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Digital Angiography in Assessment of Ventricular Function And Wall Motion During Pacing in Patients With Coronary Artery Disease

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Using digital subtraction angiography, left ventriculograms were obtained with 10 ml of iodinated contrast material in 21 patients both at rest and during atrial pacing. In 15 patients with significant coronary artery lesions (CAD) ($>$50% diameter narrowing in at least 1 major artery), ejection fraction decreased during atrial pacing from a mean of $62 \pm 14\%$ to $51 \pm 15\%$ (p $<$0.001). In 14 (93%) of 15 patients, ejection fraction decreased or was unchanged during pacing. In 6 patients with chest pain but normal coronary arteries, ejection fraction increased from a mean of $66 \pm 9\%$ at rest to $72 \pm 6\%$ during atrial pacing (p $<$0.01). Ejection fraction increased by $\geq$5% during pacing in 5 of 6 patients with normal coronary arteries. Patients with CAD also had an abnormal response in end-systolic volume during atrial pacing (50 ± 31 ml at rest versus 47 ± 24 ml during pacing) compared with patients with normal coronary arteries (46 ± 16 ml at rest versus 26 ± 9 ml during pacing; p $<$0.01). The digital ventriculograms demonstrated new or increased wall motion abnormalities during atrial pacing in 4 of 5 patients with CAD who had wall motion abnormalities at rest and in 8 of 10 patients with CAD who had normal wall motion at rest. Moreover, these wall motion abnormalities occurred in myocardial wall segments that were supplied by coronary arteries with significant lesions.

Thus, because digital subtraction angiography allows multiple left ventriculograms to be obtained during routine cardiac catheterization, intervention studies such as atrial pacing can be used to obtain a functional assessment of the severity of coronary arterial lesions.

Digital subtraction angiography enhances standard angiographic images by processing the radiographic images through a high-speed digital computer. The enhancement is such that adequate visualization of major arterial systems can be obtained with low concentrations of iodinated contrast material.[1] Because lower concentration provides adequate visualization, standard doses (30 to 40 ml) of contrast material can be injected intravenously, which is different from tradi-

tional angiography in which the same amount of contrast material must be injected directly into the arterial circulation. Several investigators have reported their results with digital angiographic imaging of carotid, renal, and other peripheral arteries,[2-5] whereas others have actively been employing this technology in cardiac imaging.[6-9] We recently reported our results comparing digital first-pass left ventriculograms obtained after intravenous administration of 30 to 40 ml of contrast material with standard left ventriculograms obtained during cardiac catheterization with intraventricular injection of the same amount of contrast material.[10] There were close correlations between the 2 techniques for ventricular volume and ejection fraction.

Another potential application of this technology is to use the digital subtraction technique to process images so that less contrast material is needed for each intraventricular injection during routine cardiac catheterization. For example, it is possible to use digital

angiography to obtain left ventriculograms with one fourth the usual amount of contrast material. Therefore, 4 times as many digital left ventriculograms can be performed compared with standard cineangiograms without increasing either the total amount of contrast material or the radiation exposure to the patient.[6] This capability of obtaining additional left ventriculograms might permit the angiographer to assess the functional capacity of myocardial segments supplied from specific coronary arteries by performing ventriculography before and after a stressful intervention during routine cardiac catheterization.

This study assesses whether small-dose left ventriculograms obtained with digital angiography at the time of routine cardiac catheterization could be used before and during atrial pacing to determine the functional significance of coronary artery disease (CAD) as defined by changes in ejection fraction and the development of wall motion abnormalities.

Methods

Digital angiographic technique: Digital angiography was performed using the method of mask mode subtraction.[11,12] This technique involved the acquisition of fluoroscopic images of the heart before and during contrast injection. Each 1/30 second fluoroscopic image was digitized by an image processing computer (Cardiac 1000, American Edwards Laboratories, Irvine, California) into a 512 by 512 by 8 bit matrix. Each picture element (pixel) in the matrix was capable of differentiating 256 shades of gray. Because the memory of the image processing computer was large enough to allow computer storage of a 512 by 512 by 12 bit matrix, 16 frames of the 512 by 512 by 8 bit images were summated and stored in memory for the mask. This mask image contained data about the soft tissues and bone structures of the chest. After the mask was obtained, each new 1/30 second video fluoroscopic image was digitized and the stored mask was subtracted from it in real time. If perfect subtraction occurred, the resultant image signals would cancel out and not reveal any soft tissue or bone structures. If iodinated contrast media were injected after the mask was obtained and during fluoroscopy, the soft tissues and bones would be subtracted but the iodine signal would be maintained so that low concentrations of contrast material in the heart could be visualized more clearly.

