Assessment of Myocardial Perfusion Following PTCA Detected with Spin-Echo Echo-Planar MR

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Abstract. Purpose: To assess myocardial perfusion following percutaneous transluminal coronary angioplasty (PTCA) in patients with acute myocardial infarction (AMI) using magnetic resonance (MR) multi-slice spin-echo echo-planar imaging (SE-EPI). Materials and Methods: Forty-eight patients with AMI were studied with MR SE-EPI before and one week after PTCA. The dynamic MR perfusion images were generated with multi-slice SE-EPI after a bolus injection of the contrast agent, gadolinium diethylene tramine pentaacetic acid (Gd-DTPA). The first-pass myocardial signal intensity versus time (SI-T) curves were obtained from the T2/T2*-weighted SE-EPI images by localizing regions of interest (ROI) in the left ventricular (LV) long-axis and short-axis imaging planes. The myocardial perfusion was assessed from the ratio of the changes of the perfusion signal intensity (SI) as well as the downslope rate of the SI-T curves. The results were compared with those of fifteen healthy volunteers. Results: Injection of Gd-DTPA resulted in a dramatic decrease of SI in normal myocardial segments. The SI of ischemic regions before PTCA decreased more slowly and to a lesser extent, than that of normal myocardial regions. The mean perfusion SI ratio of the normal territories was 61.9±6.1%, while that of ischemic regions supplied by coronary arteries with subtotal or complete occlusion was 36±12% (P<0.01 vs normal areas) before PTCA. The mean perfusion SI ratio was increased significantly after PTCA (52±21%, P<0.01 vs before PTCA). Conclusion: Multi-slice, rapid SE-EPI can be used to detect differences in myocardial perfusion before and after PTCA following AMI. This imaging approach may represent a noninvasive method for identifying functionally significant coronary stenoses and monitoring the success of coronary interventions.

Keywords: acute myocardial infarction, myocardial perfusion, cardiac, magnetic resonance imaging, echo-planar imaging, PTCA

1. Introduction

The direct noninvasive assessment of myocardial perfusion can be very useful for identifying functionally significant coronary stenoses and monitoring the success of coronary interventions or surgical therapies. Single-proton emission computed tomography (SPECT) is widely used clinically for non-invasively evaluating myocardial perfusion. Echocardiography with the bolus injection of an appropriate contrast agent can also provide perfusion information (1, 2). Positron emission tomography (PET) is a

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clinically validated method for quantifying myocardial perfusion (3), but it is not widely available, involves ionizing radiation, and has limited spatial resolution (4).

Magnetic resonance imaging (MRI) is often recognized as the gold standard for measurement of left ventricular mass and chamber size (5) as well as global and regional function (6). MRI also offers a feasible noninvasive measure of myocardial perfusion with high spatial and temporal resolution, and better tissue contrast (7,8). Myocardial perfusion can be evaluated by rapidly acquiring MR images after intravenous contrast injection and during the first-pass through heart (7, 9,10).

Many dynamic MR perfusion imaging sequences use fast gradient echo MR imaging combined with some magnetization preparation schemes, e.g. inversion recovery, saturation recovery or partial saturation (11,12). However the number of images in these approaches is limited because of the long acquisition time while using the preparation schemes. Faster alternatives were sought. Single-shot echo-planar imaging (EPI) is an MR imaging technique with shorter acquisition times that can be used for first-pass perfusion studies (13-15). Gradient echo (GRE)-EPI can be used after the injection of contrast agent to measure brain perfusion from T2*-weighted images. This approach, however, is not suitable for cardiac perfusion imaging because it has significant susceptibility artifacts and limited soft tissue contrast. Alternatively, we propose using a T2-weighted spin echo (SE)-EPI sequence which also includes T2* effects coming from EPI sequence. Although (SE)-EPI images include some T2*-weighting, it is far less than that of GRE-EPI. Similar to the analysis method used for dynamic perfusion imaging, SI-T curves during the first-pass of a contrast medium can be constructed for to estimate regional myocardial blood flow [16].

