dose with risk:benefit calculation required for the individual. The presence of magnetic resonance incompatible devices, such as pacemakers, contraindicates cardiovascular magnetic resonance, although over recent years, magnetic resonance conditional pacemakers have been marketed and are being increasingly used, with the first magnetic resonance conditional implantable cardioverter defibrillator now available in Europe. Other general limitations are availability (which is improving) (Antony et al, 2011) and cost.

Overall therefore, both transthoracic echocardiography and cardiovascular magnetic resonance have advantages and disadvantages in the assessment of heart muscle disease and should be considered complementary techniques. In the next section, the role of cardiovascular magnetic resonance in various different heart muscle diseases will be discussed.

The role of cardiovascular magnetic resonance in heart muscle diseases

The dilated, poorly functioning left ventricle

These are typically divided into ischaemic and non-ischaemic aetiologies. Myocardial infarction causes a specific late gadolinium enhancement pattern which will involve the subendocardium and may spread into the mid and epicardium (*Figure 3*). Visualizing infarction like this is a good test for diagnosing ischaemic cardiomyopathy and can be used as a 'gatekeeper' for coronary angiography (Assomull et al, 2011). Left ventricular impairment without much infarction may suggest hibernating myocardium and predicts a good response to revascularization – although the patient must be fit enough for the revascularization procedure, receive adequate revascularization, avoid further infarction and not have dual pathology. Minimal infarction also predicts a good response to medical therapy. Visualizing infarction also helps with resynchronization; in patients with ischaemic cardiomyopathy being considered for cardiac resynchronization pacemaker therapy, lateral left ventricular scar predicts poor response, but the operator may be able to use the cardiovascular magnetic resonance information to target an area for the pacemaker lead which will avoid the area of scar (Leyva et al, 2011).

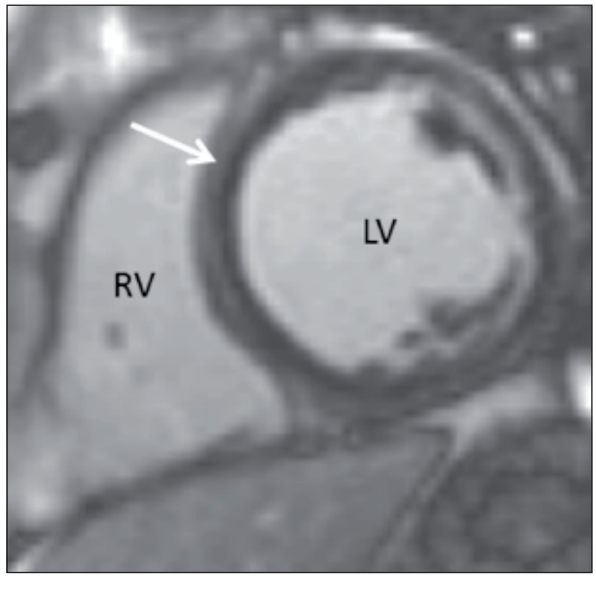
For non-ischaemic dilated cardiomyopathy, the late gadolinium enhancement pattern may provide clues to the aetiology. Specific features overall may be found in sarcoidosis (extracardiac findings, infarct-like late gadolinium enhancement), myocarditis (oedema and late gadolinium enhancement pattern – often present in the basal to mid inferolateral wall), muscular dystrophies (late gadolinium enhancement in the basal inferolateral wall), haemochromatosis (decreased T2* from iron) and arrhythmogenic left ventricular cardiomyopathy (fat on T1-weighted sequences late gadolinium enhancement, often seen in the basal to mid inferolateral wall). However, in many cases no cause for the dilated cardiomyopathy is found and it is therefore known as idiopathic. In such patients, 30–40% will have late gadolinium enhancement affecting the mid wall, particularly in the septum. Gulati et al (2013) found that the presence and extent of such late gadolinium enhancement is predictive of a worse prognosis (*Figure 4*).

