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Use of exercise tests in assessment of the functional result of aortocoronary bypass surgery

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ABSTRACT The value of an objective exercise test for the assessment of the functional results of aortocoronary bypass was investigated in 19 patients who were studied before and six months after the operation. For positive tests the end point was defined as a net ST segment depression of 0·1 mv 80 ms after the J point of the ECG. For negative tests the end point was 85% of the age-predicted maximal heart rate response. One patient who was not able to attain either of these points after the operation was excluded. In the remaining 18 patients three indices were used in the analysis. First, the heart rate (HR) and the product of heart rate and systolic blood pressure (RPP) were measured at the defined level of ST segment depression during positive exercise tests to yield HR/ST and RPP/ST threshold respectively. Second, the HR and RPP were measured at the end point of the negative tests. Third, the duration of exercise till the end point of the tests was measured. In each patient the duration of the postoperative test was longer than that of the preoperative test. While all the patients had a positive exercise test before the operation, the test was negative in 11 after it. In 10 of these 11 patients the HR and RPP attained at the end point of the postoperative test had increased; the HR and RPP remained unchanged in one patient. Positive tests were still present in seven of the 18 patients. In five of these the HR/ST threshold and RPP/ST threshold were greater after than before operation, and they remained unchanged in two. An improvement in myocardial blood supply after aortocoronary bypass was suggested indirectly by the ability to attain, during exercise, a higher HR and RPP at the end point of the test. The test proved especially valuable in patients who retained a positive exercise test after the operation.

Aortocoronary bypass is widely used in the treatment of coronary artery disease. While it has been shown that the operation is associated with an acceptable rate of graft patency, evidence that it leads consistently to reversal of regional myocardial ischaemia especially in patients with more than one bypass graft has been scarce.[1 2] Recently a non-invasive exercise test with an objective end point was used to study the effects of physical training in patients with angina pectoris caused by coronary artery disease.[3] It was shown that the ability to attain during exercise a greater heart rate and systolic blood pressure at a predetermined level of ischaemic ST segment depression, could be attributed to an improvement in myocardial blood supply.[3]

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The present study was planned prospectively to investigate whether, using this method in patients in whom a bypass operation had been performed, there was an improvement in myocardial blood supply.

Subjects and methods

Nineteen consecutive patients, in whom the diagnosis of angina pectoris caused by coronary artery disease was established by the ischaemic response during exercise electrocardiography and by selective coronary arteriography, were investigated before and after aortocoronary bypass. Patients with hypertension, valve disease, or cardiac arrhythmia, patients with resectable aneurysm of the left ventricle, and patients who had to be maintained on digoxin, beta-blockers, or nifedipine were excluded from the study. In the 19 patients beta-blocker therapy was stopped under medical supervision during admission to hospital before the operation, for at least five days to allow exercise testing. Critical coronary arterial stenosis, defined as a decrease in the diameter of 75% or more in one or more of the major vessels was a prerequisite for the operation. The operative technique was identical in all the patients and included extracorporeal circulation before incision of the coronary arteries. Saphenous vein grafts were used to bypass the coronary lesions.

Exercise electrocardiography was performed in all patients the week before and six months after the operation, and the results were analysed without previous knowledge of the extent of the coronary lesions or the details of the operation.

EXERCISE TEST

The patients attended the laboratory at least two hours after the most recent meal. They were tested on an electrically braked bicycle ergometer (Elema Schonander, type 380). The exercise test consisted of two stages, the first involving continuous exercise and the second discontinuous exercise as previously described.[3]

Continuous test

In this stage the patients pedalled at 60 rpm against the presented workload, initially 150 kpm.min^{-1} (24·5 W), and then stepwise increases at three-minute intervals, each of 150 kpm.min^{-1} (24·5 W). Three possible end points of the test were defined: a positive test when the end point was ST segment depression on the ECG recorded from CM_5 position; a negative test indicated by the absence of ST segment depression when the patient attained 85% of age-predicted maximal heart rate response; and an indeterminate test when the exercise had to be terminated because of chest pain, multiple ventricular ectopic beats, or fatigue, and not because of the occurrence of ST segment depression, or because the patient attained the described target in terms of heart rate response.[4]

