Review Article

Heart failure in patients with normal coronary anatomy: Diagnostic algorithm and disease pattern of various etiologies as defined by cardiac MRI

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Abstract: In a subgroup of patients with acute heart failure coronary artery disease can be excluded. To explain symptoms and optimize therapy cardiac magnetic resonance (CMR) imaging can contribute to elucidate the underlying pathology in non-ischemic heart disease. A diagnostic algorithm for the work-up of these patients using CMR is suggested. The review discusses various modules of a dedicated CMR protocol. It explains diagnostic markers and challenges of CMR imaging in non-ischemic heart disease. Based on these suggestions the literature in the field is reviewed.

Key Words: Coronary artery disease (CAD); cardiovascular magnetic resonance (CMR); imaging; diagnostic algorithm

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Introduction

The incidence of heart failure is increasing (1). Some of these patients present with acute heart failure syndrome (AHFS) and an unclear underlying etiology (2). About 60% of these patients do have coronary artery disease (CAD) (3), so coronary angiography and potentially revascularization are indicated in most cases. However, in about 40% of cases, the etiology of heart failure remains unclear even after coronary angiography, as coronary artery disease was ruled out or its extent could not explain the obvious myocardial dysfunction. Appropriate treatment decisions require clarification of the underlying disease. For the clinical work-up of these patients cardiovascular magnetic resonance (CMR) imaging has shown to be of particular benefit (4). CMR not only depicts cardiac size and function but also tissue composition and can thereby reveal the underlying cause of heart failure in a considerable number of patients.

Suggested CMR protocol

In clinical routine echocardiography is and will remain the basic tool for cardiac imaging in the acute setting. Many of the patients discussed here have already undergone echocardiography. Some information about cardiac size, global and regional myocardial function usually is available given a sufficient acoustic window was present. Still, more information is necessary to clarify the etiology of heart failure. The referral for CMR is therefore warranted. Based on the long-term experience in our center the following protocol is suggested. The society of cardiovascular magnetic resonance has published similar suggestions in 2008 (5).

(I) Scout/localizer images

(II) Steady state free precession cine imaging in 3 long axes

(III) Steady state free precession cine imaging in short axes

(IV) T2-weighted imaging in 3 long axes and as many short axes as possible

(V) First pass rest perfusion in 3 long axes

(VI) Late gadolinium enhancement in 3 long axes and multiple short axes

This scan will take, depending on the numbers of repetitions necessary and the amount of contrast given, between 20 and 40 minutes.

Cine imaging

Cine imaging basically reproduces echo information regarding cardiac cavity size and wall motion. Steady state free precession cine loops acquired during breath hold represent the current state of the art. There are options available to shorten acquisition time or increase coverage with a certain trade-off in image quality or resolution. In general temporal resolution is poorer than in echocardiography, but image contrast, endocardial contour detection and reproducibility is much better. CMR is the gold standard for left ventricular mass. So far routine CMR approaches to assess diastolic function are limited to time-consuming volume over time curves.

T2-weighted edema imaging

Acute ischemic or inflammatory myocardial injury results in transient myocardial edema. There is an ongoing debate about the pathophysiological details behind edema evolvement and the best CMR sequence to detect it (6). Nevertheless most CMR users agree that edema is an early phenomenon in acute myocardial injury (7). CMR detects edema in acute infarction, acute myocarditis and Takotsubo cardiomyopathy as well as those sarcoidosis patients that are admitted with an acute event like ventricular arrhythmias. In acute infarction the edema is typically larger than the scar and most often transmural. Inflammatory edema can be patchy and smaller and can located in epicardial locations corresponding to late gadolinium enhancement lesions. If black blood fast spin echo images are acquired it can sometimes be difficult to differentiate edema (bright signal within the myocardial wall) from slow flow (bright signal within the ventricular lumen). Cine loops in the same location should be inspected for comparison. In uncertain cases an additional orthogonal slice should be acquired to confirm an area of questionable increased signal intensity as true edema.

Perfusion imaging

Perfusion imaging is not essential in this setting. As contrast agent has to be administered anyway this can be used for early imaging after contrast. Resting perfusion is clinically useful, if embolic infarction is the suspected underlying mechanism for heart failure. This might be the case even if coronary angiography was considered normal, as small, occluded peripheral branches may have been overlooked. For this reason perfusion images should be acquired in long axis orientation to cover the LV apex. Resting perfusion detects acute infarction as a perfusion defect even after successful revascularization if CMR is done within a few days after the event. If there is no clinical rationale for perfusion imaging in this scenario angiography may be an alternative to be done at this point.

Late gadolinium enhancement imaging

LGE imaging is the key to reveal a certain myocardial disease beyond mere wall motion abnormalities.It reveals the amount of viable myocardium with potential for functional improvement (8). From our experience it is essential to invest great effort for optimal choice and adjustment of the inversion time to suppress normal myocardium (9). Additional orthogonal slices should be acquired to confirm or rule out any questionable lesions. Comparison with cine images in the same position and slice thickness may help to confirm whether a questionable lesion actually has an intramyocardial position or is extramyocardial (e.g., lumen, pericardial fat or fluid). Fat also appears hyperintense on LGE images and can be identified by dedicated fat suppression methods (10) and its hyperintense signal on corresponding cine and pre-contrast T1-weighted spin echo images. Basically the position within the wall differentiates the etiology of LGE lesions: While the classical myocardial infarction of coronary etiology is subendocardial or transmural within a single coronary territory, non-ischemic lesions cover the intramural or epicardial portion of the myocardial wall and may be scattered across various coronary territories (11). Mewton *et al*. reviewed CMR assessment of diffuse myocardial fibrosis (12). However, not all patients with acute heart failure but normal coronaries do have late gadolinium enhancement lesions.