Increased left ventricular wall thickness

There are many causes of increased left ventricular wall thickness. These can be inherited or acquired. The most common inherited cause is hypertrophic cardiomyopathy, defined as the presence of unexplained myocardial hypertrophy (i.e. no increased afterload present, such as aortic stenosis or hypertension) (Elliott et al, 2008). Patients can present with breathlessness, chest pain, occasionally syncope and rarely (but devastatingly) with sudden death and are found to have an abnormal electrocardiogram and left ventricular hypertrophy on echocardiography – often but not exclusively, asymmetric (*Figure 5a*).

Most patients with hypertrophic cardiomyopathy have a supra-normal ejection fraction (as the increased wall thickness replaces left ventricular cavity space), but 10%

Figure 4. Short axis late gadolinium enhancement images in a patient with idiopathic dilated cardiomyopathy. Late gadolinium enhancement is seen in the mid wall of the septum (white arrow) and does not involve the subendocardial layer, hence being non-ischaemic (as compared to* Figure 3*). LV = left ventricle, RV = right ventricle.



will eventually develop a 'dilated' phenotype with thinning and progressive ejection fraction decline. Imaging is often characteristic. The hypertrophy is often highly regional and left ventricular cavity or outflow tract obstruction may be present at rest or stress. Most hypertrophic cardiomyopathy patients will have varying extents of non-ischaemic late gadolinium enhancement with a number of characteristic patterns. Higher amounts of late gadolinium enhancement are predictive of developing a dilating phenotype and weakly predictive of arrhythmic events and possibly sudden cardiac death (Appelbaum et al, 2012).

Cardiovascular magnetic resonance is useful to ensure that mimics (genocopies and phenocopies) are not missed. Anderson-Fabry disease, a rare but treatable X-linked disorder causing a deficiency in the enzyme alpha galactosidase resulting in accumulation of intracellular sphingolipid (*Figure 5c*), can mimic hypertrophic cardiomyopathy. Anderson-Fabry disease has extracardiac 'red flags' such as renal impairment, a characteristic bathing trunk rash and peripheral pain. On imaging, the hypertrophy is usually more concentric, more biventricular and with less obstruction. There is commonly basal inferolateral late gadolinium enhancement. A new observation is of a low native myocardial T1 on cardiovascular magnetic resonance – probably from the global intracellular fat – a very unique and highly sensitive and specific finding for this disease (*Figure 6*) (Sado et al, 2013). Of note, the quantitative assessment of native myocardial T1, T2 and T2* using mapping techniques is a rapidly emerging field. Direct quantification of these parameters offers many advantages, particularly in the assessment of diseases which diffusely affect the myocardium. *Table 1* shows some of the uses of these techniques.

Definitive diagnosis of Anderson-Fabry disease may be a blood test for alpha galactosidase (males) and blood genetic testing (males and females). Other mimics include hypertensive heart disease (especially Afro-Caribbean), other storage diseases, acute myocarditis with gross oedema, and amyloidosis which will be discussed in more detail.

