Ventricular Function Before and After Direct Revascularization Surgery

A Proposal for an Index of Vascularization to Correlate Angiographic and Ventriculographic Findings

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SUMMARY
In order to determine the effect of direct bypass surgery on the total coronary arterial supply to the heart, a numerical construct was devised to incorporate the development of new obstructive lesions and the presence of patent or nonpatent grafts. This construct, termed a vascularization index (VI), was used to evaluate left ventricular function and anginal symptoms after coronary artery bypass surgery in 56 patients. Patients with an increase in local or total arterial blood supply (positive ΔVI) often had similar directional changes in segmental wall motion and ventricular ejection fraction. Patients with a decrease in local or total arterial blood supply (negative ΔVI), due to either nonpatent grafts or progression of atherosclerotic disease, also usually had similar directional changes in segmental wall motion and ventricular ejection fraction. (Although nearly all patients reported a decrease in anginal symptoms after surgery, ΔVI could not identify degree of improvement.) Use of an integrated approach in describing pre and postoperative myocardial blood supply appears to be the most reliable method of explaining changes in left ventricular function.

Additional Indexing Words:
Coronary artery bypass grafts
Coronary artery arteriography
Coronary artery disease
Ejection fraction

If direct coronary artery revascularization surgery is more physiologic than past surgical attempts to alleviate angina pectoris, improvement in myocardial perfusing capacity (as well as symptoms) should correlate with improvement in parameters of function of the left ventricle. To date, improvement in function of the left ventricle in patients studied beyond the immediate postoperative period has not been consistently observed. To evaluate the impact of direct revascularization surgery — in conjunction with changes in underlying coronary artery morphology and uncertainties of graft closure — a vascularization index (VI) was devised to obtain a numerical construct of the total coronary arterial supply. Changes in the vascularization index (ΔVI) following bypass surgery were compared to changes in 1) the clinical severity of angina pectoris and 2) selected measurements of function of the left ventricle. The latter was done in order to determine whether improvement both in symptoms and in the angiographic image of the coronary arteries following surgery was associated with favorable alterations in ventricular performance.

Methods

Patient Population
Two hundred and two patients with coronary artery disease underwent direct coronary revascularization surgery for incapacitating angina pectoris at the Peter Bent Brigham Hospital between July 1970 and July 1972. Sixty-seven of these 202 patients (80 men and 7 women; mean age 48 yr) were evaluated both before and after surgery. Fifty-six of these 67 patients had high quality pre and postoperative left ventriculograms, were free of mitral valvular regurgitation and other cardiac valvular lesions, and did not undergo resection of a left ventricular aneurysm. These 56 patients constitute the study group. Seven patients sustained myocardial infarctions within three days of surgery, and two five and seven months later. Eighteen of the 56 patients were free of angina following surgery, two having sustained peri-operative myocardial infarctions. Two other patients...
were free of angina following postoperative infarction at five and seven months. Thirty-three patients had persistence or return of mild to moderate anginal symptoms (NYHA functional classes I and II) including three with peri-operative infarctions. These 53 patients were restudied to evaluate patency of grafts and changes in native circulation. The three remaining patients were studied because they had angina of severity equal to or greater than prior to surgery (NYHA functional classes III and IV). Mean time between first catheterization and surgery was 1.8 months, and mean time from operation to postoperative evaluation was 12.6 months.

Pre and Postoperative Studies

Pre and postoperative evaluation included a history of angioplasty, serial pre and postoperative electrocardiograms, right and left heart catheterization, selective left ventriculography in the right anterior oblique projection, and selective cineangiography of each coronary artery and each graft vessel. Standard radiographic techniques previously reported from this laboratory were used throughout the study.7 The left ventricular ejection fraction was used to represent over-all ventricular function since it has been, in our experience, the single most useful and readily obtainable prognostic hemodynamic measurement in coronary artery disease.3, 4 The operative technique used in coronary bypass vein grafts at our hospital has also been reported previously.9

