Prospective Assessment of Regional Myocardial Perfusion Before and After Coronary Revascularization Surgery by Quantitative Thallium-201 Scintigraphy

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Because thallium-201 uptake relates directly to the amount of viable myocardium and nutrient blood flow, the potential for exercise scintigraphy to predict response to coronary revascularization surgery was investigated in 47 consecutive patients. All patients underwent thallium-201 scintigraphy and coronary angiography at a mean (± standard deviation) of 4.3 ± 3.1 weeks before and 7.5 ± 1.6 weeks after surgery. Thallium uptake and washout were computer-quantified and each of six segments was defined as normal, showing total or partial redistribution or a persistent defect. Persistent defects were further classified according to the percent reduction in regional thallium activity; PD 25-50 denoted a 25 to 50% constant reduction in relative thallium activity and PD > 50 denoted a greater than 50% reduction. Of 82 segments with total redistribution before surgery, 76 (93%) showed normal thallium uptake and washout postoperatively, versus only 16 (73%) of 22 with partial redistribution (probability \( p = 0.01 \)). Preoperative ventriculography revealed that 95% of the segments with total redistribution had preserved wall motion, versus only 74% of those with partial redistribution (\( p = 0.01 \)).

Of 42 persistent defects thought to represent myocardial scar before surgery, 19 (45%) demonstrated normal perfusion postoperatively. Of the persistent defects that showed improved thallium perfusion postoperatively, 75% had normal or hypokinetic wall motion before surgery, versus only 14% of those without improvement (\( p < 0.001 \)). Whereas 57% of the persistent defects that showed a 25 to 50% decrease in myocardial activity demonstrated normal thallium uptake and washout postoperatively, only 21% of the persistent defects with a decrease in myocardial activity greater than 50% demonstrated improved perfusion after surgery (\( p = 0.02 \)).

Thus, preoperative quantitative thallium-201 scintigraphy appears useful in predicting response to revascularization surgery, and some persistent defects may revert to normal thallium uptake after surgery. Importantly, the preoperative distinction between viable and nonviable myocardium can be reasonably established by quantitating the amount of persistent reduction in thallium uptake and correlating this with preoperative wall motion.

Coronary revascularization surgery is being performed with increasing frequency to relieve symptoms of atherosclerotic coronary artery disease (1). Of continued interest to many is the preoperative detection of ischemic but viable myocardium (2–6), the mechanism of postoperative relief of angina (7,8) and the ultimate effects of surgery on left ventricular function and perfusion (9,10). Because symptoms, morbidity and mortality of coronary disease are all the direct consequences of inadequate myocardial perfusion, employing techniques that assess nutrient blood flow distribution to the myocardium seems rational for studying the effects of revascularization surgery.

Thallium-201 myocardial perfusion scintigraphy has become a clinically important technique for detecting and evaluating patients with coronary artery disease (11). Because uptake of thallium-201 after exercise is directly related to the amount of viable myocardium and regional blood flow (12–15), this noninvasive technique appears suitable for evaluating the effects of revascularization surgery. Indeed,
several studies (16–22) have already correlated postoperative scintigraphic findings with graft patency and follow-up data. However, in only 29% of the patients in these studies were pre- and postoperative scintigrams obtained, all of which utilized qualitative imaging techniques for estimating myocardial distribution of thallium. Because quantitative scintigraphic analysis permits objective evaluation of both thallium uptake and washout kinetics and is more sensitive than qualitative methods, it seems advantageous for making pre- and postoperative comparisons (23, 24).

On the basis of experimental animal studies of transient ischemia and infarction (12–15) and current interpretation of stress-redistribution thallium scintigrams, it may be assumed that: 1) myocardial segments showing normal thallium uptake and washout after exercise should remain normal after surgery; 2) segments showing initial defects after exercise with delayed redistribution should represent ischemic but viable regions that should revert to normal after revascularization, and 3) myocardial regions demonstrating persistent defects on serial images should represent scar, with little improvement expected if vessels perfusing such zones were to be grafted. In order to validate these assumptions, we prospectively examined pre- and postoperative exercise scintigraphic, angiographic and ventriculographic data in an unselected group of patients with angina pectoris referred for coronary bypass surgery. Our aims were to investigate the functional significance of a wide range of preoperative perfusion defects as assessed by quantitative thallium-201 scintigraphy and to determine the corresponding changes in myocardial perfusion resulting from coronary revascularization.