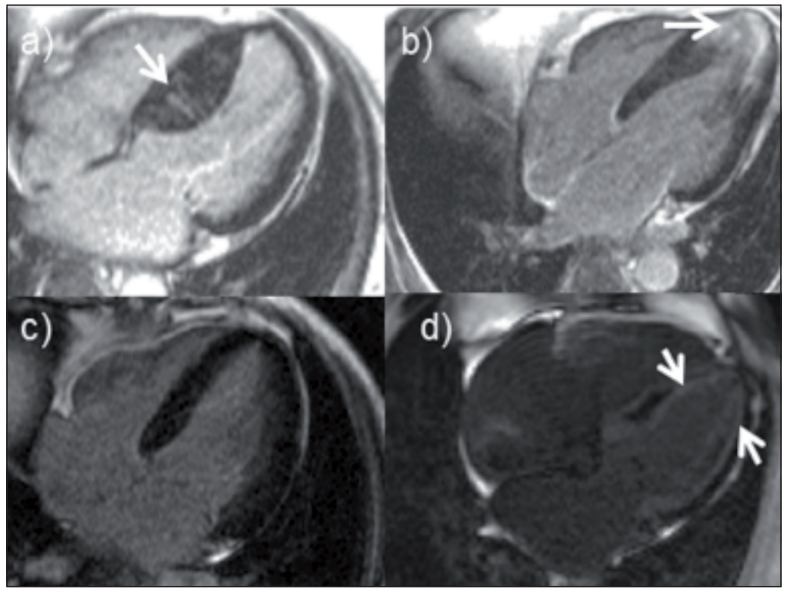
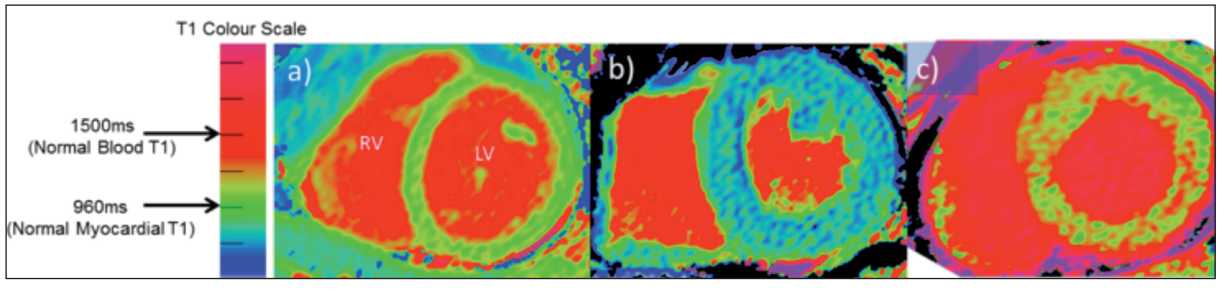


Figure 5. Different patterns of increased left ventricular wall thickness and late gadolinium enhancement. a. Asymmetrical septal increased wall thickness (arrowed) with patchy septal late gadolinium enhancement. This is a classical presentation of hypertrophic cardiomyopathy. b. Increased wall thickness only at the left ventricular apex, which also has late gadolinium enhancement (arrowed). This patient has apical predominant hypertrophic cardiomyopathy. In c and d there is a concentric increase in left ventricular wall thickness. c. There is no late gadolinium enhancement but the native myocardial T1 performed earlier in the study (not shown) was found to be low. This patient has Anderson-Fabry disease. d. There is global subendocardial late gadolinium enhancement in a zebra stripe septal pattern and altered gadolinium kinetics. This is diagnostic of cardiac light chain (AL) amyloidosis.

Table 1. Cardiovascular magnetic resonance rate constant changes in disease

Parameter	Pathophysiology causing an increase in parameter value	Pathophysiology causing a decrease in parameter value
Native myocardial T1	Fibrosis, oedema or infiltration	Fat, iron overload or haemorrhage
Native myocardial T2	Oedema	Iron overload
Native myocardial T2*	None known	Iron overload

Figure 6. Native myocardial T1 mapping. a. A healthy volunteer basal ventricular short axis slice is shown. Each pixel is assigned a colour determined by its T1 using the scale shown. For this sequence, normal myocardium measures 960 ms and is assigned to be green. b. A patient with Anderson-Fabry disease and left ventricular hypertrophy is shown. The myocardial T1 is decreased (and hence shows with a blue shade). This is a highly sensitive and specific finding for a diagnosis of Anderson-Fabry disease. c. A patient with AL amyloidois and left ventricular hypertrophy is shown. Here the myocardial T1 is increased (and hence shows with a red shade). The very long T1 (coloured purple) around the heart shows a small pericardial effusion. These findings are typical in AL amyloidosis with cardiac involvement.

