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Protocols and Indications for Magnetic Resonance (Stress) First-Pass Perfusion Imaging of the Myocardium

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Summary

First-pass perfusion imaging with MRI under pharmacologically induced stress for the detection of myocardial ischemia has gained a lot of interest over the past years. With adenosine as the main pharmacological 'stressor'. Issues regarding the best contrast dose and injection speed have become clear. Several perfusion sequences have been studied over the past. Even some large multi-centre trail results have been published. Some issues are still extensively research, like interpretation strategies and patient population in regard to protocols. This review highlights the technique of adenosine perfusion MRI and other perfusion techniques. The short history and current important literature are reviewed. Furthermore building blocks for different stress perfusion examinations are discussed.

Myocardial perfusion imaging with cardiovascular magnetic resonance imaging (CMR) is a dynamic technique to analyse the first-pass of a bolus of contrast agent through the myocardium. In which a heavily T1-weighted perfusion sequence is used, with acquiring multiple slice positions of the left ventricle, with 40–60 images per slice position (Fig. 1).

Early reports already showed the feasibility of first-pass myocardial perfusion using CMR (1). It proved possible first in a rat and later humans. Clear first-pass wash-in and wash-out was observed. One year later observations of signal enhancement after revascularization were published (2). These reports stated the possibility of performing myocardial perfusion imaging with CMR in a resting condition.

In case of a normal myocardial perfusion, the myocardium of the left ventricle will homogeneously enhance after a bolus of gadolinium. Perfusion abnormalities (perfusion defects) can occur after for instance a myocardial infarction and are visible as regional areas of low signal intensity, which can be related to the distribution area of a coronary artery.

Other possible explanation for a perfusion defect is a significant stenosis of a coronary artery giving rise to diminished flow and subsequent diminished perfusion of the myocardium supplied by the stenotic vessel (Fig. 2). Which in this regard represents myocardial ischaemia.

As only very high-grade coronary stenoses give rise to perfusion defects under conditions of rest the way had to be paved for detecting myocardial ischaemia related perfusion defects.

In 1992, Schaefer et al. (3) reported in Radiology that it was possible to detect regional perfusion abnormalities using pharmacological induced 'stress' (dipyridamol).

The concept of stress perfusion MR imaging was born, but image quality and spatial coverage was limited. In that time only a single slice of the myocardium. Technical improvements have led to a current spatial coverage of 3–8 slices (with a slice thickness of 8–12 mm) dependent on the temporal resolution.

Severity and extend of myocardial ischaemia are related to prognosis and revascularization is guided by coronary stenosis morphology and its haemodynamic consequences (4). This makes the non-invasive objectification of myocardial ischaemia important.

Well-known 'stress'-tests for the detection of myocardial ischaemia, like for instance bicycle exercise testing or SPECT imaging are limited in their diagnostic accuracy or spatial resolution.

ECG alterations, left ventricular wall motion abnormalities and perfusion abnormalities under stress conditions are all means of objectifying myocardial ischaemia, which can be performed with different imaging modalities. The advantage of perfusion imaging lies in the earlier occurrence of perfusion abnormalities in the ischaemic cascade (5) as compared to wall motion abnormalities or ECG changes.

Besides dipyridamol, dobutamine and adenosine are used as pharmacological stressors for myocardial perfusion MR imaging. Dipyridamol can be used for perfusion imaging, but its important drawback is the long half life,

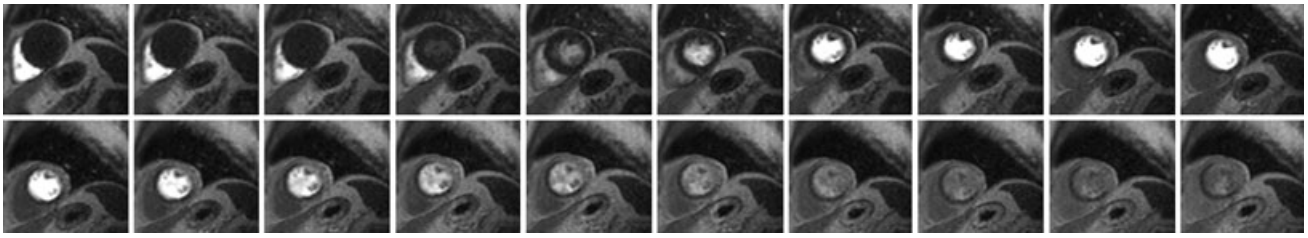


Fig. 1. Twenty consecutive images of the first-pass perfusion of a mid-ventricular short-axis slice under adenosine infusion. Signal enhancement in the right ventricular cavity can be observed in the first image (top row). Images 4–7 (top row) show contrast arrival in the left ventricular cavity. Myocardial enhancement can be observed in the subsequent images, with the last images of the bottom row representing wash-out. Furthermore a large perfusion defect is present, see also figure 2 in which one frame is enlarged. For normal diagnostic purposes viewed in cine mode.