Coronary and Bypass Angiography

Changes in coronary artery anatomy were assessed by simultaneous evaluation of pre and postoperative selective cineangiograms of coronary arteries. Three observers viewed the films independently and final interpretation was by consensus. The following definitions have been presented previously,10 but are briefly summarized. In postoperative angiograms, proximal lesions included lesions located between the coronary ostium and the site of graft-to-coronary anastomosis. Anastomotic lesions were defined as lesions at the site of anastomosis not associated with contiguous proximal or distal obstructions. Distal lesions were defined as lesions distal to the graft anastomosis and separated from the anastomosis by a segment of normal artery lumen at least one centimeter long. A lesion distal to but contiguous with the anastomosis was considered to have an indeterminant site or origin. Three lesions with indeterminant origins were excluded from the analysis. Progression of an obstructive lesion was defined as: 1) a change to total obstruction; 2) an increased narrowing of a prior stenosis to 75% or more of lumen diameter and/or 3) the development of a new lesion of greater than 75% of normal lumen diameter in either operated or nonoperated coronary arteries. For stenoses present in preoperative angiograms, changes in lumen diameter following surgery of less than 50% were considered to be insignificant or at the limit of accurate radiographic delineation. Further requirements for progression proximal to the graft anastomosis were non-opacification by angiographic contrast dye of a long proximal segment of the coronary artery and nonvisualization of significant tributary vessels. Opacification of every graft or the blind outpocketing from the aorta of an occluded graft vessel allowed the determination of patency or occlusion of grafts to be made in each instance.

Evaluation of Performance of the Left Ventricle

Left ventriculography was performed with multi-holed angiographic catheters using power injections of 35 to 50 ml of 76% meglumine sodium diatrizoate over a 3-4 second period. Systolic ejection fraction was calculated from the equation:

\[ \text{Ejection fraction} = \frac{\text{End-diastolic volume} - \text{End-systolic volume}}{\text{End-diastolic volume}} \]

with the appropriate volumes determined from sequential end-diastolic and end-systolic silhouettes of the left ventricle in a single-plane (30 degrees right anterior oblique) projection using a grid-calibration system and area-length formulae for a prolate ellipsoid as reported previously.11 The aortic valve and apex were used as reference points; no attempt was made to correct for downward displacement of the base or rotation of the heart nor was a regression equation used to correct to true volumes. The ejection fraction in normal subjects is 0.66 ± 0.15 (mean ± 2 SD) in our laboratory.7 Values less than 0.50 (more than 2 SD from the norm) are considered abnormal; this value is similar to that cited by the American Heart Association (< 0.45).12 Interval changes in ejection fraction of < 10 were considered within the range of reproducibility of the technique and therefore were not considered significant in this study.10

The long axis (L) and six transverse radii (R_{1-e}) were superimposed on both the end-diastolic and the end-systolic silhouettes (fig. 1), thereby dividing the left ventriculographic silhouette into anterior (R_{1-a}) and inferior (R_{1-i}) regions. These regions are assumed to represent areas of distribution of the left anterior descending coronary artery and the right coronary artery (in a right dominant system). The relationship between revascularization of the LAD and RCA and changes in the motion patterns of the respective anterior and inferior walls of the left ventricle was

Figure 1

The long axis (L) and three transverse diameters (D_{1-e}) and their respective radii (R_{1-e}) were superimposed on both end-diastolic and end-systolic silhouettes. The relationship between revascularization of the LAD and RCA and alterations in motion of the anterior and inferior walls of the left ventricle, respectively, was determined by changes in the percent of systolic shortening of the respective radii; thus anterior segment contraction is represented by mean R_{1-a} shortening and inferior segment contraction by mean R_{1-i} shortening. Since normal variation in techniques may account for changes of ± 10% in our laboratory, a "+" contraction was considered as greater than 10% systolic shortening in the postoperative study compared to the preoperative one, a "−" contraction was < −10% shortening, and no change was ± 10% shortening between studies.
studied by comparing pre and postoperative changes in the percent shortening of these radii. Left anterior oblique or biplane ventriculograms were not performed routinely. This precluded segmental analysis of revascularization to the lateral-free wall of the heart and, therefore, the majority of branches of the left circumflex artery system.