Our catheterization laboratory is equipped with a Siemens Cardioskop U-arm x-ray unit. Images were focused on a 7-inch cesium iodide image intensifier and the images were converted into an electrical signal by a Plumbicon television camera. The video output signal from the television camera was connected to the image processing computer where it was logarithmically amplified before computer digitization. The subtracted images were processed in real time and displayed on television monitors in the catheterization laboratory. For this study, the fluoroscopic exposure level was set at 8 mA and 70 to 90 kVp depending on the size of the subject. The 8 mA setting is 2 to 3 times the electrical current typically used in fluoroscopy. A 5-mm thick aluminum filter was used to eliminate low-energy radiation. The measured incident exposure rate on the image intensifier was 2 to 17 μR/frame depending on the kVp. After mask mode subtraction processing, the images were reconverted to analog format for storage on videotape (Sony Betamax, model SL0323MD, 1/2-inch recorder) (Fig. 1). After the study, analog images could be replayed through the computer and the image redigitized. This postprocessing of the images permitted manipulation of the contrast and gray scale levels through the computer to enhance visualization and boundary detection. The computer contained software programs to calculate left ventricular volume and ejection fraction using the area-length method.[13] A more comprehensive description of our imaging system is presented in a previous report.[10]

Clinical studies: Patients undergoing left ventriculography during routine cardiac catheterization for clinically indicated reasons were asked to participate in this study. Patients with left main coronary artery obstruction and those with unstable angina were excluded from the study. Informed consent was obtained for each patient who agreed to participate. Drugs such as long-acting nitrates and beta-adrenergic antagonists were withheld for 24 hours before the study. Twenty-one patients (14 men and 7 women) who had a clinical history of chest pain were evaluated by atrial pacing. The mean age was 54.3 years (range 38 to 70) and the mean weight was 82.4 kg (range 54.5 to 120.5). Fifteen patients had at least 1 anatomically significant coronary artery lesion. Significant coronary artery stenosis was defined as $\geq$50% diameter narrowing of the coronary artery in at least 1 projection. Two or more projections were obtained for each coronary artery in standard and caudocranial views. At least 2 of these projections were orthogonal. The lesions were as follows: 9 in the left anterior descending artery, 8 in the circumflex system, and 11 in the right coronary artery. Six patients had normal coronary arteries as defined by <25% diameter narrowing of all coronary branches. Percent coronary artery stenoses in each patient are presented in Table I.

After coronary angiography was completed, a 7-French Cordis pigtail catheter was passed retrograde across the aortic valve into the left ventricle. A digital left ventriculogram was taken at rest in the 30° right anterior oblique position by injecting 10 ml of Vascoray® or Hypaque® 75 at a rate of 5 ml/s. A 6-French Cordis bipolar temporary pacemaker wire was passed from the right femoral vein under fluoroscopic control and placed against the lateral border of the right atrium. The pacemaker wire was connected to a Medtronic external pulse generator (model 5375). The right atrium was stimulated at

FIGURE 1. End-diastolic (**A**) and end-systolic (**B**) images obtained by injecting 10 ml of contrast material over 2 seconds into the left ventricle. The video signals are processed in real time by the method of mask mode subtraction. Images are recorded on videotape and displayed in real time on a television monitor.
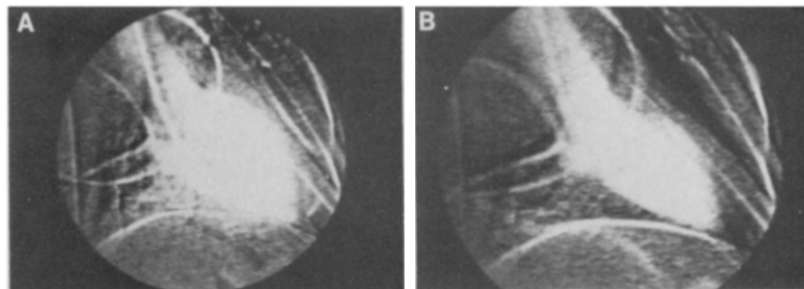
REAL TIME SUBTRACTION