Methods

Study patients. The study group comprised 47 consecutive patients who had primary isolated coronary artery bypass graft surgery at the University of Virginia Medical Center. Each patient underwent diagnostic cardiac catheterization and symptom-limited exercise thallium-201 scintigraphy before and after surgery. Postoperative studies were obtained without respect to symptoms, after obtaining informed written consent.

Forty-three men and four women (mean age ± standard deviation 54 ± 8 years), were studied (Table 1). Twenty-three patients had a history of enzyme-confirmed myocardial infarction. Of these, 12 had pathologic Q waves at the time of study entry and 11 did not. Fifteen patients had a subnormal left ventricular ejection fraction (< 55%) and the mean value for the group was 60 ± 13% (range 32 to 83). Forty-two patients (89%) had typical exertional angina before surgery, four (9%) had atypical angina and one (2%) denied chest pain but had a markedly positive ST segment response to exercise. In the four patients with only mild angina, the indication for surgery was left mainstem coronary stenosis in three and severe three vessel disease in one. Overall, 40 patients (85%) had exercise-induced ST segment depression or limiting angina and 46 patients (98%) had an abnormal thallium-201 scintiscan.

<table>
<thead>
<tr>
<th>Age (yr)</th>
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<tbody>
<tr>
<td>Sex (male)</td>
<td>43 (91%)</td>
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<tr>
<td>Duration of angina (mo)</td>
<td>39 ± 43</td>
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<tr>
<td>Functional class</td>
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<td>I</td>
<td>4 (8%)</td>
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<tr>
<td>II</td>
<td>14 (30%)</td>
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<tr>
<td>III</td>
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<tr>
<td>IV</td>
<td>8 (17%)</td>
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<td>Extent of coronary disease</td>
<td>2.6 ± 1.1</td>
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<tr>
<td>Ejection fraction (%)</td>
<td>60 ± 13</td>
</tr>
<tr>
<td>Ischemic ST segment ↓ or angina</td>
<td>40 (85%)</td>
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<tr>
<td>Abnormal scintigram</td>
<td>46 (98%)</td>
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Values expressed as mean ± standard deviation or number of patients.

Table 1. Preoperative Clinical Characteristics of 47 Patients

Exercise testing. All patients were exercised on a treadmill using either the Naughton (25) or the Bruce (26) protocol at a mean (± standard deviation) of 4.3 ± 3.1 weeks before surgery. The Bruce protocol was employed in all patients at a mean of 7.5 ± 1.6 weeks after surgery. During both the pre- and postoperative tests, all patients were exercised to symptom-limited end points, a fall in systolic blood pressure greater than 10 mm Hg below the peak value at the previous stage, frequent (more than 10/min), multifocal or paired extrasystoles or ST segment depression greater than 3 mm.

Myocardial perfusion scintigraphy. A dose of 1.5 mCi of thallium-201 (New England Nuclear Corporation) was administered intravenously, followed by a 10 ml saline flush as the patient approached the exercise test endpoint. Exercise was continued for an additional 30 to 60 seconds if symptoms, electrocardiographic changes and blood pressure were stable. Imaging commenced 10 minutes after injection with the patient supine in the anterior projection, followed sequentially by 45° left anterior oblique and 70° left anterior oblique projections, respectively. The anterior and 45° left anterior oblique images were repeated 1 hour and 2 to 3 hours after thallium administration. Before surgery, the late imaging sequence (redistribution phase) commenced 2.5 ± 0.6 hours after injection in the anterior projection and 2.7 ± 0.6 hours in the 45° left anterior oblique projection. All images were recorded for a preset time of 10 minutes with an Ohio Nuclear 420 portable gamma camera using an all-purpose (GAP) medium resolution collimator and a 25% window centered on the 80-keV X-ray peak. Usually 500,000 to 600,000 counts were collected per image. In addition to conventional scintiphotographic imaging on transparency film, all studies were stored in a computer (MDS-MUGA cart or A3) for standardized image formation and quantification of relative thallium-201 activity in the myocardium by methods previously described (27).