The range of heart rate during pre and postoperative ventriculography differed by less than 20 beats/min (average <10) in 53 of the 56 patients. This finding makes it unlikely that augmentation of contractility, or induction of asynery, was due to changes in heart rate. Similarly there were no systematic changes in blood pressure, LVEDP, heart volumes, or cardiac output for the group of 56 patients.

Vascularization Index

In order to determine the effect of direct bypass surgery on the anatomy of the three individual coronary artery systems, and on the total coronary arterial supply to the heart, a numerical construct was devised to incorporate the development of new obstructive lesions and the presence of patent or nonpatent grafts. Fixed numerical values were assigned to each obstructive lesion in the pre and postoperative angiographic study (fig. 2). Both pre and postoperatively minimal or nonsignificant lesions (<70% stenosis) were assigned the value 0; a 70–90% stenosis was assigned the value −0.5, and a more than 90% lesion was assigned the value −1.0. Postoperatively, a patent graft was assigned the value +1.0 and an occluded graft 0. As described in detail in two examples (figs. 3 and 4), if a minimal preoperative lesion (scored as 0) progressed postoperatively to a 70–90% stenosis the lesion was then scored −0.5; if it progressed to a total occlusion (or >90% occlusion) it was scored −1.0. Advancement of occlusive disease in all regions, proximal, anastomotic and distal, were equally weighted in the numerical grading. The appearance of a new major collateral channel between the right coronary artery and the left anterior descending coronary artery in the presence of an occluded graft to the LAD occurred in one patient and the value of +1 was assigned. In all other patients, changes in anatomy of collateral vessels did not follow any recognizable trends.

For each individual coronary artery system (both grafted and nongrafted), the values for obstructive lesions in the preoperative angiograms were arithmetically summed. This sum was termed the LAD, RCA, or LCF preoperative vascularization index (preop VI) for that coronary artery system and in a numerical representation of the state of the anatomy for that vessel system prior to surgery (figs. 3 and 4). A similar procedure was followed for the postoperative angiogram for that same coronary artery system taking into account the presence of a patent or occluded graft and the advancement of obstructive lesions (figs. 3 and 4). This was termed LAD, RCA, or LCF postoperative vascularization index (postop VI) and represents the anatomic state of that coronary artery system following surgery. A change in the anatomy of an individual coronary artery system (including graft vessels) was evaluated by subtracting the preop VI from the postop VI. This change in the VI (for the LAD, RCA, or LCF) represents the change in morphology for that coronary artery system occurring between the two angiographic studies. This change presumably is the result of operative intervention, although it is recognized that advancement of the underlying atherosclerotic process undoubtedly plays a role as well. By convention, a positive value for ∆VI signifies an improvement in coronary anatomy; a value of zero reflects no net change in coronary arterial supply and a negative value for ∆VI reflects a deterioration in the anatomic state of that individual coronary artery system.

Application of numerical grading system and vascularization index. Top) Representation of preoperative coronary anatomy. The 75% RCA stenosis was scored −0.5. The total obstruction of the LAD was scored −1. These two values constitute the preop VI for the RCA and LAD, respectively. The total preop VI (arithmetic sum of the preop VI for each of the three coronary arteries) was −1.5. Bottom) Representation of postoperative coronary anatomy. The preexisting lesions in the RCA and LAD were unchanged and were scored as above. The two patent grafts, one to the RCA and one to the LAD were each scored +1. The postop VI for the RCA was now +0.5. The ∆VI (RCA) is the result of subtracting preop VI from postop VI, thus +0.5 minus −0.5 = +1. The postop VI (LAD) was 0 (arithmetic sum of value −1 for 100% stenosis and value +1 for patent graft). The ∆VI (LAD) was +1. Total postop VI (arithmetic sum of postop VI for three coronary arteries) was +0.5. Total ∆VI is the result of subtracting preop total VI from postop total ∆VI (+0.5 minus −1.5 = +2). The positive total ∆VI indicates significant improvement in arterial supply to the heart.