Diagnostic algorithm

Certain phenotypic patterns suggest various underlying pathologies. In *Figure 1* we suggest an algorithm for a systematic work-up of patients with heart failure despite normal coronaries.

Normal LV size and regional wall motion abnormality

Regional wall motion abnormality in a patient with acute heart disease points to coronary heart disease. Even if coronary angiography was normal, embolic infarction can explain regional hypokinesia, focal edema and scar. Either a

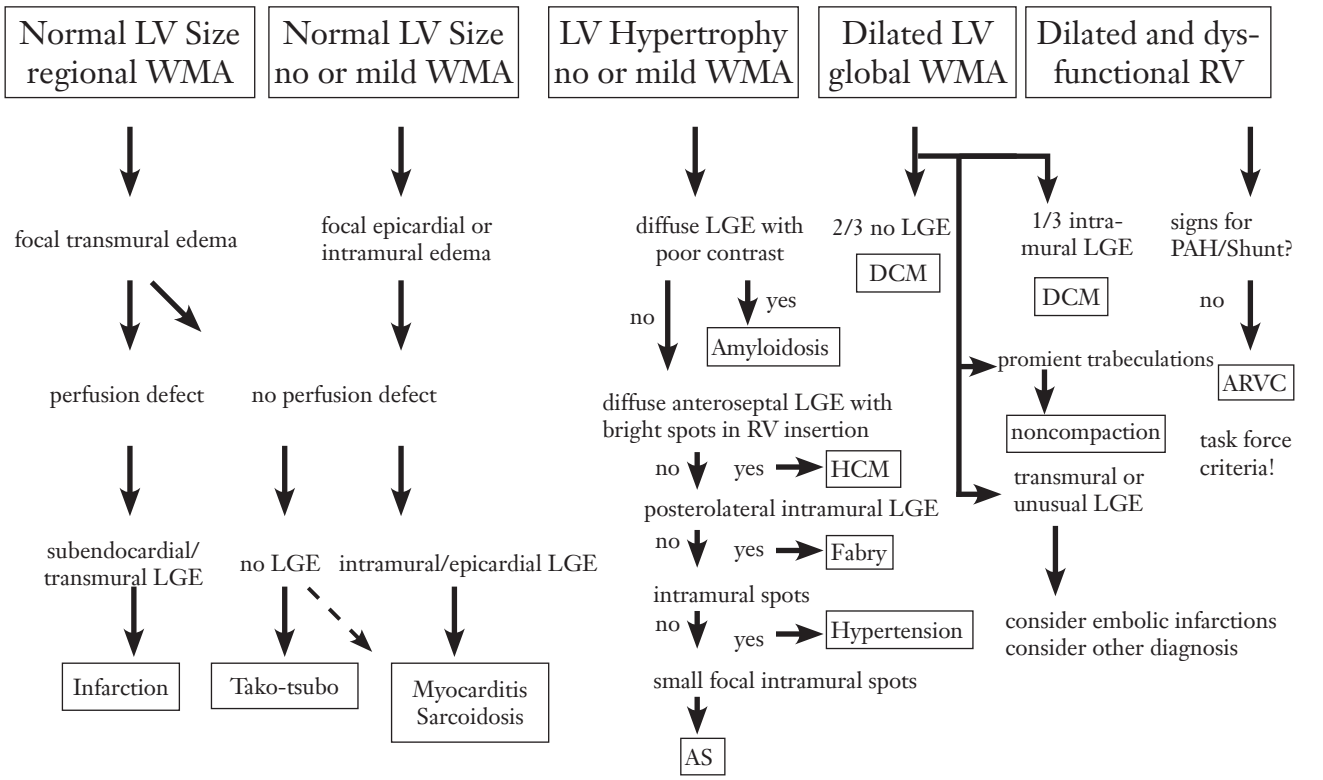

Figure 1 Diagnostic algorithm for patients with acute heart failure but normal coronaries using CMR

small distal coronary side branch had been thrombotically occluded without leaving a stump as an angiographic hint, or the occluded vessel was spontaneously recanalized before angiography was done. Paradoxical thromboembolism across a patent foramen ovale can result in myocardial infarction (*Figure 2*) (4,13). A acute small non-revascularized infarction will be visible as perfusion defect on resting perfusion images (*Figure 2A*). If CMR suggests embolic infarction a transesophageal echocardiography is indicated to search for the source of embolism.

Takotsubo cardiomyopathy presents as apical ballooning typically in postmenopausal women after a stressful event including cerebral injury (14). Apical edema may be present. The key element for diagnosis is the exclusion of apical infarction scar despite the prominent wall motion abnormality. It is important to confirm normalized wall motion within weeks during follow-up.