The purpose of this paper was to test the hypothesis that MR multi-slice SE-EPI could be used to detect differences in myocardial perfusion before and after PTCA for acute myocardial infarction.

2. Materials and methods

2.1. Human Subjects

Forty-eight patients (42 male and 6 female; age range, 45-78 years; mean age, 62±10 years) with symptoms of acute MI were studied. All of the patients were examined with MRI within 20 days of the myocardial ischemic onset (mean 10.8 days). Patients were all in sinus rhythm and no patients had left ventricular hypertrophy or dilated cardiomyopathy. After MRI examination, all patients with AMI underwent catheterization with conventional digital coronary angiography and left ventriculography. The stenoses severity greater than or equal to 75% diameter was considered to be significant. There are 5 cases with no stenosis, 17 cases with single branch vessel stenosis, and 9 cases with 2 branches stenosis, and 7 cases with 3 branches stenosis within 38 patients. Twenty-nine patients were treated by both PTCA and stent placement. As a control group, fifteen healthy volunteers (ten male and five female; age range, 29-52 years; mean age, 38±12 years) were also studied by MR myocardial perfusion. All of the healthy volunteers had no history of cardiovascular disease and no electrocardiographic (ECG) or echocardiographic evidence of heart disease.

2.2. MR Imaging

All studies were performed on a 1.5-T Signa scanner, S.X Genesis Echospeed scanner equipped with 20mT/m gradient and 120T/m/s maximum slew rate (GE Medical Systems, Milwaukee, WI) equipped with SE-EPI pulse sequence. LV function was assessed to identify ischemic and/or injured regions. The exam was accomplished by first imaging along the transverse axis of the heart, then the long axis of the LV, and finally the short-axis of the LV. The T1-weighted (T1-WI) imaging parameters were: ECG triggered, Torso phased array coil, slice thickness of 5mm, slice spacing 1.5mm, matrix 256x190, field of view (FOV) 32x32cm, bandwidth ±15.6KHz, number of excitations (NEX) 2, and a minimum echo time. The T2-weighted imaging (T2WI) was performed with a fast spin-echo (FSE) sequence at the same scan planes, with echo-train length (ETL) 12, TE 87ms. Cine MRI for measurement of global cardiac function and myocardial wall thickening was also acquired in the mid-LV along long-axis and short-axis planes using fast gradient echo (FGRE) with a flip angle of 30 degrees, bandwidth of ±32KHz, FOV of 32x32cm, slice thickness of 10mm, 256x190 matrix, minimum TE, and one NEX.

2.3. Myocardial Perfusion

Myocardial perfusion was studied by imaging in the regions of normal and dysfunctional (hypokinesis, akinesis) myocardium with SE-EPI before and after PTCA for the patients with AMI. Three or four myocardial slices were acquired along LV short-axis and long-axis planes during intravenous bolus (0.05 mmol/kg body weight, injection rate 3.0-4.0 ml/sec) injection of Gd-DTPA via the antecubital vein followed
with a bolus of normal saline flush (dose, 20 ml; injection rate, 3.0-4.0 ml/sec), all using a power injector (SpectrisTM, Medrad Inc; Indianola, PA). The SE-EPI scan was started after 4-6 seconds of the contrast agent injection. During diastole, short-axis planes were imaged from the mid-papillary muscle level 20-30 mm to the apex, with a minimum of approximately 15 min between bolus contrast agent injections to allow wash-out of Gd-DTPA.

Cardiac-gated perfusion images were continuously acquired with 30-40 images per slice location, one image during each heartbeat. Breath holding was practiced before MR exam and was used to minimize respiratory motion artifacts during MR perfusion scans. Perfusion MR imaging parameters were as following: GP Flex coil; single-shot SE-EPI; dynamic scan (30-40 images per slice); the effective TE, 88 msec; field of view, 360x360 mm; scan matrix, 128x128; flip angle, 90 degrees; slice thickness, 8mm; overlap, 2mm; flow compensation; electrocardiogram trigger delay, 160-220msec. All SE-EPI perfusion images were acquired along the long-axis and short-axis plane of LV. The signal intensity measured by the following SE-EPI sequence was dependent on T2/T2*.