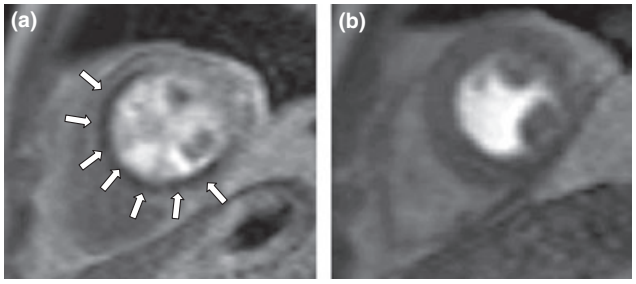


Fig. 2. Two single frames of the same mid-ventricular short-axis slice of the same patient, under adenosine infusion (a) (frame identical to fifth image bottom row of figure x, now enlarged) and rest perfusion (b). Under adenosine infusion a large perfusion defect is present (low signal area pointed out by the arrows). Rest perfusion shows a normal homogeneous perfusion of the myocardium, indicating myocardial ischaemia.

therefore dipyridamol has lost popularity as a pharmacological stressor in favour of adenosine.

Dobutamine a synthetic catecholamine is actually the only real pharmacological stressor with both an inotropic and chronotropic effect (leading to a considerable increase in systolic blood pressure and heart rate). For perfusion imaging it has a limited role, because of the inotropic and chronotropic effect it is better suited for wall motion analysis of the left ventricle (6, 7). Wall motion abnormalities under dobutamine infusion are also indicative of myocardial ischaemia, but occur as mentioned later in the ischaemic cascade. Contra-indication for adenosine, the presence of a prior myocardial infarction, local expertise, etc. can however be reasons to choose for a dobutamine stress CMR test (wall motion analysis). Because of the earlier occurrence of perfusion abnormalities before wall motion abnormalities, dobutamine perfusion-imaging can be performed on peak dose dobutamine in case of an atypical wall motion abnormality to confirm that it is indeed myocardial ischaemia, or not (8).

Adenosine is an endogenous nucleotide, with strong vasodilator capabilities, it accomplishes maximal vasodilatation of normal vessels. No further dilatation of significant coronary stenoses is possible (already physiological maximal vasodilatation), thereby creating a coronary steal-effect. In terms of imaging a relative hypo-perfusion of the myocardium supplied by the stenotic vessels.

Adenosine is therefore not a real 'stressor'. The term stress is used to indicate that it is a test to detect myocardial ischaemia. It is also referred to as adenosine vasodilator stress or just adenosine perfusion. The short half life makes it very controllable.

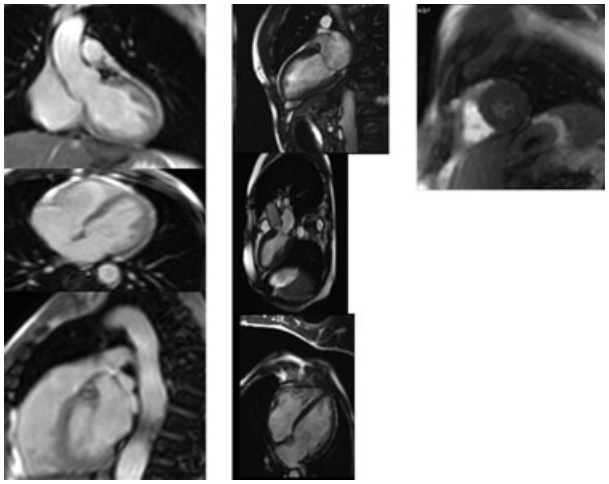
'Stress' perfusion imaging with MRI is therefore currently mostly performed with adenosine as a pharmacological stressor. This article will therefore focus mainly on perfusion imaging for the detection of myocardial ischaemia under adenosine infusion.

The objectives of this article are to review different protocols regarding adenosine first-pass perfusion imaging. How to perform and interpret the examination. Furthermore, some current relevant issues in perfusion MR imaging are addressed. Practical advices will be given and future perspectives will be discussed.

