Physiologic Improvement following Coronary Artery Bypass Surgery

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SUMMARY  In this study the effects of coronary artery bypass surgery on ventricular function were evaluated at rest by quantitative analysis of segmental wall motion on cineventriculography, and during maximal treadmill exercise by measurement of serial cardiac outputs (Fick method) with the use of indwelling pulmonary artery and radial artery catheters. The patient had single vessel coronary disease and exertional angina. Following placement of a bypass graft to the proximally occluded left anterior descending coronary artery, and despite the presence of arterial hypoxemia secondary to interstitial pulmonary fibrosis, a striking increase in maximal cardiac output occurred, mediated by a rise in both maximal heart rate and stroke volume. In this patient, resting ventricular volumes and ejection fraction were normal both before and after surgery, but preoperative abnormalities in extent of segmental wall motion, identified quantitatively, were restored to normal after bypass grafting. These investigations indicate that bypass surgery can provide substantial physiologic benefits in addition to providing subjective relief of anginal symptoms.

IN ADDITION TO RELIEVING anginal symptoms, coronary artery bypass surgery can improve left ventricular function by augmenting myocardial blood flow. Although resting ventricular function does not often improve after bypass surgery,1-3 an increased maximal heart rate, rate-pressure-product, and exercise duration on multistage treadmill testing are characteristically observed postoperatively.4-6 In such patients, cardiac output and oxygen uptake increase significantly at maximal exercise postoperatively (P < 0.01), but a reduction in stroke volume has been observed after surgery.7 To further evaluate the effects of bypass surgery, circa 1976, on left ventricular function we have applied computer techniques to quantitatively evaluate segmental wall motion on cineventriculograms at rest and have measured serial cardiac output by means of indwelling radial artery and pulmonary artery catheters during symptom-limited maximal treadmill exercise.

The patient reported here underwent hemodynamic studies during exercise before and after aortocoronary bypass surgery of one artery. Despite the presence of chronic pulmonary dysfunction, a striking increase in maximal cardiac output occurred after surgery, mediated by a rise in both maximal heart rate and stroke volume. By conventional criteria resting ventricular function was normal before and after surgery, but preoperative abnormalities in segmental wall motion, identified quantitatively, were restored to normal following bypass surgery.

Methods

Angiographic Evaluation

Single plane cineventriculograms were done before and six months after surgery. Left ventricular chamber volumes were computed using the area-length method.8 Focal abnormalities of time and extent of contraction were evaluated by computer-assisted frame-by-frame analysis of the cineventriculograms which were taken at 60 frames per second.9,10 The left ventricle was divided into 20 segments and the extent of contraction graphically displayed for each segment throughout the cardiac cycle via a computer readout. The segmental ejection fraction (0-100%) denotes the extent of motion of the ventricular segment from its position in end diastole in a direction perpendicular to the long axis constructed from the mid-aortic valve to the apex.10

Exercise Hemodynamic Studies

Symptom-limited maximal exercise testing using the Bruce multistage treadmill protocol was carried out before and six months after surgery. With informed consent a Swan-Ganz catheter was placed into the pulmonary artery and an arterial catheter into the radial artery under local anesthesia. Pressure measurements and cardiac outputs (Fick method) were determined at rest, during each stage of exercise, and during the early recovery period.11-13

Case Report

This 65-year-old retired shipbuilder had a six month history of exertional chest pain which severely limited his physical activity. The pain was promptly relieved by rest and nitroglycerin. He had no prior history of cardiovascular disease and the resting ECG showed T-wave inversion in the precordial leads but no evidence of previous myocardial infarction. The chest X-ray showed a normal heart size and evidence of chronic interstitial lung disease. Arteriographic studies showed a 100% occlusion of the proximal left anterior descending coronary artery (LAD) with partial retrograde filling from the right coronary artery (fig. 1). Three weeks later the patient underwent bypass surgery with placement of an aortocoronary bypass graft into the midportion of the LAD (fig. 2). The vessel at this location was smooth-walled and 2 mm in diameter and the graft flow rate was 60 ml/min, measured with an electromagnetic flow probe after cardiopulmonary bypass prior to closure of the chest. His postoperative recovery was uneventful and the patient was discharged on the fifth postoperative day. Serum CK-MB isoenzyme activity, assayed quantitatively, remained below 15 U/L postoperatively (normal = 0-6 U/L, negligible myocardial cell necrosis = 6-20 U/L, mild to moderate necrosis = 20-50 U/L, severe necrosis = > 50 U/L).14 The postoperative ECG showed resolution of precordial T-wave depression.