TABLE I   Effect of Atrial Pacing on Ejection Fraction, Wall Motion, and Left Ventricular End-Diastolic Pressure (LVEDP)

| Pt | Diameter Stenosis (%) | | | | Abnormal ECG During Pacing | Chest Pain During Pacing | Wall Motion | | Heart Rate (beats/min) | | Ejection Fraction (%) | | LVEDP | | |
	LAD	CX	RCA	Diag			Rest	Paced					Baseline (mm Hg)	Resting 10 ml Dig Angio (mm Hg)	Paced 10 ml Dig Angio (mm Hg)
Abnormal Coronary Arteries															
1	80						N	Ant Hypo	83	140	0.80	0.70	11	12	
2	60	100	50			+	N	Ant-Inf Hypo	62	110	0.66	0.46	18	16	
3	85	85	95	50		+	Anti-Api Ak	Anti-Api Ak	62	110	0.32	0.31	40	41	40
4	60	50		100	+	+	N	N	58	110	0.66	0.71	8	9	10
5	50	65	95			+	Inf Ak	Inf Ak	60	120	0.43	0.31	14	16	20
6	25	60	25		+		N	N	50	108	0.82	0.70	19	16	18
7	50		100	60		+	Inf Hypo	Inf Ak, Ant Hypo	73	135	0.57	0.27	17	20	20
8	90	75	65	55			N	Ant-Api Hypo	54	110	0.63	0.44	16	16	32
9	70		100	50			N	Ant Hypo	50	120	0.76	0.61			
10			70		+		Inf Hypo	Inf Dys	68	140	0.53	0.44	22	22	22
11			65			+	Inf-Bas Hypo	Inf Dys	72	146	0.47	0.44	20	20	24
12		40	100	35	+		N	Inf Hypo	85	110	0.56	0.53	10	10	15
13	40	80		65			N	Api Ak	78	150	0.60	0.53	24	24	24
14			95				N	Inf Hypo	62	130	0.79	0.71	16	16	24
15	75	60	70			+	N	Ant-Bas Hypo; Inf Hypo	68	120	0.72	0.45	14	15	15
Mean									65.7	123.9	0.62	0.51	17.8	18.1	22.0
± SD									±11.0	±14.9	±0.14	±0.15	±7.8	±7.8	±8.0
Normal Coronary Arteries															
16							N	N	74	140	0.60	0.66	18	19	22
17							N	N	90	150	0.80	0.75	20	20	20
18							N	N	68	135	0.63	0.72	21	21	23
19						+	N	N	74	120	0.62	0.72	16	16	22
20							N	N	55	140	0.61	0.66	13	13	15
21						+	N	N	66	110	0.74	0.80	16	18	
Mean									71.2	132.5	0.66	0.72	17.3	17.8	20.4
± SD									±11.6	±14.8	±0.08	±0.06	±2.9	±2.9	±3.2

AK = akinesia; Ant = anterior; Api = Apical; Bas = basal; Cx = circumflex; Diag = diagnosis; Dig Angio = digital angiogram; Dys = dyskinesia; ECG = electrocardiogram; Hypo = hypokinesis; Inf = inferior; LAD = left anterior descending; n = normal; RCA = right coronary artery.

2 mA, initially at a rate of 20 beats/min above the patient's resting heart rate. The rate was increased in increments of 10 beats/min every minute until the patient experienced chest pain or until 85% of the maximal predicted heart rate was reached. If atrioventricular Wenckebach heart block developed, 1 mg atropine was administered intravenously and the pacing study was continued. When the end-point heart rate was achieved, another 10 ml digital left ventriculogram was performed. The pacemaker was then turned off. To correct for magnification, an 8 by 8 cm grid was placed on the x-ray table after the study was performed at a height corresponding to one half the patient's anteroposterior thoracic dimension. The image intensifier and x-ray tube were adjusted to the position used in the study and the grid was fluoroscopically imaged and recorded on videotape for subsequent analysis of ventriculograms.

Left ventricular pressure was recorded through the fluid-filled 7-French pigtail catheter using a Statham P23ID transducer. Left ventricular end-diastolic pressure was measured from the pressure tracing as the point after the "a" wave where the rapid upstroke of the left ventricular pressure curve began. Pressure was recorded before the digital angiography studies, after the initial resting 10-ml digital study, and then after the 10-ml digital study obtained during atrial pacing. In the latter 2 situations, left ventricular pressure was recorded within 3 minutes after the contrast material was injected. The mean end-diastolic pressure at rest and after the

FIGURE 2. Comparison of left ventricular end-diastolic volume obtained with 10 ml digital subtraction angiography before and after atrial pacing. The patients were divided after coronary angiography into those with significant coronary artery disease (≥50% diameter narrowing) and those with normal coronary arteries.

baseline 10-ml digital study was compared using Student's t test.

