Quantitative Assessment of Myocardial Viability After Infarction by Dobutamine Magnetic Resonance Tagging

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Background—The assessment of return of function within dysfunctional myocardium after acute myocardial infarction (MI) using contractile reserve has been primarily qualitative. Magnetic resonance (MR) myocardial tagging is a novel noninvasive method that measures intramyocardial function. We hypothesized that MR tagging could be used to quantify the intramyocardial response to low-dose dobutamine and relate this response to return of function in patients after first MI.

Methods and Results—Twenty patients with a first reperfused MI (age, 53 ± 12 years; 16 male; 11 inferior MIs) were studied. Patients underwent breath-hold MR-tagged short-axis imaging on day 4 ± 2 after MI at baseline and during dobutamine infusion at 5 and 10 μg · kg⁻¹ · min⁻¹. At 8 ± 1 weeks after MI, patients returned for a follow-up MR tagging study without dobutamine. Quantification of percent intramyocardial circumferential segment shortening (%S) was performed. Low-dose dobutamine MRI was well tolerated. Overall, mean %S was 15 ± 11% at baseline (n = 227 segments), increased to 16 ± 10% at 5 μg · kg⁻¹ · min⁻¹ dobutamine (P = NS), 21 ± 10% at peak (P < 0.0001 vs baseline and 5 μg · kg⁻¹ · min⁻¹), and 18 ± 10% at 8 weeks (P < 0.004 vs baseline and peak). The increase in %S with peak dobutamine was greater in dysfunctional myocardium (103 segments, +9 ± 10%) than in normal tissue (124 segments, +4 ± 12%, P < 0.0001). In dysfunctional regions, %S also increased from 6 ± 7% at baseline to 14 ± 10% at 8 weeks after MI (P < 0.0001). In dysfunctional regions that responded normally to peak dobutamine (≥5% increase in %S), the increase in %S from baseline to 8 weeks after MI (+9 ± 9%) was greater than in those regions that did not respond normally (+5 ± 9, P < 0.04). Midmyocardial and subepicardial response to dobutamine were predictive of functional recovery, but the subendocardial response was not.

Conclusions—The response of intramyocardial function to low-dose dobutamine after reperfused MI can be quantified with MR tagging. Dysfunctional tissue after MI demonstrates a larger contractile response to dobutamine than normal myocardium. A normal increase in shortening elicited by dobutamine within dysfunctional midwall and subepicardium predicts greater functional recovery at 8 weeks after MI, but the response within the subendocardium is not predictive.

Key Words: magnetic resonance imaging ■ myocardial infarction ■ myocardial contraction ■ mechanics ■ stunning, myocardial

A fter MI, some viable myocardial tissue remains dysfunctional despite restoration of perfusion. This phenomenon has been called “stunned myocardium.” The assessment of viability of dysfunctional myocardium after MI is an important clinical issue, because the patient’s eventual LV function and prognosis depend on it as may the choice of subsequent pharmacological therapy. To evaluate viability, defined as contractile reserve of dysfunctional myocardium, imaging methods such as DSE have been applied. Limitations of such methods include the subjective qualitative assessment and resultant variability in the interpretation of the images. Other limitations include the effects of through-plane motion, which results in imaging different myocardial regions at end diastole and end systole. In addition, echocardiography cannot examine the transmural variation in mechanical function.

Low-dose dobutamine has been used in conjunction with cine MRI to evaluate viability after infarction in a qualitative fashion. MR tissue tagging can noninvasively quantify local myocardial segment shortening throughout the LV myocardium at sites across the LV wall thickness. We have previously used MR tagging to characterize regional intramyocardial function throughout the LV in patients after first anterior MI and single-vessel disease of the left anterior descending coronary artery. We have also shown that we can safely administer dobutamine in conjunction with MR tissue tagging in normal subjects up to doses of 20 μg · kg⁻¹ · min⁻¹ and quantify the response of LV myocardium both
Eight weeks later ($\pm$ 1 week), the patients returned for an MR study that consisted of short-axis tagging as described above, including all slices from apex to base, but without dobutamine (Figure 1C).