Protocols

Different strategies apply when creating a 'stress' perfusion CMR protocol and performing the examination. An adenosine 'stress' – only approach can be used in a relatively low-risk population in patients without a prior myocardial infarction. In case of regional hypo-perfusion under 'stress' a rest perfusion can be performed. When clinically indicated (for instance a prior myocardial infarction) delayed contrast enhancement (DCE) imaging can be performed in the same protocol. Figures 3–5 display these protocols in images. The building blocks for these protocols are stress perfusion imaging, rest perfusion imaging, cine imaging in spare time between contrast boluses (for left ventricular functional parameter assessment) and DCE.

When performing stress and rest perfusion imaging, the stress perfusion imaging is typically performed first, because this is the most important part of the examination, this way there is no signal influence by a prior contrast bolus and if the examination has to be stopped for whatever reason at least this part of the examination is



■ **Fig. 3.** Stress-only protocol: after localizer images and standard cine images only a stress perfusion sequence.

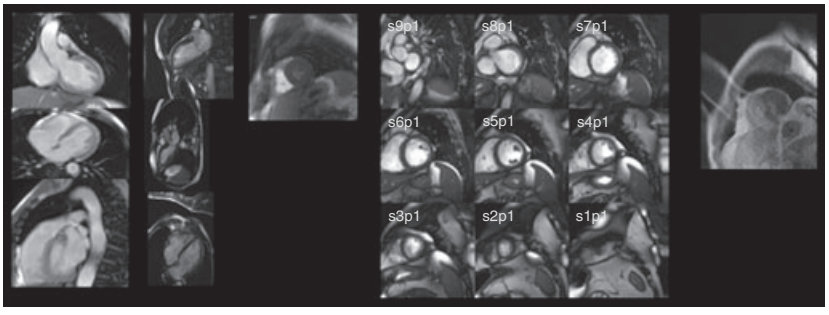
done. Between stress and rest perfusion imaging one should wait several minutes, not because of the effect of the adenosine (this effect is gone in seconds), but because of the signal influence caused by the first contrast bolus. In this spare time a stack of short axis cine images of the left ventricle can be acquired for left ventricular functional parameter assessment, which after quantification can give an idea as to parameters like ejection fraction, etc. (9).

A protocol employing 'stress'-only (Fig. 3) has the advantage of reduced imaging time, only one contrast agent bolus, no spatial matching required between 'stress' and rest perfusion and no signal influence by the first contrast agent bolus, it can be used in patients without a prior myocardial infarction to determine in little time if there is an indication for coronary angiography, validations for this approach are currently under examination. Advantages of a more comprehensive protocol (Figs 4 and 5) are improved CAD detection (10) and more easily recognition of artefacts (11). A choice has to be made according to the presence of a prior myocardial infarction and experience, with less experience rest perfusion and DCE are probably more helpful.

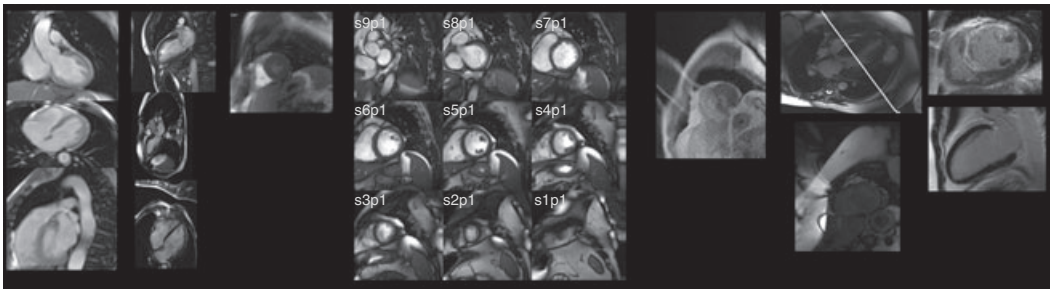
Preparations

Before scanning the patient with adenosine, some essential instructions should be given to the patient. Xanthine containing substances like coffee, tea, cola and chocolate block the effect of adenosine and should be stopped 24 h prior to the examination to make it a diagnostic study. Another check-up is to whether the patient uses dipyridamol. Dipyridamol potentiates adenosine, therefore it has to be stopped if possible or considered a contra-indication. Another precaution is to check (again) for contra-indications like asthma, acute coronary syndrome and recent myocardial infarction and pre-existing AV-block. Besides these contra-indications, of course general contra-indications for MR imaging like renal insufficiency, claustrophobia and non MR-compatible metallic implants apply.