Normal LV size and no or mild wall motion abnormality

In patients with normal-sized left ventricle and no or subtle wall motion abnormalities myocarditis or sarcoidosis is a potential diagnosis. In young male patients with viral myocarditis CMR often detects focal myocardial edema either regional similar to a posterolateral infarction or in multifocal spotty pattern in the epicardial portion of the lateral wall (15). It is important to scan these patients early as edema disappears 2-3 weeks after the initial presentation. Typically these patchy spots of edema correspond to focal myocardial fibrosis on late gadolinium enhancement images. The LGE lesions typically persist but tend to slowly shrink over time.

In sarcoidosis some of the patients feature LGE lesions. Patel *et al*. reported five different patterns of LGE in sarcoidosis (16). In our experience we typically see pattern

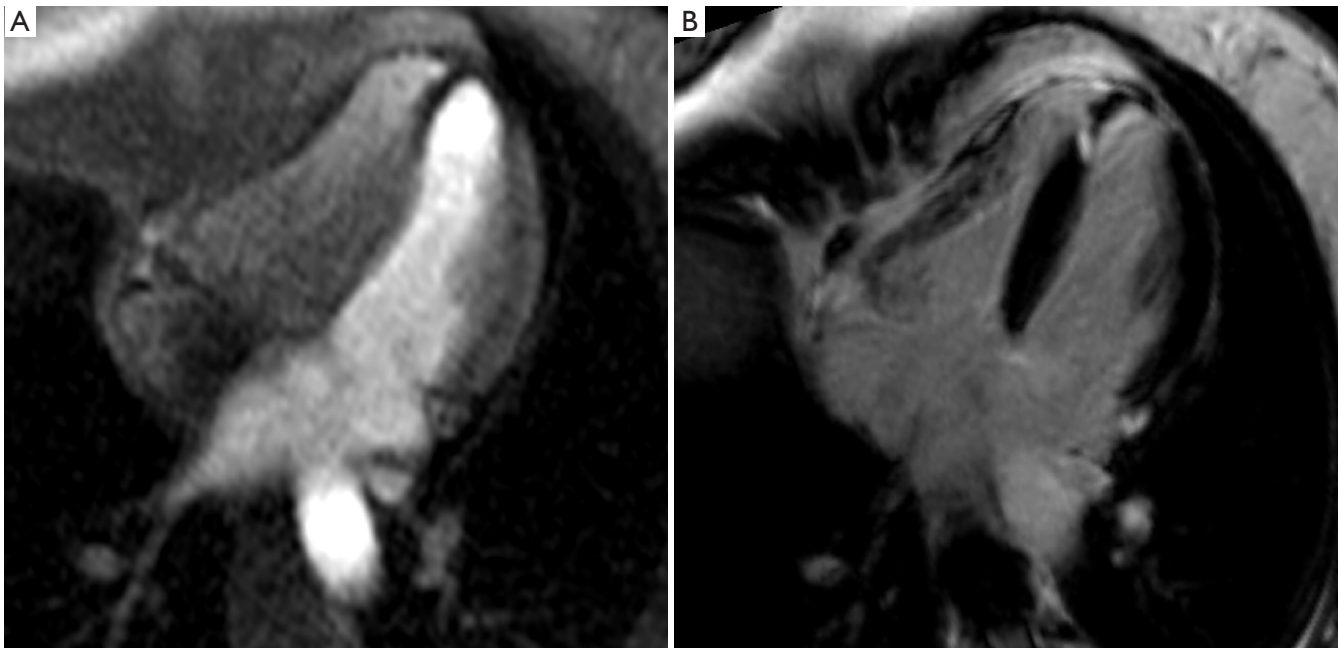

Figure 2 A 42-year-old female was admitted with chest pain. Troponin was positive, ECG indicated inferolateral ST-elevation. Instant coronary angiography was normal, but an apical wall motion abnormality was noted. CMR was done the next day. A: Resting perfusion in 4-chamber-view shows an apical area of hypointense signal indicating a perfusion defect. B: Late gadolinium enhancement in the same orientation reveals a bright transmural apical area indicating scar with a large hypointense core. This dark core does not represent viable myocardium but microvascular obstruction in the case of non-revascularized infarction of embolic origin. A patent foramen ovale was found as the most likely route of embolism

D according to Patel *et al*., i.e. bright epicardial rims with certain focal transmural spots (*Figure 3*). Occasionally a patchy myocarditis-like-pattern E (according to Patel *et al*.) might occur. Pathology reports indicate fibrotic lesions in epicardial and intramural locations (17,18). In patients presenting with an acute event (e.g., ventricular tachycardia, acute chest pain) focal edema may be detectable in areas corresponding to LGE lesions (*Figure 3*) (19,20). This pattern remains typical even if sarcoidosis presents with a dilated left ventricle (21).

LV hypertrophy

All forms of heart failure with left ventricular hypertrophy (LVH) tend to feature preserved systolic LV function and impaired diastolic function. Left atrial size is a long-term marker of diastolic dysfunction and can easily be quantified by CMR (22,23). There is no easy way to measure diastolic function by CMR beyond that due its limited temporal resolution. Some groups have calculated diastolic peak filling rates based ontime-volume-curves across the cardiac cycle (24,25). Others have added septal tissue velocity measurements to characterize diastolic dysfunction (26).

Hypertrophic cardiomyopathy

The phenotype of hypertrophic cardiomyopathy (HCM) comprises several subtypes (27). In most cases the hypertrophy is most obvious in the septum and rather asymmetric than symmetric. Obstruction of the left ventricular outflow tract may or may not be part of the disease. Late gadolinium enhancement is present in roughly 60% of cases based on the 3 largest observational trials to date (28-30).

