JACC Vol. 19, No. 2
February 1992:297–306

METHODS

Quantification of Left Ventricular Performance During Transient Coronary Occlusion at Various Anatomic Sites in Humans: A Study Using Tantalum-178 and a Multiwire Gamma Camera

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To study the functional significance of transient coronary occlusion on systolic and diastolic left ventricular function relative to the anatomic site of occlusion, first-pass radionuclide angiography with a mobile multiwire gamma camera using tantalum-178 (dose activity ≤84 mCi/elution) was performed in 46 patients undergoing balloon coronary angioplasty. First-pass images were acquired immediately before angioplasty and during the last 30 s of a 60-s balloon inflation in 23 left anterior descending arteries, 18 right coronary arteries, 8 circumflex arteries and 3 diagonal coronary arteries.

Occlusion of the left anterior descending artery resulted in significant decreases in left ventricular ejection fraction (54.6 ± 12.7% to 32.3 ± 10.6%, p = 0.0001) and peak filling rate (2.48 ± 0.68 to 1.75 ± 0.64 end-diastolic volumes/s, p = 0.0001), accompanied by severe abnormalities in regional function and left ventricular dilation. Right coronary artery occlusion caused inferior hypokinesia, but did not significantly change left ventricular ejection fraction (48.5 ± 12.4% vs. 45.8 ± 12.5%, p = NS) or peak filling rate (2.05 ± 0.81 vs. 2.09 ± 0.81 end-diastolic volumes/s, p = NS). Circumflex artery occlusion resulted in mild wall motion deterioration and a borderline decrease in ejection fraction (54.7 ± 11.4% to 50.5 ± 12%, p = 0.057). Diagonal artery occlusion did not cause significant changes in left ventricular ejection fraction or filling rate. The decrease in left ventricular ejection fraction during coronary occlusion was 9 ± 25% and 27 ± 22%, respectively, in those arteries with and without collateral supply (p = 0.052).

These data provide strong evidence for the critical importance of the left anterior descending artery and the secondary role of the other coronary arteries in maintaining global systolic and diastolic left ventricular function and suggest a protective role of collateral vessels during coronary occlusion.

(J Am Coll Cardiol 1992;19:297–306)

Transient interruption of coronary blood flow by an inflated balloon during percutaneous transluminal coronary angioplasty affords an unparalleled in vivo model to study the effects of acute ischemia on ventricular function in humans. Gated radionuclide angiography, an inherently three-dimensional technique, is the standard of excellence for the noninvasive assessment of ventricular performance. However, it has not been used during angioplasty because the excessive time (minimum 2 to 2.5 min) required for acquisition of blood pool radionuclide angiography is clearly incompatible with the brief (typically 30 to 60 s) occlusions ordinarily performed during angioplasty. First-pass radionuclide angiography, which temporally separates the two ventricles, is an ideal technique for assessing rapid changes in left and right ventricular function but until recently, its use required a multicrystal gamma camera for rapid count acquisition. The traditional multicrystal camera (Baird System 77) was bulky, not portable and, even with the recent system modifications that have made it relatively mobile, it is still difficult if not impossible to use in most cardiac catheterization laboratories.

An alternative instrument for first-pass radionuclide angiography is the multiwire camera, developed by one of us (J.L.L.) and validated in our laboratory (1,2). This system, when used in combination with tantalum-178, a radionuclide with a short half-life (9.3 min), acquires images of high count statistics and improved resolution, thus allowing accurate quantitative assessment of global and regional ventricular function. Its recent packaging into a compact, mobile, fully integrated unit has made it an ideal means of studying the rapid changes in left ventricular function resulting from

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Manuscript received May 13, 1991; revised manuscript received July 10, 1991, accepted July 23, 1991.

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0735-1097/92/$5.00

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coronary artery occlusion by a balloon catheter during angioplasty.

Because most previous investigations on the effects of coronary inflation during angioplasty have studied relatively few patients, a differential effect on ventricular function with respect to the anatomic site of coronary occlusion has not been convincingly demonstrated. Such information would be valuable not only in understanding the relative contribution of each of the coronary arteries to overall left ventricular function, but also in predicting the expected degree of ventricular dysfunction that would ensue if a given coronary artery were permanently occluded, either iatrogenically as a complication of angioplasty or spontaneously through plaque fissuring and thrombus formation. Accordingly, the purpose of our investigation was to quantify the changes in systolic and diastolic left ventricular function, both global and regional, during transient coronary occlusion at various anatomic sites during angioplasty.

Methods

Study patients. This investigation was approved by the Baylor College of Medicine and The Methodist Hospital Institutional Review Boards for Human Research. All patients provided written informed consent. Forty-six patients (35 men and 11 women) ranging in age from 35 to 78 years (mean 58.5 ± 10.7) were studied. All had a history of angina pectoris of relatively recent onset (mean ± SD 2.4 ± 1.5 weeks). Sixteen patients had had a myocardial infarction 1 to 204 weeks (mean 44 ± 70) before angioplasty. No patient in this series had prior coronary artery bypass graft surgery and none had angioplasty of a totally occluded artery. Coronary angiography performed 1 to 8 days before angioplasty showed significant stenoses (defined as >50% lumen diameter stenosis) in all patients. Single-vessel disease was present in 29 patients, double-vessel disease in 12 and triple-vessel disease in 5. Forty-three patients underwent single-vessel angioplasty. One patient underwent angioplasty of the left anterior descending, right coronary and left circumflex arteries; one additional patient had angioplasty of the left anterior descending and circumflex arteries. Finally, one patient underwent sequential angioplasty procedures in the proximal and mid portions of the left anterior descending artery followed by angioplasty of the right coronary artery. The right coronary artery was dominant in all patients who underwent angioplasty of this artery. Forty-five patients were receiving one or more antianginal medications: a calcium channel blocking agent in 35, nitrates in 30 and a beta-adrenergic blocking agent in 18. Thirty-two patients used two or more drugs and 13 took one of these drugs. With the exception of sublingual nitroglycerin, all medications were withheld on the day of angioplasty.