Under adenosine infusion patients may get a flushing senation and warmth, these possibilities should be explained to the patient as normal side-effects. Other potential side-effects are headaches, atypical chest pain, mild reductions in blood pressure, bradycardia and AV-block. These side-effects have been systematically



■ **Fig. 4.** Stress-rest protocol: with rest perfusion following stress perfusion and cine imaging in spare time.



■ **Fig. 5.** Stress-rest-DCE protocol.

reported in over 3000 MR studies (12). All these side-effects were transient, resolved in a few minutes and did not require medical intervention.

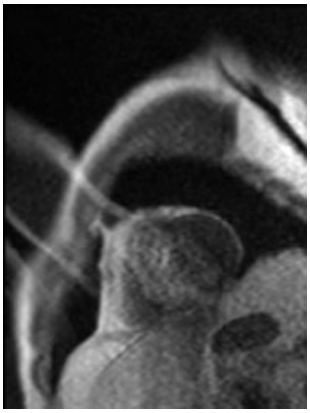
Even if an AV-block occurs, the antidote is simple, namely pressing the stop button of the adenosine pump. For the patient and the doctor this pretty much means just taking a deep breath. A crash-car should however be present for the theoretical chance of a serious adverse event, with aminophyline as an antidote present. Regular exercise drills should be trained and a physician should be present in the MR-suite during the adenosine infusion.

After these check-ups the patient is placed on the MR table, intravenous line(s) placed, a blood pressure cuff is applied for monitoring and of course ECG leads are placed. Furthermore breathing instruction for the perfusion sequence is given.

Examination

First localizer images are acquired for subsequent steps, from these images perfusion slices are planned (Fig. 6). Before starting the adenosine infusion, the following step should be to perform a perfusion dry-run. This means starting a perfusion sequence without contrast applied and with only a single image acquired per slice position. This way one can make sure that the most apical and most basal slice are proper positioned. Anticipate for the fact that during adenosine infusion the heart rate will increase and probably also the length axis shortening of the left ventricle, the most basal slice may then be to basal and show parts of the left ventricular outflow tract rendering it a non diagnostic slice. Another advantage of this dry-run is to make sure that there is no disturbing back folding, in case of back folding over the left ventricle the field of view should be enlarged or positioning should be changed, with the back folding in this case over non left ventricle areas (Fig. 7). After these verifications the acquired images per slice should again be set to 40–60 and then the adenosine infusion may begin.

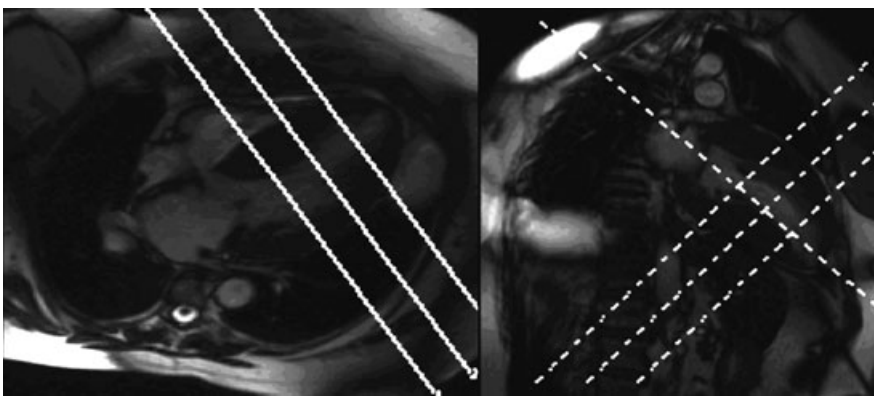
Adenosine is infused intravenously (140 μg/kg/min) and first-pass perfusion imaging is performed after 3 min of continuous adenosine infusion, using a bolus of contrast agent (gadolinium-DTPA) of 0.05–0.1 mmol/kg, with a flow rate of 3–5 mL/s followed by a saline flush. For this purpose a heavily T1-weighted dynamic sequence is used, acquiring images in multiple slice positions (at least 3–4) consisting of 40–60 images per position in one breath hold (Fig. 1).



■ **Fig. 7.** Example of dry-run sequence with back folding.