Discontinuous test

After 40 minutes rest, patients with positive tests performed a second test in which incremental work loads were separated by rest periods. The initial load was the same as that which initially resulted in the highest heart rate response before the onset of positive ST depression. Subsequent loads were increased stepwise by 25 kpm.min^{-1} (4·1 W) until the described positive end point of the test. The heart rate (beats.min^{-1}) was obtained from the ECG. The systemic blood pressure was measured, using en electronic sphygmomanometer (Elag-Koln), at every workload when the heart rate attained a steady value.

In positive tests, ST segment depression—that is, the end point of the test—was defined as a net ST segment depression of 0·1 mv 80 ms after the J point of the ECG, in the presence or absence of anginal pain. This end point served as the reference level at which the duration of the continuous test was measured. The heart rate (HR) and systolic blood pressure (SBP) at this level of ST segment depression during the discontinuous test were measured to yield the HR/ST threshold and the threshold of the product of HR and SBP (RPP/ST threshold).

In negative tests, the values of HR and RPP attained at the end point of the continuous test were included in the analysis.

Accuracy of measurements

Adequate reproducibility of the measurement of HR/ST threshold has been previously demonstrated in anginal patients. The 95% tolerance limit with 95% confidence of repeated measurement is 2·5 beats.min^{-1}.[3]

The performance of the electronic sphygmomanometer (Elag-Koln) was validated by comparing it with a random zero sphygmomanometer (Sreeharan and Linden, 1979; unpublished observations). Sixty-six pairs of observations in 11 patients showed that the regression slope did not differ significantly from unity; SBP (Elag-Koln) average data being greater than SBP of the random zero sphygmomanometer by an average of 1 mmHg (0·133 kPa) (SEM 0·65 mmHg; 0·086 kPa). The random error (two SD) of the difference between duplicate observations was 6·2 mmHg (0·82 kPa) for Elag-Koln and 6·0 mmHg (0·80 kPa) for the random zero sphygmomanometer.

Results

Nineteen male patients with an average age of 51·8 years (range 38–64 yr) were investigated. Six had a history of myocardial infarction. Details of coronary arteries bypassed are shown in table 1. All patients survived the operation and none developed a perioperative or postoperative myocardial infarction as assessed by serial electrocardiographic recordings (resting 12 lead

Table 1 *Details of coronary vessels bypassed in 19 patients*

Coronary artery	*Number of patients*		
	One vessel	*Two vessels*	*Three vessels*
AD	2	—	—
AD, RCA	—	7	—
CIRCUM, RCA	—	4	—
AD, CIRCUM	—	1	—
AD, CIRCUM, RCA	—	—	5

AD, anterior descending; circum, circumflex; RCA, right coronary artery.

electrocardiogram) and by enzyme studies. At the time of assessment none of the patients was in cardiac failure and no medical therapy had been started. All the patients were managed identically by the same surgical team and without knowledge of the results of exercise tests. At the time of the postoperative exercise tests none of the patients was incapacitated symptomatically. The body weight of each patient was within 8% of that measured before the operation.

All the patients were tested before and six months after the operation. All patients before operation had a positive result. After operation, seven patients retained a positive result, and 11 patients had a negative result; the test in the remaining patient (19) was indeterminate and was not included in the analysis (table 2).

Table 2 *Results of exercise tests in the postoperative period*

Vessel bypassed	*Positive*	*Negative*	*Indeterminate*
AD	1	—	1
AD, RCA	2	5	—
CIRCUM, RCA	1	3	—
AD, CIRCUM	—	1	—
AD, CIRCUM, RCA	3	2	—

Abbreviations as in table 1.