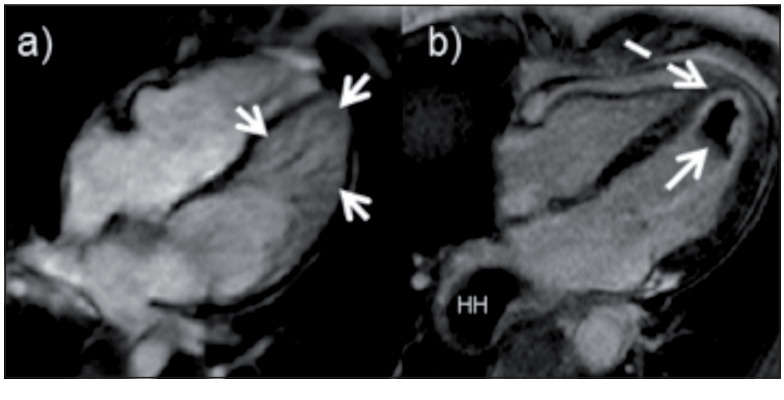


Two types of amyloidosis typically infiltrate the ventricular myocardium: immunoglobulin light-chain (AL or primary systemic) and transthyretin (ATTR). ATTR encompasses senile systemic amyloidosis in which wild type transthyretin is deposited as amyloid and hereditary forms, where genetic variants of transthyretin are implicated. In AL amyloidosis, cardiac involvement is frequent and drives the prognosis, which is poor without chemotherapy to switch off light chain production (Selvanayagam et al, 2007). Early recognition and prompt initiation of therapy is critical, and treatment is more aggressive when cardiac involvement is detected.

ATTR amyloidosis presents more indolently. It is common over the age of 80 years (senile systemic) and in some groups such as UK Afro-Caribbean patients, where mutation carriage is up to 3%. Systemic features include autonomic features or carpal tunnel syndrome, but sometimes the presentation is cardiac only. Echocardiography is the first-line imaging modality to diagnose cardiac amyloidosis and has high diagnostic accuracy in advanced disease but less in early disease or when there are confounders such as renal disease or hypertension. Tissue characterization with cardiovascular magnetic resonance is extremely useful (Maceira et al, 2005).

Using late gadolinium enhancement, cardiac amyloidosis is associated with a unique pattern of late circumferential enhancement of the subendocardium of both ventricles, with the characteristic zebra-stripe appearance of the interventricular septum (*Figure 5d*). The altered gadolinium kinetics and the subendocardial late gadolinium enhancement pattern are highly specific for amyloidosis, making cardiovascular magnetic resonance the gold standard for the non-invasive diagnosis of this disease. T1 mapping also shows high diagnostic accuracy for detecting both AL and ATTR amyloidosis providing incremental benefit, with the non-contrast T1 having particular value in those AL patients with renal failure with an estimated glomerular filtration rate <30 ml/min, contraindicating the use of gadolinium (Karamitsos et al, 2013; Fontana et al, 2014). T1 mapping-based techniques provide quantitative data, having the potential to be the first non-invasive marker of cardiac amyloid burden (*Figure 6c*), and is now being used as an end point in a clinical therapy trial for amyloidosis.

Figure 7. a. Hypertrabeculation at the left ventricular apex and mid walls (arrowed). This patient has a diagnosis of left ventricular non compaction. b. Different patient with a large apical thrombus (arrowed) with surrounding subendocardial enhancement (dotted arrow). The apical wall motion was normal. The patient was found to have a high eosinophil and a diagnosis of hypereosinophilic syndrome made. Note is also made of a large hiatus hernia (marked HH).



Heart muscle diseases predominantly affecting the left ventricular apex

Cardiovascular magnetic resonance allows detailed assessment of the left ventricular apex. Hypertrophic cardiomyopathy can sometimes present with an apical predominant phenotype (*Figure 5b*). Here the long axis cine images will demonstrate the presence and amount of hypertrophy, whether or not an apical aneurysm is present and the extent of apical cavity obliteration in systole. Late gadolinium enhancement will show the presence or absence of fibrosis in apical predominant hypertrophic cardiomyopathy which may be related to monomorphic ventricular tachycardia that can be found in this condition. Another inherited condition, left ventricular non-compaction, can often predominantly affect the apex, where increased trabeculation will be present (*Figure 7a*).