To dynamically follow the wash-in and wash-out of a contrast agent it is important to have a high temporal resolution. Most clinically used perfusion sequences allow to acquire 3–4 slices in different positions with single heart beat resolution. This is however dependent on the heart rate. A heart rate of 60 bpm equals approximately an R-R interval of 1000 ms. An increase in heart rate decreases the R-R interval and thereby reducing possible image acquisition time and as a consequence spatial coverage. Under adenosine infusion the heart rate increases with 10–15 beats per minute, which leaves enough spatial coverage. In case of a large increase in heart rate novel parallel imaging sequences, like time-adaptive sensitivity encoding can be used. These parallel imaging techniques increase spatial coverage at the expense of some signal-to-noise ratio (SNR) loss (13). Newer acquisition techniques like k-t SENSE allow for a substantial acceleration of data acquisition, which can be used to increase spatial resolution or SNR (14).

The protocol choice should match the perfusion sequence. The choice for the sequence depends on factors



■ **Fig. 6.** acquisition steps for planning three short-axis and one long axis slice for the following perfusion sequence.

like if you want to perform a visual or quantitative analysis, the heart rate and whether you want to use a stress-only protocol. For a stress-only examination our choice is for the highest signal and contrast-to-noise ratio (CNR). For quantitative analysis fewer artefacts are important and for imaging at really high heart rates we need parallel imaging to maintain enough spatial coverage.

The best perfusion sequence has yet to be determined. SR-GRE-EPI, SR-FLASH and SR-SSFP are often used. SR-SSFP give higher SNR and CNR (15), but probably some more artefacts. A good overview of available perfusion sequences is given by Kellman and Arai (16).

The injection speed of the contrast agent bolus has to be from 3 to 5 mL/s (17, 18), because a small homogeneous bolus is needed to track the first-pass of the contrast agent and resulting signal intensity changes.

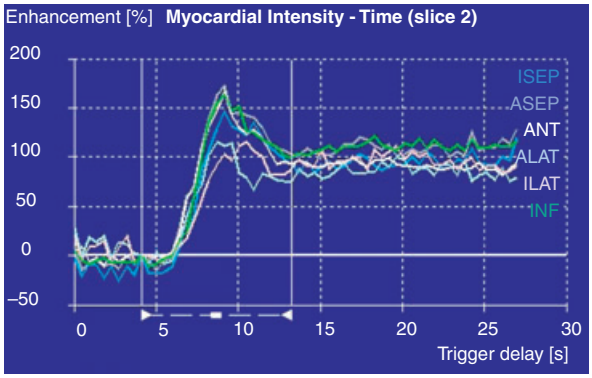
The contrast dose is dependent on whether you want to perform a visual or a (semi-) quantitative analysis. For a (semi-) quantitative approach a low dose of 0.05 mmol/kg is required to maintain a linear relationship between signal intensity change and contrast dose. Interpretation of these perfusion images is however most of the time performed visually or qualitatively. For routine clinical practice it is the most often used analysis. The optimal gadolinium dose for visual analysis is 0.1 mmol/kg, with significantly more artefacts at higher gadolinium doses (17, 18). After contrast arrival in the left ventricle the adenosine infusion can be stopped and the examination further completed dependent on the chosen protocol.

Interpretation

In the report of the analysis, the radiologist states the myocardial segments with the perfusion defect, the degree of transmurality and to which coronary artery these segments belong. Heart rate and blood pressure compared to rest are also mentioned. Left ventricular functional parameters and information regarding rest perfusion or DCE is provided depending again on the protocol.

Artefacts are important to discriminate from 'true' perfusion defects. They occur early, are subendocardial real focal defects, occurring during the upslope of signal intensity change and then disappearing. They are caused by a high gadolinium concentrations or low spatial resolution. By using a systematic visual analysis one can differentiate between a normal perfusion, a defect caused by myocardial ischaemia and an artefact. Systematically look for a relationship with a coronary distribution area, whether it involves neighbouring segments. Assess whether there are any changes in signal intensity, knowing that especially artefacts give these fluctuations and assess whether the defect persists after peak enhancement, more suggestive for a 'true' perfusion defect (10, 19–24).

A quantitative analysis with MR is possible. In which at signal–intensity time curves peak signal intensity and upslope are used as parameters for hypo-perfusion. For a quantitative analysis a lower dose of 0.05 mmol/kg is used, as mentioned, to maintain a linear relationship between contrast-dose and signal intensity. Post-processing is necessary, in which endocardial and epicardial contours have to be drawn, resulting in signal intensity time curves (Fig. 8). This can be rather time consuming. Studies comparing visual with a quantitative analysis show similar good results (25–27), comparable with our experience.