**Image Analysis**

Quantitative 1-dimensional analysis was performed with the VIDA (Volumetric Image Display and Analysis, University of Iowa) software package loaded on a SUN workstation. VIDA allows a digital display of the pixel signal values on a line normal to the tag stripes, allowing the reproducible identification of the tag stripe centers. These points are stored, and interstripe distances can be measured from end diastole to end systole. %S was measured at subendocardial, midmyocardial, and subepicardial sites at tag stripe pairs perpendicular to the LV wall at septal, anterior, lateral, and inferior myocardial locations on each slice. Shortening was measured as end-diastolic minus end-systolic interstripe distance divided by end-diastolic interstripe distance times 100, expressed as a percentage. Measurements were made at baseline and at each dobutamine dose (5 and $10 \mu g \cdot kg^{-1} \cdot min^{-1}$).

**Data Analysis and Interpretation**

%S was calculated at each of 4 time points (baseline, 5 and $10 \mu g \cdot kg^{-1} \cdot min^{-1}$ dobutamine, and 8 weeks after MI) at 36 myocardial sites per patient: subendocardial, midmyocardial, and subepicardial for each of 4 locations (septal, anterior, lateral, and inferior) in each of 3 short-axis slices (apical, mid-ventricle, and base). %S in the 3 transmural locations within each segment was analyzed individually and then averaged, creating 12 regions per patient. %S in these regions was compared with that of subjects from our normal database on a regional basis. Segments with %S $>2$ SD below the mean for normal subjects were called dysfunctional. The peak response to low-dose dobutamine was recorded. On the basis of previous data, the mean normal response in %S from baseline to 10 $\mu g \cdot kg^{-1} \cdot min^{-1}$ is an increase of 5%. We considered any increase in %S to peak dobutamine of $<5\%$ as demonstrating reduced functional reserve. Baseline and 8-week follow-up short-axis slices were matched by use of anatomic landmarks such as RV insertion sites, papillary muscle location, and relative apex-base location. Analysis of 8-week follow-up tagged images was used to assess return of function. Segments with %S $>2$ SD below the mean for normal subjects at follow-up at 8 weeks after MI were called dysfunctional.

**Statistical Analysis**

Groups of regions were characterized by baseline function (normal or dysfunctional) and by response to dobutamine (normal or abnormal) as defined above. %S was compared by group and by transmural location between baseline, 5- and $10 \mu g \cdot kg^{-1} \cdot min^{-1}$ dobutamine, and week 8 by repeated-measures ANOVA with Fisher’s subtesting. Two-way ANOVA was used to compare improvement in function from baseline to 8 weeks between groups, both on a transmural basis and by location across the wall. Linear regression analysis was performed for %S at peak response to dobutamine and %S at 8 weeks on a per transmural region basis and by patient, for peak CK and %S at baseline after MI and at peak response to dobutamine. Results are displayed as mean $\pm$ SD. A value of P<0.05 was considered significant.

**Results**

We studied 20 patients (16 male), 53 $\pm$ 12 years old, 4 $\pm$ 2 days after reperfused acute MI (Table 1). Nine patients had an anterior wall MI, and 11 had an inferior wall MI. Most (n=16) were reperfused by primary angioplasty, 1 by tissue plasminogen activator, and 3 patients failed tissue plasminogen activator and were reperfused by rescue PTCA. Peak creatine phosphokinase was 2386 $\pm$ 1901 U/L. Time to reperfusion was known for 17 of the patients (317 $\pm$ 201 minutes).
Fourteen MIs were Q-wave and 6 were non–Q-wave infarctions. All patients had a patent infarct-related artery as documented by coronary angiography before enrollment and no significant ($>$70%) lesions in other coronary arteries. All had documentation of regional LV dysfunction within the risk region by either left ventriculography or 2-dimensional echocardiography before enrollment. At the time of the first MR study, 19 patients were taking aspirin, 16 $\beta$-blockers, 8 ACE inhibitors, 5 nitrates, 3 calcium channel antagonists, and 1 digoxin.

No patients developed symptoms during or after dobutamine infusion. There was no significant change in heart rate or blood pressure during the test (73±14 bpm at baseline, 71±12 bpm at 5 $\mu$g · kg$^{-1}$ · min$^{-1}$ dobutamine, and 76±13 bpm at 10 $\mu$g · kg$^{-1}$ · min$^{-1}$, $P=NS$, and 127±21/77±11 mm Hg at baseline, 120±20/73±14 mm Hg at 5 $\mu$g · kg$^{-1}$ · min$^{-1}$ dobutamine, and 130±19/71±12 mm Hg at 10 $\mu$g · kg$^{-1}$ · min$^{-1}$, $P=NS$).