Patient preparation. Without premedication, percutaneous transluminal coronary angioplasty was performed through a femoral artery approach. Patients were monitored during the procedure with a three-lead electrocardiogram (ECG) (leads I, aVL and aVF). Continuous recordings of the ECG were obtained throughout each coronary inflation. A 9F arterial sheath was introduced percutaneously into the femoral artery and subsequently used for the angioplasty procedure. A 7F sheath was introduced into the femoral vein. Heparin (10,000 U) was given intravenously after insertion of the sheaths. The coronary artery undergoing angioplasty was initially opacified in multiple views. A steerable guiding catheter was advanced to the ostium of the left or right coronary artery and an appropriately sized (2.5- to 3.5-mm) balloon catheter introduced over the guide wire. After positioning of the catheter across the stenosis, the balloon was inflated at a pressure ranging from 4 to 10 atm for 60 s. Most patients underwent two to four dilations. Arterial blood pressure was monitored at the tip of the guiding catheter during the balloon inflation.

First-Pass Radionuclide Angiography

Tantalum-178 generator. First-pass radionuclide angiography was performed by administering 20 to 84 mCi of generator-produced tantalum-178 in a total volume of 1.2 ml as a bolus injection into the venous sheath and rapidly flushing with 20 ml of 5% glucose in water. The total activity obtained from the tungsten-178/tantalum-178 generator during each elution was injected each time. The variability in doses depended on the generator's yield, which decreased in proportion to the half-life of the tungsten-178 parent isotope (half-life 21.7 days). The yield was also dependent on the time since the previous elution and asymptotically approached the maximal level with a half-life of 9.3 min (that is, in 9.3 min, the yield was 50% of maximum and in 18.6 min, the yield was 75% of maximum). The total body radiation exposure per mCi of tantalum-178 injected was 0.53 mrem or 5% of that produced by 1 mCi of technetium-99m pertechnetate. The critical organ was the bladder, which received a dose of 6 mrem/mCi, also 5% of that of technetium-99m.

We previously described the tungsten-178/tantalum-178 generator in detail (3). Recent advances include packaging the system into a radiation-shielded and temperature-controlled case, with a total weight of 48 kg and external dimensions of 52 × 32.5 × 30 cm. This generator was taken to the catheterization laboratory on a wheeled cart for on-site elutions as needed. Elution was initiated by pushing an external button located in the generator's external frame. The buffered eluate in a volume of 1.2 ml was automatically collected in an external syringe preinserted into the shielded output port containing a sealed septum. The elution was completed in 20 s and the tantalum-178 was promptly assayed in an external dose calibrator.

Multiwire gamma camera. The multiwire gamma camera has been previously described in detail (1,2). The multiwire detector is functionally identical to the one previously used by our group, but it has recently been mounted on an extensible telescoping arm with a maximal horizontal extension of 100 cm, greatly facilitating positioning from either

Table 1. Global Left Ventricular Function During Baseline Study and Left Anterior Descending Coronary Artery Occlusion in 23 Cases

	LVEF (%)		PER (EDV/s)		PFR (EDV/s)		EDVI		SVI		COI	
	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl
LAD (all)	54.6 ± 12.7	32.3 ± 10.6	2.66 ± 0.65	1.53 ± 0.43	2.48 ± 0.68	1.75 ± 0.64	354 ± 102	421 ± 119	187 ± 39	131 ± 45	14.4 ± 3.5	10.7 ± 3.3
(n = 23)	p = 0.0001		p = 0.0001		p = 0.0001		p = 0.0087		p = 0.0001		p = 0.0001	
LAD (prox)	53.4 ± 15.2	26.6 ± 9.5	2.63 ± 0.81	1.31 ± 0.38	2.41 ± 0.64	1.64 ± 0.6	357 ± 122	421 ± 126	182 ± 46	107 ± 38	14.6 ± 3.7	9.2 ± 2.8
(n = 10)	p = 0.0001		p = 0.0001		p = 0.0012		p = 0.070		p = 0.0003		p = 0.0017	
LAD (mid)	55.6 ± 11	36.6 ± 9.5	2.69 ± 0.54	1.7 ± 0.4	2.53 ± 0.73	1.84 ± 0.67	351 ± 88	421 ± 118	190 ± 34	150 ± 42	14.3 ± 3.5	11.8 ± 3.3
(n = 13)	p = 0.0001		p = 0.0001		p = 0.0019		p = 0.067		p = 0.0038		p = 0.0095	

Cardiac output index (COI), end-diastolic volume index (ENDI) and stroke volume index (SVI) are expressed in arbitrary units. Base = baseline; EDV = end-diastolic volume; LAD = left anterior descending artery; LVEF = left ventricular ejection fraction; mid = middle; Occl = occlusion; PER = peak ejection rate; PFR = peak filling rate; prox = proximal.

side of the patient's bed. The detector is capable of being manually rotated 180° in the horizontal and vertical directions. The large dimension (25 × 25 cm^2 for the useful field of view) coupled with light weight and mobility of the detector facilitated positioning and ensured that the heart was well inside the field of view.

An on-board 16-MHz/80286 microcomputer with a 640 × 480-pixel color display system was used for image acquisition, processing and display. A digitized ECG provided ECG gating.

