Assessment of magnetic resonance velocity mapping of global ventricular function during dobutamine infusion in coronary artery disease

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Abstract

Background—Magnetic resonance imaging (MRI) is a versatile technique for examination of the cardiovascular system but only recently has assessment of myocardial ischaemia in coronary artery disease (CAD) become possible, for example by demonstrating abnormalities of regional ventricular contraction during stress. Global ventricular function during stress was assessed by MRI of aortic flow, which has not been previously attempted.

Design—Variables measured by MRI reflecting the effect of ischaemia on global ventricular function during dobutamine stress were correlated with thallium-201 myocardial perfusion tomography.

Patients—10 normal controls and 25 patients with CAD.

Setting—Tertiary cardiac referral centre.

Methods—Novel MRI sequences and analysis systems were used to measure the following variables during staged dobutamine infusion to 20 μg/kg/min: stroke volume, cardiac output, cardiac power output, peak flow, peak flow acceleration, aortic back flow, and flow wave velocity. Heart rate, blood pressure, double product, and maximum tolerated dobutamine dose were also measured. Multiple regression analysis was used to compare changes during stress with 201TI tomography.

Results—All parameters except for stroke volume and diastolic blood pressure increased in the controls. In the patients with CAD a significant relation was shown between the extent of reversible ischaemia and the change in peak flow acceleration (P < 0·00001), peak flow (P = 0·002), cardiac power output (P = 0·036), maximum dobutamine dose (P = 0·039), and systolic blood pressure (P = 0·04). Peak flow acceleration accounted for 58-4% of the variation in reversible ischaemia, and after allowing for this, only cardiac power output remained independently predictive adding a further 4·2% to the model (adjusted r² = 0·626). A decrease in peak flow acceleration with an increase in dobutamine infusion indicated moderate or severe ischaemia (r² = 10·2, P = 0·017).

Conclusions—MRI may be used to assess variables of aortic flow during stress, which includes acceleration with high temporal resolution. Peak flow acceleration was the most sensitive indicator of the effect of ischaemia on global ventricular function.

Keywords: magnetic resonance imaging; coronary artery disease; ventricular function; dobutamine infusion

The functional significance of coronary artery disease (CAD) may be studied by the assessment of myocardial perfusion, regional left ventricular wall motion, or haemodynamic variables reflecting global left ventricular ejection. The prognostic importance of functional abnormality in CAD is well described, and at least equivalent to coronary arteriography. Magnetic resonance imaging (MRI) is a new technique for investigating the heart, but studies in CAD are few, and to date have involved the assessment of infarction, changes in regional ventricular contraction during dipyridamole or dobutamine, and preliminary coronary angiography and myocardial perfusion studies. Very little work on global ventricular function during stress has been performed. The aim of this study was to develop techniques for measurement of global ventricular function by MRI and to examine the effect of ischaemia.

MRI is capable of accurate measurements of blood flow and could therefore assess global left ventricular function from variables of flow in the ascending aorta. Doppler echocardiography has been used in a similar manner during dynamic exercise in normal individuals and in patients with CAD with either isometric or dynamic exercise. Movement artefact at higher stress levels has made interpretation difficult, however, and other attempts have used vasodilatation with dipyridamole, but results have been conflicting. Dynamic exercise in the magnet is difficult at present because of movement artefact and space restriction, therefore for this study we used dobutamine infusion. As part of this study, velocity mapping which is capable of measuring aortic acceleration with high temporal resolution was developed and applied for the first time in CAD.
Patients and methods

PATIENTS AND NORMAL PARTICIPANTS
Twenty three of 25 patients with a history of chest pain who were selected prospectively from the waiting list for coronary angiography were men. Mean (range) age was 53-9 (39-65) years, and 10 had previous myocardial infarction (seven inferior, two anterior, and one apical). No patient had heart failure and none was receiving diuretics or angiotensin converting enzyme inhibitors. Ten normal male volunteers without symptoms or signs of CAD were also studied (mean (range) age 51-0 (33-68) years). There was no significant difference between the age and gender of the groups. All patients and normal volunteers gave informed consent to the study. The study was approved by the local committee on ethical approval for research.

