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MYOCARDIAL PERFUSION

Combined Long- and Short-Axis Myocardial Perfusion Cardiovascular Magnetic Resonance

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ABSTRACT

Purpose: To date, myocardial perfusion cardiovascular magnetic resonance (CMR) has been reported in single and multiple short-axis slices. Three short-axis planes can assess 16 segments of the standard 17-segment myocardial model, but this approach fails to assess the ventricular apex that requires at least one long-axis plane. We therefore evaluated the feasibility and benefit of combined long- and short-axis perfusion CMR to enable complete 17 segments coverage for comprehensive myocardial perfusion assessment. *Methods and Materials:* Using a hybrid echo planar imaging (EPI) sequence, we performed rest and adenosine stress first-pass perfusion CMR studies with 3 short-axis (basal, mid, apical) planes, and additional long-axis planes in the same cardiac cycle in a broad range of cardiology patients. *Results:* Perfusion CMR was performed in 53 consecutive patients using the combined short-long-axis imaging protocol. Twenty-nine of those studied had known or suspected coronary artery disease (CAD), 18 hypertrophic cardiomyopathy, and 6 suspected microvascular perfusion abnormalities. In 39 patients (70%), it was possible to acquire 5 slices at rest and stress including both the horizontal and vertical long axes. In 15 patients (27%), only one long-axis could be acquired, and in 2 patients (5%) only 3 slices (short axis) could be obtained. However, in none of the patients with known or suspected CAD was apical ischemia demonstrated by the long-axis views, despite apical ischemia having been demonstrated with recent SPECT studies in 8 of these patients. *Conclusion:* Rest-stress myocardial perfusion CMR is able to achieve complete segmental coverage of the myocardium using the combined short-long axis approach using an EPI sequence in 97% of a long series of consecutive cardiology

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patients, while maintaining excellent spatial resolution. However, the long-axis views were not found to be able to demonstrate inducible perfusion defects in the apex.

Key Words: Cardiovascular magnetic resonance; Perfusion; Myocardial; Segment.

INTRODUCTION

Recent publication of the standardized myocardial segmentation and nomenclature for tomographic imaging of the heart by the American Heart Association (Cequeira et al., 2002) has aimed to make all cardiac imaging modalities, including cardiovascular magnetic resonance (CMR), define, orient, and display the heart in the same way. This standardized 17-segment model will allow greater cooperation and comparison between the techniques.

Myocardial perfusion CMR is a powerful and emerging new tool in the assessment of coronary artery disease (CAD). It has excellent spatial resolution compared to conventional nuclear perfusion techniques and even at its current relatively early stage of clinical development is providing new insights into difficult conditions (Panting et al., 2002). It involves no ionising radiation making repeated clinical studies and ethical approval for serial myocardial perfusion research less problematic. In addition, it can be combined with other aspects of CMR [volumes and mass (Bellenger et al., 2000), viability (Kim et al., 2000), coronary angiography (Kim et al., 2001)] in the same study. However, some issues remain. The temporal resolution of perfusion CMR has limited the number of slices that can be acquired per cardiac cycle, especially during the tachycardia of stress. Faster sequences such as hybrid echo planar imaging (EPI) and more recently parallel acquisition techniques (Zhang et al., 2003) have increased the number of slices that can be acquired per cardiac cycle typically to at least 3. However, these have been acquired in the short-axis (SA) plane, and this excludes the apex (segment 17 of the standard model). In order to visualize the apex by perfusion CMR, it is necessary to adopt one of two strategies: acquire multiple long-axis views (perhaps 4 slices at 45° angle to each other), or acquire combined SA and long-axis views (a minimum of one long-axis view). Previous work has demonstrated the ability of perfusion CMR to acquire short- and long-axis views at rest in healthy volunteers. We therefore hypothesized that the improved temporal resolution of perfusion CMR using an EPI sequence would allow complete segmental coverage of the myocardium, including the apical cap, with a combination of short- and long-axis views acquired in each cardiac cycle. We also set out to assess whether the long-axis views gave additional information over the SA views alone, in particular whether the long-axis views were able to detect induced apical perfusion defects missed by the SA views.