Image acquisition. Baseline first-pass radionuclide angiography was acquired in all patients in the anterior view using a 32 × 32-pixel by 16-bit matrix and a time resolution of 25 ms/frame approximately 10 min after insertion of the intravascular sheaths and before placing of the guiding catheter. The detector was subsequently moved away from the patient's chest and the angioplasty catheter was inserted. The location of the balloon across the coronary stenosis was verified by small injections of contrast medium during fluoroscopy and a first inflation performed for 60 s was followed by balloon deflation. Without moving the balloon, guiding catheters or the table, the cine camera was moved away from the patient's chest and the multiwire detector was repositioned in the anterior view for the occlusion study approximately 5 min after the first inflation. Acquisition commenced 30 s after balloon inflation, simultaneously with the intravenous bolus injection of tantalum-178 and continued for 30 s. The entire procedure from beginning of the elution of the generator to completion of each acquisition required only 60 to 90 s.

Image processing. Image processing of first-pass radionuclide angiography with our system has been previously described in detail (1). Recent improvements in software now allow processing of the left ventricular phase in approximately 5 min with a minimum of operator input. Briefly, the processing steps are as follows. The computer provides cinematic display of the first transit of tantalum-178 through the heart. A vena caval region of interest is drawn by the operator and the computer plots a time-activity histogram of this region of interest, from which the adequacy of the bolus injection can be checked (<1 s transit time is adequate). The operator then selects a frame in the middle of the left ventricular phase and draws an approximate left ventricular region of interest, which is utilized by the computer to select the beats to be combined into a representative cycle. The operator then selects a frame in the middle of the right ventricular phase and draws an approximate right ventricular region of interest. These regions are utilized by the computer to select the beats to be combined into the representative right ventricular cycle and normalize and subtract the pulmonary background frame according to a previously described procedure (1). The end-diastolic frame is displayed in expanded format with overlaid phase mask and ventricular borders.

The operator then traces the left ventricular region of interest utilizing the phase mask to define the valve planes and the ventricular border. The phase mask is color-coded and sharply demonstrates the difference in phase between the atria and the ventricles. The border of the phase shift is used as the border of the atrioventricular valves. Finally, the operator marks the long axis of the left ventricle (from the mid portion of the aortic valve plane to the apex), which is used for volume calculations and as a reference for the regional analysis. The left ventricle is automatically divided by the computer into six segments: inferobasal, inferoapical, apical, anteroapical, anterolateral and anterobasal. Time-activity and flow curves for the entire ventricle and its six segments are then generated by the computer. From these curves, the global and regional ejection fraction as well as the peak ejection rate and peak diastolic filling rate (both normalized to the end-diastolic volume) are automatically computed. This type of segmental ventricular function analysis is obviously count-based and only partially depends on the wall motion depicted in the cinematographic display of the radionuclide angiogram. Left ventricular volumes were calculated by the computer using the area-length method (4,5). Because a calibration factor has not as yet been validated for this system, the volumes are only relative and were expressed as volume indexes in arbitrary units. Likewise, the cardiac output index was expressed as the product of the stroke volume index times the heart rate (also in arbitrary units).

Image display. Left ventricular cinematic images were displayed side by side on the computer's high resolution, large (29 × 25 cm^2) color screen for visual analysis of wall motion. In addition, automatic display of a color-coded

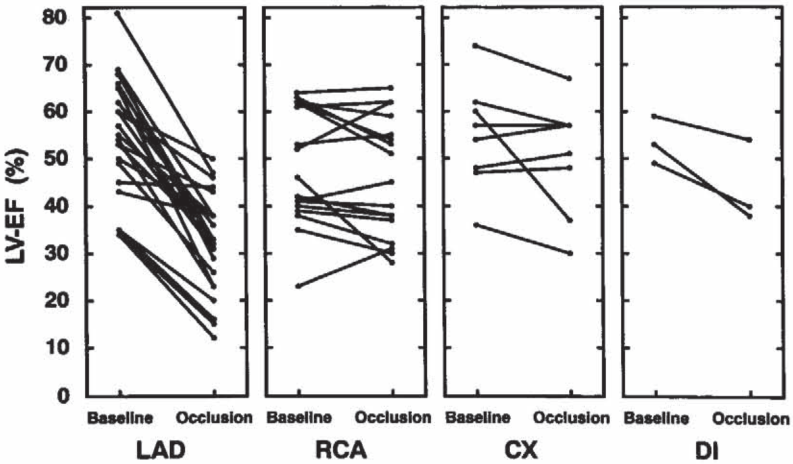

Figure 1. Change in left ventricular ejection fraction (LV-EF) for each patient. Note the significant ($p < 0.0001$) decreases in left ventricular ejection fraction during left anterior descending (LAD) artery occlusion, but not during occlusion of the left circumflex (CX), diagonal (DI) or right (RCA) coronary arteries.

regional ejection fraction image, depicting the ejection fraction for each left ventricular pixel, facilitated analysis of segmental ventricular function. In this regional ejection fraction image, each color corresponded to a certain value of ejection fraction as follows: 0% to 10%, dark blue; 11% to 20%, light blue; 21% to 30%, gray; 31% to 40%, green; 41% to 50%, yellow; 51% to 60%, orange; 61% to 70%, red; 71% to 80%, violet; 81% to 90%, purple; 91% to 100%, white.

Effect of collateral circulation on left ventricular function during coronary occlusion. The presence and quality of collateral circulation to the artery undergoing angioplasty were graded in the preangioplasty angiogram by an independent expert angiographer, who had no knowledge of the radionuclide angiographic results, as follows: 0 = no collateral vessels, 1+ = visible collateral vessels but without opacification of the artery distal to the angioplasty site, 2+ = faint opacification of the stenosed artery and 3+ = bright opacification comparable to that of the arterial segment proximal to the stenosis.