DOBUTAMINE INFUSION
Dobutamine 2 mg/ml was infused into a peripheral vein using a syringe pump. Incremental doses of 5, 10, 15, and 20 
\( \mu g/kg/min \) were used for a minimum of 5 min at each stage, the maximum dose being determined by chest pain or other intolerable symptoms, significant arrhythmia, diastolic blood pressure >110 mm Hg, or systolic pressure >240 mm Hg or <10 mm Hg from a previous stage. The electrocardiogram (lead CM5) was monitored continuously and the blood pressure was measured each minute.

MAGNETIC RESONANCE IMAGING
A Picker International MR2055 scanner operating at 0.5 T was used to acquire transaxial spin echo images (echo time 40 ms) through the superior mediastinum and an oblique image containing as much as possible of the aortic arch. Magnetic resonance velocity mapping was performed using a cine gradient echo sequence in the transaxial plane perpendicular to the ascending and descending aorta at the level of the right pulmonary artery (fig 1). Field of view was 40 cm, slice thickness 10 mm, flip angle 45°, and there were two excitations of 128 phase encoding steps. This technique has been previously validated in vitro and in vivo and shown to provide flow measurements in the aorta with an accuracy of 5%.

Two acquisitions were performed at each stage of stress. The first used 16 frames/cycle and echo time of 6 ms to measure instantaneous aortic flow throughout the cycle and to allow the calculation of stroke volume, cardiac output, cardiac power output, aortic back flow, and peak flow (fig 2). The second used an echo time of 3.6 ms and 15 frames clustered as tightly as possible around the ascending part of the aortic flow curve, to measure peak flow acceleration (ms^-2) in the ascending and descending aorta, and the flow wave velocity between these two points (fig 3). The
Flow pertain and points are positive and negative values in the velocity maps. The area under the net flow curve represents the stroke volume.

Figure 5 Plot of calculated flow against time showing separate forward and retrograde flows in the ascending aorta and the net flow (dotted line). The data points are calculated by separating pixels with positive and negative values in the velocity maps.

Figure 6 Plot of data points calculated from the high resolution velocity maps in systole with the fitted curve. Peak flow acceleration was calculated from the zemeth of the derivative curve.

Cardiac power output (W) =

\[
\text{cardiac output (l/min) \times (mean BP - mean RAP) \times 0.0022}
\]

Flow acceleration was calculated by fitting the instantaneous flow measurements from the higher temporal resolution acquisition with a four harmonic Fourier function and differentiating the fitted curve (fig 6). The time for the foot of the flow wave to travel between the ascending and descending aorta was also measured from these fitted curves and used to compute flow wave velocity (fig 7).

The thallium tomograms were analyzed visually by dividing the myocardium into nine segments (anterior, lateral, inferior, septal, each with apical and basal portions, and the apex). Activity in each segment was assessed semiquantitatively using a five point scale from 0 (absent) to 4 (normal). A change in score of one or more between stress and redistribution images was defined as redistribution. Abnormal segments without change or with a reduction in score were defined as fixed defects.
Table 1  Mean (SD) haemodynamic values in normal controls during dobutamine infusion