Figure 2

Grading system for coronary artery lesions.
A comparison of the pre and postoperative anatomy of all three coronary artery systems was made (figs. 3 and 4). The preop VI for each of the three coronary artery systems was arithmetically summed. This was termed the total preoperative vascularization index (total preop VI) and is a numerical representation of over-all coronary morphology at the time of the preoperative angiographic study. The same procedure was followed for the postoperative angiographic study and a total postoperative vascularization index (total postop VI) was derived. Changes in over-all arterial anatomy (including graft vessels) between the pre and postoperative angiograms were evaluated by subtracting the total preop from the total postop VI. This change in the total vascularization index (ΔVI) reflects alterations in over-all arterial morphology (including graft vessels) between the two angiographic studies. ΔVI thus separates the patients into three groups: patients with improvement in arterial anatomy have a positive ΔVI; patients with no net change in anatomy have a value of 0 for ΔVI; and patients with deterioration of over-all coronary arterial morphology have a negative ΔVI.

Results
Selection of Coronary Arteries for Bypass Grafting

Ninety-eight coronary arteries had angiographic evidence of significant disease. Ninety-six of these arteries were considered operable at the time of surgery. Two left circumflex coronary arteries with significant proximal stenoses were not bypassed because of technical inaccessibility of the lesions at surgery. The 96 coronary arteries received 98 saphenous vein bypass grafts. (Two patients who had bypass grafts to the left anterior descending coronary artery also had grafts to the first diagonal branch of the left anterior descending artery which were included as part of the LAD system.) Of the 96 coronary artery systems that received grafts, 33 had lesions distal to the anastomosis, including 26 of approximately 50% lumen diameter, and seven with lesser obstructions. Of the 72 vessels not bypassed, only the two noted above had angiographic evidence of significant disease. Fifty-six vessels were free of obstructive lesions and 14 had minimal degrees of stenosis which were thought to be hemodynamically insignificant.

Graft Patency and Symptoms

The over-all graft patency rate was 63%. There were 36 nonpatent grafts. Seven were in five patients who sustained infarcts between the first and second studies. Nineteen of the 36 nonpatent grafts were to arteries exhibiting distal disease in the preoperative study, including eight with distal stenoses of approximately 50%. There was no significant difference among graft patency rates for the three coronary arteries. There was no significant difference in the graft patency rate relative to the number of arteries bypassed per patient. The relationship between postoperative angina pectoris and patency of bypass grafts is shown in table 1. Fifty-three of 56 patients (94%) were improved after surgery. In these 53 patients, 66% of grafts were patent and at least one graft was patent in 46 patients (87%). In every instance, the return or persistence of angina pectoris following surgery could be explained by either the occlusion of one or more grafts or the advancement of obstructive disease ingrafted or nongrafted coronary arteries. In 19 of 33 patients with return of mild to moderate angina pectoris (NYHA functional classes I-II), over-all coronary artery anatomy was improved.

Progression in Coronary Arteries

Unoperated coronary arteries had a 14% over-all frequency of progression. The following segmental distribution of progression of obstructive lesions was found in operated coronary arteries: 32% proximal, 10% anastomotic, and 10% distal. While progression in distal and anastomotic segments of operated coronary arteries did not differ significantly from progression in unoperated coronary arteries, progression proximal to the anastomosis was significantly more frequent than progression in unoperated arteries.
Assessing LVF After Revascularization

The relationship between postoperative angina pectoris and ΔVI is shown in Table 1. Although 53 of 56 patients were symptomatically improved after surgery, ΔVI could not identify degree of improvement. There was no difference in the frequency of proximal, anastomotic, and distal lesions in the three groups of patients separated by ΔVI (table 1). Since they were more likely to have at least one graft still patent at time of restudy, patients with two or three grafts tended to have more improvement in total vascularization index than patients with only one graft (P < 0.05) (table 2).

A comparison of postoperative changes in the anatomy of individual coronary artery systems (ΔVI) with alterations in regional contraction patterns in the left ventricle was possible in 60 instances in 50 patients. Twenty-two of the 60 instances were in 22 patients with single vessel grafts and the remaining 38 instances were in 28 patients with two coronary bypass grafts. (Eighteen left circumflex artery grafts in these 28 patients were excluded from analysis as noted earlier, as were all grafts in six patients with triple bypass grafts.) ΔVI for each of 60 coronary arteries correlated with changes in regional contraction patterns in the 50 patients noted above (fig. 5) and total ΔVI in the total group of 56 patients correlated with changes in left ventricular ejection fraction (fig. 6). Graft patency or progression considered alone failed to correlate with postoperative changes in ejection fraction.