METHODS

Ethical approval was obtained for the research studies from the local ethics committee, and each subject gave informed consent. All studies were performed on a 1.5 T scanner (Siemens Sonata, Erlangen, Germany). Perfusion CMR studies were performed in 53 consecutive cardiology patients. Each patient underwent a rest first-pass perfusion study followed by an adenosine (140 μg/kg/min) stress perfusion study 20 min later. Each subject abstained from caffeine or other adenosine antagonists for 24 h prior to the study. An EPI sequence (Ding et al., 1998) was used in each study [EPI factor 4 center out path, field of view (FOV) $34-40\times26-30$ cm, raw data matrix 128×96, TR 5.6 ms, TE 1.17 ms, flip angle 30°, nonselective saturation prepulse before each slice, saturation recovery time to centre of k-space 60 ms, image time 110 ms, spatial resolution 2.7×3.6 mm to 3.1×4.1 mm, slice thickness 8 mm]. No filtering was applied to the reconstruction of the sequence. The FOV was set at the minimum that did not result in any wrap-around into the left ventricular (LV) myocardium. In each study, 0.1 mmol/kg gadolinium-DTPA (Magnevist, Schering) was given at rest and stress, injected at 7 ml/s by power injection (Medrad) via an 18 G cannula in the right antecubital fossa followed by a 10-ml normal saline flush. The subjects were asked to hold their breath in end-expiration from the start of the perfusion sequence for as long as was comfortable. Images were acquired over 50 cardiac cycles. We aimed to acquire 3 SA views (apical, mid, and basal), and 2 long-axis views (vertical and horizontal long axis) in each cardiac cycle. The typical gap between each SA view was 6–10 mm, adjusted to the length of the LV. This protocol aimed to achieve coverage of all 17 segments; 6 basal segments, 6 mid segments, 4 apical segments, and the long-axis views covering the apical cap. The images were acquired immediately after the R wave. The SA images were acquired first (apex to base), followed by the vertical long-axis (VLA) then