<table>
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<tr>
<th>Dobutamine (µg/kg/min)</th>
<th>HR</th>
<th>SBP</th>
<th>DBP</th>
<th>DP</th>
<th>CO</th>
<th>SV</th>
<th>CO</th>
<th>PF</th>
<th>PFA</th>
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<td>101 (15)</td>
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<td>9-2 (1-4)</td>
<td>4-4 (1-1)</td>
<td>-16-8 (9-8)</td>
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<td>5</td>
<td>79-3 (16)</td>
<td>158 (12)</td>
<td>82-1 (9-1)</td>
<td>12-5 (2-7)</td>
<td>121 (26)</td>
<td>9-3 (2-0)</td>
<td>2-30 (0-55)</td>
<td>42-7 (4-5)</td>
<td>16-8 (3-3)</td>
<td>4-6 (0-86)</td>
<td>-17-3 (8-1)</td>
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<tr>
<td>10</td>
<td>95-9 (22)</td>
<td>170 (12)</td>
<td>82-7 (7-5)</td>
<td>16-2 (3-4)</td>
<td>110 (22)</td>
<td>10-3 (1-8)</td>
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<td>48-5 (6-0)</td>
<td>24-5 (4-4)</td>
<td>5-0 (1-1)</td>
<td>-18-6 (9-1)</td>
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<td>15</td>
<td>115 (23)</td>
<td>172 (15)</td>
<td>82-7 (10)</td>
<td>19-5 (3-4)</td>
<td>97-8 (16)</td>
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<tr>
<td>P &lt;0.001</td>
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<td>0.18</td>
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HR, heart rate (bpm); SBP/DBP, systolic/diastolic blood pressures (mm Hg); DP, double product (mm Hg/min x 10^-3); SV, stroke volume (ml); CO, cardiac output (l/min); CPO, cardiac power output (W); PF, peak flow (l/min); PFA, peak flow acceleration (l/s^2); BF, backflow (ml/cycle); FWV, flow wave velocity (m/s).

Abbreviations as given in table 1.

Coronary angiograms were analysed visually without knowledge of magnetic resonance or thallium findings. A significant stenosis was defined as a diameter reduction of more than 50% compared with that of an adjacent normal segment.

STATISTICAL ANALYSIS

The differences in age between the normal volunteers and the patients were analysed using an unpaired t test, and differences of gender using the χ^2 test. The distribution of the number of reversibly ischaemic thallium segments according to the number of diseased coronary arteries was analysed using Spearman’s rank correlation coefficient. The correlation between age and the change from baseline to peak stress in the haemodynamic variables was examined using linear regression analysis. The changes in haemodynamic variables at each stage of dobutamine infusion were analysed using analysis of variance with repeated measures, which treated the dose levels as unordered factors. The relation between the change in haemodynamic variables from baseline to peak stress and the extent of reversible ischaemia was first examined by univariate regression analysis and subsequently by a forward stepwise multiple regression analysis. Comparisons between variables from baseline to peak stress were made using the paired t test. Comparisons between groups with or without a fall in peak flow acceleration were made with the χ^2 test.

Results

MEAN HAEMODYNAMIC VARIABLES IN NORMAL VOLUNTEERS

There were significant rises in heart rate and double product at each stage of dobutamine infusion compared with those at baseline (table 1). There was an increase in systolic blood pressure but no significant change after dobutamine 10 µg/kg/min. There was no significant change in diastolic blood pressure. Stroke volume increased at dobutamine 5 µg/kg/min but thereafter decreased. Cardiac output and power output increased progressively. Peak flow increased significantly to 10 µg/kg/min and there was a substantial and progressive increase in peak flow acceleration. There was no significant change in back flow/cycle but because of the increase in heart rate there was a significant increase in back flow/min. In neither case was there a change in back flow expressed as a proportion of forward flow. There was a small increase in flow wave velocity, although the change failed to reach statistical significance.

MEAN HAEMODYNAMIC VARIABLES IN PATIENTS WITH CORONARY ARTERY DISEASE

The mean haemodynamic response at each level was complicated by the mixture of patients for whom each level was either intermediate or maximal (table 2). Of the 23 patients with reversible ischaemia, 23, 21, 16, and eight patients tolerated 5, 10, 15, and 20 µg/kg/min of dobutamine respectively. There were significant changes in all variables except for diastolic blood pressure. Aortic back flow/beat did not change but back flow/min increased with heart rate.

Because of the different responses at each stage, the mean responses did not differ significantly from those of the volunteers for any variable at any stage of stress, except for flow wave velocity which was significantly greater than normal at dobutamine 20 µg/kg/min. A reduction in some of the variables between
Assessment of magnetic resonance velocity mapping of global ventricular function during dobutamine infusion in coronary artery disease

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Univariate regression analysis of the change in haemodynamic variables against the extent of reversible myocardial ischaemia</th>
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<tr>
<td></td>
<td>HR</td>
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<td>r</td>
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<td>P</td>
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Abbreviations as given in table 1, Dmax, maximum tolerated dobutamine dose.