Details of the 11 patients in whom the result of the exercise test changed from positive before to negative after operation, are shown in table 3. In 10 of these, the HR and RPP attained at the end point of the exercise test were greater after operation. Each patient was able to exercise at a higher level of HR and RPP in the later test and in every instance the increase in level of HR attained during exercise exceeded the tolerance limit of measurement. In the remaining patient (16) the changes in HR were within the tolerance limit of measurement and there was a decrease in RPP.

Table 3 *Changes in the response to exercise testing in 11 patients in whom the test was negative after the operation*

Patient	*End point angina*		*End point heart rate (beats.min⁻¹)*		*End point rate pressure product**		*Duration (min)*	
	before	*after*	*before*	*after*	*before*	*after*	*before*	*after*
1	+	−	110	145	165 (21·9)	203 (27·0)	8	15
2	+	−	130	145	169 (22·5)	203 (27·0)	4	13
3	+	−	110	150	165 (21·9)	225 (29·9)	9	15
4	+	−	110	140	176 (23·4)	252 (33·5)	8·5	16
5	+	−	118	138	189 (25·1)	235 (31·3)	8	12
6	+	−	110	135	165 (21·9)	203 (27·0)	10	15
7	+	−	82	145	98 (13·0)	232 (30·9)	6	15
8	+	−	118	140	189 (25·1)	232 (30·9)	8	12
9	+	−	100	135	180 (23·9)	270 (25·9)	4	12
10	+	−	122	138	210 (27·9)	235 (31·3)	12	15
16	+	−	143	145	257 (34·2)	247 (32·9)	9	12

*Units of rate pressure product: mmHg. min^{-1} 10^2 (kPa. min^{-1} 10^2); conversion factor 7·52.
+Anginal pain at the end point.
−No anginal pain at the end point of the exercise.

Considering all the patients in this group, HR increased from an average 113·9 beats.min^{-1} (range 82–143) to an average 141·5 beats.min^{-1} (range 135–150), a mean increase of 27·6 beats.min^{-1} ($2p<0·001$; paired *t* test). The mean RPP increased from 178·5 mmHg.min^{-1} 10^2 (range 98–257) [23·74 kPa.min^{-1} 10^2 (range 13·0–34·2)] to an average 230·6 mmHg.min^{-1} 10^2 (range 203–270 [30·67 kPa.min^{-1} 10^2 (range 27·0–35·9)], that is, a mean increase of 52·2 mmHg.min^{-1} 10^2 (6·94 kPa.min^{-1} 10^2; $2p<0·001$; paired *t* test).

While before operation the end point of the test was always associated with anginal pain, none of these 11 patients experienced anginal pain in the second test. The duration of exercise performed by each patient was greater in the postoperative than in the preoperative test ($2p<0·001$; paired *t* test).

In seven patients, the result of the exercise test remained positive after the operation—that is, ST segment depression during exercise was retained (table 4). The HR/ST threshold showed changes which exceeded the tolerance limit of measurement during sequential exercise testing in five patients only. Each patient was able to exercise after operation at a greater HR and RPP at the same level of ischaemic ST segment depression compared with the preoperative test. In the remaining two patients (17, 18) the changes in HR/ST threshold were within the tolerance limit of measurement, and the changes in RPP/ST threshold were small. In these seven patients the HR/ST threshold increased from an average 111·3 beats.min^{-1} (range 94–130) to an average 127·0 beats.min^{-1} (range 110–145), a mean increase of

Table 4 *Changes in the response to exercise testing in seven patients with a positive test after the operation*

Patient	End point angina		End point heart rate (beats.min^{-1})		Rate pressure product*		Duration (min)	
	Before	After	Before	After	Before	After	Before	After
11	+	−	125	140	213 (28·3)	238 (31·7)	4	12
12	+	−	94	122	122 (16·2)	201 (26·7)	3	12
13	+	+	98	130	147 (19·6)	228 (30·3)	3	9
14	+	+	130	145	221 (29·4)	247 (32·9)	6	11
15	+	−	105	125	168 (22·3)	188 (25·0)	8	8·5
17	+	−	115	117	265 (35·2)	269 (35·8)	6	11
18	+	−	112	110	146 (19·4)	138 (18·4)	5	9

Units and abbreviations as in table 3.