2.4. Data Processing

All images were transferred to a Sun workstation for data processing using Functool software (GE Medical Systems, Milwaukee, WI). Signal intensity was measured by using circular or rectangular ROI, composed of at least 25 pixels. Five circular ROIs in the LV long-axis slice and ten ROIs in the LV short-axis slice were selected and matched to the affected regions determined by catheterization. The ROIs were adjusted to maintain a relatively fixed midcardiac wall position among image frames during the bolus profile in order to correct for in-plane cardiac and respiratory motion. SI-T curves were obtained and plotted by averaging the image signal intensities over each of ROIs.

Myocardial perfusion was assessed from SI-T curves using the following procedure. Due to T2/T2* weighted SE-EPI sequence used, myocardial signal intensity decreased as Gd-DTPA initially entered the myocardium. The baseline values of signal intensity were taken from an average of those obtained prior to Gd-DTPA administration. Both absolute and relative decreases of signal intensity were measured (16), and the perfusion SI ratio was given by:

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\text{Perfusion SI Ratio (\%)} = \frac{[\text{Baseline SI-Through SI}]}{\text{Baseline SI}} \times 100\%,
\]

where the baseline SI was the baseline signal intensity, and through SI was the minimum signal intensity during the first pass. The down-slope rate of SI-T curves of each perfusion study was calculated with the equation, down-slope rate = SI decrease/time, as decreased previously (17). ROI analysis was performed independently by two investigators.

2.5. X-ray Coronary Angiography

Coronary angiography was performed within two days of the completion of the MR myocardial perfusion using digital subtract angiography (Philips, V3000). In the 48 patients, the stenotic severity was obtained by measuring the luminal diameter of the stenotic vessel.

2.6. Statistics Analysis

All data were expressed as mean values plus or minus the standard deviation (SD). Differences in the perfusion SI ratios were analyzed using the paired or unpaired Student’s t-test. A significance level of less than 0.05 was considered significant.

3. Results

3.1. MR Imaging

The mean LV ejection fraction measured from cine MRI was increased from 43.0±12.3% to 52.1±14.3% after PTCA (ranges, 24-59% before and 33-65% after PTCA, P<0.05, Fig.1). Systolic wall thickening in the ischemic area increased from 10.2±3.2% to 14.1±2.7% after PTCA (P<0.05, Fig. 2).
3.2. Analysis of MR Myocardial Perfusion SI Curves

In the absence of Gd contrast administration, there was no significant SI change in SE-EPI images over time and therefore the SI-T curves were flat (Fig. 3). The SI-T curves of ROIs in the right ventricle (RV) and LV blood chamber and the myocardium are shown in Fig. 4 after contrast administration. Following intravenous Gd-DTPA contrast injection, SI changes were first noted in the right ventricular chamber, then in the LV chamber, and finally, in the LV myocardium (Fig. 4). SI-T curves of the normal LV chamber showed an initial steep descent as contrast was entered into the myocardium. In all cases, SI-T curves of the normal myocardium of LV showed a sharp descent (wash-in) and a subsequent slow recovery toward baseline intensity over time with the washout of the contrast agent. The SI of normal myocardium decreased at a slower rate than that of blood in the ventricular chamber (Fig. 4B). Relative signal intensity of the RV chamber, LV chamber and normal LV myocardium decreased from 80.4±18.3, 79.6±21.1 and 82.1±19.3 (baseline signal intensity), respectively, to 26.8±11.2, 12.4±5.6 and 35.4±12.2. The ratio of SI showed a significant difference in RV chamber blood (63.8%), LV chamber blood (84.4%) and normal myocardium (56.9%). Transmural cardiac perfusion was studied with this technique by placing several ROIs across the myocardial wall. In five normal subjects, transmural data was acquired and a relative perfusion gradient from the subepicardium to the subendocardium was observed (Fig. 5). The mean SI decreases were: 76±32% in...
subendocardium, 64±19% in midcardium, 56±20% in subepicardium (P<0.05). The maximal SI loss of normal myocardium in most cases occurred 4±1 seconds later than that of LV. All MR perfusion results were compared with x-ray angiography. The sensitivity and specificity for MR perfusion to detect a significant coronary stenosis at x-ray angiography were 89.5% and 93.3%, respectively.