Table 5 | Forward stepwise multiple regression analysis of the changes in haemodynamic variables from baseline to peak stress against the extent of reversible myocardial ischaemia |
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<tr>
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<td>Regression coefficient</td>
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the penultimate and final stages of stress was however predictive of ischaemia, most significantly peak flow acceleration. A decrease in peak flow acceleration at peak stress was more common with severe (more than four segments) or moderate (three to four segments) ischaemia than with mild ischaemia (one to two segments) or in normal controls (table 3). The two patients who tolerated only 5 μg/kg/min of dobutamine were excluded from this analysis.

Changes in haemodynamic variables from baseline to peak stress
Table 4 gives the results of univariate regression analysis between extent of myocardial ischaemia and change in each haemodynamic variable from baseline and peak stress in patients with CAD. There were significant correlations for peak flow acceleration, peak flow, cardiac power output, maximum dose tolerated, and systolic blood pressure. Forward stepwise linear regression analysis showed that the most significant variable was the change in peak flow acceleration ($F = 32.3$, $r = -0.764$, $P < 0.00001$) which accounted for 58.4% of the variation in the extent of reversible ischaemia (table 5). After allowing for this the only other variable with independent significance was cardiac power output ($F = 4.7$, $P = 0.042$), but its additional contribution to the model was only 4.2% (combined adjusted partial $r^2 = 0.626$).

Figure 8 shows the change in peak flow acceleration plotted against the extent of reversible ischaemia. Although there was a good correlation with the extent of reversible ischaemia, it was not possible in most cases to distinguish patients with mild reversible ischaemia from those without ischaemia.

Side effects of dobutamine infusion
All volunteers tolerated dobutamine 20 μg/kg/min but with a variety of minor symptoms. Only one volunteer had no side effects. Skin tingling, particularly of the scalp, was reported by five participants and thumping in the chest by three. Palpitation was most profound at low doses in keeping with the predominantly inotropic effect of dobutamine at low doses. Premature ventricular contractions occurred in two individuals and premature atrial contractions in one. One reported chest tightness. Other effects included headache (one), nausea (one), and flushing (one).

Twenty one of the 25 patients with CAD developed chest pain. Arrhythmia occurred in 11 patients, mostly premature ventricular contractions (eight patients). Premature atrial contractions occurred in two patients, ventricular bigeminy in two, and ventricular couplets in one. Other side effects included tingling in 14 patients, and nausea, dyspnoea, flushing, and headache in one patient each.

Thallium-201 emission tomography
Reversible ischaemia was demonstrated by thallium tomography in 23 of 25 patients with CAD during dobutamine infusion: 22 of whom had significant CAD. One woman with angina on effort and an abnormal exercise electrocardiogram had unequivocal reversible ischaemia despite normal coronary arteries and syndrome X was subsequently diagnosed. There was a correlation between the extent of the thallium perfusion defect and the number of diseased coronary arteries ($r_s = 0.40$, $P = 0.05$) with the mean (range) number of segments with reversible ischaemia in zero, one, two, and three vessel disease being 1.7 (0–5), 2.3 (1–5), 3.6 (1–7), and 6.3 (5–7) respectively.

Discussion
Magnetic resonance imaging in coronary artery disease
MRI has found useful clinical application in the heart for congenital heart disease, abnormalities of the aorta, and a variety of less common conditions, but there has been little than other than the assessment of resting ventricular function, its present clinical application to CAD is limited. Coronary artery imaging is progressing and the first clinical results are now being reported, while development of MRI of myocardial perfusion is moving into the clinical phase. More work has been performed in the assessment of abnormalities of regional ventricular contraction during stress and good correlation with 201TI imaging has been shown, but there has been little study of the variables of global ventricular function during stress with MRI. This is the first study to apply high temporal resolution velocity mapping for measurement of aortic acceleration.