■ **Fig. 8.** Graphic representation of myocardial signal intensity change (enhancement) over time after a bolus of contrast agent for six different myocardial segments. MASS v6.1.2 (Medis, Leiden, the Netherlands).

Current status

In summary, a choice has to be made for the protocol and used sequences, the gadolinium dose, 0.1 for a visual analysis and 0.05 mmol/kg gadolinium for a quantitative analysis. The injection speed has to be between 3 and 5 mL/s for a compact bolus. Spatial coverage set at at least 3–4 slices. 'Stress-only' has the advantage of reduced imaging time, one contrast agent bolus, no spatial matching required, and no signal influence by the first bolus. Advantages of a more comprehensive protocol are detection of subendocardial/subclinical myocardial infarction (10) and easier recognition of artefacts (11). Visual analysis is the most used analysis method in clinical practice. Quantitative analysis is probably more objective and less experience related, but still very time-consuming. Besides these issues more and more validation for adenosine perfusion MR is published.

Bernhardt et al. (20) for instance performed a study in which they assessed whether adenosine perfusion MR can predict the need for revascularization with CAG as a reference standard and it proved a useful prediction to guide therapy.

Reported diagnostic accuracies over the last 3 years for adenosine perfusion CMR range from 78% to 100% for sensitivity, 68% to 93% for specificity, negative predictive value from 77% to 100% and positive predictive value from 71% to 95% (10, 11, 17–22, 28–33). Differences in these reported accuracies are caused by differences in the studied population, the used sequence and used protocols,

the contrast dose, spatial coverage and the used reference modality and the stenoses grade defined as significant.

Higher diagnostic accuracies are reached when adenosine perfusion CMR was not compared to coronary angiography but to a functional reference standards, like fractional flow reserve for instance (32). In this way, haemodynamically relevant stenosis could be distinguished from non-haemodynamically relevant stenosis.

The prognostic role of a normal adenosine perfusion MR examination, has been studied in a few studies (31, 34, 35). In a study by Ingkanisorn et al. (31), the prognosis of a negative adenosine perfusion MR study in patients presenting to the Emergency Room with stable chest pain was assessed with no events at 1-year follow-up in case of a normal adenosine perfusion examination. Also the sum of the total cardiac risk factors was less predictive than the MR results.

Paetsch et al. (36) compared adenosine stress perfusion and dobutamine stress wall motion analysis in a single examination in the same patients. With the highest overall accuracy for dobutamine stress wall motion analysis, but the highest sensitivity for adenosine perfusion MR. Results from the MR-impact study (a multi-centre, multi-vendor study) show that adenosine perfusion MR with a dose of 0.1 mmol/kg gadolinium is superior to SPECT imaging in a direct comparison with quantitative CAG as the reference standard (37).

This brings us to the current clinical indication for adenosine perfusion CMR. The detection of myocardial ischaemia in the setting of new or recurrent chest pain. Prognosis and risk stratification. Follow-up after interventional treatment (23). Determining the functional significance of known angiograpically determined lesions, and microvascular dysfunction (38).

Future perspectives for adenosine perfusion MR are the routine use of 3T imaging (39–41). More published results from multi-centre randomized trials. Protocols further optimized for the patient population, further sequence design, especially focusing on parallel imaging, and less time-consuming quantification.

In conclusion, MR perfusion imaging of the myocardium is being implemented into routine clinical practice more and more. Adenosine 'stress' perfusion MR is an accurate tool for the detection of myocardial ischaemia. Heterogeneity still exists between used protocols and reported accuracies. The used protocol should be tailored for the patient population.