This can be seen and quantified using cine imaging (Captur et al, 2013). Left ventricular non-compaction can be associated with dilated cardiomyopathy and apical thrombus. The latter can be seen using cine images and then following gadolinium contrast administration (thrombus is avascular and so will not take up the contrast). Lastly, cardiovascular magnetic resonance is useful in the work up of eosinophilic heart diseases. These can present with concentric or apical hypertrophy, apical thrombus, subendocardial late gadolinium enhancement (particularly at the apex) and apical oedema on T2 imaging (*Figure 7b*) (Syed et al, 2008).

Right ventricular predominant heart muscle disease

There are many secondary causes of right ventricular predominant heart disease. Shunts, tricuspid and pulmonary valve disease, pulmonary hypertension and pulmonary disease can all result in right ventricular dilatation and loss of function. Between transthoracic echocardiography (valve disease, pulmonary pressure estimation and shunt assessment), thoracic computed tomography (pulmonary vasculature and intrinsic lung disease) and cardiovascular magnetic resonance (shunt assessment and calculation of right ventricular size and ejection fraction), all of these potential aetiologies can be evaluated. Right ventricular involvement is common in diseases that affect the left ventricle but under-recognized. Arrhythmogenic right ventricular cardiomyopathy is the exemplar right-sided disease and, although rare, can have a disproportionate impact on imaging services to exclude it. Arrhythmogenic right ventricular cardiomyopathy may

pass through a phase where imaging is normal – almost like a channelopathy. In addition, left ventricular involvement has been under-recognized. Cardiovascular magnetic resonance adds considerable value for arrhythmogenic right ventricular cardiomyopathy because it can detect ventricular involvement (*Figure 8*), but also because it is a useful test to detect mimics.

These may be broadly divided into three groups: displacement of the heart (e.g. pectus excavatum), right ventricular loading (shunts such as atrial septal defects and anomalous pulmonary venous drainage), and non-arrhythmogenic right ventricular cardiomyopathy scar (e.g. sarcoidosis) (Quarta et al, 2013). These may be as prevalent as overt arrhythmogenic right ventricular cardiomyopathy. Cardiovascular magnetic resonance is still challenging in arrhythmogenic right ventricular cardiomyopathy but many of the major difficulties found in echocardiography of the right ventricle are overcome. Nevertheless, arrhythmogenic right ventricular cardiomyopathy can be a difficult diagnosis to make, with consensus guidelines suggesting major and minor cardiovascular magnetic resonance criteria but with imaging only one part of the whole diagnostic workup (Marcus et al, 2010).

Heart muscle disease in the acute patient presenting with chest pain, positive troponin and non-contributory coronary angiogram

This particular specific scenario is discussed as it is an increasingly common referral in the UK for cardiovascular magnetic resonance myocardial tissue characterization. In around 12% of such cases, the cardiovascular magnetic resonance shows that a myocardial infarction has occurred (subendocardial late enhancement) despite the 'normal' angiogram (Assomull et al, 2007). This might be the result of an embolic event, a recanalized vessel, or thrombus has occurred at the ostium of a branch vessel making all of the vessel disappear. However, more commonly the diagnosis is of myocarditis. Here, cardiovascular magnetic resonance will show oedema on T2-weighted imaging and often late gadolinium enhancement in a non-ischaemic pattern most commonly in the basal inferolateral wall (*Figure 9b*).

Some specific forms of myocarditis can also be found. In takotsubo cardiomyopathy, the patient has frequently experienced a stressful life event and presents with akinetic mid to apical left ventricular segments, but a normal angiogram. Cardiovascular magnetic resonance will demonstrate oedema in the mid to apical segments and sometimes late gadolinium enhancement (*Figure 10*).

In giant cell myocarditis, there is often left ventricular systolic impairment along with oedema and late gadolinium enhancement (*Figure 9a*) although the diagnosis can only be made following histological sampling.

Figure 8. End diastolic and end systolic images taken from a 4-chamber cine imaging stack of a patient presenting following successful resuscitation from an out of hospital cardiac arrest. The right ventricle is dilated and has poor overall systolic function with most of the free wall showing akinetic or dyskinetic wall motion. This met major cardiovascular magnetic resonance criteria for a diagnosis of arrhythmogenic right ventricular cardiomyopathy.