Electrocardiographic (ECG) monitoring was performed at rest and during atrial pacing using leads II and V_6. Acute ischemic changes were interpreted as 1 mm horizontal S-T depression persisting 0.08 second after the J point.
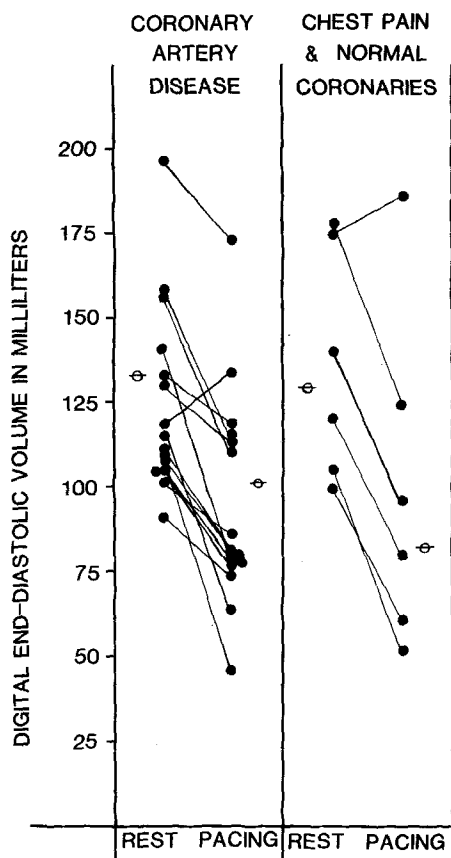
Analysis: The rest and pacing images recorded on videotape were reviewed and the heart beats in which the greatest concentration of dye was seen in the left ventricle were chosen for analysis. Images from these cardiac cycles were redigitized by the computer system so that the boundary of the left ventricle could be electronically traced directly on the video image. An end-diastolic frame was chosen by identifying the image with the largest iodinated area and the end-systolic frame was identified as the image with the smallest contrast-filled area. End-diastolic and end-systolic volumes at rest and during atrial pacing were calculated by the computer using the area-length method corrected for magnification by the grid.[13,14] Ejection fractions were computed from the volume calculations. Statistical analysis was performed with Student's t test for paired data comparing end-diastolic volumes, end-systolic volumes, and ejection fractions at rest with those obtained during atrial pacing.

Coronary arteriograms were reviewed for the presence and significance of atherosclerotic lesions. Lesions were defined as anatomically significant when the diameter at the stenosis was measured by calipers to be >50% narrowed compared with the arterial segment proximal to the lesion. A panel of 3 cardiologists reviewed all the coronary angiograms. Wall motion abnormalities at rest or induced by atrial pacing were qualitatively assessed. Digital ventriculograms were interpreted by 1 member of the panel and reviewed by the other 2 members. The panel was not specifically blinded to the results of the coronary angiograms. However, in over 75% of the cases, wall motion analysis was made without knowledge of the coronary angiogram interpretation. Regions of normal and abnormal wall motion seen on digital ventriculograms were related to the presence or absence of anatomically significant coronary artery narrowing in the artery supplying those myocardial regions. Arterial lesions were defined as functionally significant if rest- or pacing-induced wall motion abnormalities were appreciated.

Results

Patient characteristics: Table I summarizes our patient data and includes the heart rate and ejection fraction data at rest and during atrial pacing in 21 patients. Twelve of the 15 patients with CAD had New York Heart Association class III or IV symptoms of angina. However, all patients were free of pain ≥24 hours before catheterization. The mean heart rate at rest was 66 ± 11 beats/min in patients with CAD and 71 ± 12 in those with normal coronary arteries (p = NS (not significant)). The mean heart rate achieved during atrial pacing was 124 ± 15 beats/min (range 108 to 150) in the group with CAD. Patients with normal coronary arteries were paced to a mean rate of 132 ± 15 beats/min (range 120 to 150) (p >0.2 compared with the paced heart rate achieved in patients with CAD). In 1 patient with CAD a complication developed during electrical stress testing. This patient had transient (6 seconds) complete heart block but suffered no sequelae.

Hemodynamic effects: The mean resting left ventricular end-diastolic pressure was 18 ± 8 mm Hg in patients with CAD and the left ventricular end-diastolic pressure was 17 ± 3 mm Hg in those with normal coro-

nary arteries (p = NS). After the baseline 10-ml digital left ventriculogram, no significant change was noted in left ventricular end-diastolic pressure which was 18 ± 8 mm Hg in patients with CAD and 18 ± 3 mm Hg in those with normal coronary arteries.