The follow-up study was performed at 8±1 weeks after the MI. None of the patients had events between the 2 studies. Heart rate at the time of the 8-week study was 66±20 bpm, and blood pressure was 129±22/76±13 ($P=NS$ from baseline study for both). At 8 weeks after MI, 18 patients were taking aspirin, 17 $\beta$-blockers, 7 ACE inhibitors, 3 calcium channel blockers, 2 digoxin, and 1 nitrates.

Of 240 transmural regions, 12 per patient, 227 (95%) had data suitable for analysis at baseline, at 5 and 10 $\mu$g · kg$^{-1}$ · min$^{-1}$ dobutamine, and at 8-week follow-up. Mean %S was 15±11% at baseline (n=227 segments) and increased to 16±10% at 5 $\mu$g · kg$^{-1}$ · min$^{-1}$ dobutamine ($P=NS$), 21±10% at peak ($P<0.0001$ versus baseline and 5 $\mu$g · kg$^{-1}$ · min$^{-1}$), and 18±10% at 8 weeks ($P<0.002$ versus baseline and $P<0.004$ versus peak). One hundred twenty-four regions demonstrated normal baseline function, with a %S of 23±7%. This did not change at 5 $\mu$g · kg$^{-1}$ · min$^{-1}$ dobutamine (24±7%), increased to 26±6% at peak ($P<0.0002$ versus baseline and 5 $\mu$g · kg$^{-1}$ · min$^{-1}$), but did not improve at 8 weeks (22±8%, $P=NS$ versus baseline).

One hundred three regions were dysfunctional at baseline after MI as previously defined. Overall, %S in dysfunctional
segments increased from 6±7% at baseline to 11±9% at 5 μg · kg⁻¹ · min⁻¹ dobutamine (P<0.004 versus baseline), 15±9% at peak (P<0.0001 versus baseline and 5 μg · kg⁻¹ · min⁻¹), and 14±10% at 8 weeks after MI (P<0.0001 versus baseline and P<0.004 versus 5 μg · kg⁻¹ · min⁻¹). The response in %S to peak dobutamine was greater in dysfunctional myocardium (9±10%) than in normal tissue (4±12%, P<0.0001). There was a modest correlation within dysfunctional segments between %S at peak dobutamine and rest %S at 8 weeks (y=0.50x+6, r=0.47, P<0.0001). Peak CK correlated negatively with %S early after MI (y=18.4–0.001x, r=−0.52, P<0.02), but the negative correlation was stronger with %S with dobutamine stimulation (y=24.1–0.001x, r=−0.63, P<0.003) (Figure 2).

Of the 103 dysfunctional regions, 67 demonstrated a normal response to peak dobutamine infusion (%S increased by >5% from baseline). In these regions, %S was 7±7% at baseline, 15±9% at 5 μg · kg⁻¹ · min⁻¹ (P<0.0001 versus baseline), 19±8% at peak (P<0.0001 versus baseline), and 16±10% at 8-week follow-up (P<0.0001 versus baseline) (Figure 3). Thirty-six dysfunctional regions did not respond normally to dobutamine infusion and at baseline had a %S of 5±6%, not different from baseline function in the regions that did respond normally to dobutamine (7±7%). Peak %S with dobutamine in the regions that did not respond normally was only 7±6% (P=NS). However, resting %S did increase significantly at follow-up (10±9%, P=0.003 versus baseline) (Figure 3). The increase in %S from early after MI to 8 weeks after MI in the regions that responded normally to dobutamine (+9±9%) was greater than that in the abnormal response group (+5±9%, P<0.04) (Figure 3). Of the 103 regions that were dysfunctional at baseline, 47 returned to normal function and 56 remained dysfunctional at 8 weeks of follow-up. The sensitivity of the normal response to peak dobutamine (≥5%) for return of function to normal on a per-region basis was 87%, but the specificity was only 43%. The positive predictive accuracy was 56%, and the negative predictive accuracy was 83%.

On examination of shortening in the 3 intramural levels (subendocardial, midwall, subepicardial) within each myocardial region, 685 of a possible 720 segments (36 per patient) were suitable for analysis at all 3 time points (Table 2). The increase in %S from baseline to 8-week follow-up was similar between layers. At baseline in dysfunctional regions, subendocardial regions had %S of 7±8%, which

![Figure 2. Linear regression analysis for peak CK on x axis and %S at peak dobutamine stimulation for all 12 regions for each patient studied demonstrating negative correlation (y=24.1–0.001x, r=−0.63, P<0.003).](http://circ.ahajournals.org/)

![Figure 3. %S in 2 groups of regions, those with normal response (≥5% increase) to peak dobutamine and those with abnormal response (<5% increase) shown at baseline before dobutamine infusion (hatched bars) and at 8 weeks after infarction. Increase in %S from baseline to 8 weeks after MI in normal-response group is significantly greater than that in abnormal response group (P<0.04).](http://circ.ahajournals.org/)
increased to $16 \pm 11\%$ at follow-up ($P<0.0001$); midmyocardium, increased %S from $4 \pm 6\%$ to $14 \pm 11\%$ ($P<0.0001$); and subepicardial regions, increased %S from $0 \pm 6\%$ to $10 \pm 11\%$ ($P<0.0001$).