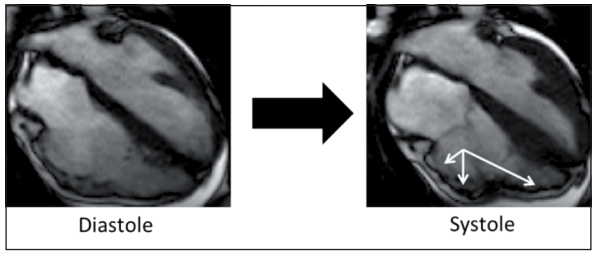


Figure 9. Short axis late gadolinium enhancement images of two patients presenting with chest pain, abnormal electrocardiogram and normal coronary angiogram. a. Transmural late gadolinium enhancement is seen in the anterior and anterolateral wall (arrow). Late gadolinium enhancement is also seen in an epicardial pattern in the septum and inferolateral wall (dotted arrows). The late gadolinium enhancement was associated with regional wall motion abnormality and an increase in T2 signal. Cardiac biopsy showed giant cell myocarditis which was treated with a high dose of steroid therapy. b. Epicardial late gadolinium enhancement is seen in the inferolateral wall. This was not associated with any regional wall motion abnormality and is a typical presentation of a viral myocarditis which was self limiting and did not require specific therapy.

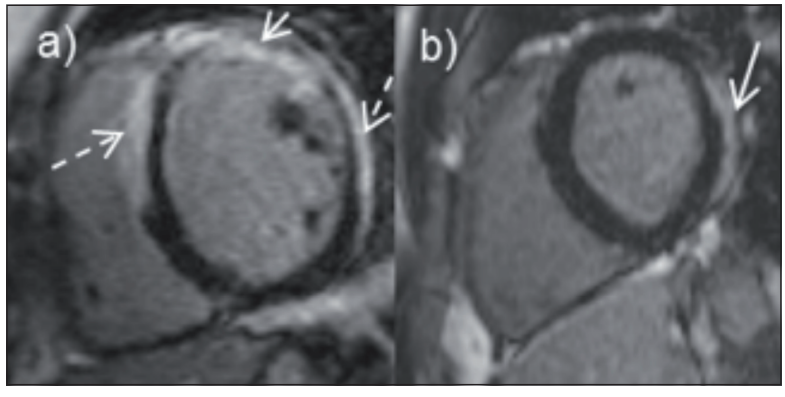
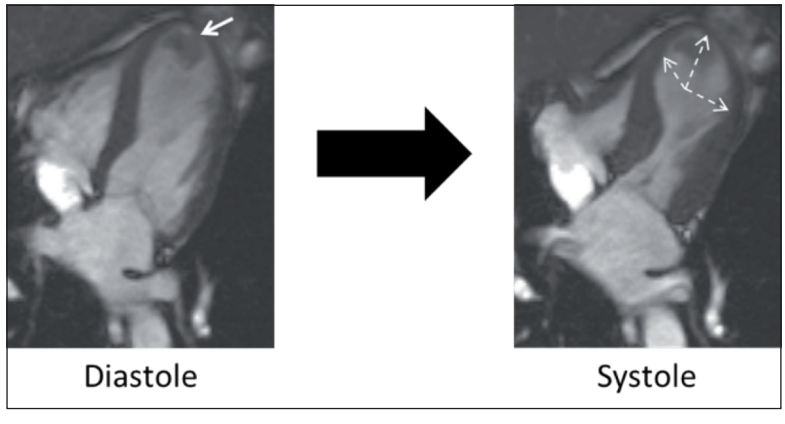


Figure 10. End diastolic and end systolic taken from a cine stack of a patient presenting with chest tightness, ST elevation, positive troponin and a normal angiogram. a. Apical thrombus is seen. b. Apical segments are all shown to be akinetic. The T2 in the apical segments was elevated, with late gadolinium enhancement also present. A diagnosis of takotsubo cardiomyopathy was made.