The clinical utility of our quantitative technique for assessing serial changes in myocardial thallium activity has been described (23, 28–30). To summarize the technique briefly, quantitation of thallium images was undertaken by first performing a background subtraction using a modified bilinear interpolation method similar to the one described by Goris et al. (31). Slightly more complex weighting functions were used that differed from the original for-
scopic data. Maximal luminal diameter narrowing for each major coronary artery was estimated visually and differences of interpretation were resolved by consensus with a third angiographer present. Stenoses were considered significant if graded as 50% or greater obstruction.

Cineangiograms of the native and graft circulations and left ventriculograms were obtained at a mean of 7.7 ± 1.8 weeks after surgery without respect to symptoms, on the day after the postoperative scintigraphic study. The Judkins technique was used exclusively. Selective methods were used to identify patent grafts, aided by previous surgical placement of metallic rings around the orifices of the aortosaphenous vein anastomoses. Grafts were considered occluded if there was failure to enter a graft orifice after intensive catheter search and if a patent graft could not be demonstrated on supraavalvar power injection aortography.

Pre- and postoperative wall motion was assessed qualitatively by dividing the left ventricle into anterolateral, apical and inferior walls in the anterior view and the septal, inferoapical and posterolateral walls in the 45° left anterior oblique view. Each segment was evaluated for the presence and severity of asynergy according to the terminology used by Herman and Gorlin (35). Wall motion was graded by two independent observers without knowledge of clinical or scintigraphic data. Complete agreement occurred in 93% of studies (87 of 94). In cases of disagreement, differences were resolved by consensus, using a third observer.

**Coronary bypass surgery.** At operation, an attempt was made to revascularize all major and branch vessels with 50% or greater stenosis. Myocardial protection consisted of core cooling to 25 to 28°C with iced saline solution in the pericardial well and cold cardioplegia infused every 15 to 30 minutes. In all cases, the technique of revascularization was aortocoronary bypass grafting (either simple or sequential) utilizing autologous reversed saphenous vein. In six patients, an endarterectomy was performed before graft insertion because of extensive distal disease. In 47 patients, 135 stenosed vessels received a graft (2.9 ± 1.2 vessels per patient).

**Statistical analysis.** Continuous data are recorded as mean ± standard deviation. To determine differences between means of

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**Figure 1.** Top, Schematic representation of anterior (left) and 45° left anterior oblique (right) scintigraphic images used for analysis of segmental thallium-201 uptake and washout. Bottom, Criteria for designating a scan segment as abnormal based on quantitative evaluation of initial and delayed images.
Figure 2. Preoperative (PRE-OP) sequential 45° left anterior oblique (LAO) scintigraphic images (top) obtained 10 minutes, 1 hour and 2.5 hours after injection, and the corresponding thallium-201 time-activity curves (bottom). The time-activity curves confirm normal uptake and washout of thallium in the low posterolateral segment, total redistribution in the high posterolateral segment and partial redistribution in the anteroseptal segment.

independent observations, a one-way analysis of variance was performed. Chi-square analysis (with Yates' correction) was used to determine differences between proportions.

**Results**

Forty-two patients (89%) were asymptomatic at the time of their postoperative evaluation. Four of the remaining five patients noted significant but incomplete anginal relief, and one patient with atypical angina before surgery claimed no change after surgery. Postoperatively, the mean functional class of the patients was significantly improved to 1.1 ± 0.3, compared with the preoperative functional class (2.7 ± 0.9, p <0.001).

**Postoperative graft patency.** Of 135 vein grafts to major or branch coronary vessels, 121 (90%) were patent at the time of follow-up cineangiography. All patients had at least one patent graft and the mean number of patent grafts per patient was 2.6 ± 1.1. The patency rate was 98% for left anterior descending artery grafts (44 of 45), 86% for diagonal branch grafts (12 of 14), 82% for circumflex or marginal branch grafts (32 of 39) and 89% for grafts to the right coronary artery (33 of 37).