Hypertension

The most frequent reason for LV hypertrophy is long-lasting arterial hypertension. Typically it results in symmetric hypertrophy both in the septal and the lateral wall. Intramural LGE has been found in 13 out of 26 (50%) hypertensive patients with marked myocardial hypertrophy on CMR (31).

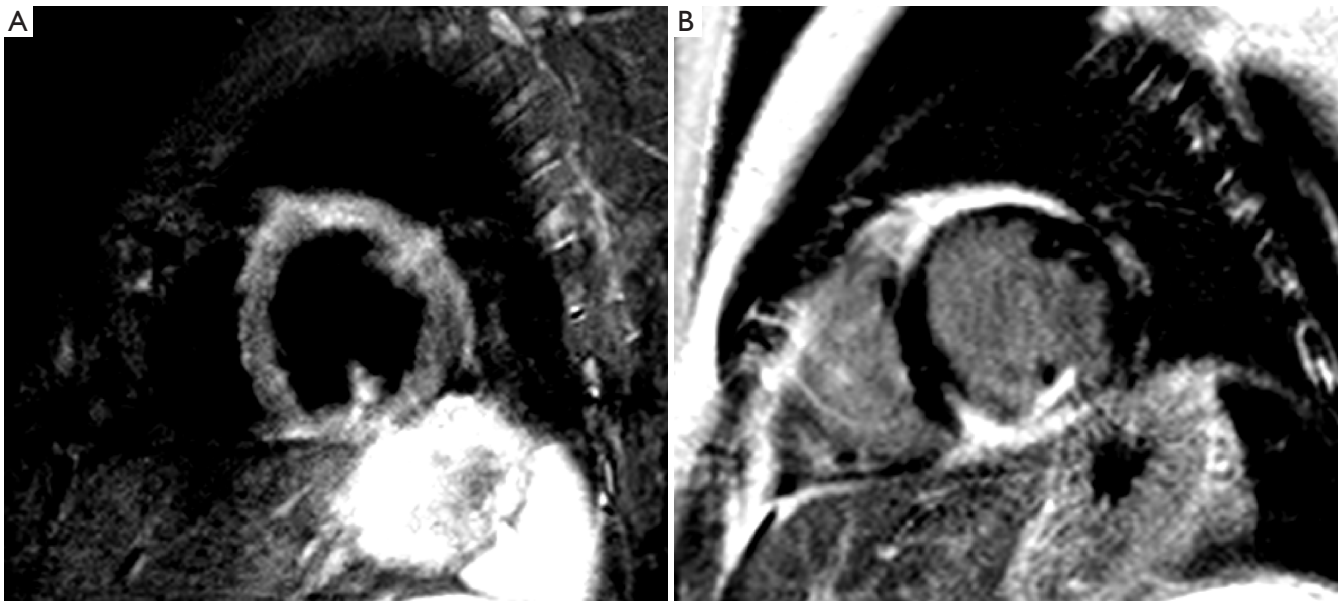

Figure 3 A 31-year-old male presented with shortness-of-breath and palpitations during exercise. Troponin was positive, coronary angiography was normal. Viral myocarditis was suspected. A: Short axis triple-inversion fast spin echo reveals focal areas of hyperintense signal in the anterior and inferior wall. B: Bright areas (epicardial rims) of hyperenhancement in the LGE image. Transbronchial biopsy confirmed sarcoidosis

Amyloidosis

In some patients with unclear LVH (*Figure 4A*) it appears impossible to suppress the myocardium in LGE images despite various attempts with different inversion times (*Figure 4B*) (32,33). Cardiac amyloidosis with extensive rapid myocardial uptake of the myocardium might explain this phenomenon. A preserved systolic LV function, dilated atria, pericardial and pleural effusions support the diagnosis, even if unspecific on their own. If amyloidosis is suspected before CMR, LGE imaging should be started earlier than usual (i.e. within minutes after contrast administration) (34). Hypointense myocardium on T2-weighted STIR images and increased early contrast uptake might further support the diagnosis of cardiac amyloidosis (35).

Aortic stenosis

Cine imaging in the 3-chamber-view easily reveals aortic valve thickening and high-velocity transvalvular flow as a bright jet. A set of orthogonal cine images across the valve reliably allows the planimetry of the aortic valve orifice area (36). In patients with aortic stenosis focal lesions of late gadolinium enhancement have been found that are associated with a worse prognosis (37,38). Whether this phenomenon is really independent from LV hypertrophy, is not yet totally resolved.

Fabry disease

X-chromosomal Anderson-Fabry disease features reduced galactosidase-activity resulting in glycogen storage in various tissues including the myocardium. Of note, even female patients can be affected (39). Interestingly the posterolateral wall appears to be a preferred location for tissue changes detected by LGE images (40). Once LGE lesions are present they seem to not to be influenced by enzyme replacement therapy (41).