Analysis of these transmural levels by response to peak dobutamine are shown in Table 2. The response to dobutamine was predictive of return of function within the midmyocardium and subepicardium. The increase in %S from baseline to 8 weeks was greater in the normally responding segments in the midmyocardium ($+13 \pm 11\%$) than in abnormally responding segments ($+6 \pm 7\%$, $P<0.006$) and in the subepicardium ($+13 \pm 11\%$ versus $+3 \pm 10\%$, $P=0.001$) (Table 2). However, the response to dobutamine within subendocardial segments was not predictive of return of function. The increase in function from baseline to 8 weeks after MI was similar in the normalresponse and abnormal-response groups ($+9 \pm 11\%$ and $+7 \pm 11\%$, $P=NS$). Subendocardial %S at 8 weeks was similar in the 2 groups ($16 \pm 10\%$ and $16 \pm 12\%$).

**Discussion**

This study confirms the safety of low-dose dobutamine infusion in humans early after acute MI in an MR scanner. The contractile response to dobutamine can be quantified in a regional and transmural manner with this technique. Overall, dysfunctional myocardium demonstrated a greater contractile response to dobutamine stimulation than normal tissue. The response to dobutamine in dysfunctional myocardium correlated modestly with that at rest at 8 weeks after MI within that region. Infarct size as estimated by peak CK demonstrated a negative correlation with response to dobutamine in dysfunctional myocardium. The increase in shortening from baseline to 8 weeks after MI in regions that responded normally to peak dobutamine was greater than that in abnormally responding regions. Heterogeneity of the predictive value of the response to dobutamine was found between layers of myocardium. A normal increase in shortening elicited by peak dobutamine within dysfunctional midwall and subepicardium predicted greater functional recovery at 8 weeks after MI, whereas the response within the subendocardium was not predictive.

A large proportion of examined segments (103 of 227, $45\%$) were dysfunctional, which may reflect both stunning within the risk region and contractile depression in adjacent and remote noninfarcted areas, as demonstrated previously in patients with reperfused first anterior MI. Contractile reserve may be greater in dysfunctional than normal myocardium, in part because of the inclusion of noninfarcted regions that are structurally normal but dysfunctional on the basis of elevated wall stress or abnormal coronary flow reserve. These regions may demonstrate completely normal function with low doses of dobutamine.

Of the dysfunctional segments, 46% returned to normal function. More segments demonstrated normal response to dobutamine than returned to normal function. Potential explanations include the possibility that if patchy necrosis in reperfused infarction was limited to the subendocardium, dobutamine response may be intact, yet when reexamined at 8 weeks, function at rest remains impaired because the subendocardium plays a major role in regional function at rest. In fact, %S at 8 weeks in the subendocardium in patients who responded normally to dobutamine was less than with dobutamine stimulation. The strict definition of viability in this study as return to normal function rather than any improvement in function is another explanation for limited specificity of the dobutamine response. Future comparative studies may offer insight into what quantitative improvement by MR tagging is associated with visible improvement in wall motion by MRI or by echocardiography.

Our findings are in agreement with those of Meza et al., who recently demonstrated in a canine model that the presence of contractile reserve in itself does not exclude the presence of regional necrosis. In their study, dogs with MI documented by TTC staining had significant improvement in regional function (percent thickening fraction went from $-7 \pm 22\%$ after reperfusion to $14 \pm 13\%$ with $10 \mu g \cdot kg^{-1} \cdot min^{-1}$ dobutamine). In subgroup analysis, dogs with subendocardial infarction demonstrated near normal wall thickening with dobutamine stimulation, and dogs with transmural infarction had no improvement in regional function with dobutamine.