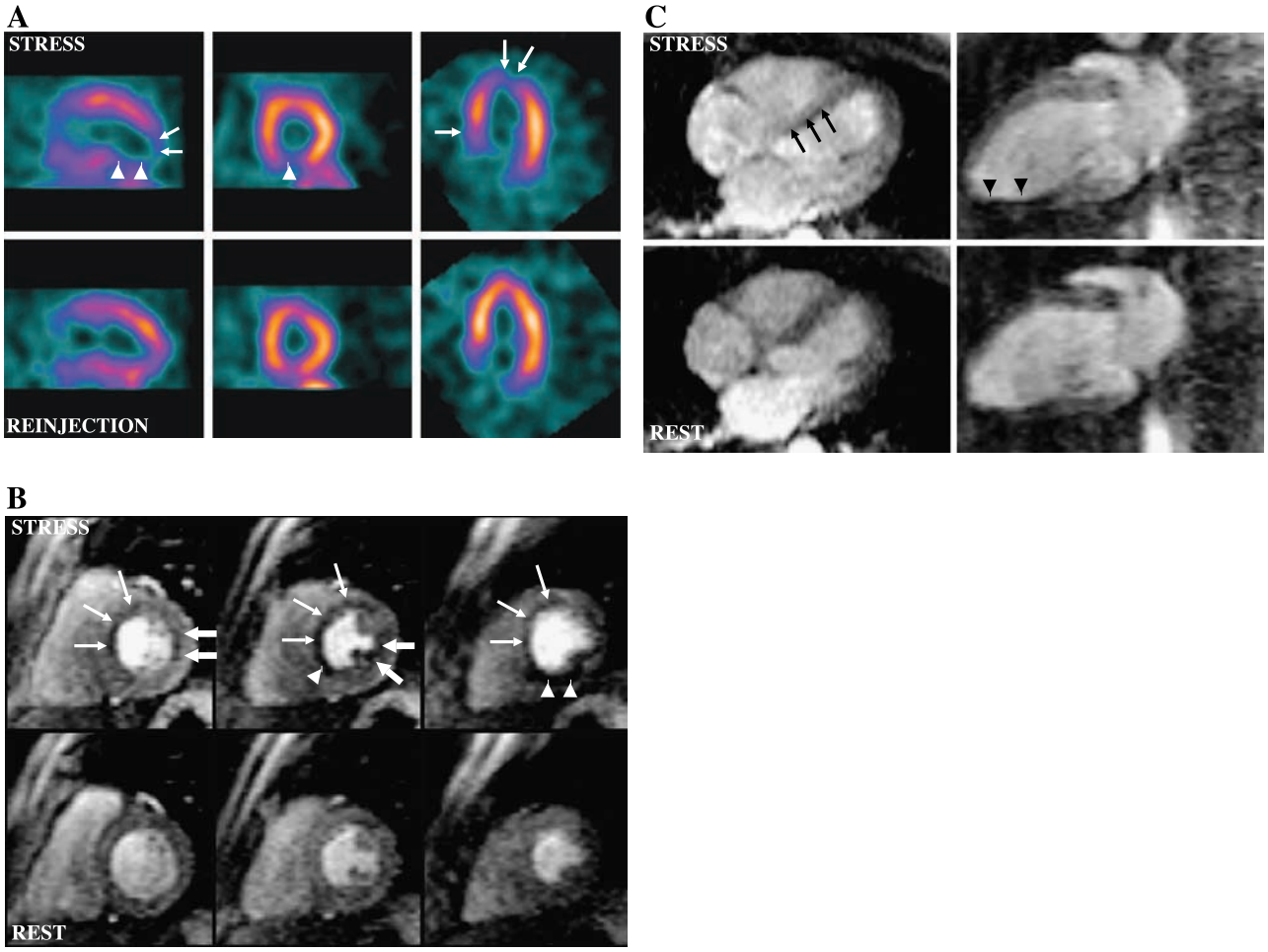

Figure 1. A thallium-201 perfusion study in a patient with 70% proximal LAD stenosis, 50% proximal LCX stenosis, and 80% proximal RCA stenosis (A). The thallium scan demonstrated inducible perfusion abnormalities in the septum, inferior wall, antero-apical wall, and apex (thin arrows show LAD territory, arrow heads show RCA territory). The lateral wall had normal stress perfusion. In the same patient, inducible perfusion abnormalities demonstrated by perfusion CMR with an EPI sequence in the antero-septal, inferior, infero-septal, lateral walls (thin arrows LAD territory, fat arrows LCX territory, arrow heads RCA territory) (B, C). The lateral wall perfusion abnormality detected with CMR was not seen with SPECT. The apical perfusion defect seen on SPECT was not seen on CMR with the long-axis views. The short- and long-axis views were acquired every cardiac cycle (B and C, respectively).

horizontal long-axis (HLA) views. If the RR interval was insufficient to allow acquisition of all 5 slices (RR interval<570 ms, HR>105 bpm), the HLA view was dropped. If the RR interval was still insufficient, the VLA view was dropped (RR interval<460 ms, HR>130 bpm). No more than 5 slices were acquired each cardiac cycle. The same image planes were acquired at rest and stress.

The studies in patients with known or suspected CAD were qualitatively analysed by two experienced observers (AE and PG) for the presence of induced perfusion defects. Each study was analyzed for perfusion defects from the SA views alone, and then reanalyzed with viewing the long-axis views alongside the SA views. Consensus was reached in studies where the two observers initially disagreed on the analysis for induced perfusion defects.

RESULTS

Of the 53 patients studied, 29 had known or suspected CAD, 18 hypertrophic cardiomyopathy, and 6 suspected microvascular perfusion abnormalities. The