15·7 beats.min^{-1} ($2p<0·002$; paired *t* test). The RPP/ST threshold increased from an average 183·1 mmHg min^{-1} 10^2 (range 122–265) [24·35 kPa. min^{-1} 10^2 (range 16·2–35·2)] to an average 215·6 mmHg.min^{-1} 10^2 (range 138–269) [28·67 kPa. min^{-1} 10^2 (range 18·4–35·8)] that is a mean increase of 32·4 mmHg min^{-1} 10^2 (4·31 kPa.min^{-1} 10^2; $2p<0·05$; paired *t* test). While ischaemic ST segment depression was always associated with anginal pain in preoperative tests, only two out of the seven patients experienced anginal pain in postoperative tests. After operation the duration of exercise performed by each patient was longer than before ($2p<0·005$; paired *t* test).

Discussion

There is widespread concern regarding the lack of unequivocal evidence that aortocoronary bypass effects a relatively long-lasting improvement or prolongs life in patients with symptomatic coronary artery disease in spite of reports of an acceptable incidence of graft patency.[1 2] The reported studies on the effectiveness of myocardial revascularisation have shown variable results, partly because of the use of subjective methods and partly because of the difficulty in demonstrating reversal of ischaemia in more than one ischaemic region, especially in patients who retain evidence of myocardial ischaemia after the operation. Qualitatively for instance, the subjective relief of angina pectoris may be brought about by other factors in addition to improvement in the supply of blood to the myocardium—for example, perioperative myocardial infarction, denervation of the ischaemic zone, and a placebo effect.[2 5-7]

Objective studies on the ability of bypass surgery to improve the supply of blood to the myocardium, have used both invasive and non-invasive techniques.

INVASIVE METHODS

The results of studies of left ventricular function in terms of segmental contractility, pressure, volume and flow parameters, myocardial blood flow, and regional myocardial perfusion have yielded variable results in respect of sequential improvement or deterioration in a given patient, despite graft patency.[8-20]

Using these methods, especially in patients with more than one bypass graft, it is difficult to determine which coronary lesions are the critical ones in any given patient. Similar difficulties have been experienced in the use of myocardial imaging during exercise; in patients with multi-vessel disease it has been difficult to detect all the disease sites.[21] For example, a normal scan, at rest and during exercise, does not totally exclude an occluded graft, and a perfusion defect during exercise has been obtained when the grafts were patent.[22] Thus, from these studies it is possible to conclude that a successful bypass in terms of anatomical patency of the grafts does not necesarily indicate functional improvement in oxygen availability to ischaemic regions of the myocardium, so that the functional effects cannot be predicted.

NON-INVASIVE METHODS

Exercise electrocardiography provides an objective and non-invasive method of provoking ischaemic ST segment depression,[4] and has potential for the quantitative evaluation of the balance between myocardial oxygen requirement and availability[23 24] It is yet to be demonstrated conclusively that myocardial imaging would provide a more sensitive technique in detecting myocardial ischaemia as compared with exercise electrocardiography.[25 26] A recent account of the assessment of aortocoronary bypass using exercise thallium-201 myocardial imaging and exercise electrocardiography suggested that the latter "may be misleading after aortocoronary bypass operation".[27] However, a symptom-limited exercise test was used, "a target heart rate was not used" and the heart rate response attained by each patient was not given. It is not possible from the data in that report to conclude whether the absence of abnormal electrocardiographic changes during exercise would label the test results negative or indeterminate. Also because the end point of both exercise electrocardiography and exercise imaging was not objectively determined, it is not clear whether both tests were terminated at an intensity sufficient to provoke myocardial ischaemia. For example, after coronary bypass, a positive exercise test was said to develop "at heavy work loads" in four patients in whom exercise thallium imaging showed no evidence of ischaemia. Therefore in that report,[27] it is not possible to compare the results of exercise electrocardiography with those of exercise imaging.