References

1. Atkinson DJ, Burstein D, Edelman RR. First-pass cardiac perfusion: evaluation with ultrafast MR imaging. Radiology 1990; 174: 757–762.
2. Manning WJ, Atkinson DJ, Grossman W, Paulin S, Edelman RR. First-pass nuclear magnetic resonance imaging studies using gadolinium-DTPA in patients with coronary artery disease. J Am Coll Cardiol 1991; 18: 959–965.
3. Schaefer S, van TR, Saloner D. Evaluation of myocardial perfusion abnormalities with gadolinium-enhanced snapshot MR imaging in humans. Work in progress. Radiology 1992; 185: 795–801.
4. Gibbons RJ, Balady GJ, Beasley JW et al. ACC/AHA guidelines for exercise testing: executive summary. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Exercise Testing). Circulation 1997; 96: 345–354.
5. Nesto RW, Kowalchuk GJ. The ischemic cascade: temporal sequence of hemodynamic, electrocardiographic and symptomatic expressions of ischemia. Am J Cardiol 1987; 59: 23C–30C.
6. Kuijpers D. Diagnosis of coronary artery disease with dobutamine-stress MRI. Eur Radiol 2005; 15 (Suppl. 2): B48–B51.
7. Nagel E, Lehmkuhl HB, Bocksch W et al. Noninvasive diagnosis of ischemia-induced wall motion abnormalities with the use of high-dose dobutamine stress MRI: comparison with dobutamine stress echocardiography. Circulation 1999; 99: 763–770.
8. Lubbers DD, Janssen CH, Kuijpers D et al. The additional value of first pass myocardial perfusion imaging during peak dose of dobutamine stress cardiac MRI for the detection of myocardial ischemia. Int J Cardiovasc Imaging 2008; 24: 69–76.
9. Lubbers DD, Willems TP, van der Vleuten PA et al. Assessment of global left ventricular functional parameters: analysis of every second short-axis Magnetic Resonance Imaging slices is as accurate as analysis of consecutive slices. Int J Cardiovasc Imaging 2008; 24: 185–191.
10. Klem I, Heitner JF, Shah DJ et al. Improved detection of coronary artery disease by stress perfusion cardiovascular magnetic resonance with the use of delayed enhancement infarction imaging. J Am Coll Cardiol 2006; 47: 1630–1638.
11. Thomson LE, Fieno DS, Abidov A et al. Added value of rest to stress study for recognition of artifacts in perfusion cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2007; 9: 733–740.
12. Bernhardt P, Steffens M, Kleinertz K et al. Safety of adenosine stress magnetic resonance imaging using a mobile cardiac magnetic resonance system. J Cardiovasc Magn Reson 2006; 8: 475–478.
13. Irwan R, Lubbers DD, van der Vleuten PA, Kappert P, Gotte MJ, Sijens PE. Parallel imaging for first-pass myocardial perfusion. Magn Reson Imaging 2007; 25: 678–683.
14. Plein S, Kozerke S, Suerder D et al. High spatial resolution myocardial perfusion cardiac magnetic resonance for the detection of coronary artery disease. Eur Heart J 2008; 29: 2148–2155.
15. Schreiber WG, Schmitt M, Kalden P, Mohrs OK, Kreitner KF, Thelen M. Dynamic contrast-enhanced myocardial perfusion imaging using saturation-prepared TrueFISP. J Magn Reson Imaging 2002; 16: 641–652.
16. Kellman P, Arai AE. Imaging sequences for first pass perfusion – a review. J Cardiovasc Magn Reson 2007; 9: 525–537.
17. Giang TH, Nanz D, Coulden R et al. Detection of coronary artery disease by magnetic resonance myocardial perfusion imaging with various contrast medium doses: first European multi-centre experience. Eur Heart J 2004; 25: 1657–1665.
18. Wolff SD, Schwitter J, Coulden R et al. Myocardial first-pass perfusion magnetic resonance imaging: a multicenter dose-ranging study. Circulation 2004; 110: 732–737.
19. Sakuma H, Suzawa N, Ichikawa Y et al. Diagnostic accuracy of stress first-pass contrast-enhanced myocardial perfusion MRI compared with stress myocardial perfusion scintigraphy. AJR Am J Roentgenol 2005; 185: 95–102.
20. Bernhardt P, Engels T, Levenson B, Haase K, Albrecht A, Strohm O. Prediction of necessity for coronary artery revascularization by adenosine contrast-enhanced magnetic resonance imaging. Int J Cardiol 2006; 112: 184–190.
21. Pilz G, Bernhardt P, Klos M, Ali E, Wild M, Hofling B. Clinical implication of adenosine-stress cardiac magnetic resonance imaging as potential gatekeeper prior to invasive examination in patients with AHA/ACC class II indication for coronary angiography. Clin Res Cardiol 2006; 95: 531–538.