**Exercise test results.** Compared with preoperative values, postoperative testing revealed a significant increase in mean maximal heart rate (114 ± 22 versus 152 ± 21 beats/min, p <0.001), systolic blood pressure (147 ± 23 versus 172 ± 23 mm Hg, p <0.001), heart rate-systolic blood pressure product (16.8 ± 4.6 × 10³ versus 26.5 ± 5.9 × 10³, p <0.001) and work load in metabolic equivalents (METS) (5.6 ± 2.2 versus 7.4 ± 2.2, p <0.001). The average increase in each of these variables was 38, 19, 67 and 51%, respectively. The rate-pressure product failed to increase in only one patient and increased by more than 25% in 38 patients (81%) after surgery.

**Thallium-201 myocardial perfusion scintigraphy.** Figure 3 depicts the scintigraphic findings in 282 scan segments before and after surgery. Preoperatively, 136 segments (48%) were normal, 104 showed either total (n = 82) or partial (n = 22) redistribution and 42 demonstrated either moderate (PD 25-50) or severe (PD >50) persistent defects. Postoperatively, 242 segments (86%) showed normal uptake and washout of thallium, 14 demonstrated total or partial redistribution and 26 had a persistent defect. In agreement with our original assumption, the vast majority (88%) of the redistribution abnormalities observed before surgery normalized after surgery (92 of 104). An unexpected finding was that 19 (45%) of the 42 preoperative persistent defects showed normal thallium uptake and washout postoperatively. Figures 4 and 5 illustrate examples of redistribution and persistent thallium-201 defects that disappeared after surgery.

Figure 6 illustrates the frequency with which the various types of perfusion abnormalities normalized after surgery. Although 76 (93%) of 82 segments with total redistribution became normal, only 16 (73%) of 22 with partial redistribution showed normal uptake and washout of thallium postoperatively (p = 0.01). Sixteen (57%) of 28 segments with moderate persistent defects (PD 25-50) became normal after surgery. In contrast, only 3 (21%) of 14 of the more severe persistent defects (PD >50) showed normal thallium uptake and washout postoperatively (p = 0.02).
Figure 3. Thallium-201 perfusion patterns in 282 scan segments before and after coronary artery bypass graft surgery. (NL = normal; PD = persistent defect (25-50 or >50%); PRd = partial redistribution; TRd = total redistribution)

Figure 7 depicts the quantitatively determined percent reduction in regional thallium uptake for those persistent defects that normalized (n = 19) or improved (n = 2) after surgery versus those that did not (n = 21). The mean percent reduction in regional thallium activity for the persistent defects that improved was 36 ± 9% compared with 54 ± 13% for those showing no improvement (p < 0.001). Despite this difference in mean values, there was considerable overlap in the entire group of patients with preoperative persistent defects. This indicates that our arbitrary definition of a moderate versus a severe persistent defect was not entirely satisfactory in predicting postoperative improvement.

Correlations with preoperative regional wall motion. The relation between segmental thallium-201 perfusion and regional wall motion before surgery is depicted in Figure 8. Of 282 scan segments, appropriate right anterior or left anterior oblique ventriculograms were available in 250 (89%). As expected, segments with normal preoperative perfusion (that is, normal thallium uptake and washout) and those with total redistribution were associated with normal or hypokinetic wall motion in 98% (115 of 117) and 95% (69 of 73), respectively. By comparison, only 74% (14 of 19) of the segments with partial redistribution had preserved preoperative wall motion (p = 0.01). Lastly, 59% (16 of 27) of the less severe persistent defects demonstrated normal or hypokinetic wall motion preoperatively versus only 14% (2 of 14) of those with greater than 50% reduction in thallium activity (p = 0.01).

Thus, the overall pattern of our scintigraphic and ventriculographic data appear to indicate a continuum of severity of thallium defects starting with totally reversible defects, progressing to partial redistribution, to those show-
Figure 5. A, Preoperative (PRE-OP) thallium-201 scintigraphic data indicate a persistent defect in the posterolateral region. The count rate from this myocardial region is decreased 45% at 10 minutes and maintains a constant ratio with a presumed normal anteroseptal region over the 2-3 hour imaging interval. B, Postoperative (POST-OP) thallium-201 scintigraphic data indicate normal uptake and washout from the posterolateral region. Left ventriculography performed 1 day later revealed reversal of posterolateral akinesia to normal wall motion and an increased ejection fraction from 50 to 65% postoperatively. LAO = left anterior oblique.