Reproducibility of radionuclide angiography variables. The intraobserver reproducibility of ejection fraction, peak ejection rate and peak diastolic filling rate was assessed by having an experienced observer reprocess 63 first-pass acquisitions an average of 4 months after the original processing. Interobserver reproducibility was assessed by having a second experienced observer independently process all of the studies.

Statistical analysis. Comparisons of variables with normal distribution at baseline and during coronary occlusion were done by Student's paired *t* tests for comparisons within each group and by unpaired *t* tests for comparisons between groups. Data without normal distribution were analyzed by the Wilcoxon signed-rank test. Intra- and interobserver reproducibility were tested by linear regression. The data are presented as mean values ± SD. A p value <0.05 was considered significant.

Results

Hemodynamics during acute coronary occlusion. During transient, brief coronary occlusion, a mild decrease in systolic blood pressure (from 128 ± 24 to 117 ± 21 mm Hg, $p < 0.01$), increase in diastolic blood pressure (71 ± 11 to 82 ± 12 mm Hg, p = 0.0001) and no change in heart rate (76 ± 13 to 77 ± 12 beats/min, p = NS) occurred.

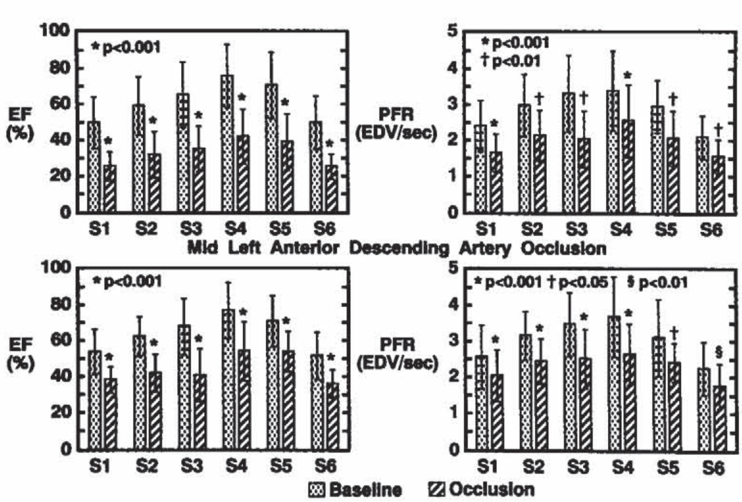

Figure 2. Regional changes in left ventricular function during occlusion of the left anterior descending coronary artery at the proximal (**upper panels**) and mid (**lower panels**) locations. EDV = end-diastolic volume; EF = ejection fraction; PFR = peak diastolic filling rate; S1 to S6 = the inferobasal, inferoapical, apical, anteroapical, anterolateral and basal segment, respectively. p values compare values at baseline with those during occlusion.

Table 2. Global Left Ventricular Function During Baseline Study and Right Coronary Artery Occlusion in 17 Cases

	LVEF (%)		PER (EDV/s)		PFR (EDV/s)		EDVI*		SVI*		COI*	
	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl
RCA (all)	48.5 ± 12.4	45.8 ± 12.5	2.35 ± 0.71	2.3 ± 0.69	2.05 ± 0.81	2.09 ± 0.83	353 ± 73	389 ± 94	169 ± 43	174 ± 48	12.9 ± 3.7	12.9 ± 3.5
(n = 17)	p = 0.145		p = 0.624		p = 0.786		p = 0.086		p = 0.588		p = 0.918	

*Expressed in arbitrary units. RCA = right coronary artery; other abbreviations as in Table 1.

Anatomic sites of coronary angioplasty. Studies were obtained during occlusion of the left anterior descending artery in 23 patients (proximal to the first diagonal branch in 10, between the first and second diagonal branches in 12 and distal to the second diagonal branch in 1), during circumflex artery occlusion in 8 patients (3 in the circumflex trunk and 5 in the first obtuse marginal branch) and during right coronary artery occlusion in 17 patients (7 in the proximal artery before the origin of the right ventricular acute marginal branch and 10 distal to the marginal branch). Angioplasty of the first diagonal branch of the left anterior descending artery was performed in three patients.

Left anterior descending artery occlusion (Table 1). Occlusion of the left anterior descending artery caused significant deterioration of global systolic and diastolic left ventricular function, an increase in end-diastolic volume index and a decrease in stroke volume and cardiac output indexes. These changes were generally more severe during occlusion of the proximal artery, which caused a decrease of approximately 50% in left ventricular ejection fraction (Fig. 1).

Although not as striking as that in the proximal artery, occlusion of the mid anterior descending artery also caused substantial deterioration of left ventricular function. In a few cases, the decrease in left ventricular ejection fraction was greater during occlusion of the mid than of the proximal artery. The deterioration of left ventricular function was almost universal, but in a few patients it was only mild or even absent.

During left anterior descending artery occlusion, significant deterioration of segmental systolic and diastolic left ventricular function occurred. Somewhat surprisingly, this deterioration affected not only the apical and anterolateral segments, but also to a lesser degree the inferior segments (Fig. 2).

Right coronary artery occlusion (Table 2). There was only a minimal statistically insignificant decrease in global ventricular systolic functional variables during right coronary artery occlusion. Specifically, left ventricular ejection fraction did not change significantly (Fig. 1). Occlusion of the proximal right coronary artery tended to cause a greater decrease in left ventricular ejection fraction than did occlusion of the mid artery, but neither was statistically significant.