22. Cury RC, Cattani CA, Gabure LA et al. Diagnostic performance of stress perfusion and delayed-enhancement MR imaging in patients with coronary artery disease. Radiology 2006; 240: 39–45.
23. Fenchel M, Franow A, Stauder NI et al. Myocardial perfusion after angioplasty in patients suspected of having single-vessel coronary artery disease: improvement detected at rest-stress first-pass perfusion MR imaging – initial experience. Radiology 2005; 237: 67–74.
24. Crean A, Merchant N. MR perfusion and delayed enhancement imaging in the heart. Clin Radiol 2006; 61: 225–236.
25. Schwitter J, Nanz D, Kneifel S et al. Assessment of myocardial perfusion in coronary artery disease by magnetic resonance: a comparison with positron emission tomography and coronary angiography. Circulation 2001; 103: 2230–2235.
26. Ishida N, Sakuma H, Motoyasu M et al. Noninfarcted myocardium: correlation between dynamic first-pass contrast-enhanced myocardial MR imaging and quantitative coronary angiography. Radiology 2003; 229: 209–216.
27. Chiu CW, So NM, Lam WW, Chan KY, Sanderson JE. Combined first-pass perfusion and viability study at MR imaging in patients with non-ST segment-elevation acute coronary syndromes: feasibility study. Radiology 2003; 226: 717–722.
28. Plein S, Greenwood JP, Ridgway JP, Cranny G, Ball SG, Sivananthan MU. Assessment of non-ST-segment elevation acute coronary syndromes with cardiac magnetic resonance imaging. J Am Coll Cardiol 2004; 44: 2173–2181.
29. Paetsch I, Foll D, Langreck H et al. Myocardial perfusion imaging using OMNISCAN: a dose finding study for visual assessment of stress-induced regional perfusion abnormalities. J Cardiovasc Magn Reson 2004; 6: 803–809.
30. Plein S, Radjenovic A, Ridgway JP et al. Coronary artery disease: myocardial perfusion MR imaging with sensitivity encoding versus conventional angiography. Radiology 2005; 235: 423–430.
31. Ingkanisorn WP, Kwong RY, Bohme NS et al. Prognosis of negative adenosine stress magnetic resonance in patients presenting to an emergency department with chest pain. J Am Coll Cardiol 2006; 47: 1427–1432.
32. Rieber J, Huber A, Erhard I et al. Cardiac magnetic resonance perfusion imaging for the functional assessment of coronary artery disease: a comparison with coronary angiography and fractional flow reserve. Eur Heart J 2006; 27: 1465–1471.
33. Kuhl HP, Katoh M, Buhr C et al. Comparison of magnetic resonance perfusion imaging versus invasive fractional flow reserve for assessment of the hemodynamic significance of epicardial coronary artery stenosis. Am J Cardiol 2007; 99: 1090–1095.
34. Pilz G, Jeske A, Klos M et al. Prognostic value of normal adenosine-stress cardiac magnetic resonance imaging. Am J Cardiol 2008; 101: 1408–1412.
35. Jahnke C, Nagel E, Gebker R et al. Prognostic value of cardiac magnetic resonance stress tests: adenosine stress perfusion and dobutamine stress wall motion imaging. Circulation 2007; 115: 1769–1776.
36. Paetsch I, Jahnke C, Wahl A et al. Comparison of dobutamine stress magnetic resonance, adenosine stress magnetic resonance, and adenosine stress magnetic resonance perfusion. Circulation 2004; 110: 835–842.
37. Schwitter J, Wacker CM, van Rossum AC et al. MR-IMPACT: comparison of perfusion-cardiac magnetic resonance with single-photon emission computed tomography for the detection of coronary artery disease in a multicentre, multivendor, randomized trial. Eur Heart J 2008; 29: 480–489.
38. Panting JR, Gatehouse PD, Yang GZ et al. Abnormal subendocardial perfusion in cardiac syndrome X detected by cardiovascular magnetic resonance imaging. N Engl J Med 2002; 346: 1948–1953.
39. Araoz PA, Glockner JF, McGee KP et al. 3 Tesla MR imaging provides improved contrast in first-pass myocardial perfusion imaging over a range of gadolinium doses. J Cardiovasc Magn Reson 2005; 7: 559–564.
40. Gutberlet M, Noeske R, Schwinge K, Freyhardt P, Felix R, Niendorf T. Comprehensive cardiac magnetic resonance imaging at 3.0 Tesla: feasibility and implications for clinical applications. Invest Radiol 2006; 41: 154–167.
41. Theisen D, Wintersperger BJ, Huber A, Dietrich O, Reiser MF, Schonberg SO. Myocardial perfusion imaging with Gadobutrol: a comparison between 3 and 1.5 Tesla with an identical sequence design. Invest Radiol 2007; 42: 499–506.