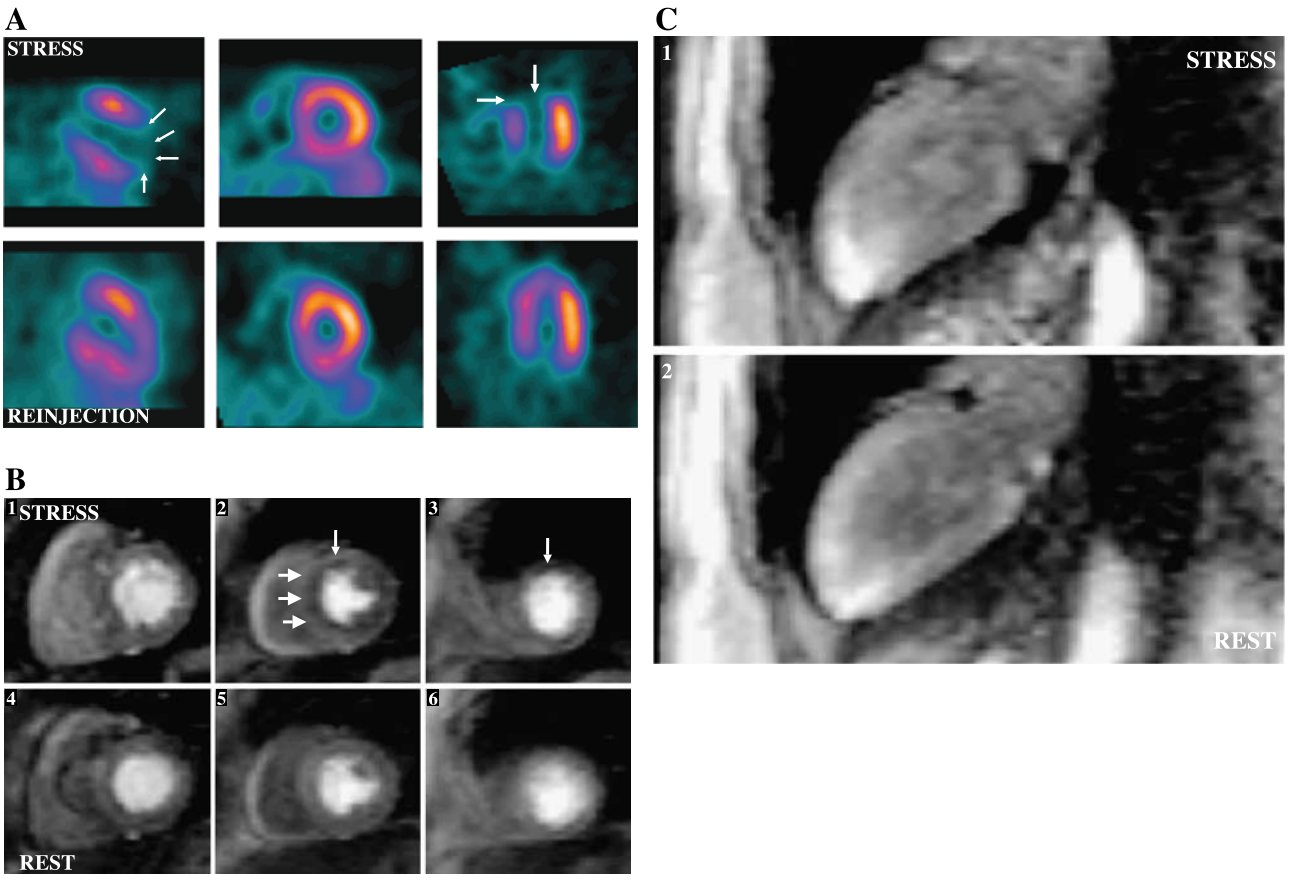

Figure 2. A thallium-201 perfusion study in a patient with 90% stenosis of the proximal LAD, and <50% stenoses in the RCA and LCX (A). The thallium-201 scan demonstrated severe inducible perfusion defects in the mid- to apical anterior wall, apex, apical inferior wall, and apical septum (arrows). Minor subendocardial infarction in this territory was suspected. In the same patient, (B, C) inducible perfusion abnormalities demonstrated by perfusion CMR with an EPI sequence in the mid- to apical septum, and apical anterior wall (B, C; arrowed). On the VLA view, no perfusion abnormalities were seen. The patient was too tachycardic at stress to acquire an HLA view. No myocardial infarction was demonstrated with IR-FLASH late enhancement imaging. The short- and long-axis views were acquired every cardiac cycle (B, C).

mean age of the patients was 55 years (range 25 to 76 years), and 40 (71%) were male. All slices had to be obtained at rest and stress. Of the 53 perfusion studies, in 37 patients (70%) it was possible to acquire 5 slices (3 short axes and 2 long axes), and in 13 patients (25%) it was possible to acquire 4 slices (3 short axes, 1 long axis). In only 2 patients (5%) was it possible to only acquire 3 slices (all SAs).

In 10 (34%) of those studied with known or suspected CAD, an induced perfusion defect was seen on the SA views alone. Of these 10 studies, the long-axis views confirmed the presence of the defect in 5 (50%) of the studies. In the 19 studies in which no induced perfusion defect was seen on the SA views, no perfusion defect was seen with the long axis views either. Sixteen of the patients had also undergone a recent single photon emission computed tomography (SPECT) study, of which 8 reported apical ischemia. In all 29 studies, the long-axis views did not demonstrate an inducible apical perfusion defect. See Figs. 1 and 2.