Angiographic results: Figure 2 demonstrates end-diastolic volumes before and during pacing in 15 patients with CAD and in 6 patients with chest pain but normal coronary arteries. Left ventricular end-diastolic volume decreased during atrial pacing in 14 of 15 patients with CAD. Mean end-diastolic volume was 125 ± 28 ml at rest and decreased to a mean volume of 95 ± 35 ml (p <0.001) during pacing. In the 6 patients with normal coronary arteries, end-diastolic volume decreased from a mean of 137 ± 34 ml at rest to a mean of 99 ± 49 ml (p <0.02) during atrial pacing. There was no significant difference between mean end-diastolic volumes at rest or during pacing between the 2 groups. Also, there was no significant difference in the percent change in mean end-diastolic volume from rest to pacing between the 2 groups.

Left ventricular end-systolic volume decreased during atrial pacing in all 6 subjects with normal coronary arteries (Fig. 3), whereas end-systolic volume decreased in only 8 of 15 patients with CAD. In patients with CAD, mean end-systolic volume was 50 ± 31 ml at rest and 47

± 24 ml during atrial pacing (p >0.2 compared with that at rest). In patients with normal coronary arteriograms, the mean resting end-systolic volume was 46 ± 16 ml, and decreased during atrial pacing to a mean end-systolic volume of 26 ± 9 ml (p <0.01 compared with that at rest). Although end-systolic volumes at rest were similar in the 2 patient groups, the decrease in end-systolic volume was significantly greater in patients with normal coronary arteries compared with those with CAD (p <0.05).

Ejection fraction data in the 2 groups of patients are shown in Figure 4. In the 15 patients with CAD, mean ejection fraction at rest was 62 ± 14 and decreased an average of 11 percentage points to 51 ± 15 during atrial pacing (p <0.001). Ejection fraction decreased or was unchanged in 14 of the 15 patients. In the 6 patients with chest pain but normal coronary arteries, resting ejection fraction was 66 ± 9% (no significant difference compared with that of the group with CAD) and increased during pacing to 72 ± 6 (p <0.01 compared with that in patients with CAD). During atrial pacing, the ejection fraction increased by at least 5 percentage points in 5 (83%) subjects and decreased in 1 subject.
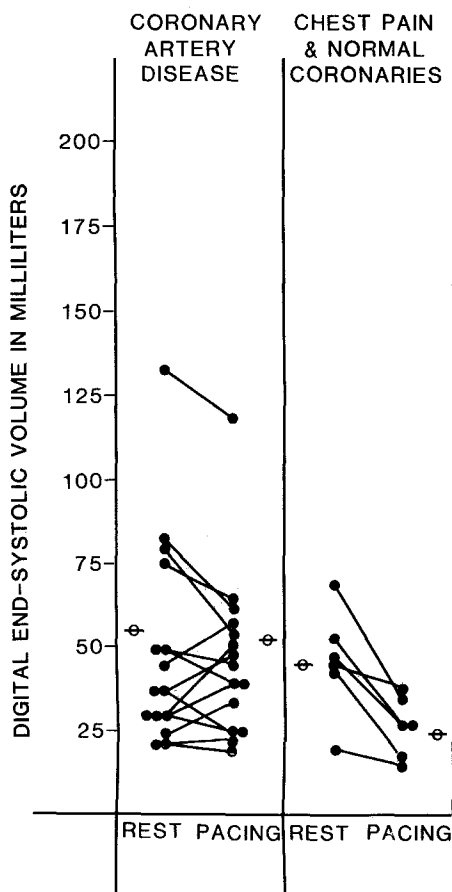
FIGURE 3. Comparison of left ventricular end-systolic volumes obtained with 10 ml digital subtraction angiography before and after atrial pacing.
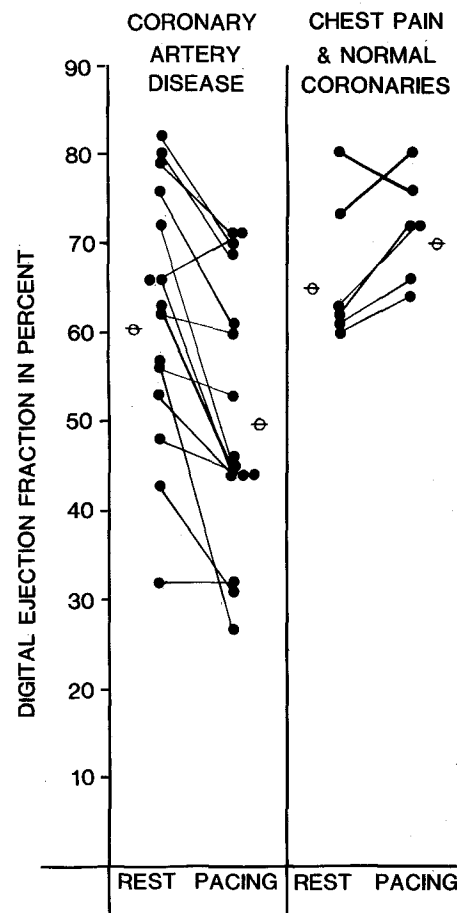
FIGURE 4. Comparison of left ventricular ejection fractions obtained with 10 ml digital subtraction angiography before and after atrial pacing. Fourteen of 15 patients with coronary artery disease had a decrease or no change in ejection fraction, compared with 5 of 6 patients with normal coronary arteries who had an increase in ejection fraction.