Dilated left ventricle

Dilated cardiomyopathy

The left ventricle and most often even the left atrium are dilated. The walls are thin. If the right ventricle is also dilated, this is a marker for an adverse prognosis (42). About a third of dilated cardiomyopathy (DCM) patients feature a midwall late gadolinium enhancement, associated with a worse outcome (43,44). It is unclear why some of the

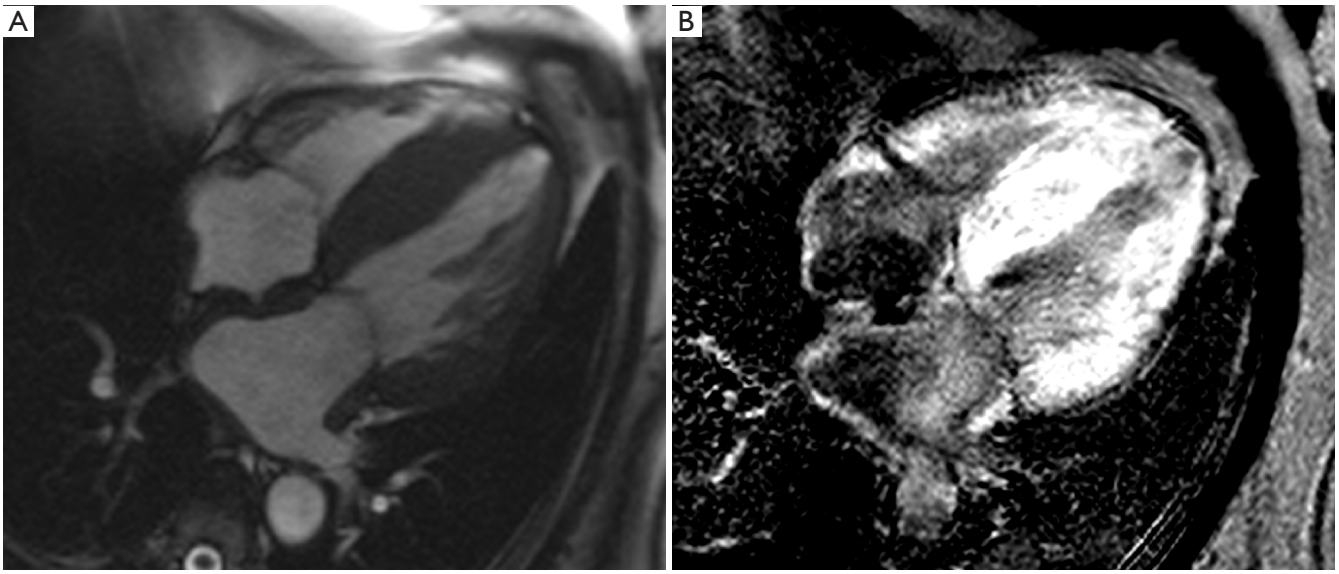

Figure 4 A 58-year-old male presented with fatigue. Troponin was positive, coronary angiography was normal. A: Cine imaging in 4-chamber-view reveals septal hypertrophy that resembles hypertrophic cardiomyopathy or advanced hypertensive heart disease. Pericardial or pleural effusions are absent. B: On late gadolinium enhancement it was not possible to suppress the myocardium, but unusual contrast patterns with bright myocardium und hypointense blood did occur. Myocardial biopsy confirmed transthyretin amyloidosis

patients do show LGE and some do not or whether those with LGE have a post-inflammatory origin.

If a transmural or other LGE pattern occurs, consider sarcoidosis (21) or embolic infarction. Myocardial biopsy is recommended in cases of new-onset heart failure with normal-sized or dilated left ventricle and hemodynamic compromise or in those with new-onset heart failure and ventricular arrhythmias or heart block and failure to improve within one to two weeks (45).

Non-compaction cardiomyopathy

Some heart failure patients with dilated ventricles feature prominent apical and lateral trabeculations with a thin compact myocardial layer. Arrest of intrauterine myocardial development is one explanation for non-compaction cardiomyopathy. There is a wide morphologic spectrum with overlap into appearingly normal hearts, DCM and HCM (46). Petersen *et al*. suggested diagnostic criteria for CMR in long axis images (47). Dawson *et al*. published reference values for wall thickness of compact and non-compact myocardium across all segments in short axis (48), while Jacquier *et al*. quantified the extent of trabeculations in short axis images (49). LGE might be present in a minority of patients (50,51).

Dilated and dysfunctional right ventricle

Arrhythmogenic right ventricular cardiomyopathy

A dilated RV with reduced RVEF and regional akinesia or dyskinesia are indicative for arrhythmogenic right ventricular cardiomyopathy (ARVC). A diagnosis is not based on CMR alone, but on a combination of imaging, history, ECG etc. (52). The left ventricle can be involved. Typically the patients do not present with heart failure but with ventricular arrhythmias. A severe tricuspid regurgitation is not a typical feature of ARVC.

Other reasons for right heart failure

A dilated pulmonary artery, tricuspid regurgitation, enlarged right atrium and focal late gadolinium enhancement in the right ventricular insertion points are markers for pulmonary arterial hypertension. In case of unclear enlargement of the right cardiac cavities an intracardiac shunt should be excluded via flow measurements across the aortic and pulmonary valve to verify a normal Qp/Qs ratio. If pulmonary arterial hypertension can be ruled out, a primary tricuspid valve problem can occasionally explain enlarged right cardiac cavities. In patients with congenital heart disease a history of previous surgery is most often known.

Discussion

Once coronary artery disease had been ruled out in a patient with heart failure modern cardiologic reasoning does not come to an end but excitement begins.