Right coronary artery occlusion caused only a slight decrease in inferoapical and anteroapical segmental ejection fraction (Fig. 3). No significant changes occurred in regional diastolic left ventricular function.

Left circumflex artery occlusion (Table 3). Occlusion of the left circumflex artery caused a statistically significant albeit modest decrease in global left ventricular ejection fraction and peak diastolic filling rate (Fig. 1). No significant changes occurred in left ventricular volume indexes.

Occlusion of the circumflex artery caused a significant decrease in anteroapical and anterolateral regional ejection fraction and a borderline ($p = 0.055$) decrease in apical ejection fraction (Fig. 4). The changes in regional peak diastolic filling rate were not statistically significant.

Diagonal artery occlusion (Table 4). During occlusion of the first diagonal branch of the left anterior descending artery, changes in global systolic and diastolic left ventricular function were not statistically significant. However, all three patients with such occlusion had a ≥5-unit decrease in left ventricular ejection fraction during occlusion and one of the three had a substantial reduction in global left ventricular ejection fraction (from 53% at baseline to 38% during occlusion) (Fig. 1). A significant increase in left ventricular volume index occurred during diagonal artery occlusion.

A significant decrease in anterolateral, anteroapical, apical, inferoapical and basal segmental ejection fraction occurred during diagonal artery occlusion, accompanied by a mild (not significant) decrease in segmental filling rates (Fig. 5).

Severity of ventricular dysfunction versus anatomic site of coronary occlusion. Patients were further categorized with respect to the magnitude of the decrease in global ejection fraction into those with a severe (>10 units), moderate (6 to

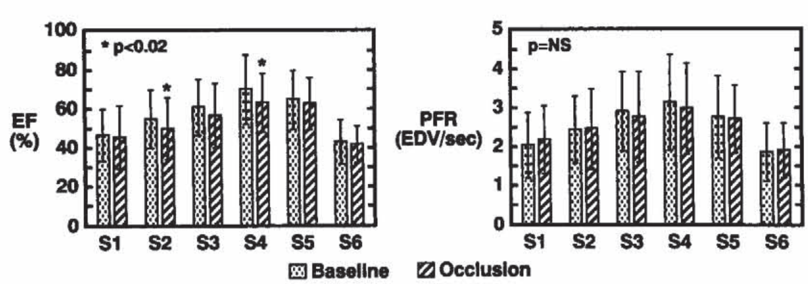

Figure 3. Regional changes in left ventricular function during right coronary artery occlusion. Changes in ejection fraction in segments 2 and 4 were significant ($p < 0.02$). Changes in diastolic function were not significant. Abbreviations as in Figure 2.

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Table 3. Global Left Ventricular Function During Baseline Study and Circumflex Coronary Artery Occlusion in Eight Cases

	LVEF (%)		PER (EDV/s)		PFR (EDV/s)		EDVI*		SVI*		COI*	
	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl
LCx (all)	54.7 ± 11.4	50.5 ± 12	2.78 ± 0.54	2.43 ± 0.59	2.3 ± 0.93	2.38 ± 0.97	342 ± 56	386 ± 119	188 ± 45	191 ± 58	14 ± 3.5	13.8 ± 4.9
(n = 8)	p = 0.203		p = 0.045		p = 0.65		p = 0.230		p = 0.687		p = 0.761	

*Expressed in arbitrary units. LCx = left circumflex coronary artery; other abbreviations as in Table 1.

10 units) and mild (0 to 5 units) reduction, which occurred in 82%, 9% and 9% of patients, respectively, during left anterior descending artery occlusion; 11%, 24% and 65%, respectively, during right coronary artery occlusion and 12%, 23% and 65%, respectively, during circumflex artery occlusion. The frequency of a significant decrease in ejection fraction was greater during left anterior descending artery than during right coronary artery or circumflex artery occlusion ($p < 0.001$). Examples of radionuclide angiograms during baseline study and occlusion of the proximal left anterior descending artery and right coronary artery are illustrated in Figures 6 and 7, respectively.

Relation between systolic and diastolic left ventricular function. For the group as a whole, there was a good correlation between left ventricular ejection fraction and peak diastolic filling rate both at baseline study (ejection fraction 0.256 + 0.118 peak filling rate, $r = 0.73$, $p < 0.0001$) and during coronary occlusion (ejection fraction 0.146 + 0.130 peak filling rate, $r = 0.75$, $p < 0.0001$). Good correlation between ejection fraction and peak diastolic filling rate was also present during baseline study and during coronary occlusion in patients who underwent angioplasty of the left anterior descending artery ($r = 0.74$ and 0.76, respectively) or other coronary arteries ($r = 0.75$ and 0.76, respectively).

Reproducibility of radionuclide angiographic variables (Table 5). Excellent intra- and interobserver reproducibility were found for ejection fraction, peak ejection rate and peak diastolic filling rate.

Effect of collateral circulation on left ventricular function during coronary occlusion. Collateral vessels to the arteries subjected to angioplasty were present in 11 patients and were considered qualitatively good (grade II or III) in 4 and fair or poor (grade I) in 7. The percent stenosis was 91 ± 5% in arteries with collateral vessels compared with 81 ± 8% in those without collateral vessels ($p = 0.0002$). The decrease in left ventricular ejection fraction during coronary occlusion was 9 ± 25% in those with and 27 ± 22% in those without collateral vessels ($p = 0.052$).