In this study, MRI of normal individuals established that the technique was feasible and yielded data on the normal responses to dobutamine infusion (table 1). Most of the measured variables increased incrementally with increasing doses of dobutamine, with the...
main exceptions of diastolic blood pressure which was unchanged, systolic blood pressure which rose to a plateau, and stroke volume which rose and then declined. The group response of patients with CAD did not show significant differences from these results because of the variable dobutamine dose tolerated. Therefore, analysis of the change from baseline to peak stress for each variable was more useful, and correlation was performed with the extent of ischaemia, because greater changes in global ventricular function would be expected in those with greatest ischaemia. This analysis showed that peak flow acceleration was the variable most closely correlated with the extent of reversible myocardial ischaemia. In addition, when peak flow acceleration decreased despite an increasing dose of dobutamine, moderate or severe ischaemia was likely to be present. While other variables were predictive of ischaemia by themselves (peak flow, cardiac power output, maximum dobutamine dose, and systolic blood pressure), their significance was low or none in the multiple regression model after acceleration was introduced. There was an inverse relation between the increase in peak flow acceleration during stress and the extent of ischaemia (fig 8), which suggested that severity of the abnormality may be graded, but there was significant scatter and overlap between the normal response and that of mild ischaemia. This suggests that acceleration may be insensitive to low level ischaemia.

ANIMAL STUDIES OF AORTIC ACCELERATION

Acceleration of aortic flow is generated by ventricular contraction and is related to the velocity of myocardial shortening, which is a variable reflecting myocardial contractility. Canine aortic flow studies show that while inotropic stimulation increases peak flow, acceleration, and the rate of rise of left ventricular pressure, the largest rise occurs in acceleration, and that larger decreases in maximum acceleration occur with an earlier onset than in other variables demonstrating abnormalities when regional ischaemia is induced. Similar results have been obtained using other interventions to alter contractility. Doppler echocardiography has been used to show that peak aortic acceleration is more closely related to the extent of myocardial ischaemia in dogs than ejection fraction, peak velocity, and stroke volume. The results of our study are in accord with these animal data.

PREVIOUS STUDIES OF AORTIC FLOW ACCELERATION DURING STRESS IN HUMANS

Doppler echocardiography in normal controls shows that velocity and acceleration increase with exercise, although acceleration is less dependent on postural changes. Peak acceleration during dynamic exercise in patients with CAD is more closely correlated than peak velocity or systolic velocity integral with the presence of reversible ischaemia demonstrated either from the electrocardiogram or thallium images. Changes in peak velocity and mean acceleration during isometric stress have also been shown to correlate with the severity of angiographic CAD. Other exercise studies have not measured acceleration. There are practical difficulties in measuring aortic flow during dynamic exercise, however, and pharmacological intervention has been attempted. During dipyridamole infusion, differentiation of patients with CAD from normal individuals using peak acceleration has been reported, but the results have not been reproduced. The fact that dipyridamole vasodilatation does not always induce myocardial ischaemia in patients with CAD suggests that it may not be as reliable as dobutamine for provoking functional abnormalities. There are very few studies of Doppler echocardiography during dobutamine infusion for the assessment of aortic flow. Studies of normal participants and patients after myocardial infarction have documented increases in velocity and maximum acceleration during dobutamine infusion, but the relation of these changes to the extent of reversible ischaemia has not previously been studied.

COMPARISON WITH OTHER MEASURES OF VENTRICULAR FUNCTION

The left ventricular ejection fraction measured by radionuclide ventriculography is commonly used to separate ischaemic and normal responses to exercise, and extensive ischaemia leads to larger decreases in ejection fraction. Velocity mapping is unable to determine the ejection fraction, but peak flow acceleration and ejection fraction are correlated and both show an increase with stress and a decline with the onset of ischaemia. Like ejection fraction, depression of resting peak aortic acceleration after myocardial infarction is associated with a poor prognosis. In an invasive haemodynamic study during dobutamine infusion in CAD, stroke volume was the best variable for detecting ischaemia, but acceleration was not measured. The stroke volume rose in patients without ischaemia, but rose and then decreased in those with ischaemia. In our study, stroke volume rose significantly at dobutamine 5 μg/kg/min in normal controls and patients with CAD, but thereafter it decreased in each group such that it was below the baseline level at 15 and 20 μg/kg/min. It is difficult to explain this difference and both studies were conducted with the patient supine. Others, however, have also shown that stroke volume is an insensitive measure of ischaemia.