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Results

Symptomatic

After surgery the patient stated that he had complete relief of anginal symptoms and a "renewed zest for living." His level of physical activity increased substantially and included resumption of outdoor activities.

Resting Angiographic Studies

Preoperatively the ejection fraction was .62, and the end-diastolic volume (EDV) was 56 ml/m². Postoperatively the ejection fraction was .67 and the EDV was 58 ml/m². Preoperatively, segmental wall motion, both in terms of time and extent of contraction was normal in all segments except at the apex (fig. 3a), where segments 7, 8 and 9 exhibited hypercontraction and segments 10, 11 and 12 had markedly impaired contraction with segment 10 showing early systolic outward motion. Postoperatively all ventricular segments contracted normally and symmetrically (fig. 3b). The bypass graft was widely patent on repeat study (fig. 2).

Exercise Hemodynamic Studies

Preoperatively, the patient had a severely limited exercise capacity and, despite maximum effort, was not able to complete stage I of the multistage treadmill exercise protocol. Cardiac output during exercise increased nearly twofold to 7.4 L/min, his maximum cardiac output as evidenced by a prolonged plateau at this level despite a steadily increasing exercise work load. Attainment of maximal cardiac output was associated with limiting symptoms of dyspnea and angina (fig. 4). The heart rate response to exercise was markedly restricted and mean systolic arterial pressure fell from 103 to 97 mm Hg. These findings are typical of severely impaired cardiac function in patients with angina.13 The arteriovenous oxygen difference widened about twofold before surgery. Postoperatively, the cardiac output rose to a maximum level of 10.4 L/min and exercise was terminated because of symptoms of exhaustion without angina or ST-segment depression. Stroke volume was unchanged at supine rest, but increased while sitting at rest and again during exercise after bypass surgery. At maximal exercise, the heart rate response rose 16% while stroke volume increased 20% (fig. 5). As a consequence, cardiac output increased 37%. With a 17% increase in arteriovenous oxygen difference, maximal oxygen uptake rose 56%. The patient had impaired pulmonary gas exchange before surgery, which did not change after surgery; arterial PO₂ and PCO₂ were, respectively, 84 and 31 mm Hg at rest and 71 and 33 mm Hg at rest.
maximal exercise preoperatively, and 73 and 39 mm Hg at rest and 70 and 32 mm Hg at maximal exercise postoperatively.

Maximum oxygen uptake was 1.42 L/min after surgery compared with 0.9 L/min before surgery. Postoperative maximum oxygen uptake was nevertheless somewhat less than the predicted normal for this patient, based on his age, sex, and habitual activity status (FAI = 37%), owing to his chronically impaired pulmonary gas exchange.

Discussion
Symptomatic improvement can occur following bypass surgery in the absence of physiologic improvement in ventricular function at rest and/or exercise. Relief of anginal symptoms can occur in some patients in whom all grafts are found to be occluded\(^{19}\) and in others who sustain a perioperative infarction of the angina-producing myocardial segment.\(^{16}\) In this latter circumstance, deterioration in resting ventricular function is often observed.\(^{17}\) But in most instances, the man-made collateral circulation provided by patent bypass grafts improves myocardial blood flow, thereby providing both symptomatic and physiologic improvement.\(^{18}\)

Increased levels of cardiac output, up to fourfold above resting levels, requires a similar increase in coronary blood flow in order to satisfy the resulting increased myocardial oxygen demands.\(^{19}\) Gould et al.\(^{20}\) and others,\(^{21}\) have shown that stenotic lesions less than 85–90% arterial diameter narrowing do not affect resting coronary flow, but stenoses more than 40–50% will restrict maximal coronary flow, or coronary flow reserve. A bypass graft placed into a coronary artery beyond a stenosis of less than 85% would therefore not be expected to increase resting coronary flow, but it should improve coronary flow reserve in coronary arteries with proximal stenoses of greater than 40–50%.