Discussion

Advantages of the multiwire camera and tantalum-178. Transient coronary occlusion by the inflated balloon during angioplasty is an excellent model for ascertaining the effects of abrupt cessation of coronary flow on ventricular function in humans. In the present investigation, we used a new instrument, the mobile multiwire gamma camera, to study the effects of transient coronary flow interruption on global and regional left ventricular function during occlusion of each of the major coronary arterial branches. The high count rate of the multiwire camera (1,2), coupled with the use of the radionuclide tantalum-178, allows accurate assessment of global and regional ventricular function (1,2,6). Intrinsic to the first-pass technique is the temporal separation between the right and left hearts, which permits analysis of the left and right ventricular phases without overlap between the two ventricles. Acquisition of first-pass images with this instrument requires little time (30 s), allowing the study to be done conveniently and with minimal procedural disturbance during the brief duration of coronary occlusion by the inflated balloon.

Changes in global left ventricular function during occlusion of the left anterior descending coronary artery. The major finding of our investigation was that transient occlusion of the left anterior descending artery, especially in its proximal portions, severely impaired global and regional left ventricular function, whereas occlusion of all other coronary arteries caused regional deterioration but only minor and inconsistent changes in global left ventricular function. Severe ejection fraction deterioration (>10 units) occurred in the great majority (82%) of patients during left anterior descending artery occlusion, but in only 11% and 12% of patients

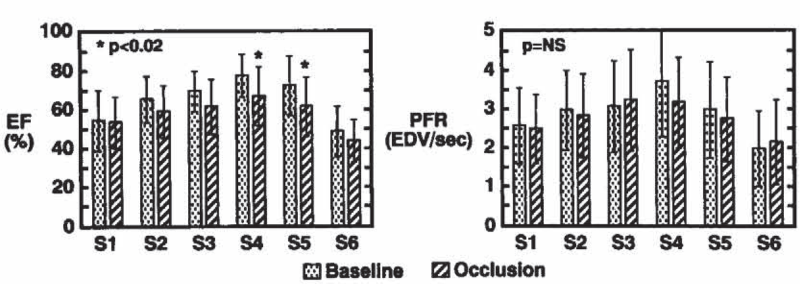

Figure 4. Regional changes in left ventricular function during left circumflex artery occlusion. Changes in ejection fraction were significant in segments 4 and 5 ($p < 0.02$) and borderline in segment 3 ($p = 0.055$). Changes in diastolic function were not significant. Abbreviations as in Figure 2.

Table 4. Global Left Ventricular Function During Baseline Study and Diagonal Coronary Artery Occlusion in Three Cases

	LVEF (%)		PER (EDV/s)		PFR (EDV/s)		EDVI*		SVI*		COI*	
	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl	Base	Occl
Diag (all)	53.6 ± 5	44 ± 8.7	2.5 ± 0	2.1 ± 0.34	2.1 ± 0.35	2 ± 0.75	253 ± 97	322 ± 92	136 ± 51	140 ± 30	9.5 ± 2	10.4 ± 1.5
(n = 3)	p = 0.079		p = 0.183		p = 0.549		p = 0.0056		p = 0.842		p = 0.630	

*Expressed in arbitrary units. Diag = diagonal coronary artery; other abbreviations as in Table 1.

during right coronary artery and circumflex artery occlusion, respectively. These findings are consistent with our previous report (7), which demonstrated large perfusion defects during exercise thallium-201 tomography in patients with isolated left anterior descending artery stenosis in contrast to the smaller defects typically seen in patients with isolated right coronary artery or circumflex artery stenosis.

Moderate left ventricular dilation also occurred during left anterior descending artery occlusion, accompanied by a decrease in left ventricular stroke volume and cardiac output indexes. Our current software uses the area-length method to estimate ventricular volumes. Because we did not have a validated calibration coefficient (for size magnification), the volumes were relative, not absolute. Other methods have been used for volume measurements by radionuclide angiography, including count-based techniques that are substantially affected by count attenuation and scatter. Nonetheless, these findings are consistent with our previous observations (8) of very early left ventricular dilation in patients with acute anterior infarction.

Changes in peak diastolic filling rate paralleled the changes in systolic function, with a greater decrease occurring in patients with left anterior descending artery occlusion. These observations are also in keeping with our previous reports on the interdependence of the left ventricular ejection fraction and peak diastolic filling rate in patients with acute myocardial infarction (8), as well as during experimental coronary occlusion in dogs (9). Because we normalized the peak filling rate to the end-diastolic volume, which increased during occlusion, the actual changes in absolute peak filling rate (in ml/s) may have been less than the changes in normalized filling rate.

Several investigators (10–18) have assessed the alterations in global and regional left ventricular function during balloon inflation using two-dimensional echocardiography or contrast angiography. These investigators have predominantly studied patients undergoing angioplasty of the left anterior descending artery. Likewise, ECG (10,11,14,19–22), hemodynamic (15,17,22–26) and metabolic changes produced by transient coronary occlusion (15) have been previously investigated. Ischemic changes commence within a few seconds of coronary inflation, reach a maximum within 30 to 50 s (14,27) and develop in a predictable pattern, beginning with diastolic followed by systolic function abnormalities, ischemic ECG changes and chest pain (10,11, 15,17), which occurs in 33% to 70% of patients (10,12,14,18–20,28). Both the pattern and time course of the ventricular functional abnormalities are in keeping with the changes observed in dogs during experimental coronary occlusion (29,30). Because these investigations without exception have focused on patients undergoing angioplasty of the left anterior descending coronary artery, these findings cannot be extrapolated to occlusion of other coronary arteries.

