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Review

Cardiovascular magnetic resonance for the assessment of coronary artery disease

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ABSTRACT

Over the past decade, cardiovascular magnetic resonance (CMR) has become an established non-invasive imaging modality in cardiology. It provides clinicians and researchers with an unparalleled versatility of diagnostic parameters such as cardiac morphology, function, myocardial texture and vascular flow. One of the most relevant applications of CMR is the assessment of patients with suspected or known coronary artery disease (CAD). In large clinical trials, CMR has proven its robustness, diagnostic performance and prognostic value in CAD. In patients with known or suspected chronic CAD, detection of ischaemia and myocardial viability for guiding therapeutic decisions is a major strength of CMR. Patients with ischaemic congestive heart failure (CHF) may benefit from CMR for planning of device implantation or monitoring intracavital thrombi. Finally, the use of CMR in the emergency department for the assessment of patients with acute chest pain is an emerging field, in which CMR's capability to characterize myocardial tissue regarding e.g. necrosis, edema or microvascular obstruction (MVO) may prove clinically useful. The CMR technology is safe, free of ionizing radiation and proved higher diagnostic accuracy and superior cost efficiency compared with other standard diagnostic modalities.

1. Introduction

Even though the treatment of cardiovascular disease (CVD) has made tremendous advances in the recent years, CVD, in particular coronary artery disease (CAD), continues to cause a large portion of mortality and morbidity in the Western world [1]. However, ranging from new conservative strategies and innovative interventional methods to the use of assist devices in end-stage congestive heart failure, the therapeutic armamentarium for CAD is nowadays wider than ever before. This versatility of treatment options requires diagnostic modalities that account for the different stages and characteristics of myocardial ischaemia to guide clinical decision making.

Cardiovascular magnetic resonance (CMR) has emerged as a multifunctional imaging capability to assess various parameters of cardiovascular function and morphology such as ejection fraction, coronary artery status, myocardial viability, tissue characterization (e.g. scar, fibrosis, and edema), vascular flow and others. In the past decade, long examination times and uncomfortably small bore sizes were major limitations that prevented CMR from being more widely used. Today those limitations have almost entirely been overcome. Technical developments like parallel imaging techniques [2,3], k–t-undersampling strategies [4,5] or compressed sensing [6,7] helped to reduce scanning times for comprehensive examination to less than 45 min. Moreover, today all major MRI vendors provide wide bore scanners with at least 70 cm inner diameter that allow convenient conditions also for obese patients.

Given the high epidemiological relevance of CAD and the advances that CMR has made over the past years, this review aims to summarize clinical indications and potential diagnostic contributions that CMR has in patients with chronic CAD, congestive heart failure due to CAD and patients with acute coronary syndrome (ACS). Thereby, this review also gives insight into the practical aspects of CMR as well as into emerging fields of the technique.

2. CMR in chronic CAD

The primary role of CMR in patients with suspected or known CAD is the assessment of myocardial ischaemia and the determination of myocardial viability, particularly in patients with previous myocardial infarction.

2.1. Ischaemia detection

Myocardial ischaemia cannot be seen as a distinct state but more as a continuum that ranges from small perfusion deficits in asymptomatic

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patients to impaired ventricular function and acute myocardial infarction (AMI) [8]. Fig. 1 depicts the different stages of ischaemia and how they can be assessed by CMR.

In clinical practice, the two basic methods for the determination of ischaemia are CMR-perfusion imaging during hyperaemia using vasodilators such as adenosine or regadenoson as well as dobutamine stress CMR (DSMR) for the detection of impaired regional wall motion. Both methods have excellent prognostic characteristics in patients with known or suspected CAD. For a two year follow-up after the examination, detection of ischaemia by CMR has a negative predictive value of 98% and thereby an annual event rate of about 1% in case of a negative and about 5% in case of a positive test result [9,10]. Ischaemia detection by CMR is indicated for the initial diagnosis in patients with suspected CAD (if the exercise ECG or stress echocardiography is insufficient or inconclusive) [11–14], for risk stratification and the identification of functionally significant stenosis in patients with known CAD [14–17] and in symptomatic patients with previous coronary revascularization [18,19].