The ejection fraction was compared to ΔVI in the subgroup of seven patients with two postoperative angiographic studies spaced between six and 29 months apart (fig. 7). Alterations in coronary artery anatomy described by ΔVI were often associated with similar directional changes in ejection fraction. Thus, of seven measurements with positive ΔVI, there were five with increased EF, but of seven with zero or negative ΔVI, there was only one with increased EF. Graft patency with little progression accounted for the positive ΔVI at the time of the first postoperative study. The ejection fraction was improved at this time in three patients. By the second study, some of the grafts had occluded and progression had occurred. These changes accounted for the negative ΔVI with coincident deterioration of the ejection fraction. In some patients, either graft patency or progression of obstructive lesions may, at one time, predominate in the determination of ΔVI; thus, patients were also grouped according to primary interval changes, i.e., presence of patent grafts or progression of stenoses in native coronary arteries (table 3). Ejection fraction remained the same or increased in 31 of 32 patients in whom the major interval change was the introduction of one or more patent grafts (P < 0.001). Conversely,

### Table 1

**Relationship of Symptom State to Graft Patency, Progression of Obstructive Lesions, Changes in Total Vascularization Index**

<table>
<thead>
<tr>
<th></th>
<th>No angina (N = 18)</th>
<th>No angina after MI (N = 2)</th>
<th>Mild-moderate angina (N = 33)</th>
<th>Severe angina (N = 3)</th>
<th>Total (N = 56)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Graft patent</td>
<td>84</td>
<td>33</td>
<td>57</td>
<td>17</td>
<td>63</td>
</tr>
<tr>
<td>% Proximal progression</td>
<td>26</td>
<td>33</td>
<td>36</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>% Anastomotic progression</td>
<td>3</td>
<td>0</td>
<td>13</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>% Distal progression</td>
<td>10</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>VI - positive</td>
<td>11</td>
<td>0</td>
<td>19</td>
<td>1</td>
<td>31</td>
</tr>
<tr>
<td>VI - no change</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>VI - negative</td>
<td>3</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

(P < 0.01). Progression was independent of both the number of grafts per patient and the state of patency of the grafts.

### Table 2

**Relation Between Number of Grafts (and Patent Grafts) to Changes in the Vascularization Index in 56 Patients**

<table>
<thead>
<tr>
<th></th>
<th>One graft</th>
<th>Two grafts</th>
<th>Three grafts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pts</td>
<td>Grfts patent 1 0</td>
<td>Pts 2 1 0</td>
<td>Pts 3 2 1 0</td>
</tr>
<tr>
<td>Total</td>
<td>22 12 10</td>
<td>28 12 11 5</td>
<td>6 3 1 2 0</td>
</tr>
<tr>
<td>VI positive</td>
<td>7 5 2</td>
<td>19 11 7 1 5</td>
<td>3 1 1 0</td>
</tr>
<tr>
<td>VI no change</td>
<td>6 2 4</td>
<td>4 0 3 1 0</td>
<td></td>
</tr>
<tr>
<td>VI negative</td>
<td>9 5 4</td>
<td>5 1 1 3 1</td>
<td>0 0 1 0</td>
</tr>
</tbody>
</table>

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when the major interval change was progression of stenoses in the native coronary arteries, irrespective of the presence of patent grafts, then six of 13 patients had depression of the left ventricular function as measured by the ejection fraction. When all grafts were closed, all six patients had zero or negative ΔVI, and four had no change in or diminished ejection fractions.

There was also a definite relationship between postoperative ECG changes and ΔVI. Of nine patients (seven early and two late) with new postoperative Q waves, seven had negative ΔVI, depressed ejection fractions, and depressed segmental ventricular contraction patterns in areas corresponding to the appearance of the new Q waves. Two patients, however, had a positive ΔVI and improvement in ejection fraction despite the appearance of new Q waves in the ECG.