Changes in regional function during left anterior descending artery occlusion. In the present investigation, occlusion of the left anterior descending artery caused an expected deterioration in anterolateral and apical regional function. Similar findings have been reported with use of two-dimensional echocardiography (10–14). In addition, unexpected deterioration was also seen in the inferior left ventricular segments. A similar observation was reported by other investigators (11,15,16). Dorrey et al. (16) also demonstrated that the abnormalities in inferior wall motion during transient left anterior descending artery occlusion could be prevented by nitroglycerin administration. In some of our patients, the left anterior descending artery crossed the apex and undoubtedly perfused at least part of the distal inferior wall. However, the deterioration in the inferior segments occurred universally, suggesting that additional mechanisms are operative. One of these may be the tethering effect of ischemic myocardium on the adjacent, normally perfused myocardium, a phenomenon well described in the experimental laboratory (30,31). An additional reason may be the three-dimensional geometry of the left ventricle.

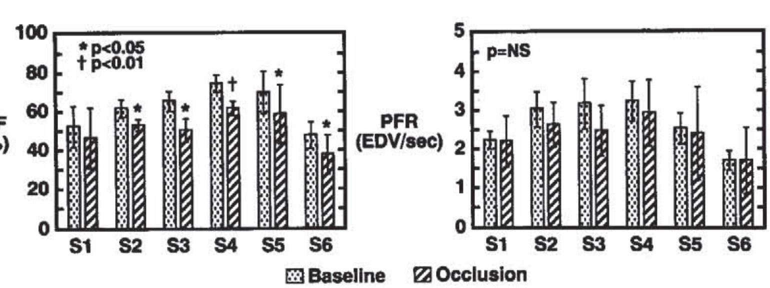

Figure 5. Regional changes in left ventricular function during diagonal artery occlusion. Changes in ejection fraction in segments 2 to 6 were significant. Changes in diastolic function were not significant. Abbreviations as in Figure 2.

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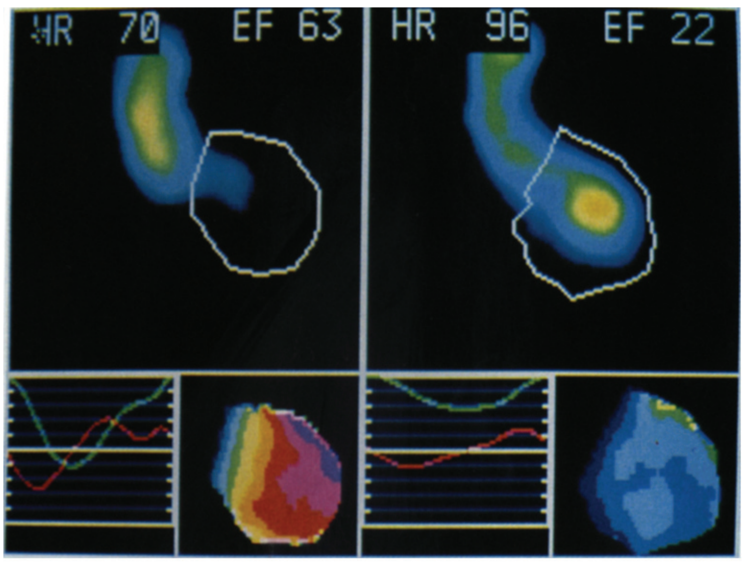

Figure 6. Patient 19. End-systolic frame superimposed on the end-diastolic silhouette (**outer white ring**) at baseline (**left**) and during 30-s proximal left anterior descending coronary artery occlusion (**right**). Normal wall motion is present at baseline study. The apparent cavity obliteration is due to the threshold chosen for the display. Left ventricular ejection fraction (EF) decreased from 63% to 22%. Regional ejection fraction image (**bottom right**) shows diffuse left ventricular deterioration. HR = heart rate.

Segmental ejection fraction is in part dependent on left ventricular edge motion, but because each myocardial segment is a three-dimensional contractile unit resembling a cone with its base at the left ventricular borders and its apex in the center of the left ventricular cavity, disturbances of contractile function involving the central regions of the left ventricular cavity, such as those that probably occur during left anterior descending artery occlusion, may affect segmental ejection fraction of any left ventricular segment. Furthermore, any segment depicted in the anterior view, although apparently assuming a bidimensional configuration, is in reality a three-dimensional composite of the anterior and posterior ventricular segments. In our study, the reduction in regional ventricular function could be best appreciated by inspecting the regional ejection fraction images, where deterioration of the central and peripheral left ventricular regions was readily seen.

Transient occlusion of the left anterior descending artery in its mid portion as a rule also caused marked abnormalities in left ventricular global and regional ejection fraction, although these were of a lesser magnitude than those occurring after occlusion of the proximal artery. There was, however, substantial variability and in a few cases the changes in left ventricular function were greater during occlusion of the mid than of the proximal portion of the artery. These data are in keeping with our previous observations (7) of wide variability of perfusion defect size during thallium-201 tomography in patients with proximal or mid left anterior descending artery stenosis of comparable angiographic severity.

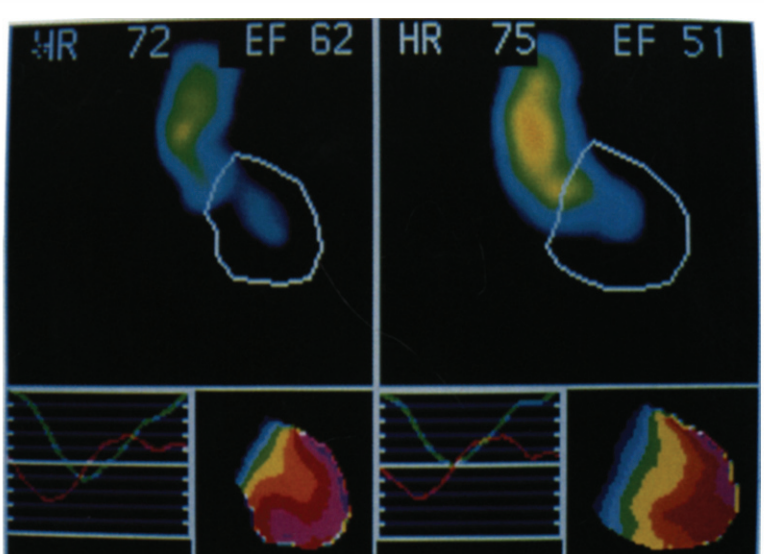

Figure 7. Patient 8. Proximal right coronary artery occlusion. Left ventricular ejection fraction (EF) and wall motion are normal (62%) at baseline study (**left**). During occlusion (**right**), a modest decrease in ejection fraction (51%) is seen. Regional ejection fraction image (**bottom right**) shows a decrease in inferior segment ejection fraction. HR = heart rate.