Wall motion abnormalities: The resting digital angiograms demonstrated wall motion abnormalities in all 5 patients who had dysfunctional contraction patterns visualized on standard cineangiogram. The areas of abnormal wall motion at rest and after pacing are listed in Table I.

Four patients had inferior wall dysfunction at rest and each of these patients had severe right coronary artery obstruction. During atrial pacing, more extensive impairment of inferior wall motion developed in these 4 patients and dyskinesia of the inferior wall developed in 2. One patient had extensive anteroapical akinesia at rest with an ejection fraction of 32%. He developed chest pain at a paced heart rate of 110 beats/min but did not develop new areas of wall motion dysfunction despite the presence of significant disease in 4 vessels. In the 10 patients with CAD who had normal wall motion at rest, 8 patients developed new areas of abnormal contraction in muscle segments that were supplied by coronary arteries with significant anatomic obstruction. In 4 of these 8 patients, the new area of wall motion abnormality was located in the anterior wall and was associated with significant obstruction in the proximal left anterior descending coronary artery. In 2 of the 8 patients, the new area of wall motion abnormality was located in the inferior wall and was associated with significant obstruction in the right coronary artery. In 2 patients abnormal wall motion developed in both the anterior and inferior walls corresponding to significant disease in both the left anterior descending and right coronary arteries.

One patient (Patient 6 in Table I) with normal wall motion at rest had a decrease in ejection fraction of 12 percentage points, but no segmental wall motion abnormality was visualized in the right anterior oblique projection. The only significant anatomic obstruction in the patient was in the circumflex artery. One patient with significant 3-vessel disease (Patient 4 in Table I) had an increase in ejection fraction of 5 percentage points during atrial pacing with normal wall motion during both studies. In this patient chest pain developed at a paced rate of 110 beats/min and the digital ventriculogram was taken within 30 seconds of the onset of chest pain.

Discussion

It is well described that coronary angiography may underestimate the extent of coronary artery narrowing or even completely miss significant lesions due to overlapping or foreshortening of vessels.[15-17] Special angulated views help to reduce this problem.[18-20] However, it is not unusual for angiographers to disagree as to the severity of a coronary lesion on the basis of visual inspection of the angiograms.[21] A functional assessment of the hemodynamic effects of a specific lesion would be useful in that it might aid in evaluating the severity of that lesion.

One way to assess clinically the presence of myocardial ischemia is to measure ejection fraction during stress intervention such as exercise.[22] Borer et al[23] found that a decrease in ejection fraction measured by radionuclide angiography during supine bicycle exercise was more sensitive and specific than ischemic electrocardiographic changes detected during standard treadmill stress testing. Moreover, they demonstrated that wall motion abnormalities could be detected on radionuclide angiograms when myocardial ischemia developed. However, it is sometimes difficult to relate wall motion abnormalities visualized by radionuclide angiography to specific coronary artery lesions because they frequently are obtained from different views with markedly different image resolution and at different times. Previous reports have shown that atrial pacing can be used to induce angina or ischemic electrocardiographic changes when the same pressure-rate product is achieved compared with exercise stress tests.[24-26]

In the present study, we used digital angiography and atrial pacing to assess ventricular volume, global ejection fraction, and segmental wall motion in the catheterization laboratory at the same time and in the same view that 1 of our coronary arteriograms was taken. A dose of 10 ml of contrast material and high fluoroscopic exposure levels were used which made it possible to obtain multiple ventriculograms without deleterious hemodynamic effects from excessive amounts of contrast material.[27] We did not attempt to evaluate ventricular function in patients with intermediate (25 to 50%) diameter narrowing of the cornary arteries because we wanted a comparison in lesions in which the anatomic severity is accepted as being hemodynamically significant. Therefore, only patients with moderate or severe coronary artery stenosis, (that is, >50% diameter narrowing) were included in the CAD group.