In this patient, the aortocoronary bypass graft to his proximally occluded LAD very likely improved resting coronary flow, as evidenced by improved apical segmental wall contraction, as well as improved coronary flow reserve, which enabled the patient to achieve a substantially higher level of stroke volume and cardiac output during more stressful exercise. Unfortunately, there are no satisfactory nonoperative techniques currently available for measuring myocardial blood flow in ml/min in human patients.\(^{29}\)

Improved myocardial blood flow — supplying oxygen and other metabolites and removing cellular waste products — is clearly the mechanism by which higher levels of cardiac output can be achieved after successful coronary bypass grafting. Mechanisms of pain relief which do not increase myo-
Cardiac blood flow, such as medical treatment with beta blocking agents or surgical interventions which produce a placebo effect or perioperative infarction, will not improve maximal cardiac output. Anginal chest pain does not by itself limit cardiac output during exercise. McDonough and coworkers have shown that the development of angina pectoris on maximal treadmill testing coincides with a plateau and then a fall in cardiac output (i.e., maximal cardiac output) and is associated with signs of acute left ventricular dysfunction manifested by a rising left ventricular filling pressure. Medical treatment with nitrates and beta blocking agents and physical training can relieve anginal symptoms and improve exercise duration by reducing myocardial oxygen demand. But these interventions do not increase maximal heart rate, or cardiac output, nor do they bring about a rise in rate-pressure-product (adjusted when necessary for changes in ejection time), which relates directly to myocardial oxygen consumption. We have shown that physical training does not improve cardiac performance in patients with coronary heart disease, but rather reduces myocardial oxygen demand by improving peripheral muscle efficiency, resulting in a widening of the arteriovenous oxygen difference along with a compensatory erythrocytosis or exer-
tional hemoconcentration. Mather and Guinn in a prospective, randomized study of medical versus surgical treatment of angina pectoris found that the medically treated patients had a significant increase in duration of treadmill exercise, but the rate-pressure-product did not increase. In contrast, patients who had bypass surgery had a statistically significant increase in rate-pressure-product along with a highly significant increase in exercise duration. Lapin et al. showed that an improved heart rate response on exercise correlates well with graft patency, and substantial improvement in exercise capacity following bypass surgery.

**Figure 4.** Maximal cardiac output on treadmill testing before and after single aortocoronary bypass surgery. *Patient received no medications within 12 hours of testing postoperatively and had not been treated with beta blocking agents.*

**Figure 5.** Changes in components of oxygen delivery at supine and upright rest, submaximal and maximal exercise six months after aortocoronary bypass surgery. Oxygen uptake ($V_{O_2}$) is represented by the volume of the block. The three components — stroke volume ($SV$), heart rate (HR), and arteriovenous oxygen difference ($\Delta AVO$) — are represented by the dimensions of the block. The product of $SV$ and HR, or the cardiac output ($Q$) is represented on the right surface. Note the substantial increase in stroke volume in upright posture, both at rest and at two levels of exercise.
manifested noninvasively by an increase in exercise duration and maximal heart rate response, has been widely documented.15, 20

In this patient, mild arterial hypoxemia secondary to interstitial pulmonary fibrosis might be expected to restrict stroke volume, cardiac output and maximal oxygen uptake as demonstrated in normal men exposed to high altitude hypoxia.26, 27 Yet, with no correction of the hypoxemia, all three variables increased with exercise postoperatively when the saphenous vein graft augmented coronary blood flow to the left anterior descending artery.

Coronary artery bypass surgery is the first procedure which can substantially improve myocardial blood flow.14 The resulting physiologic improvement is manifested by improved ventricular performance, particularly during exercise, where coronary blood flow levels substantially higher than resting coronary flow levels are required to meet the increased oxygen demands of the exercise-stressed heart. As shown in this case report, important physiologic benefits can result from coronary bypass surgery. There is an urgent need for larger scale studies of this type to document the frequency and degree of these benefits in the various categories of patients who are considered candidates for bypass surgery.

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