Table 5. Intra- and Interobserver Correlation for Left Ventricular Ejection Fraction, Peak Ejection Rate and Peak Filling Rate

	r Value	Slope	y Int	SEE	No.
Intraobserver					
Ejection fraction	0.997	1.00	−0.28	1.07	63
Peak ejection fraction	0.994	1.00	0.005	0.07	63
Peak filling rate	0.990	1.02	−0.4	0.10	63
Interobserver					
Ejection fraction	0.994	1.00	−0.32	1.52	93
Peak ejection fraction	0.992	1.01	−0.04	0.09	93
Peak filling rate	0.984	1.01	−0.04	0.12	93

y Int = y intercept.

Changes in left ventricular function during occlusion of the right, circumflex and diagonal coronary arteries. Our finding of only mild or moderate deterioration in global left ventricular function after occlusion of these coronary arteries is in agreement with the mild reduction in global ejection fraction experienced by patients with myocardial infarction due to right coronary artery or circumflex artery occlusion. In contrast, severe deterioration of global left ventricular ejection fraction is the rule during anterior myocardial infarction (8,32–34). The minimal functional repercussion of the right coronary and circumflex stenoses may explain the excellent prognosis of these lesions (35). However, the observation of only mild deterioration in segmental left ventricular function during occlusion of these arteries was somewhat perplexing. Several explanations may be entertained. The right coronary artery is considered to be subjected to less potent intramural compression forces because of its location over the low pressure right cardiac chambers during most of its course, a factor that may facilitate acute coronary collateral flow recruitment. In addition, the inferior left ventricular wall often receives a double (or even triple) coronary supply, especially from the circumflex posterolateral branches and distal left anterior descending artery, in addition to the right coronary artery.

During circumflex artery occlusion, the left ventricular posterolateral segments would be preferentially affected. Because our radionuclide studies were obtained in the anterior projection only, these posteriorly located segments could not be optimally assessed. However, some deterioration of the anterobasal segment was seen, probably as the result of anterior/posterior overlap. Although we only studied three instances of diagonal artery occlusion, there was a trend toward greater deterioration of global and segmental left ventricular function during occlusion of these arteries in comparison with right coronary artery or circumflex artery occlusion.

Factors associated with ventricular dysfunction during coronary occlusion. Several factors in addition to the site of occlusion may be related to the magnitude of left ventricular dysfunction after acute coronary occlusion. One of these is the duration of symptoms; a longer duration suggests a more gradual progression of stenosis and may cause less dysfunction as a result of collateral vessel formation. In our study, we could not demonstrate such an effect of symptom duration, perhaps because most of our patients had angina of recent onset. Another factor may be the severity of coronary stenosis. Very severe stenosis is often accompanied by collateral circulation, and thus less depression of left ventricular function during abrupt flow interruption, whereas less severe stenosis is usually not associated with collateral circulation and hence severe deterioration occurs when the artery is abruptly occluded. In the present series in which severity of stenosis was fairly uniform (mean 83% ± 8%), we could not demonstrate such a mitigating effect of severity of stenosis on left ventricular dysfunction during abrupt coronary occlusion. Similarly, collateral circulation to the arteries undergoing angioplasty—as visualized on the coronary cineangiograms, an admittedly suboptimal reference standard—was poor or absent in the majority of our patients, none of whom had a complete coronary occlusion. Only four of our patients had collateral vessels that were considered qualitatively good (grade II or III), whereas seven patients had poor collateral vessels (grade I). Nevertheless, patients with collateral vessels had less deterioration of left ventricular ejection fraction during coronary occlusion in comparison with patients without collateral vessels. Although left anterior descending artery stenosis was more frequent in patients without than in those with collateral vessels (36% vs. 54%), the difference was not statistically significant.

Limitations of the study. Theoretically, one might argue that because our left ventricular data were acquired at approximately 40 to 45 s after inflation of the balloon catheter (if one assumes a 10-s transit time from the venous injection site to the left ventricle), we may not have observed the greatest possible deterioration of left ventricular function, which might have occurred later with a longer period of coronary occlusion. However, several studies (14,27) during coronary angioplasty in humans have demonstrated that the loss of myocardial contractile function begins within a few seconds of coronary occlusion, is already profound by 30 s and is maximal within 30 to 50 s. In any case, because all of our studies were performed at similar times after balloon inflation, the time to maximal contractile abnormalities is probably not a significant factor with respect to the importance of the site of coronary occlusion.

Clinical implications. Our data support the pivotal role of the left anterior descending artery for maintaining the integrity of left ventricular function. These data also suggest a much smaller and variable contribution of the right coronary and left circumflex arteries to global left ventricular function. These data are in agreement with our previous observation (7) of a much larger extent of perfusion abnormalities by exercise thallium-201 tomography in patients with left anterior descending stenosis than in those with right coronary artery or circumflex artery stenosis.

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