In response to atrial pacing, ejection fraction decreased or did not change in 14 of 15 (93%) patients with anatomically significant coronary artery lesions, whereas 5 of 6 (83%) patients with normal coronary arteries had an increase in ejection fraction of at least 5 percentage points. Moreover, digital angiograms revealed the development of new or the exacerbation of existing wall motion abnormalities during atrial pacing in all but 2 patients with significant CAD who had either no change or a decrease in ejection fraction. The wall motion abnormalities corresponded to ventricular muscle segments that were perfused by significantly narrowed coronary arteries. Of the 2 patients who had no change or a decrease in the ejection fraction without developing a new segmental wall motion abnormality in the right anterior oblique projection, 1 had significant stenosis of the circumflex artery. Because we did not obtain ventriculograms in the left anterior oblique projection during atrial pacing, we could not assess lesions affecting primarily the lateral wall of the left ventricle. The patient with CAD who had no change in ejection fraction during pacing (Patient 3) had a low ejection fraction at rest with diffuse anteroapical akinesis. In this patient chest pain developed at a heart rate of 110 beats/min. There also was 1 other patient who had significant 3-vessel disease in whom an increase in ejection fraction and no wall motion abnormality developed during atrial pacing. Chest pain developed in this patient at a relatively low pacing rate of 110 beats/min and the digital ventriculogram was taken within 30 seconds of the onset of chest pain. Occasionally during atrial pacing it is difficult to determine if the patient is subjectively experiencing angina or just dis-

comfort from the unusual sensation of induced tachycardia. In the previous 2 patients, a positive response might well have been achieved if atrial pacing had been continued for a longer period after the onset of chest pain.

Although these results suggest that patients with significant CAD can be identified by atrial pacing studies, we must be cautious in this analysis because inadequate visualization of ventricular walls and submaximal stress may produce a negative result. In addition, other conditions besides CAD can produce wall motion abnormalities and a decrease in ejection fraction during stress, such as cardiomyopathy and valvular heart disease.[28] Also, this study has a bias in its patient selection in that patients were excluded if they had left main artery disease, unstable angina, valvular heart disease, or cardiomyopathy with normal coronary arteries. However, the patients that were entered into the study represent the typical distribution for our hospital population of patients with symptoms of ischemic heart disease.