The relation between type of preoperative wall motion abnormality and postoperative pattern of thallium uptake in areas designated as persistent defects is shown in Figure 9. Of 41 segments for which appropriate ventriculograms were available, 20 showed improved thallium uptake after surgery and 21 did not. As illustrated, 75% of the segments that improved after surgery had normal or hypokinetic wall motion on the preoperative ventriculogram. In contrast, only 19% of the segments that did not improve postoperatively had normal or hypokinetic wall motion before revascularization (p < 0.001). There were only five persistent defects associated with akinesia before surgery that showed improved thallium uptake after surgery. Interestingly, three of these five segments showed a concomitant reversal of akinesia to normal or hypokinetic wall motion postoperatively. The meaning of this finding is unclear because we expected the three myocardial segments demonstrating both akinesia...
on ventriculography and persistent thallium defects on scintigraphy preoperatively to represent scar and, hence, to show no improvement in perfusion and function after surgery. These segments, however, constituted only 14% (3 of 22) of all akinetic or dyskinetic segments. Most segments demonstrated akinesia and persistent thallium defects do not improve.

Correlations with global left ventricular function. We also examined serial changes in left ventricular ejection fraction after surgery in the 47 patients in this study. Figure 10 summarizes these data by classifying patients as those who did (Group A) and those who did not (Group B) demonstrate normal thallium uptake and washout after surgery. The baseline preoperative ejection fraction was significantly higher in Group A than in Group B (67 ± 9 versus 52 ± 15%, p <0.001). This was not unexpected because patients in Group B had a greater prevalence of prior myocardial infarction than those in Group A (16 [84%] of 19 versus 7 [25%] of 28, p <0.001). Stated differently, patients with prior infarction had a greater incidence of residual thallium perfusion abnormalities after surgery, compared with those without prior infarction (16 [70%] of 23 versus 3 [12%] of 24, p <0.001). Also, no patient in Group A demonstrated a PD>50 segment on the preoperative scintigram.

Of note, there was no significant increase in mean ejection fraction at rest after surgery in either Group A or Group B, although 91% of the patients showed improved perfusion in the distribution of at least one diseased coronary vessel. However, when patients with a normal preoperative ejection fraction were excluded, the remaining 15 patients from both groups did show a significant increase after surgery (43 ± 7 versus 51 ± 10%, p = 0.04).

Discussion
In this study, we prospectively investigated the significance of a wide range of preoperative myocardial perfusion abnormalities as determined from thallium-201 scintigraphy...
Pre- and Postoperative Changes in Myocardial Perfusion

The patterns of abnormal myocardial perfusion observed in this study during the preoperative scintigraphic assessment included focal stress-induced defects with complete redistribution, larger defects with partial redistribution, moderate persistent defects demonstrating a 25 to 50% reduction in relative thallium activity and no redistribution within the time interval of the imaging procedure and severe persistent defects with greater than 50% reduction in relative thallium activity. The frequency with which these defects normalized after surgery was significantly related to the severity of the preoperative abnormality. Perfusion defects that demonstrated total redistribution in the delayed images before operation consistently reverted to normal thallium uptake and washout after revascularization. Myocardial regions showing partial redistribution on the preoperative scintigrams usually, but not invariably, demonstrated improvement after bypass surgery, whereas only 57% of the moderate persistent defects and 21% of the severe persistent defects showed improvement. The improvement in perfusion in segments showing abnormal thallium kinetics preoperatively was associated with higher levels of exercise, which would be expected to enhance detection of perfusion defects in the absence of successful revascularization. Thus, our results demonstrate that by applying quantitative criteria to thallium-201 scintigraphy and by careful comparison of the pre- and postoperative images, scintigraphy appears useful for...
assessing myocardial viability and, hence, the potential response to revascularization surgery preoperatively.