Discussion
The success of direct aortocoronary revascularization surgery to palliate angina pectoris in patients with coronary heart disease and to improve function of the left ventricle depends on: 1) continued patency of applied grafts, 2) the rate of development of progressive obstructive lesions in grafted arteries, 3) advancement of the underlying atherosclerotic process in nongrafted arteries, and 4) the completeness of revascularization such that ischemia does not persist in a patchy fashion.

Relationship of Revascularization Surgery to Performance of the Left Ventricle

Significant abnormalities of left ventricular wall motion occur in the setting of 1) old scar resulting from prior myocardial infarction and 2) regional ischemia resulting in segmental alterations in contraction. Although areas with chronic scar tissue would not be expected to improve in wall motion, improvement of blood supply to ischemically depressed myocardium should improve the contraction pattern.
Postoperative myocardial infarction in 7–21% of patients following bypass surgery\(^\text{14, 15}\) may explain failure of performance of the left ventricle to improve in this subgroup of patients. If 20–25% of the wall of the left ventricle is permanently inactive, the remaining contracting myocardium may not be sufficient structurally or functionally to maintain adequate ejection.\(^\text{16}\) The three coronary artery systems may differ in their relative contribution to the maintenance of left ventricular performance. Isolated disease of the right coronary artery usually does not depress left ventricular function significantly and thus revascularization of this vessel is less likely to improve function than revascularization elsewhere.\(^\text{17, 18}\)

Reports of lack of improvement in function of the left ventricle in the presence of patent grafts\(^\text{1, 5, 19–21}\) and, conversely, the absence of deterioration of function with occluded grafts\(^\text{22}\) could be explained by the failure to consider the effects of progression on the total coronary arterial blood supply. The unavailability of a comprehensive construct reflecting the combined effects of graft patency and progression on blood supply to the heart may have hampered overall assessments of the effect of bypass surgery on left ventricular function.

### The Role of the Vascularization Index

In this report, the degree of total myocardial revascularization achieved by direct coronary bypass surgery was assessed by comparison of pre and postoperative coronary angiograms. A vascularization index was devised to reflect the state of coronary anatomy. The change in the total vascularization index (\(\Delta VI\)) clearly defined three groups of patients relative to improvement, no net change, or deterioration in coronary artery anatomy available to provide perfusion. Although 94% of patients in this study were symptomatically improved after revascularization, \(\Delta VI\) could not identify degree of improvement. However, \(\Delta VI\) did correlate significantly with quantitative assessment of regional contraction patterns of the left ventricle and its ejection fraction. Thus, patients with improvement in VI clearly had improvement in performance of the left ventricle as measured by objective criteria. We realize that in some patients the primary interval change in the anatomy of the arterial supply to the heart may be either the introduction of patent grafts or the progression of obstructive lesions in the native coronary vessels. We feel, however, that for an over-all approach to patient evaluation, the integration of changes in the state of the native coronary arteries with the presence of patent or occluded grafts through the vascularization index is better. The contribution of these two factors was seen to differ with time in the seven patients with two sequential postoperative angiographic studies. \(\Delta VI\) allows adequate description of both coronary anatomy and left ventricular function while permitting identification of subgroups of patients whose status is well defined by either addition of patent grafts or progression in native vessels. In this regard, progression of obstruction in native coronary arteries tends to be associated with deterioration of function of the left ventricle more than does occlusion of grafts or progression elsewhere.

The alleviation of ischemia and the preservation of left ventricular function depends on a balance between blood flow, graft patency, and the progression of obstructive lesions in grafted and nonoperated coronary arteries. This study demonstrated unequivocal improvement in certain measures of function of the left ventricle in the presence of improvement in coronary perfusing anatomy and conversely, deterioration in left ventricular function in those patients with deterioration in coronary anatomy. The physiologic soundness of direct revascularization surgery is thus supported. The change in the derived vascularization index (\(\Delta VI\)) is a simple, direct expression of the effect of revascularization surgery on coronary arterial anatomy and closely reflects the consequences of changes in anatomy on the performance of the left ventricle.
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