CMR can contribute to elucidate the underlying mechanism for patients with acute heart failure but normal coronaries. The manuscript explains how this might work in daily routine. Assomull *et al*. described a series of 60 consecutive patients that presented with chest pain, positive troponin but normal coronaries. CMR including cine, T2-weighted and late gadolinium enhancement imaging could clarify the underlying disease in 65% of the patients (4). Late gadolinium enhancement is the key tool of the CMR armory in this setting but not the only one (53). Mather *et al*. published a very instructive case collection to illustrate the diagnostic potential of CMR in the patient population discussed here (54). It is important to investigate patients as soon as they are clinically stable, as temporary markers like myocardial edema or perfusion defects might no longer be detectable during later follow-up (4,55,56). To underscore the potential of CMR White *et al*. investigated the findings in 82 patients after resuscitation due to sudden cardiac death or sustained ventricular tachycardia (57). CMR found myocardial disease in 74% and thereby more often than in a control group without CMR (51%). In general it is considered pivotal in acute heart failure patients to elucidate how much myocardium is still viable and therefore has potential for improvement (8). CMR is ready for this task.

Of course a patient with enlarged ventricle, reduced systolic function and heart failure will most likely have CAD. Within the context of this discussion we assume that CAD has already been ruled out. Several authors have suggested to differentiate ischemic and non-ischemic heart failure simply by LGE CMR (11,58-60). If typical subendocardial infarction scars are present, the patient presumably has CAD, if no scars or intramural fibrosis is present, non-ischemic heart disease might be the reason for heart failure. It should be very clear to the reader that the exclusion of myocardial scar does not rule out coronary artery disease (61). Even severe three-vessel-disease can be present without any scar due to collateral blood supply. Assomull *et al*. conceded this option as a mere theoretical but unlikely scenario (62). The clinician should also evaluate whether a certain LGE lesion really explains the extent of functional impairment or whether it may represent "bystander disease" if the remodeling is out of proportion (62).

Conclusions

In patients acutely admitted with heart failure and normal coronaries CMR can contribute to elucidate the underlying mechanism. A diagnostic algorithm is suggested to differentiate various pathologic conditions. CMR should therefore considered to be part of the regular work-up for these patients (1).

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References

1. Harinstein ME, Flaherty JD, Fonarow GC, et al. Clinical assessment of acute heart failure syndromes: emergency department through the early post-discharge period. Heart 2011;97:1607-18.
2. Weintraub NL, Collins SP, Pang PS, et al. Acute heart failure syndromes: emergency department presentation, treatment, and disposition: current approaches and future aims: a scientific statement from the American Heart Association. Circulation 2010;122:1975-96.
3. Adams KF Jr, Fonarow GC, Emerman CL, et al. Characteristics and outcomes of patients hospitalized for heart failure in the United States: rationale, design, and preliminary observations from the first 100,000 cases in the Acute Decompensated Heart Failure National Registry (ADHERE). Am Heart J 2005;149:209-16.
4. Assomull RG, Lyne JC, Keenan N, et al. The role of cardiovascular magnetic resonance in patients presenting with chest pain, raised troponin, and unobstructed coronary arteries. Eur Heart J 2007;28:1242-9.
5. Kramer CM, Barkhausen J, Flamm SD, et al. Standardized cardiovascular magnetic resonance imaging (CMR) protocols, society for cardiovascular magnetic resonance: board of trustees task force on standardized protocols. Journal of cardiovascular magnetic resonance: official journal of the Society for Cardiovascular Magnetic Resonance 2008;10:35.
6. Friedrich MG, Kim HW, Kim RJ. T2-weighted imaging to assess post-infarct myocardium at risk. JACC Cardiovasc Imaging 2011;4:1014-21.
7. Walls MC, Verhaert D, Min JK, et al. Myocardial edema imaging in acute coronary syndromes. Journal of magnetic resonance imaging. J Magn Reson Imaging 2011;34:1243-50.
8. Pang PS, Komajda M, Gheorghiade M. The current and