Myocardial SI-T curves in healthy volunteers exhibited an initial decrease, which was relatively rapid in all myocardial segments after contrast administration. In contrast, the ratio of the decrease of SI in the ischemic regions was significantly less than that in normal myocardium (Fig. 7B). SI in ischemic myocardium did not decrease significantly during passage of the bolus and showed very clear demarcation of the ischemic region (Fig. 7B). The mean relative change of signal intensity in 36 patients was 61.9±6.1% in the normal territories compared to a significantly lower mean relative perfusion change of 36.1±12% in regions supplied by coronary arteries with subtotal or complete occlusion (Fig. 7. C). After PTCA, the mean perfusion ratio was increased significantly to 52±21% (P<0.01 vs. before PTCA, P=NS vs. normal, Fig. 7. E). In a subset of 15 subjects studied at 3-6 months post PTCA, mean perfusion SI ratio was 61±26% (P=NS, compared with 7-10 days after PTCA). The mean maximum down-slope of the SI-T curves in the ischemic regions (6.37±2.1 SI / images) was significantly less than that in the non-ischemic regions (11.33±3.2 SI / images, P<0.01).

Figure 3. In the absence of Gd-DTPA contrast administration, there was no significant SI change in SE-EPI images over time and therefore SI-T curves were flat (Fig. 3B). When subject could not maintain a breath-hold, artifacts were obvious in SI-T curve (Fig. 3B). A: perfusion image; B: SI-T curves; LV: left ventricle.

Figure 4. Following intravenous Gd-DTPA contrast injection, SI changes first in the right ventricular chamber (1), then the LV chamber (2), and finally, in the LV myocardium (3). A: perfusion image; B: SI-T curves. RV: right ventricle; LV: left ventricle; Myo: myocardium.
Figure 5. The different perfusion ratio showed gradient change from subepicardium to subendocardium. Subepi= subepicardium; Mid= midcardium; Subendo= subendocardium. * = P<0.05 vs. subepicardium, † = P<0.05 vs. midcardium, A: perfusion image; B: perfusion SI-T curves; C: perfusion grads changes. RV: right ventricle; LV: left ventricle.

Figure 6. Mean perfusion ratio was significantly lower in AMI before PTCA compared with normal myocardial area, and increased significantly after PTCA compared with before PTCA. *=P<0.01 vs. control, †=P<0.05 vs. pre-PTCA. # = P<0.05 vs. control.
Figure 7. A patient with acute myocardial infarction (male, 55 years). The perfusion images along LV short-axis show that the anterior-septum wall of LV was slightly thin (Fig. 7A); and the SI-T curve demonstrated the abnormal (Fig. 7B). The down-degree of the SI of perfusion in anterior-septum wall was decreased. The X-ray coronary artery angiography showed that the stenosis LAD (Fig. 7C). After PTCA and stent placement the stenosis was expended, and LAD was become normal (Fig. 7F). The myocardial perfusion reexamination ten day after PTCA, the thickness of LV was normal (Fig. 7D). The SI-T curves showed that the anterior-septal wall of LV became normal (Fig. 7E). RV: right ventricle; LV: left ventricle; LAD: left anterior descending.

4. Discussion

Myocardial ventricular contractile function is affected by myocardial perfusion, which can be reduced by significant obstructive coronary disease, and improved by successful PTCA interventions. Invasive x-ray coronary angiography is considered to be the gold standard for evaluating anatomic changes with the coronary arteries. With the development of new techniques, MRI is becoming a non-invasive diagnostic modality for assessing cardiac morphology, function, perfusion and viability with high resolution during the same examination. Ultra-fast MRI can acquire dynamic information related to the passage of a contrast agent through the coronary circulation and thereby provide an indirect assessment of myocardial perfusion.