Conclusions

Cardiovascular magnetic resonance is an increasing used, complementary imaging technique to transthoracic echocardiography in the work up of patients with heart muscle disease. It offers the particular advantages of myocardial tissue characterization, accurate assessment of the left and right ventricular volumes, function and mass and also evaluation of the left ventricular apex. **BJHM**

Conflict of interest: none.

Anderson LJ, Holden S, Davis B et al (2001) Cardiovascular T2-star (T2*) magnetic resonance for the early diagnosis of myocardial iron overload. *Eur Heart J* **22**(23): 2171–9

Antony R, Daghem M, McCann GP et al (2011) Cardiovascular magnetic resonance activity in the United Kingdom: a survey on behalf of the British Society of Cardiovascular Magnetic Resonance. *J Cardiovasc Magn Reson* **13**: 57 (doi: 10.1186/1532-429X-13-57)

Appelbaum E, Maron BJ, Adabag S et al (2012) Intermediate-signal-intensity late gadolinium enhancement predicts ventricular tachyarrhythmias in patients with hypertrophic cardiomyopathy. *Circ Cardiovasc Imaging* **5**(1): 78–85 (doi: 10.1161/CIRCIMAGING.111.963819)

Assomull RG, Lyne JC, Keenan N et al (2007) The role of cardiovascular magnetic resonance in patients presenting with chest pain, raised troponin, and unobstructed coronary arteries. *Eur Heart J* **28**(10): 1242–9

Assomull RG, Shakespeare C, Kalra PR et al (2011) Role of cardiovascular magnetic resonance as a gatekeeper to invasive coronary angiography in patients presenting with heart failure of unknown etiology. *Circulation* **124**(12): 1351–60 (doi: 10.1161/CIRCULATIONAHA.110.011346)

Bostrom P, Frisen J (2013) New cells in old hearts. *N Engl J Med* **368**(14): 1358–60 (doi: 10.1056/NEJMcibr1300157)

Captur G, Muthurangu V, Cook C et al (2013) Quantification of left ventricular trabeculae using fractal analysis. *J Cardiovasc Magn Reson* **15**: 36 (doi: 10.1186/1532-429X-15-36)

Dass S, Suttie JJ, Piechnik SK et al (2012) Myocardial tissue characterization using magnetic resonance noncontrast t1 mapping in hypertrophic and dilated cardiomyopathy. *Circ Cardiovasc Imaging* **5**(6): 726–33 (doi: 10.1161/CIRCIMAGING.112.976738)

Eghbali M, Weber KT (1990) Collagen and the myocardium: fibrillar structure, biosynthesis and degradation in relation to hypertrophy and its regression. *Mol Cell Biochem* **96**(1): 1–14

Eitel I, Friedrich MG (2011) T2-weighted cardiovascular magnetic resonance in acute cardiac disease. *J Cardiovasc Magn Reson* **13**: 13 (doi: 10.1186/1532-429X-13-13)

Elliott P, Andersson B, Arbustini E et al (2008) Classification of the cardiomyopathies: a position statement from the European Society Of Cardiology Working Group on Myocardial and Pericardial Diseases. *Eur Heart J* **29**(2): 270–6

Ferreira VM, Piechnik SK, Dall'armellina E et al (2012) Non-contrast T1-mapping detects acute myocardial edema with high diagnostic accuracy: a comparison to T2-weighted cardiovascular magnetic resonance. *J Cardiovasc Magn Reson* **14**: 42 (doi: 10.1186/1532-429X-14-42)

Fontana M, Banypersad SM, Treibel TA et al (2014) Native myocardial T1 mapping in transthyretin amyloidosis. *JACC Imaging* **7**(2): 157–65 (doi: 10.1016/j.jcmg.2013.10.008)

Francis JM, Pennell DJ (2000) Treatment of claustrophobia for cardiovascular magnetic resonance: use and effectiveness of mild sedation. *J Cardiovasc Magn Reson* **2**(2): 139–41

Grothues F, Smith GC, Moon JC et al (2002) Comparison of interstudy reproducibility of cardiovascular magnetic resonance with two-dimensional echocardiography in normal subjects and in patients with heart failure or left ventricular hypertrophy. *Am J Cardiol* **90**(1): 29–34