future management of acute heart failure syndromes. Eur Heart J 2010;31:784-93.
9. Kim RJ, Shah DJ, Judd RM. How we perform delayed enhancement imaging. J Cardiovasc Magn Reson 2003;5:505-14.
10. Kellman P, Hernando D, Shah S, et al. Multiecho dixon fat and water separation method for detecting fibrofatty infiltration in the myocardium. Magn Reson Med 2009;61:215-21.
11. McCrohon JA, Moon JC, Prasad SK, et al. Differentiation of heart failure related to dilated cardiomyopathy and coronary artery disease using gadolinium-enhanced cardiovascular magnetic resonance. Circulation 2003;108:54-9.
12. Mewton N, Liu CY, Croisille P, et al. Assessment of myocardial fibrosis with cardiovascular magnetic resonance. J Am Coll Cardiol 2011;57:891-903.
13. Wöhrle J, Kochs M, Hombach V, et al. Prevalence of myocardial scar in patients with cryptogenic cerebral ischemic events and patent foramen ovale. JACC Cardiovasc Imaging 2010;3:833-9.
14. Eitel I, von Knobelsdorff-Brenkenhoff F, Bernhardt P, et al. Clinical characteristics and cardiovascular magnetic resonance findings in stress (takotsubo) cardiomyopathy. JAMA 2011;306:277-86.
15. Cocker MS, Abdel-Aty H, Strohm O, et al. Age and gender effects on the extent of myocardial involvement in acute myocarditis: a cardiovascular magnetic resonance study. Heart 2009;95:1925-30.
16. Patel MR, Cawley PJ, Heitner JF, et al. Detection of myocardial damage in patients with sarcoidosis. Circulation 2009;120:1969-77.
17. Bagwan IN, Hooper LV, Sheppard MN. Cardiac sarcoidosis and sudden death. The heart may look normal or mimic other cardiomyopathies. Virchows Archiv: an international journal of pathology 2011;458:671-8.
18. Shirani J, Roberts WC. Subepicardial myocardial lesions. Am Heart J 1993;125:1346-52.
19. Srichai MB, Addrizzo-Harris DJ, Friedman K. Cardiac sarcoidosis. J Am Coll Cardiol 2011;58:438.
20. Quarta G, Holdright DR, Plant GT, et al. Cardiovascular magnetic resonance in cardiac sarcoidosis with MR conditional pacemaker in situ. Journal of cardiovascular magnetic resonance: official journal of the Society for Cardiovascular Magnetic Resonance 2011;13:26.
21. Adlan AM, Prasad SK, Varnava AM. Sarcoidosis presenting as dilated cardiomyopathy. Heart 2011;97:1896.
22. Anderson JL, Horne BD, Pennell DJ. Atrial dimensions in health and left ventricular disease using cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2005;7:671-5.
23. Maceira AM, Cosin-Sales J, Roughton M, et al. Reference left atrial dimensions and volumes by steady state free precession cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2010;12:65.
24. Rider OJ, Francis JM, Ali MK, et al. Beneficial cardiovascular effects of bariatric surgical and dietary weight loss in obesity. J Am Coll Cardiol 2009;54:718-26.
25. Utz W, Engeli S, Haufe S, et al. Myocardial steatosis, cardiac remodelling and fitness in insulin-sensitive and insulin-resistant obese women. Heart 2011;97:1585-9.
26. Paelinck BP, de Roos A, Bax JJ, et al. Feasibility of tissue magnetic resonance imaging: a pilot study in comparison with tissue Doppler imaging and invasive measurement. J Am Coll Cardiol 2005;45:1109-16.
27. Noureldin RA, Liu S, Nacif MS, et al. The diagnosis of hypertrophic cardiomyopathy by cardiovascular magnetic resonance. Journal of cardiovascular magnetic resonance: official journal of the Society for Cardiovascular Magnetic Resonance 2012;14:17.
28. Rubinshtein R, Glockner JF, Ommen SR, et al. Characteristics and clinical significance of late gadolinium enhancement by contrast-enhanced magnetic resonance imaging in patients with hypertrophic cardiomyopathy. Circ Heart Fail 2010;3:51-8.
29. Bruder O, Wagner A, Jensen CJ, et al. Myocardial scar visualized by cardiovascular magnetic resonance imaging predicts major adverse events in patients with hypertrophic cardiomyopathy. J Am Coll Cardiol 2010;56:875-87.
30. O'Hanlon R, Grasso A, Roughton M, et al. Prognostic significance of myocardial fibrosis in hypertrophic cardiomyopathy. J Am Coll Cardiol 2010;56:867-74.
31. Rudolph A, Abdel-Aty H, Bohl S, et al. Noninvasive detection of fibrosis applying contrast-enhanced cardiac magnetic resonance in different forms of left ventricular hypertrophy relation to remodeling. J Am Coll Cardiol 2009;53:284-91.
32. Maceira AM, Joshi J, Prasad SK, et al. Cardiovascular magnetic resonance in cardiac amyloidosis. Circulation 2005;111:186-93.
33. Syed IS, Glockner JF, Feng D, et al. Role of cardiac magnetic resonance imaging in the detection of cardiac amyloidosis. JACC Cardiovasc Imaging 2010;3:155-64.
34. Vogelsberg H, Mahrholdt H, Deluigi CC, et al. Cardiovascular magnetic resonance in clinically suspected cardiac amyloidosis: noninvasive imaging compared to endomyocardial biopsy. J Am Coll Cardiol 2008;51:1022-30.