Unlike previous studies, we used T2-weighted SE-EPI magnetic resonance imaging techniques with intravenous Gd-DTPA injection to assess myocardial perfusion before and after PTCA. This approach provides a rapid, high-resolution imaging method for detecting SI changes in myocardium as the contrast agent passes through the myocardium. The SI change immediately following contrast in the myocardial region supplied by a stenotic coronary artery is smaller than that in a normal region. The SI change is increased significantly after revascularization. The study data demonstrate that SE-EPI combined with intravenous Gd-DTPA identifies significant differences between a normal perfusion segment and a segment supplied by diseased coronary arteries. These findings suggest that the methods of SE-EPI are likely useful for the assessment of myocardial perfusion and the effectiveness of coronary interventions.

The dynamic changes of MR signal intensity following Gd-DTPA contrast introduction can be detected with GRE or SE-EPI with long echo time (TE) during a bolus injection of the contrast agent. For GRE-EPI, the gradient-echo signals decrease with the effective spin-spin relaxation time and thus lead to the well-known sensitivity of EPI to magnetic field inhomogeneities and susceptibility differences (18,19). T2* relaxation during the acquisition of the echo train may cause ringing artifacts as well as blurring due to the truncation of high spatial frequencies for short T2* components. Therefore, the SE-EPI imaging sequence
should be affected less by susceptibility artifact than GRE-EPI, making it more suitable for cardiac perfusion imaging. Because there is greater magnetic susceptibility resulting from the blood in ventricles, it will have a greater adverse affect on the analysis results with GRE-EPI (19).

In prior work, we compared GRE-EPI and SE-EPI sequences and found GRE-EPI images were often blurred with poor signal noise ratio (SNR). So, for cardiac perfusion imaging, imaging EPI contrast can be modified with a SE-EPI readout to reduce some of the susceptibility effects of GRE-EPI. These results demonstrated that MR myocardial first-pass perfusion imaging with SE-EPI can assess the severity and extent of perfusion defects in coronary artery disease (CAD) before and after intervention or for diagnostic purposes, and can also predict whether myocardial function may recover after a myocardial infarction and revascularization (20-22).

In a canine model, MR EPI measures of perfusion were closely correlated with myocardial blood flow across a wide range induced by hypoperfusion. Because the SE-EPI imaging sequence is less sensitive to susceptibility-related artifacts than GRE-EPI, it is better suited for clinical studies of perfusion. We demonstrate here that SE-EPI techniques combined with Gd-DTPA are useful for quantifying myocardial perfusion.

Limitations: A limitation of the SE-EPI technique was that there were only three to four imaging slices, which couldn’t cover the entire LV during the first pass of a contrast bolus. However, the slices covered a majority of the LV myocardial tissue. Imaging more than four slices, requires scan times that are too long for most patients to hold their breaths. A relative disadvantage of SE-EPI is that the magnitude of the signal loss is small and the contrast-noise ratio between two different tissues is reduced.

5. Conclusions

SE-EPI was used to evaluate myocardial perfusion and the effects of PTCA and reperfusion. Our results revealed that the areas of abnormal signal corresponded to stenotic coronary territories as determined by conventional angiography. So, the down-slope of the SI-T curves reflects the myocardial perfusion state. In the future, stress evaluation with dobutamine or dipyridamole could be incorporated into this protocol to assess more subtle perfusion differences that may not be detected at rest. In summary, these initial results suggest that a multislice SE-EPI sequence can be used to demonstrate myocardial perfusion abnormalities in patients with suspected coronary disease. SE-EPI perfusion technique can be used to potential monitor the success of cardiac interventions accurately after myocardial revascularization, and possibly to identify the functional significance of different coronary artery stenoses. MR dynamic SE-EPI perfusion analyses have a high sensitivity and specificity compared with coronary artery angiography.

6. References