Exercise testing has been used to study the effect of coronary bypass first in terms of improvement in exercise performance—that is, an increase in the duration of exercise and maximal oxygen consumption. It is also used to determine the ability to increase myocardial blood supply—that is, the ability to exercise to a higher heart rate and systolic blood pressure and therefore to a higher myocardial oxygen consumption before angina occurs.[28] However, it has been recognised that changes in exercise performance can be influenced not only by the effect of revascularisation but by the response of the patient to surgical procedures,[2 29] and by the patients' physical activity and conditioning before and after operation.[30] The use of a subjective sensation such as anginal pain as the end point for a positive response has obvious limitations. It has been shown that sham procedures may influence pain patterns,[29] and that pain relief can be affected by factors other than myocardial revascularisation. Most of the exercise testing which has been used indirectly to study changes in myocardial blood supply in patients undergoing coronary bypass, has been symptom-limited.[7 9 13 16 27 30–39]

In one report heart rate and systolic blood pressure at the end point of the test were measured during treadmill exercise tests in three groups of patients before and after coronary bypass.[40] The groups included 10 patients with patent grafts, four patients with "partial revascularisation," and six patients with occluded grafts. The response at ST segment depression of 0·1 mv could be analysed in only 10 patients, seven, one, and two in each group respectively, because of abnormal baseline ECG recordings. All the seven patients with patent grafts had a negative test after the operation; in the remaining three patients who retained a positive test after the operation the heart rate and the heart rate-pressure product responses at ischaemic ST segment depression showed no improvement. However, data on the tolerance limits of measurements of the heart rate and systolic blood pressure were not given. Only a small group of patients coud be investigated. In particular, there was no mention in the report of the problem of whether patients in whom a positive test is retained could have benefited from the operation.[40] In the face of multiple grafting procedures it is important to demonstrate whether or not improvement in the supply of blood to the myocardium has occurred in spite of only "partial revascularisation".

PRESENT STUDY

In the present study the techniques of Raffo *et al*[3] were used. They measured heart rate and systolic blood pressure attained at a defined level of ischaemic ST depression (HR/ST threshold and RPP/ST threshold) during exercise in patients with angina pectoris caused by coronary artery disease. In the present investigation the levels of HR and RPP attained at the end point of exercise tests were assessed in each of 18 patients before and after coronary bypass. In 11 patients a negative exercise test was obtained after the operation, and 10 of these patients attained higher HR and RPP at the end point of the test after operation. Such results have been interpreted as indicating an ability to attain a higher level of myocardial oxygen consumption during exercise, perioperative myocardial infarction having been excluded.[28 30 32 34 40] In the present investigation none of the patients developed a perioperative or postoperative myocardial infarction before final exercise testing, and they were therefore considered to have shown changes indicating improvement in the supply of blood to the myocardium.

In seven patients, a positive exercise result persisted after the operation. Five of these patients showed an increase in HR/ST threshold and RPP/ST threshold, indicating an improvement in the ability to exercise to a higher heart rate and systolic blood pressure before the occurrence of the same level of ischaemic ST segment depression. In contrast, the remaining two patients showed no significant change in these thresholds. An increase in these thresholds after a period of physical training in patients with ischaemic heart disease has been shown to reflect an increase in myocardial oxygen consumption at the same level of ischaemic ST segment depression.[3] Such an increase after aortocoronary bypass indicates improvement in myocardial blood supply. Therefore, these five patients were considered to have benefited functionally, despite retaining evidence of myocardial ischaemia after the operation.

We conclude that a simple and non-invasive exercise test can be used to demonstrate indirectly an improvement in the supply of blood to the myocardium in patients who have undergone aortocoronary bypass. The technique has been shown to be of special value in patients who retain a positive exercise test after the operation and yet were improved.

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