Mechanisms of postoperative improvement in delayed redistribution. Such changes in thallium perfusion patterns resulting from revascularization surgery were not unexpected. There is a substantial amount of experimental data (12–15) indicating that total redistribution of thallium occurs under conditions of transient ischemia or chronic reduction in coronary blood flow at rest, as long as myocardial necrosis or scar is not present. The mechanism for delayed redistribution under these conditions has previously been described in detail (13). Thus, if enhanced coronary flow during exercise is achieved through patent grafts in these regions showing redistribution, conversion to normal initial thallium uptake after exercise should be observed. In the present study, 93% of segments showing preoperative total redistribution became normal after surgery. The data showing that total redistribution is highly predictive of a favorable response to surgery are also supported by ventriculographic data derived in this study. Almost all (95%) myocardial segments demonstrating preoperative total redistribution were associated with normal or hypokinetic wall motion at rest, suggesting myocardial cellular viability.

It is quite likely that segments demonstrating partial thallium redistribution represent a distinct subgroup. Significantly fewer (74%) of these segments had preserved preoperative wall motion. On the basis of a less favorable response to surgery that these segments showed after revascularization, it appears that this perfusion pattern indicates a mixture of ischemia and scar. Those defects with partial redistribution showing conversion to normal uptake postoperatively most likely represented predominantly ischemia on exercise scintigraphy.

Mechanism of improvement in persistent defects. We anticipated that initial postexercise thallium defects showing no delayed redistribution would represent prior myocardial infarction or scar. The response to revascularization surgery of myocardial regions showing persistent thallium defects on serial postexercise images was both unexpected and heterogeneous. More than half of the mild persistent defects showed improvement or were completely normalized after revascularization, whereas only a few of the severe persistent defects showed improvement. The regional wall motion data are consistent with these findings. Seventy-five percent of the persistent defects that normalized after surgery had normal or hypokinetic preoperative wall motion in the corresponding ventriculographic segments. This suggests that these areas may not represent nonviable or irreversibly damaged tissue. This observation is similar to that of our previously reported study (28) of serial rest thallium imaging in patients with unstable angina undergoing coronary bypass surgery in which more than half of the persistent defects reverted to normal thallium uptake postoperatively. Thus, in some patients undergoing revascularization surgery, myocardial blood flow reserve is reduced to such minimal levels that it produces persistent perfusion abnormalities on scintigraphy. However, this greatly reduced blood flow seems to be sufficient to maintain the tissue in a viable state and, if enhanced blood flow through a patent graft is achieved, the perfusion abnormality may improve or normalize on the postoperative scintigram.

Methodologic Considerations

Definition of complete or partial redistribution. Because evaluation of myocardial viability by thallium-201 depends on reliable determination of redistribution patterns, several issues related to methodology deserve further comment. The first is the lack of a precise definition of “complete” or “partial” redistribution. We have defined a persistent defect when the count rate from the myocardial region of interest is decreased significantly and maintains a constant ratio with a presumed normal myocardial sample over the 2 to 3 hour imaging interval (Fig. 5A). Redistribution is considered to occur if the ratio of the defect tends to change toward unity or normalizes in the delayed images (Fig. 2). The term “complete” redistribution is often used to describe this phenomenon, but this creates a misconception that the initial perfusion defect completely renormalizes its uptake within a specific length of time. Redistribution is the result of a compartmental exchange of thallium which occurs such that uptake within the defect region approaches the uptake of the normal region along an exponential pathway (13). Hence, there is no specific time at which the redistribution process is “complete.” In accord with common usage, we have adopted an approximate clinical definition and classified a scintigraphic abnormality as demonstrating “complete” redistribution if an initial numerically significant defect (27–30) has proceeded to a numerically insignificant level on delayed images taken 2 to 3 hours after the initial scan. If the defect ratio has progressed toward unity but still manifests a clear significant residual defect in the delayed images, this is termed “partial” redistribution.