AORTIC BACK FLOW AND FLOW WAVE VELOCITY DURING STRESS

These two variables have been little studied during stress for a possible role in the assessment of CAD. Aortic back flow is normally directed towards the left and right coronary sinuses with approximately 70% towards the left and may be important for coronary flow. Back flow is reduced and often directed towards the non-coronary sinus in CAD.
Back flow is much greater than coronary flow and the majority recirculates in the ascending aorta. Coronary flow increases during stress but our finding that back flow does not increase during stress suggests that changes in back flow are unlikely to be directly related to coronary flow, because of the large back flow recirculation. Aortic flow velocity is a measure of the speed of propagation of the flow and pressure waves. It is influenced by compliance of the wall and hence it is increased in a stiff vessel such as those found with increasing age and in patients with CAD. Our results indicate that flow wave velocity is not helpful in the assessment of myocardial ischaemia, although there was a small difference between normal volunteers and patients with CAD at dobutamine 20 µg/kg/min. This difference may be related to either higher systolic blood pressure in patients with CAD or differences in β receptor density after previous β blockade.

COMPARISON OF MRI WITH OTHER MEASUREMENT TECHNIQUES

MRI and Doppler echocardiography do not measure exactly the same variables. MRI measures flow directly with simultaneous area and mean flow measurements of the vessel, while Doppler yields a velocity distribution from which flow may be estimated. Differences in the results between the techniques are therefore to be expected. One advantage of MRI is no limitation by acoustic windows. The temporal resolution of these two techniques is comparable (MRI 6 ms v echocardiography 4 ms). MRI may be directly sensitised to acceleration rather than velocity, but this considerably lowers temporal resolution. MRI has much higher resolution and lack of ionising radiation than radionuclide ventriculography. The present disadvantages of MRI include lack of accessibility, expense, and duration of the study, though fast imaging sequences will lead to improvement.

LIMITATIONS OF THIS STUDY

This feasibility study of MRI for the assessment of global ventricular function during stress shows potential, but any clinical application would require further research. There is controversy over the dependence of acceleration on preload, afterload, and other haemodynamic variables which might confound its use clinically. Early studies suggested that peak acceleration was relatively insensitive to preload and afterload but this has not been confirmed. Other markers of global ventricular function, however, such as ejection fraction, are also dependent on loading conditions and this has nevertheless found widespread clinical use.

The effect of age on peak acceleration may also interfere with interpretation. Resting peak acceleration in the ascending aorta decreases with age, probably as the aorta dilates, although most change occurs early in life and there are wide confidence intervals for the mean values. Peak acceleration during exercise also declines with age, however, and thus reasonably stable values of the change between rest and stress might be expected. Although this study is not sufficiently large to confirm this, no relation could be demonstrated between age and change in peak flow acceleration in normal controls.

The control group used in this study was less than ideal because of the relatively limited investigations regarding the absence of coronary artery disease other than history and examination. Any covert ischaemia would be expected to dilute the differences observed between patients and normal controls. Comparison between controls and patients was associated with low statistical power because of the small number of normal volunteers. In addition, segmental analysis of ischaemia used in multiple regression analysis hindered interpretation of the predictive value of the haemodynamic variables, and there was considerable variation in the change in peak flow acceleration compared with that in the extent of ischaemia. It is important to note, however, that this study was primarily designed to investigate the feasibility of aortic flow imaging during dobutamine stress as a new technique, and while the promising results do not suggest that such a test could be used clinically at present, they are sufficiently encouraging to indicate that further more refined studies might be rewarding.

Victor Aber, statistician at the Medical Research Council, and Roger A Herr at the Royal Marsden Hospital advised on the statistical methods used. We thank Marjorie Watson, Elizabeth Burman, and Permi Jhooti for general support. This study was conducted with the aid of grants from The Medical Research Council, London, UK, The Coronary Artery Disease Research Association, London, UK, and Amersham International plc, Buckinghamshire, UK.


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