Gulati A, Jabbour A, Ismail TF et al (2013) Association of fibrosis with mortality and sudden cardiac death in patients with nonischemic dilated cardiomyopathy. *JAMA* **309**(9): 896–908 (doi: 10.1001/jama.2013.1363)

Karamitsos TD, Piechnik SK, Banypersad SM et al (2013) Noncontrast T1 mapping for the diagnosis of cardiac amyloidosis. *JACC Cardiovasc Imaging* **6**(4): 488–97 (doi: 10.1016/j.jcmg.2012.11.013)

Kramer CM, Barkhausen J, Flamm SD, Kim RJ, Nagel E (2008) Standardized cardiovascular magnetic resonance imaging (CMR) protocols, society for cardiovascular magnetic resonance: board of trustees task force on standardized protocols. *J Cardiovasc Magn Reson* **10**: 35 (doi: 10.1186/1532-429X-10-35)

Leyva F, Foley PW, Chalil S et al (2011) Cardiac resynchronization therapy guided by late gadolinium-enhancement cardiovascular magnetic resonance. *J Cardiovasc Magn Reson* **13**: 29 (doi: 10.1186/1532-429X-13-29)

Maceira AM, Joshi J, Prasad SK et al (2005) Cardiovascular magnetic resonance in cardiac amyloidosis. *Circulation* **111**(2): 186–93

Marcus FI, McKenna WJ, Sherrill D et al (2010) Diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia: proposed modification of the task force criteria. *Circulation* **121**(13): 1533–41 (doi: 10.1161/CIRCULATIONAHA.108.840827)

National Institute for Health and Clinical Excellence (2007) Cardiac resynchronisation therapy for the treatment of heart failure. http://www.nice.org.uk/Guidance/TA120 (accessed 30 June 2014)

Quarta G, Husain SI, Flett AS et al (2013) Arrhythmogenic right ventricular cardiomyopathy mimics: role of cardiovascular magnetic resonance. *J Cardiovasc Magn Reson* **15**: 16 (doi: 10.1186/1532-429X-15-16)

Sado DM, Flett AS, Moon JC (2011) Novel imaging techniques for diffuse myocardial fibrosis. *Future Cardiol* **7**(5): 643–50 (doi: 10.2217/fca.11.45)

Sado DM, White SK, Piechnik SK et al (2013) Identification and assessment of Anderson-Fabry disease by cardiovascular magnetic resonance noncontrast myocardial T1 mapping. *Circ Cardiovasc Imaging* **6**(3): 392–8 (doi: 10.1161/CIRCIMAGING.112.000070)

Selvanayagam JB, Hawkins PN, Paul B, Myerson SG, Neubauer S (2007) Evaluation and management of the cardiac amyloidosis. *J Am Coll Cardiol* **50**(22): 2101–10

Swynghedauw B (1999) Molecular mechanisms of myocardial remodeling. *Physiol Rev* **79**(1): 215–62

Syed IS, Martinez MW, Feng DL, Glockner JF (2008) Cardiac magnetic resonance imaging of eosinophilic endomyocardial disease. *Int J Cardiol* **126**(3): e50–2

Thavendiranathan P, Grant AD, Negishi T, Plana JC, Popovic ZB, Marwick TH (2013) Reproducibility of echocardiographic techniques for sequential assessment of left ventricular ejection fraction and volumes: application to patients undergoing cancer chemotherapy. *J Am Coll Cardiol* **61**(1): 77–84 (doi: 10.1016/j.jacc.2012.09.035)

KEY POINTS

- Heart muscle disease is common and frequently encountered.
- The imaging work up of heart muscle disease aims to establish aetiology, the impact on myocardial structure and function, allow the appropriate treatment strategy to be instituted and monitored and also provide prognostic information.
- Cardiac magnetic resonance is a rapidly expanding technique in the work up of heart muscle disease, providing complementary information to two-dimensional transthoracic echocardiography.
- The particular strength of cardiac magnetic resonance lies in tissue characterization, particularly the late gadolinium enhancement technique, which allows identification of fibrosis, oedema and infiltration.