Optimal time to obtain delayed postexercise images. Another question related to methodology is the optimal time to obtain the delayed postexercise images in order to determine whether a defect is, in fact, tending to normalize or remaining persistent. The numerical values of thallium concentration in various myocardial samples are subject to the limitations of Poisson statistics as well as a number of systematic errors involving, for example, positional reproducibility, nonuniformity or instability of gamma camera response and the effects of cross talk from tissues outside the sample region (36). The effect of these errors is illustrated in Figure 11, which assumes a nominal washout rate from the myocardium and error bands determined from reproducibility studies on normal patients (27). This example assumes a large, 50%, initial defect in comparison
with a totally normal myocardial sample and compares the behavior of the two myocardial segments over time assuming that the defect is: 1) absolutely persistent, or 2) normalizes along the functional path defined by multicompartamental tracer exchange studies. The statistical certainty of being able to determine whether redistribution is present or absent can be estimated: it is poor at 1 hour after injection, best at 2 to 3 hours, good at 4 hours and becomes poorly determined at 5 or more hours after injection. This can be appreciated in the example of Figure 11 by noting the extent of overlap of the error bands. The sample errors cannot be arbitrarily improved simply by longer image integration times to decrease the Poisson statistics because the error bands become dominated by the systematic error component used in our studies and assumed in this model. Thus, these statistical considerations indicate that the 2 to 3 hour imaging period provides near optimal statistical certainty for separating myocardial segments that are maintaining persistent defects from those tending to renormalize.

Preoperative distinction between viable and nonviable myocardium. Even if these statistical limitations were not present so that the slightest amount of redistribution could be detected, there still remains the question of how well this would characterize the biologic composition of myocardial tissue. A myocardial region with diminished but not absent thallium uptake in which there is either partial or no redistribution may frequently represent a complex and very heterogeneous mixture of viable and nonviable myocytes. In this milieu, we cannot expect that determination of thallium washout will specify either the exact physiologic status of myocardium or predict with certainty its response to surgical intervention. It is therefore expected, from both statistical and biologic considerations, that in the case of severe perfusion defects there will be an inevitable uncertainty in the characterization of the myocardial tissue as either viable or nonviable. The causes of this uncertainty are basic and cannot be removed by any simple means, such as by extending the imaging times.

Pre- and Postoperative Changes in Left Ventricular Function

The lack of improvement in left ventricular function that accompanied the improvement in perfusion is notable. Despite stratifying our patients based on postoperative scintigraphy, we were unable to demonstrate a significant improvement in rest ejection fraction after surgery (Fig. 10). Because our patients received 2.6 ± 1.1 patent grafts and 91% showed improved perfusion in the distribution of at least one diseased vessel, this result cannot be explained simply on the basis of inadequate myocardial revascularization.

Previous data concerning the association between surgical revascularization and improved left ventricular function at rest are conflicting (10,37–39). It is likely that differences in patient populations account for much of this reported variability. Patients with unstable angina usually show enhanced ventricular function after successful revascularization if depressed function is present preoperatively and is due to rest ischemia (10,39). In contrast, there is little reason to expect postoperative improvement in patients with chronic exertional angina who are studied at rest, a situation in which ischemia may not be present, especially when the ejection fraction is normal preoperatively (37,38,40). Because 68% of our patients had normal left ventricular function before surgery, it is understandable that we failed to show an increase in ejection fraction after surgery. Only when patients with an abnormal preoperative ejection fraction were analyzed separately did we demonstrate a significant improvement postoperatively (43 ± 7 versus 51 ± 10%, p = 0.04). In light of the observations mentioned previously, one might presume that the mechanism of this enhanced ventricular function is relief of ischemia at rest. However, because the majority of patients were on no cardiac medications when the postoperative ejection fraction was measured, we cannot exclude the possibility that changes in loading conditions might have contributed to this improvement.

Clinical Implications

Several conclusions of clinical importance can be derived from this study: 1) The increase in myocardial perfusion after coronary revascularization surgery is of sufficient magnitude to be easily detectable with quantitative thallium-201 scintigraphy. 2) Most myocardial segments with abnormal perfusion preoperatively demonstrate normal thallium kinetics postoperatively, including many that were characterized as persistent defects. 3) The presence of a persistent
perfusion defect does not necessarily indicate fibrosis or irreversibly damaged myocardium. Such areas of myocardium may show improvement in perfusion after revascularization surgery. Importantly, the preoperative distinction between viable and nonviable myocardium can be reasonably established by quantitating the amount of persistent reduction in thallium uptake and correlating this with preoperative wall motion. 4) Lastly, our results demonstrate that by applying quantitative criteria to thallium-201 scintigraphy and by careful comparison of pre- and postoperative images, myocardial perfusion imaging appears to be useful preoperatively for assessing myocardial viability and, hence, the potential response to revascularization surgery.

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