DISCUSSION

If perfusion CMR is to become an established way of diagnosing and monitoring CAD it needs to be able achieve comprehensive coverage of the myocardium. In practice this can be managed in two ways. A first step would be complete segmental coverage of all 17 segments as proposed by the AHA (Cequeira et al., 2002), which allows for gaps between imaging slices. A more challenging aim would be complete coverage of the entire ventricle without gaps, which has the advantage of eliminating any potential sampling error

from very small perfusion defects. However, as the length of the ventricle is variable and can be long in conditions such as heart failure, current technology does not allow such an approach that would work in all patients. Therefore, the first aim should be a robust clinical approach with full segmental sampling. In this consecutive group of patients, we have demonstrated that it is possible to achieve complete segmental coverage with perfusion CMR while maintaining its excellent spatial resolution with a practical rest-stress protocol using an EPI sequence and a minimum of 4 views per cardiac cycle. In 95% of the patients, sufficient views were acquired to allow all 17 segments to be analyzed. Furthermore, in the 2 cases (5%) where only 3 slices were acquired, 16 of the 17 segments were still studied. As a nonselective saturation pulse preceded each image acquired, there were no artifacts on the SA views from the long-axis views acquired.

However, while this study has proven the feasibility of acquiring both short- and long-axis views in each cardiac cycle during a perfusion CMR study, we did not find that the long-axis views provided useful images of the apical cap. In none of the studies in the patients with known or suspected CAD was an inducible apical perfusion defect seen, despite apical perfusion defects having been reported with recent SPECT studies in the same patients. The long-axis views of the apex are particularly vulnerable to partial volume artifact from moving out of plane due to alterations in breath-hold position or breathing during the perfusion scan. This is compounded by the slice thickness (8 mm) being much greater than the in-plane resolution ($\sim$3 mm). The slices are required to be this thick to achieve an adequate signal-to-noise ratio on first-pass perfusion. In midventricular SA views, the partial volume effect is minimal due to the near-cylindrical shape of the myocardium at this point. In addition, the apical cap, where the myocardium is thinner, is more affected by signal contamination from the LV blood pool. In a recently published study by Nagel et al. (2003), a perfusion CMR protocol was used in which 5 SA views (apical-basal) were acquired each cardiac cycle. The investigators in this study found the best results for the detection of CAD by analyzing only the 3 midventricular SA slices, and discarding the most apical and basal slices. This was attributed to ischemia rarely solely occurring in the apical or basal slices, the LVOT often descending into the basal slice and partial volume effects in the apical slice.

An alternative potential benefit of the long-axis views is to corroborate a perfusion defect seen on the SA views. However, despite perfusion defects seen on the SA views that were often not being seen on the long-axis views, the observers were confident that the defects seen on the SA views were genuine. Therefore, an alternative protocol would be to maximize the number of SA views acquired each cardiac cycle. Corroboration of perfusion defects could be drawn from the defect being seen in more than one closely positioned contiguous SA slice. Developing slice tracking techniques may avoid closely positioned slices imaging the same region of myocardium (Ablitt et al., 2002).

When multiple slices are acquired during a single cardiac cycle, it is necessary to acquire images through systole, as well as diastole. During systole, the myocardium is thicker, which potentially facilitates the visualization of defects, and reduces the effective severity of blood signal contamination artifact. However, systole is a period of increased cardiac motion compared with diastole, which can result in artifacts. Previous perfusion CMR work has indicated that the optimal time to study myocardial perfusion is at times during the cardiac cycle when there is less cardiac motion (Bertschinger et al., 2001; Schwitter et al., 2001). However, this has been at the expense of limiting how many slices are acquired, or acquiring slices every other cardiac cycle, which introduces the potential for sampling error in signal analysis of the upslope that is of very brief duration, particularly if arrhythmia occurs at this time (Thiele et al., 2003). We reasoned that the faster image acquisition window with the EPI sequence meant it would be less prone to motion artefact (Storey et al., 2002), and by acquiring through systole we increased the potential number of slices for study.

Limitations

The long-axis views were acquired predominantly during diastole. The apex may have been better viewed if the images had been acquired during systole, when the myocardium is thicker.

CONCLUSION

We have demonstrated that in a long series of consecutive cardiology patients it is possible to achieve complete segmental coverage of the myocardium with perfusion CMR, which conforms to the 17-segment model, while maintaining the spatial resolution of the technique. However, we found that the long-axis views gave no helpful information over the SA views alone. In particular, the long-axis views did not demonstrate any inducible apical perfusion defects, despite such defects having been seen with recent SPECT studies.

Therefore, we recommend a perfusion CMR protocol that maximizes the number of SA views.

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