Sklenar et al. showed that in some dogs with infarcts of moderate size, dobutamine administration resulted in an improvement of percent wall thickening compared with occlusion and reflow values. No change in thickening occurred in the presence of large ($>75\%$) infarctions. They found a close inverse correlation between contractile response to dobutamine and infarct size, similar to the findings in the present study of an inverse correlation between peak CK and response of %S to dobutamine.

MR tagging permits the analysis of function within subendocardial, midmyocardial, and subepicardial layers of the myocardium. Our group previously demonstrated that normal myocardium has a transmural gradient of %S under normal resting conditions, highest in subendocardial regions and
involved to translate viability into a visible increase in wall
motion. Assessment of the transmural heterogeneity of re-
-response is not possible by echocardiography.

Theoretical advantages of MR tagging include the quanti-
tative analysis of the images and minimal effect of through-
plane motion on the analysis, because end-diastolic tag
separation is uniform on all slices. Furthermore, MR tagging
provides good transmural resolution, and the resolution of
interstripes is on the order of 0.1 pixel,20 or 0.11 mm
in the present study. The definitions of viability by echocar-
diography and MR tagging differ. In the present study, viabili-
ity was strictly defined by MR tagging methods as
return to normal quantitative values. An improvement of %S
during the first 8 weeks after MI that was, for example, 5%
over the 8-week time period, yet still did not bring that region
into the normal range, might be characterized as improvement
in function by echocardiographic analysis of wall motion.

Previous Studies With MRI

Cine MRI without tagging has been used recently to examine
postinfarct viability. Dendale et al9 studied 37 patients early after
acute MI with low-dose dobutamine cine MRI and echocardi-
ography using qualitative assessment of wall motion for both
imaging modalities. Concordance between the 2 techniques in
identifying viable and nonviable segments was 81% in the 24
patients who had a follow-up study. The sensitivity and speci-
cicity of dobutamine MRI were 91% and 69%, respectively, and
those of DSE, 82% and 85%, respectively. Limitations of this
study included the qualitative analysis, the unknown status of the
infarct-related artery and the remainder of the coronary anatomy,
and the absence of MRI follow-up data.

MR tagging has recently been used in preliminary studies
to evaluate viability in the setting of chronic coronary
disease.21,22 Sayad et al21 using MR tagged images, demon-
strated that wall thickening (not intramural function) in
response to dobutamine was a good predictor of functional
recovery of dysfunctional myocardium after revasculariza-
tion. Cubukcu et al22 used MR tagging to assess response to
revascularization in 15 patients. Mean %S increased from
9±6% to 15±8% with dobutamine infusion and was 13±7%
at 3 months after revascularization, showing less functional
recovery than in the postinfarct patient group in the present
study.

Limitations

We examined a selected group of patients without residual
anatomic substrate for ischemia early after reperfused acute
MI, and therefore, our results should not be extrapolated to
patients with significant residual stenosis or to those with
chronic coronary artery disease and regional myocardial
dysfunction. The total number of patients studied is not large,
but the density of measurements made with MR tagging
allows the evaluation of regional function in a thorough
topographical and transmural manner.

During the course of the study, we began to use a
phased-array body coil rather than an elliptical-spine coil to
allow a more comfortable supine body position for the
patients enrolled. Nonetheless, each individual patient had the
8-week follow-up study done on the same coil as the baseline
study, making the results easily comparable. Matching seg-
ments from the 8-week study to the baseline study was potentially problematic, but RV insertion sites, papillary muscle location, and apex-to-base location were carefully used to ensure proper matching of slices.

Future Directions
The results of low-dose dobutamine MR tagging could be compared head to head with DSE to determine its relative utility, although exact matching of regions is a potential obstacle. Semiquantitative techniques may become available with DSE to compare with the MR techniques.\textsuperscript{23} With more rapid imaging, more myocardial regions could be sampled, and 2- and 3-dimensional analysis\textsuperscript{24,25} of the tagged MR images could be performed, yielding important information with regard to the direction of intramyocardial strains although sacrificing the transmural resolution of the 1-dimensional technique. The combination of quantitative assessment of functional reserve and assessment of myocardial perfusion by either myocardial contrast echocardiography\textsuperscript{7,26} or MR contrast imaging may be superior to either technique alone. Our group and others have recently demonstrated the utility of MR contrast infusion to evaluate patients with MI\textsuperscript{27,28} and predict return of function on the basis of contrast uptake patterns.\textsuperscript{29} Ideally, the 2 methods combined may improve on the present method and, in combination with MR evaluation of global LV structure and function and infarct artery patency,\textsuperscript{30} could provide a comprehensive assessment of the postinfarction patient.

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