There was so significant difference at rest in regard to end-diastolic or end-systolic volume between patients with CAD and those with chest pain but normal coronary angiograms. During atrial pacing, 19 of the 21 patients had a decrease in end-diastolic volume. This finding is consistent with other studies which show that atrial pacing decreases the end-diastolic volume.[29] However, the effect of atrial pacing on end-systolic volume was distinctly different between our 2 groups. In the 6 patients with normal coronary arteries, the end-systolic volume decreased a mean of 20 ml (43%) from the resting value (p <0.01), whereas in the 15 patients with CAD the mean end-systolic volume did not change significantly during atrial pacing. Therefore, the decrease in ejection fraction seen in patients with CAD was primarily due to the fact that the left ventricle could not contract down to a smaller end-systolic volume when ischemia developed during atrial pacing. Thus, the inability of the myocardium to contract during ischemia is apparently reflected in alterations of end-systolic volume during the stress of increased heart rate, whereas the end-diastolic volume continues to reflect changes in heart rate and ventricular filling despite the presence of ischemia. The implication is that ventricular function can be assessed not only by the response of global ejection fraction to stress but also by the change in end-systolic volume during pacing. These relations are summarized in Figure 5 in which the percent changes in left ventricular volumes and ejection fraction between rest and pacing are plotted for the 2 groups of patients with or without CAD. As can be seen, ejection fraction and, to a lesser degree, end-systolic volume changes during tachycardia induced by atrial pacing
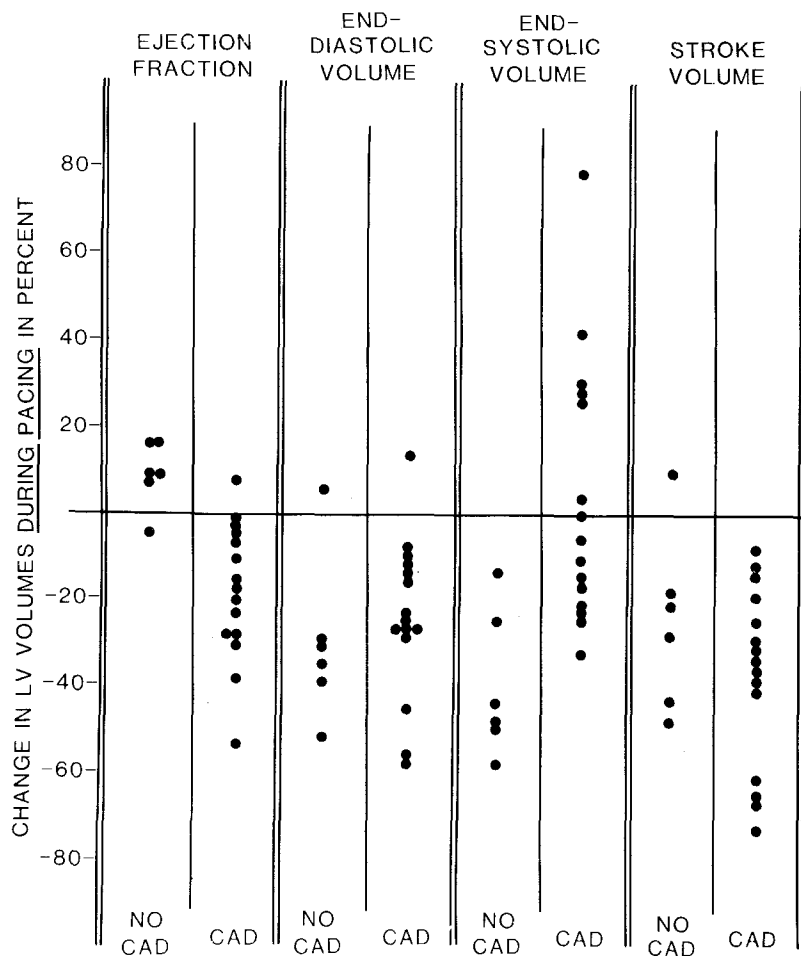
FIGURE 5. The percent change in left ventricular volume and ejection fraction during atrial pacing compared with rest is plotted for the patients with coronary artery disease (CAD) versus those with normal coronary arteries (NO CAD). Both the ejection fraction response and the percent change in end-systolic volume tended to discriminate between patients with normal coronary arteries and those with CAD.

were good discriminators of normal patients versus those with CAD.

Atrial pacing precipitated chest pain in 10 patients including 2 with normal coronary arteriograms. In none of the 6 patients with normal coronary arteries did ischemic ECG changes develop during pacing, whereas in only 3 of the 15 (20%) patients with CAD did ischemic ECG abnormalities develop (Table I). One explanation for the low sensitivity of the ECG response in our patients may be that only 2 ECG leads were used. Moreover, our patients achieved a relatively low level of maximal heart rate during atrial pacing. The low maximal heart rate was a result of our decision to stop increasing the atrial pacing rate and immediately perform digital angiography if the patient had chest pain. The fact that the ejection fraction decreased in 14 of the 15 (93%) patients with CAD whereas only 3 of the 15 (20%) had ischemic ECG changes and 8 of the 15 (53%) developed chest pain suggests that ischemia induced by atrial pacing is initially manifested as an abnormality of muscle contraction before either ECG alterations or the subjective sensation of chest pain. Upton et al[30] found similar results concerning the higher sensitivity of wall motion analysis as compared with the development of angina or S-T segment depression in patients undergoing bicycle exercise during radionuclide imaging. Their results for end-diastolic and end-systolic volume differ from ours probably because they used upright exercise whereas we used supine atrial pacing.

In summary, digital subtraction angiography permits multiple left ventriculograms to be taken during cardiac catheterization without increasing the amount of contrast or x-ray exposure to the patient and with less alteration in hemodynamics than with the traditional cineangiographic mode. Thus, functional evaluation of coronary artery stenosis is facilitated by permitting assessment of ventricular volumes, ejection fraction, and wall motion at rest and after an intervention such as atrial pacing. Similarly, it should be possible to study pharmacologic interventions or exercise stress with digital angiography in order to assess the functional significance of coronary lesions. This information could be useful in evaluating a patient with suspected or known CAD and in assessing functional improvement after coronary bypass graft surgery.

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