2.1.1. CMR-perfusion imaging

The basic principle of CMR-perfusion imaging is the visualization of the passage of a gadolinium-based contrast agent (CA) through the myocardium under hyperaemic conditions induced by a pharmacologic vasodilator. Since gadolinium is a positive CA (bright in T_1-weighted images), normally perfused myocardial segments appear bright in T_1-weighted sequences under pharmacologic hyperaemia. Significantly stenosed coronary arteries do not adequately respond to pharmacological vasodilatation and consequently, in those segments, CA influx is delayed leading to a dark delineation of ischaemic territories (Fig. 2A). Usually the CA-doses are between 0.05 and 0.1 mmol/kg body weight. The most commonly used vasodilator adenosine (140 μg/min/kg body weight administered i.v. for 3 min) has a short half life time of ~12 s and is safe in clinical use [20]. Rare side-effects of adenosine are bronchospasm and transient atrioventricular (AV) node block consequently, contraindications are high-grade AV block or sinus node dysfunction and severe obstructive lung disease/asthma as well as significant hypo- or hypertension and AMI. The selective A_{2a} specific adenosine receptor agonist regadenoson which has higher vasodilative potential and is better tolerated than adenosine, recently received approval for stress CMR in Europe [21,22]. For imaging, a T_1-weighted cardiac triggered sequence with a minimal resolution of 2–3 × 2–3 mm^2 should be acquired [23]. Since CA first-pass perfusion lasts about 10 s, the sequence is performed during a breath-hold to eliminate respiratory motion artefacts [24]. Conventional MR sequences acquire three axial slices, to visualize perfusion deficits in the basal, midventricular and apical segments of the myocardium. Novel sequences allow for the 3-dimensional assessment of myocardial perfusion and thereby enable the determination of the myocardial ischaemic burden as percentage of the myocardium [19,25]. These 3D-CMR-perfusion sequences (Fig. 2B) proved to be highly accurate and reproducible in the evaluation of functionally significant coronary artery disease as defined by FFR [26]. Up to now, most studies used a visual approach for the evaluation of perfusion datasets, however, also computer assisted quantitative imaging approaches are available. Even though stress-perfusion only protocols yielded high diagnostic performance in several studies, rest CMR-perfusion imaging can be performed to rule out false positive results due to imaging artefacts. Comparative studies between CMR-perfusion imaging at 1.5 T and 3 T showed that 3 T CMR-perfusion imaging is superior to 1.5 T for prediction of significant single- and multi-vessel CAD [27,28], however, most clinical evidence is based on analyses performed at 1.5 T. A recent study indicated that the diagnostic accuracy of CMR might be further enhanced by adding MR coronary angiography (MRCA) to a standard CMR-perfusion protocol [29]. Compared to other non-invasive imaging modalities for the assessment of myocardial perfusion, in particular to single-photon emission computed tomography (SPECT), CMR has the advantage of no exposure of ionizing radiation for the patient. An additional advantage is a higher spatial resolution. In the large multicentre, multivendor MR-IMPACT trial, 234 patients underwent conventional coronary x-ray angiography (XA), SPECT and CMR-perfusion examinations. Thereby a superiority of CMR-perfusion over SPECT was found in the comparison of standard dose perfusion-CMR with the entire SPECT population [23]. Also in multi-vessel disease (MVD), CMR-perfusion proved better performance. The superiority was recently confirmed by the CE-MARC trial ($n = 752$) where CMR showed significantly higher sensitivity (86.5% vs 66.5%) and slightly better specificity (83.4% vs 82.6%) when compared with SPECT [30]. In the secondary endpoint analysis of the MR-IMPACT II trial, superiority of CMR vs SPECT could be shown for all SPECT ($p = 0.0004$, $n = 425$) and the gated-SPECT subgroup only ($p = 0.018$, $n = 253$) as well as

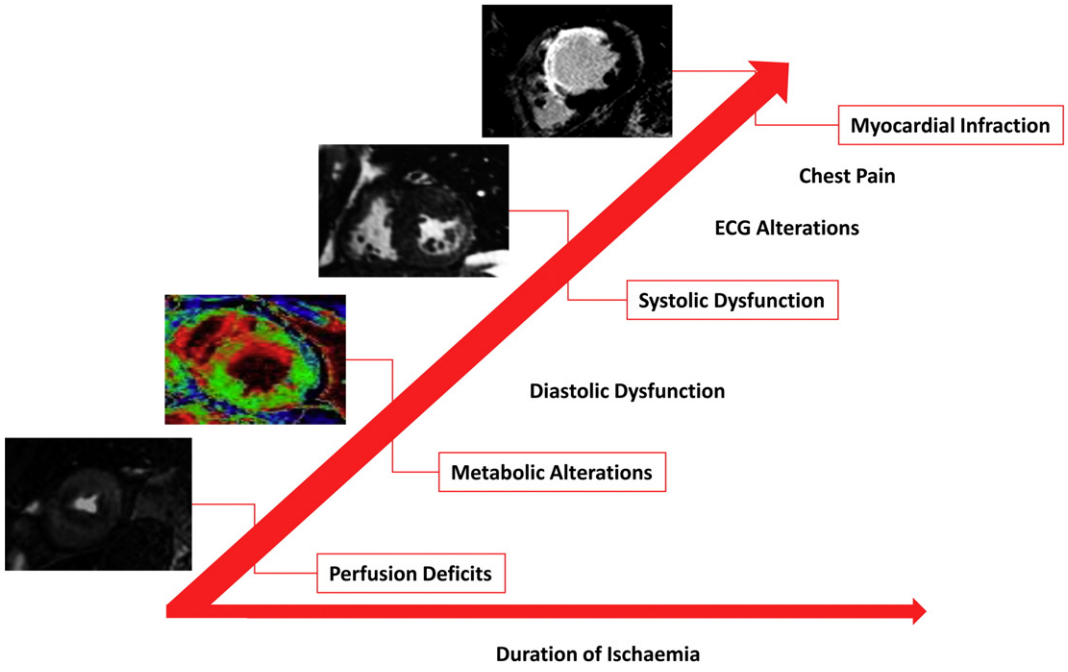

Fig. 1. The ischaemic cascade. During the evolution of ischaemia, different functional alterations of the myocardium occur that can be assessed by CMR (red boxes).