35. Wassmuth R, Abdel-Aty H, Bohl S, et al. Prognostic impact of T2-weighted CMR imaging for cardiac amyloidosis. Eur Radiol 2011;21:1643-50.
36. John AS, Dill T, Brandt RR, et al. Magnetic resonance to assess the aortic valve area in aortic stenosis: how does it compare to current diagnostic standards? J Am Coll Cardiol 2003;42:519-26.
37. Weidemann F, Herrmann S, Stork S, et al. Impact of myocardial fibrosis in patients with symptomatic severe aortic stenosis. Circulation 2009;120:577-84.
38. Dweck MR, Joshi S, Murigu T, et al. Midwall fibrosis is an independent predictor of mortality in patients with aortic stenosis. J Am Coll Cardiol 2011;58:1271-9.
39. Niemann M, Herrmann S, Hu K, et al. Differences in Fabry cardiomyopathy between female and male patients: consequences for diagnostic assessment. JACC Cardiovasc Imaging 2011;4:592-601.
40. Moon JC, Sheppard M, Reed E, et al. The histological basis of late gadolinium enhancement cardiovascular magnetic resonance in a patient with Anderson-Fabry disease. J Cardiovasc Magn Reson 2006;8:479-82.
41. Beer M, Weidemann F, Breunig F, et al. Impact of enzyme replacement therapy on cardiac morphology and function and late enhancement in Fabry's cardiomyopathy. Am J Cardiol 2006;97:1515-8.
42. Hombach V, Merkle N, Torzewski J, et al. Electrocardiographic and cardiac magnetic resonance imaging parameters as predictors of a worse outcome in patients with idiopathic dilated cardiomyopathy. Eur Heart J 2009;30:2011-8.
43. Assomull RG, Prasad SK, Lyne J, et al. Cardiovascular magnetic resonance, fibrosis, and prognosis in dilated cardiomyopathy. J Am Coll Cardiol 2006;48:1977-85.
44. Lehrke S, Lossnitzer D, Schob M, et al. Use of cardiovascular magnetic resonance for risk stratification in chronic heart failure: prognostic value of late gadolinium enhancement in patients with non-ischaemic dilated cardiomyopathy. Heart 2011;97:727-32.
45. Cooper LT, Baughman KL, Feldman AM, et al. The role of endomyocardial biopsy in the management of cardiovascular disease: a scientific statement from the American Heart Association, the American College of Cardiology, and the European Society of Cardiology. Circulation 2007;116:2216-33.
46. Oechslin E, Jenni R. Left ventricular non-compaction revisited: a distinct phenotype with genetic heterogeneity? Eur Heart J 2011;32:1446-56.
47. Petersen SE, Selvanayagam JB, Wiesmann F, et al. Left ventricular non-compaction: insights from cardiovascular magnetic resonance imaging. J Am Coll Cardiol 2005;46:101-5.
48. Dawson DK, Maceira AM, Raj VJ, et al. Regional thicknesses and thickening of compacted and trabeculated myocardial layers of the normal left ventricle studied by cardiovascular magnetic resonance. Circ Cardiovasc Imaging 2011;4:139-46.
49. Jacquier A, Thuny F, Jop B, et al. Measurement of trabeculated left ventricular mass using cardiac magnetic resonance imaging in the diagnosis of left ventricular non-compaction. Eur Heart J 2010;31:1098-104.
50. Probst S, Oechslin E, Schuler P, et al. Sarcomere gene mutations in isolated left ventricular noncompaction cardiomyopathy do not predict clinical phenotype. Circulation Cardiovascular genetics 2011;4:367-74.
51. Chaowu Y, Li L, Shihua Z. Histopathological features of delayed enhancement cardiovascular magnetic resonance in isolated left ventricular noncompaction. J Am Coll Cardiol 2011;58:311-2.
52. Marcus FI, McKenna WJ, Sherrill D, et al. Diagnosis of arrhythmogenic right ventricular cardiomyopathy/dysplasia: proposed modification of the task force criteria. Circulation 2010;121:1533-41.
53. Bohl S, Wassmuth R, Abdel-Aty H, et al. Delayed enhancement cardiac magnetic resonance imaging reveals typical patterns of myocardial injury in patients with various forms of non-ischemic heart disease. Int J Cardiovasc Imaging 2008;24:597-607.
54. Mather AN, Fairbairn TA, Artis NJ, et al. Diagnostic value of CMR in patients with biomarker-positive acute chest pain and unobstructed coronary arteries. JACC Cardiovasc Imaging 2010;3:661-4.
55. Monney PA, Sekhri N, Burchell T, et al. Acute myocarditis presenting as acute coronary syndrome: role of early cardiac magnetic resonance in its diagnosis. Heart 2011;97:1312-8.
56. Dall'Armellina E, Karia N, Lindsay AC, et al. Dynamic changes of edema and late gadolinium enhancement after acute myocardial infarction and their relationship to functional recovery and salvage index. Circulation Cardiovascular imaging 2011;4:228-36.
57. White JA, Fine NM, Gula L, et al. Utility of cardiovascular magnetic resonance in identifying substrate for malignant ventricular arrhythmias. Circulation Cardiovascular imaging 2012;5:12-20.
58. Senthilkumar A, Majmudar MD, Shenoy C, et al. Identifying the etiology: a systematic approach using

delayed-enhancement cardiovascular magnetic resonance. Heart Fail Clin 2009;5:349-67. vi.
59. Soriano CJ, Ridocci F, Estornell J, et al. Noninvasive diagnosis of coronary artery disease in patients with heart failure and systolic dysfunction of uncertain etiology, using late gadolinium-enhanced cardiovascular magnetic resonance. J Am Coll Cardiol 2005;45:743-8.
60. Valle-Munoz A, Estornell-Erill J, Soriano-Navarro CJ, et al. Late gadolinium enhancement-cardiovascular magnetic resonance identifies coronary artery disease as the aetiology of left ventricular dysfunction in acute new-onset congestive heart failure. European journal of echocardiography: the journal of the Working Group on Echocardiography of the European Society of Cardiology 2009;10:968-74.
61. Schietinger BJ, Voros S, Isbell DC, et al. Can late gadolinium enhancement by cardiovascular magnetic resonance identify coronary artery disease as the etiology of new onset congestive heart failure? Int J Cardiovasc Imaging 2007;23:595-602.
62. Assomull RG, Shakespeare C, Kalra PR, et al. Role of cardiovascular magnetic resonance as a gatekeeper to invasive coronary angiography in patients presenting with heart failure of unknown etiology. Circulation 2011;124:1351-60.

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